Motion Detection: Neuronal Circuit Meets Theory

Keisuke Yonehara[1] and Botond Roska[1,*]
[1]Neural Circuit Laboratories, Friedrich Miescher Institute for Biomedical Research, 4058 Basel, Switzerland
*Correspondence: botond.roska@fmi.ch
http://dx.doi.org/10.1016/j.cell.2013.08.027

Motion detection in fly vision has been investigated experimentally and theoretically for half of a century, yet mechanistic insights into the neuronal computation have only started to emerge. In a recent issue of *Nature*, two studies provide major insights into how motion direction is extracted from the image flow projected onto the retina.

Detecting the direction of image motion is a fundamental component of visual computation and is essential for survival. Anyone who has tried to catch a fly can testify that flies are especially talented in determining the direction of our approaching hand and choosing an escape route within a fraction of a second. In the recent issue of *Nature*, Takemura et al. (2013) and Maisak et al. (2013) report exciting new insights into the motion-detecting circuit in the *Drosophila* brain.

More than 50 years ago, Bernhard Hassenstein, a biologist, and Werner Reichardt, a physicist, proposed a simple model for fly motion detection (Figure 1A; Reichardt, 1961). The Hassenstein-Reichardt detector computes the direction of motion by correlating in time the changes in luminance across two neighboring photoreceptor units. Two key ingredients of the model are a delay element in the route originating from one of the photoreceptors and a nonlinear interaction such as multiplication of the signals arriving from the two different photoreceptors via the two ''arms'' of the model.

However, the Hassenstein-Reichardt detector is a black-box description of the input-output relationship, i.e., the computation, between the changing light pattern and the neuronal responses of the direction-selective cells. The question remains, how does the neuronal circuit in the fly visual system implement this computation?

Similar to that of vertebrates, the fly visual system is hierarchically organized. After the capture of photons by photoreceptors, the neuronal activity moves through a number of synaptic stations (Figure 1B) to the lobular plate, a central visual station that hosts the so-called lobula plate tangential cells (LPTCs). LPTCs display robust direction-selective responses (Haag and Borst, 2004; Joesch et al., 2008). Right after the photoreceptors, at the L1 and L2 cells, the visual pathway segregates into two independent channels (Rister et al., 2007), one responsible for signaling the motion of dark-to-light boundaries (ON edges, L1 cells) and the other for light-to-dark boundaries (OFF edges, L2 cells) (Clark et al., 2011; Eichner et al., 2011; Joesch et al., 2010). However, L1/L2 neurons are not direction selective. At the other end of the circuit, T4 and T5 cells provide input to LPTCs (Maisak et al., 2013). The neuronal circuit elements between L1/L2 cells and T4/T5 cells have not been well described, and the response properties of T4/T5 cells have been unknown.

Takemura et al. (2013) attacked the circuit identification problem using an anatomical approach. They developed a semiautomated pipeline using electron microscopy to reconstruct the connectome between L1/L2 cells and T4/T5 cells. They identified 379 neurons, categorized them into 56 cell types, and counted the number of synaptic contacts between them to generate a weighted view of the circuit connections. This analysis linked L1 cells to T4 cells and L2 cells to T5 cells. By focusing on the L1-T4 pathway, they identified two cell types, Mi1 and Tm3, which form the two major paths from L1 to T4 (Figure 1B). Interestingly, T4 cells had asymmetric dendritic trees and the Mi1 and the Tm3 pathways were asymmetrically distributed along the dendrites of T4, such that Tm3 cells make more synapses closer to the tip of T4 dendrites. The direction of Tm3-Mi1 displacement agrees with the predicted directional preference of most T4 cells. From these observations, the authors proposed that Mi1 and Tm3 cells constitute the two ''arms'' of a motion detector.

Takemura et al. (2013) indeed considered two different motion detector models, first the Hassenstein-Reichardt detector described above and also the Barlow-Levick detector that uses a sign inversion in the delay arm (Barlow and Levick, 1965). Due to the lack of knowledge of the sign of their circuit connections, excitatory or inhibitory, and the lack of dynamic recordings from the circuit elements, they propose different possibilities for the circuit implementation of motion detection. They argue that, if the Mi1 and Tm3 inputs were combined with the same sign, as in the Hassenstein-Reichardt detector, the Tm3 arm would introduce a longer delay than the Mi1 arm. If the inputs were combined with opposing signs, as in the Barlow-Levick detector, then the Mi1 arm would introduce a longer delay.

Maisak et al. (2013) took a different approach to advance our understanding of the computation of direction selectivity. First, they used a combination of genetic targeting and optical recordings to observe the activity of T4 and T5 cells. Note that there are four T4 and four T5

cells in each visual circuit module. Their results were remarkably clear: both T4 and T5 cells were direction selective. Each of the four T4/T5 cells preferred one specific direction: downward, upward, backward, or forward. T4 and T5 cells with the same preferred direction terminated in the same sublayer of the lobula plate, giving direction-selective inputs onto LPTC dendrites. T4 and T5 cells responded to moving ON edges and OFF edges, respectively. Second, the authors performed cell-type-specific silencing experiments, which revealed that the T4 and T5 pathways drive the ON (T4) and OFF (T5) edge motion responses of LPTCs and the turning behavior of flies.

Although these two remarkable papers do not completely elucidate the circuitry of the fly motion detector in its entirety, if the predictions of the connectome are correct, they have prepared the field for the end game: to record the activity of Mi1 and Tm3 cells for the T4 pathway and of Tm1, Tm2, and Tm4 for the T5 pathway. One would predict that these recordings would give us the key to solving this 50-year-old problem.

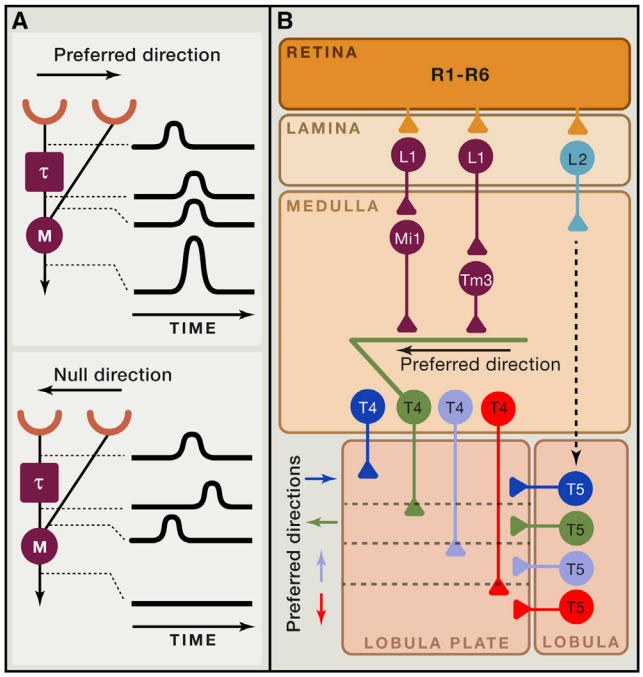

Figure 1. The Neuronal Components of a Theoretical Motion Detector Revealed

(A) Hassenstein-Reichardt detector. (Top) A light stimulus moving from left to right in the detector's preferred direction is sensed by the left photoreceptor first. Propagation of this signal is delayed by a certain period of time, τ. If the time that it takes the light stimulus to travel to the right photoreceptor and the delay time are equal, the signals from both photoreceptors simultaneously arrive at the multiplication stage (M) and yield a strong output. (Bottom) Motion in the opposite, null direction results in two signals arriving to the multiplication stage at different times. Consequently, the detector produces no output.

(B) Schematic of fly optic lobe. Visual signals from photoreceptors (R1–R6) are separated into parallel pathways at L1 and L2 cells. The two major pathways between L1 and T4 cells are Mi1 and Tm3 cells. The synapses made by Mi1 and Tm3 cells are displaced on the T4 dendrite, putatively representing the two offset inputs of a detector as depicted in (A) (Takemura et al., 2013). L1 and L2 pathways converge onto the dendrites of LPTCs via T4 and T5, respectively. T4 and T5 cells with the same directional selectivity project to the same sublayer of the lobular plate and drive motion responses and turning behavior (Maisak et al., 2013).

The importance of the study extends well beyond the fascinating field of fly vision. One of the central goals of neuroscience is to explain a neuronal computation by the connectivity and dynamics of the elements of the neuronal circuit that implements that computation and to relate the activity of a circuit to a defined behavior. Currently, the fly visual motion circuit is one of the few model systems in which this goal is realistic. These two studies have advanced us significantly in this direction, and it is likely that soon the description of the fly motion circuit will be complete and will represent one of the major triumphs of circuit neuroscience.

ACKNOWLEDGMENTS

We thank A. Wertz, S. Trenholm, and S. Oakeley for their comments on the manuscript.

REFERENCES

Barlow, H.B., and Levick, W.R. (1965). J. Physiol. *178*, 477–504.

Clark, D.A., Bursztyn, L., Horowitz, M.A., Schnitzer, M.J., and Clandinin, T.R. (2011). Neuron *70*, 1165–1177.

Eichner, H., Joesch, M., Schnell, B., Reiff, D.F., and Borst, A. (2011). Neuron *70*, 1155–1164.

Haag, J., and Borst, A. (2004). Nat. Neurosci. *7*, 628–634.

Joesch, M., Plett, J., Borst, A., and Reiff, D.F. (2008). Curr. Biol. *18*, 368–374.

Joesch, M., Schnell, B., Raghu, S.V., Reiff, D.F., and Borst, A. (2010). Nature *468*, 300–304.

Maisak, M.S., Haag, J., Ammer, G., Serbe, E., Meier, M., Leonhardt, A., Schilling, T., Bahl, A., Rubin, G.M., Nern, A., et al. (2013). Nature *500*, 212–216.

Reichardt, W. (1961). Sensory Communication, W.A. Rosenblith, ed. (New York, London: MIT Press and Wiley), pp. 303–317.

Rister, J., Pauls, D., Schnell, B., Ting, C.-Y., Lee, C.-H., Sinakevitch, I., Morante, J., Strausfeld, N.J., Ito, K., and Heisenberg, M. (2007). Neuron *56*, 155–170.

Takemura, S.Y., Bharioke, A., Lu, Z., Nern, A., Vitaladevuni, S., Rivlin, P.K., Katz, W.T., Olbris, D.J., Plaza, S.M., Winston, P., et al. (2013). Nature *500*, 175–181.