Neuron
Article

Internal Structure of the Fly Elementary Motion Detector

Hubert Eichner,[1] Maximilian Joesch,[1,2] Bettina Schnell,[1] Dierk F. Reiff,[1] and Alexander Borst[1,*]
[1]Department of Systems and Computational Neurobiology, Max-Planck-Institute of Neurobiology, 82152 Martinsried, Germany
[2]Present address: Department of Molecular and Cellular Biology, Harvard University, Cambridge, MA 02138, USA
*Correspondence: borst@neuro.mpg.de
DOI 10.1016/j.neuron.2011.03.028

SUMMARY

Recent experiments have shown that motion detection in *Drosophila* starts with splitting the visual input into two parallel channels encoding brightness increments (ON) or decrements (OFF). This suggests the existence of either two (ON-ON, OFF-OFF) or four (for all pairwise interactions) separate motion detectors. To decide between these possibilities, we stimulated flies using sequences of ON and OFF brightness pulses while recording from motion-sensitive tangential cells. We found direction-selective responses to sequences of same sign (ON-ON, OFF-OFF), but not of opposite sign (ON-OFF, OFF-ON), refuting the existence of four separate detectors. Based on further measurements, we propose a model that reproduces a variety of additional experimental data sets, including ones that were previously interpreted as support for four separate detectors. Our experiments and the derived model mark an important step in guiding further dissection of the fly motion detection circuit.

INTRODUCTION

Insect motion detection has long served as a classic example for studying fundamental principles of information processing in neural networks (Bialek et al., 1991; Fairhall et al., 2001) and has led to a mathematical description of the underlying computations (Reichardt, 1961). The resulting model, the so-called Reichardt Detector (Figure 1A; Hassenstein and Reichardt, 1956), accurately reproduces cellular and behavioral responses to motion stimuli in surprising detail (Götz, 1964; Borst et al., 2010). The core operation performed in the Reichardt Detector is a multiplication of the input signals from two neighboring photoreceptors after one of them has been temporally delayed by a low-pass filter. This computation is performed twice in a mirror-symmetrical way, the outputs of both operations being finally subtracted to enhance the detector's direction selectivity. While this model represents a faithful algorithmic description of how photoreceptor signals are processed to result in a directionally selective output, its cellular implementation is still unknown due to technical difficulties in recording from the small columnar neurons in the optic lobe that hosts the motion detection circuit. Furthermore, the biophysical implementation of a mathematically sign-correct multiplication of positive (ON) and negative (OFF) input signals poses a fundamental problem for any neuronal hardware. Thus, after more than half a century of research, not only the constituting cells and biophysics of the processing steps but also the overall internal structure of the Reichardt Detector are still open questions. However, fly motion vision has received renewed interest with the establishment of the fruit fly *Drosophila melanogaster* as a model organism in systems neuroscience (Rister et al., 2007; Katsov and Clandinin, 2008; Maimon et al., 2010; Chiappe et al., 2010) due to the availability of a wide range of genetic tools for manipulating and dissecting neural circuits (Borst, 2009).

At the front end of the circuitry, fly motion vision starts with the detection of light in the six outer photoreceptors R1–6 of the compound eye. Upon illumination, R1–6 release the neurotransmitter histamine (Hardie, 1989) and relay the luminance signal to five parallel processing streams in the first-order neuropil, the *lamina*. Two of them, the large monopolar cells L1 and L2, express histamine-gated chloride channels on their dendrites in the lamina (Gengs et al., 2002) and transmit the major input signals to the motion detection circuitry (Rister et al., 2007). In both neurons, onset and offset of histamine release cause transient hyperpolarizing and depolarizing dendritic responses, respectively, with a small sustained hyperpolarization in between (Laughlin and Hardie, 1978; Laughlin et al., 1987). L1 and L2 relay their signals via long axons to separate layers in the second-order neuropil, the *medulla*. Here, information is picked up by mostly unidentified neurons that constitute the motion detection circuit and finally transmit their output to the third-order neuropil consisting of *lobula* and *lobula plate*. In the lobula plate, large directionally selective tangential cells extend their elaborate dendrites and spatially integrate the output of local presynaptic motion detectors (Single and Borst, 1998; Borst et al., 2010). Their responses to large-field motion in the preferred direction (PD) are positive (membrane depolarizations, or firing rate increases) and negative (hyperpolarizations, or firing rate decreases) in the opposite, the so-called null direction (ND).

In this study, we build on the recent discovery that the lamina neurons L1 and L2 constitute the input channels to the motion detection circuitry in *Drosophila*. Joesch et al. (2010) recorded from directionally selective tangential cells in the lobula plate while genetically blocking synaptic transmission from L1 and/or L2. Blocking both L1 and L2 removed motion-sensitive

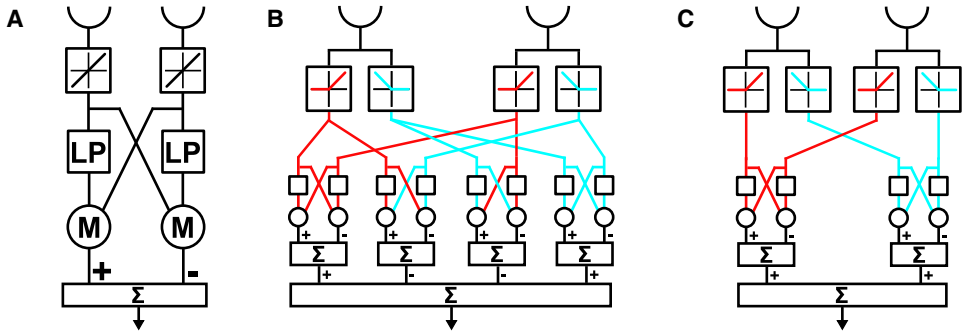

Figure 1. Different Models for Motion Detection

(A) The original Reichardt Detector, the standard model for motion detection in insects.

(B) A 4-Quadrant-Detector model. Splitting the input into ON (brightness increments) and OFF (brightness decrements) components leads to four parallel pathways, one for each combination of input signals (ON-ON, ON-OFF, OFF-ON, OFF-OFF). Each of the four detectors replicates the structure of the standard Reichardt Detector. This model is mathematically identical to the original Reichardt Detector.

(C) A 2-Quadrant-Detector as proposed by Franceschini et al. (1989). Only input combinations of the same sign are processed (ON-ON, OFF-OFF).

responses in lobula plate tangential cells. Importantly, blocking either L1 or L2 revealed that in flies, similar to vertebrates, the visual input is split into an ON and an OFF component.

Here, we adapt the Reichardt Detector to incorporate these new findings, giving rise to two alternative models. Both models require a more elaborate internal structure of the detector to allow for an implementation of separate ON- and OFF-input signals. The first model, the "4-Quadrant-Detector" (Figure 1B) (Hassenstein and Reichardt, 1956) consists of four parallel detectors that cover all four possible combinations of input signals (ON-ON, ON-OFF, OFF-ON, and OFF-OFF). From its input-output behavior, a 4-Quadrant-Detector is mathematically identical to the original Reichardt model. The second model, proposed by Franceschini et al. (1989), contains just two subunits, an ON-ON and an OFF-OFF detector (Figure 1C). Notably, this "2-Quadrant-Detector" is no longer equivalent to the original Reichardt Detector since input signals of opposite sign do not interact. These differences in response behavior should allow us to decide between the two models experimentally. We first presented apparent motion stimuli consisting of sequences of spatially displaced, persistent light increment (ON) and decrement (OFF) steps to two different fly species, *Calliphora* and *Drosophila*, while recording from lobula plate tangential cells. We consistently found strong directionally selective responses to sequences of same sign (ON-ON, OFF-OFF) and inverted responses to sequences of opposite sign (ON-OFF, OFF-ON). The latter seems to clearly speak in favor of a 4-Quadrant-Detector. However, we also found persistent directionally selective responses for interstimulus intervals that by far exceed the estimated time constant of the low-pass filter in the Reichardt Detector, indicative for a tonic representation of the brightness level at the input of the motion detector. Incorporation of an appropriate input filter (high-pass filtering and parallel tonic throughput) in the 2-Quadrant-Detector reproduced all measured responses to sequences of same as well as of opposite sign, albeit lacking specific detector units for correlating combinations of ON and OFF stimuli. Furthermore, the model displayed all the features in response to moving gratings that had been reported from tangential cells before, while imposing only half the wiring and energy demands compared to a 4-Quadrant-Detector. Our findings and the resulting model provided us with a testable hypothesis to distinguish between the 2-Quadrant- and the 4-Quadrant-Detector. Using a modified apparent motion stimulus protocol based on short brightness pulses instead of persistent brightness steps, we performed measurements that contradict the 4-Quadrant-Detector but are in agreement with a 2-Quadrant-Detector.

RESULTS

Apparent Motion Experiments

To analyze the internal structure of the elementary motion detector in flies, we used apparent motion stimuli (Riehle and Franceschini, 1984; Ramachandran and Anstis, 1986; Egelhaaf and Borst, 1992). Such stimuli consist of sequences of light increments or decrements and, thus, should be ideally suited to selectively activate subunits of one type only, e.g., the ON-ON subunit for ON-ON sequences, while leaving the other subunits unaffected. Apparent motion stimuli of all possible combinations (ON-ON, OFF-OFF, ON-OFF, and OFF-ON) should therefore allow us to discriminate between models with or without interactions between input signals of opposite sign. Our stimuli consisted of two adjacent stripes appearing sequentially with a delay of 1 s, thus mimicking motion in one of two directions. The single stripes generate either positive (ON) or negative (OFF) brightness steps, starting from an initial, intermediate brightness level (Figure 2A, rightward motion shown only). The width of the stripes was set such that the two stripes approximately activated neighboring facets forming the input to motion detectors. We measured the effect of such selective stimulation by electrophysiological recordings from directionally selective lobula plate tangential cells. For assessing the generality of our results, we measured responses in two species: using extracellular recordings of action potentials, we measured the firing rate of the horizontally sensitive neuron H1 in *Calliphora vicina*; using somatic whole-cell patch-clamp recordings, we measured the intracellular membrane potential in vertically sensitive VS cells (VS1–5) in *Drosophila melanogaster*.

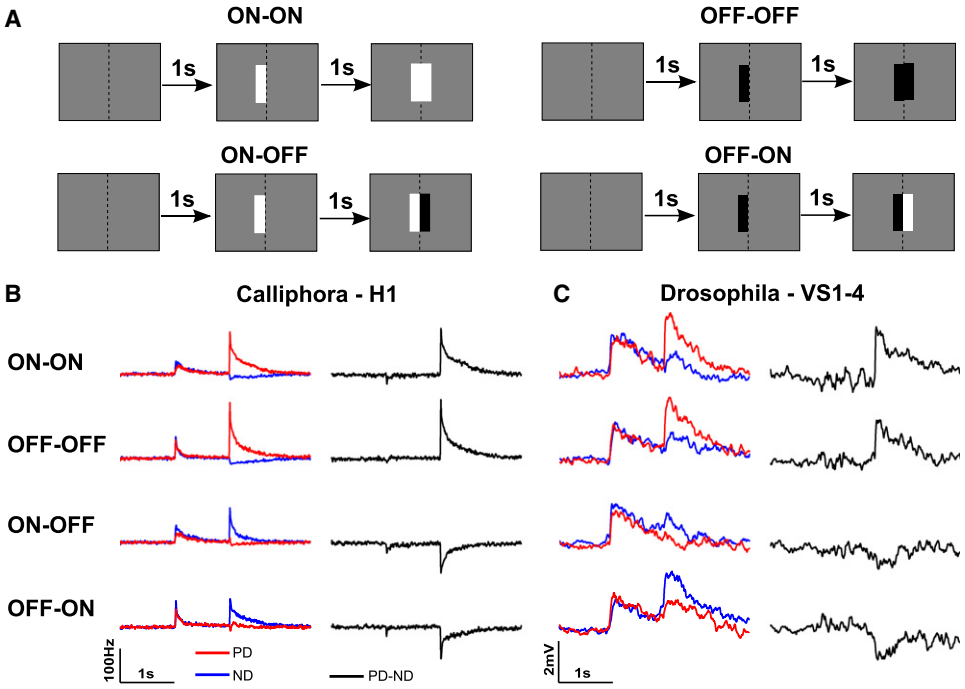

Figure 2. Responses of Lobula Plate Tangential Cells to Sequences of Brightness Steps

(A) Illustration of apparent motion step stimuli. Two stripes appear in sequence, separated by 1 s, on an intermediate background luminance. Here, only rightward apparent motion is depicted. For the experiments in vertically sensitive VS cells in *Drosophila melanogaster*, two vertically arranged stripes were used instead.

(B) Responses of H1 neurons (average from eight flies) in the blowfly *Calliphora vicina* to apparent motion step stimuli.

(C) Responses of VS cells in wild-type *Drosophila melanogaster* (average from seven flies). The red traces represent the responses to apparent motion in the cell's PD; the blue traces illustrate the responses to apparent motion in the cell's ND. The black traces represent the difference between the responses to PD and the responses to ND sequences. For both species, note the positive signals for sequences of same sign (ON-ON, OFF-OFF), and the negative signals for sequences of opposite sign (ON-OFF, OFF-ON).

The results of these experiments are shown in Figure 2B (*Calliphora*) and Figure 2C (*Drosophila*). Lobula plate tangential cells respond to single ON or OFF steps imposed on a uniformly illuminated background with an increase in firing rate or a depolarization (see responses to the appearance of the first stripe). The direction selectivity of the motion detection circuit can be observed by comparing the responses to the second stripe with the responses to the first one. For ON-ON and OFF-OFF stimuli (first and second row in Figures 2B and 2C), the response amplitudes are larger when the stimulus sequence is in the cell's PD (red lines) than when the sequence is in the cell's ND (blue lines). The opposite effect is observed for ON-OFF and OFF-ON stimulus sequences (third and fourth row in Figures 2B and 2C): here, the response to the second stimulus is smaller than the response to the first one when the sequence is in the cell's PD, and larger than the first one when the sequence is in the cell's ND. This effect is called "PD-ND inversion" and is illustrated more clearly when the response to an ND sequence is subtracted from the response to the corresponding PD sequence (black lines in Figures 2B and 2C): for ON-ON and OFF-OFF sequences, a positive signal is obtained; for ON-OFF and OFF-ON sequences, the resulting signal is negative. All this holds true for recordings from the H1 cell in *Calliphora* as well as for recordings from VS cells in *Drosophila* (compare Figure 2B with Figure 2C).

While the responses to ON-ON and OFF-OFF stimuli can be explained by both a 4- as well as by a 2-Quadrant-Detector (Figures 1B and 1C, respectively), the responses to sequences of opposite sign (ON-OFF, OFF-ON) are hard to reconcile with a 2-Quadrant-Detector. However, the phenomenon of the PD-ND inversion is in agreement with predictions from the Reichardt Detector (Figure 1A) and its mathematical equivalent, the 4-Quadrant-Detector (Figure 1B): for ON-OFF or OFF-ON sequences, signals of opposite signs are multiplied, leading to the observed PD-ND inversion. Therefore, given the splitting of the photoreceptor output into ON and OFF components, these results seem to rule out the 2-Quadrant-Detector (Figure 1C) and rather imply a motion detection circuit of the 4-Quadrant type (Figure 1B).

However, the above reasoning rests on two tacit assumptions: (1) information about the absolute brightness is fully eliminated, and only information about the change of the stimulus brightness is passed on to the rectification stage and the subsequent motion detection circuits; and (2) the threshold for the rectification stage is set at exactly the zero point of the incoming signal. As soon as we drop one of these assumptions, the signal separation becomes less strict, and a 2-Quadrant-Detector might respond to stimulus sequences of opposite sign as well. We therefore investigated to what extent the motion detection circuit is sensitive to prolonged presentation of a stripe that, after

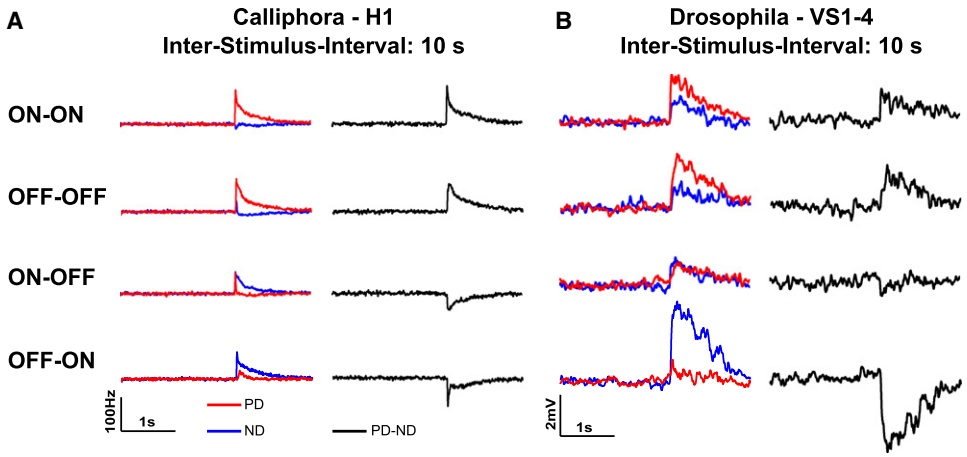

Figure 3. Responses of Lobula Plate Tangential Cells to Quasi-Isolated Brightness Steps

In contrast to the stimulus used in Figure 2, the first stripe was present for 10 s before the second stripe appeared. The direction selectivity of the response persists in both *Calliphora* (A) and *Drosophila* (B), despite the long separation of the two events. These results show the strong influence of the absolute brightness (*DC*) on the motion detection system.

a relatively long delay, is followed by the appearance of a second stripe, either toward the PD or the ND relative to the first stripe. If only information about the brightness change of the second stripe is present at the input of the motion detection circuit, presenting the second stripe on either side of the first stripe should result in identical, direction-insensitive responses for long enough delays between the two stripes. If, however, some information about the first stripe, i.e., a tonic or *DC* component, continues to be passed on to the motion detection circuit after long delays, the responses to PD and ND should differ.

To investigate this point, we presented stimuli in which the first stripe appeared on the screen 10 s before the second one. These experiments revealed clear directionally selective responses (Figures 3A and 3B; legend as in Figures 2B and 2C). Moreover, the responses were highly reminiscent of those for short interstimulus intervals depicted in Figures 2B and 2C. The extent of direction selectivity is particularly remarkable because the interstimulus interval of 10 s is almost three orders of magnitude larger than the estimated low-pass filter time constant of the motion detection circuit (Guo and Reichardt, 1987). These data clearly contradict the assumption that only information about brightness changes is passed on to the motion detection circuitry. In contrast, and in line with previous results (Borst et al., 2003; Reisenman et al., 2003), the motion detection circuit is also informed about permanent brightness levels, resulting in directionally selective responses to apparent motion stimuli even when the two events are separated by 10 s. Although a certain influence of the absolute brightness on lobula plate tangential cell responses has been observed before (Hengstenberg, 1982), our measurements illustrate, to our knowledge, for the first time to what large extent the motion detection circuit uses this information, giving strongly direction-selective responses to quasi-isolated brightness steps.

Modeling a 2-Quadrant-Detector

The results presented above provide the crucial step for proposing a modified 2-Quadrant-Detector as depicted in Figure 4A. Here, the input, ranging from dimensionless values of 0.1 (OFF) to 0.5 (ON), is first preprocessed by a circuit that aims to model the recorded responses of lamina cells L1 and L2 (Laughlin and Hardie, 1978; Laughlin et al., 1987). The signal is fed through a first-order high-pass filter (τ = 250 ms) and, after that, is added to a 10% fraction of the original input signal, representing the DC component of the lamina cell responses. The input to the ON-ON subunit is obtained by a half-wave rectification with a clip point at zero, whereas the input to the OFF-OFF subunit is computed by applying a half-wave rectification with a slightly shifted clip point at 0.05. By this way, a small component of the ON signal is included in the OFF pathway as well. Both subunits are represented as standard Reichardt Detectors, except that they now process only nonnegative input signals. The two output lines of each subunit are subtracted, with the inhibitory component being weighed by a constant of 0.92, relative to the positive output. This differential weighing accounts for the reported imbalance of the two half-detectors (Egelhaaf et al., 1989). The effect of the filter stage and the rectifiers is illustrated in Figure 4B. The upper-left panel depicts an example stimulus; the lower-left panel shows the resulting signal after high-pass filtering and adding a 10% fraction of the unfiltered stimulus. The right two panels depict the ON and OFF components extracted by the two rectifiers.

As the experiments with an interstimulus interval of 10 s showed, temporally isolated single brightness changes strongly affect the response depending on the brightness of the surrounding area. Therefore, it is unlikely that the observed responses stem from only one detector that observes both stripes. Rather, it has to be assumed that other detectors that correlate the surrounding area with either the left or the right stripe strongly affect the response as well. We therefore used an array of such 2-Quadrant-Detectors (see Experimental Procedures) for modeling the responses to apparent motion stimuli as well as to moving gratings (Figures 4C–4F).

The model reproduced the main characteristics of the measurements for ON-ON and OFF-OFF sequences delivered

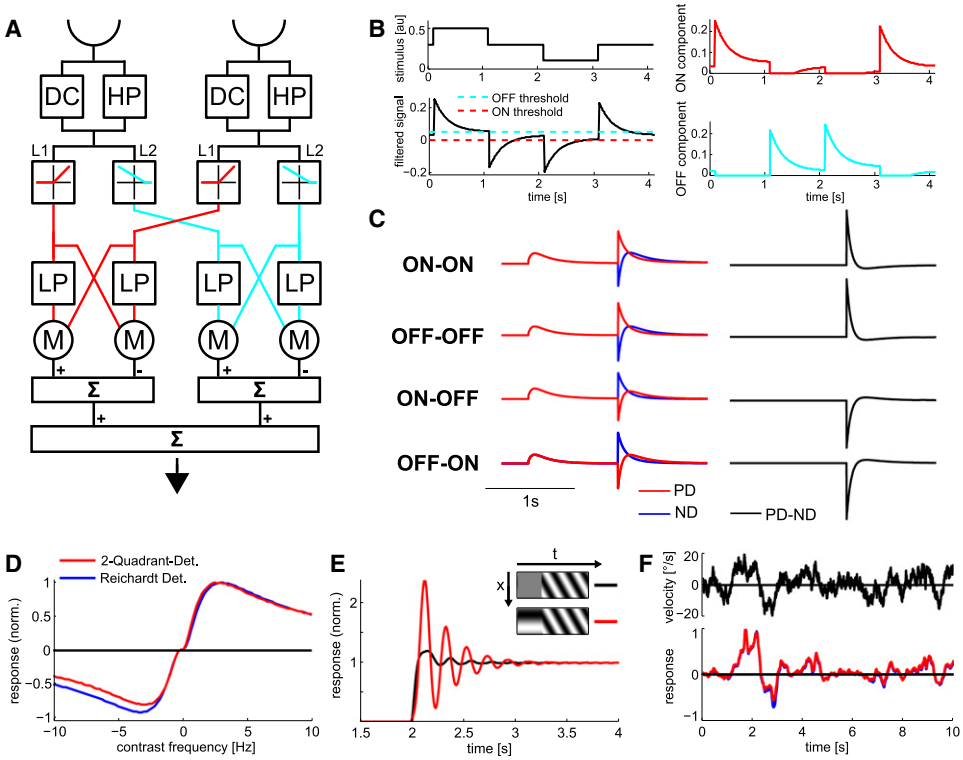

Figure 4. Proposed 2-Quadrant-Detector Model and Its Response Properties

(A) Detailed structure of the 2-Quadrant-Detector. The input is first processed by a filter stage that feeds the signal through a first-order high-pass filter (HP, $\tau = 250$ ms) but in parallel allows 10% of the original signal to pass (*DC*). These two signals then become added. The result is fed into two parallel half-wave rectifiers, one forming the input to the ON (shown in red), the other to the OFF (shown in blue) pathway. The cutoff for the ON rectifier is set at zero. For the OFF rectifier, it is shifted slightly toward positive signals (exaggerated here for illustration purposes) to account for the observed small ON component in the OFF pathway (Reiff et al., 2010). As for the original Reichardt Detector, the ON and OFF subunits consist each of two first-order low-pass filters (LP, $\tau = 50$ ms), two multipliers, and a subtraction stage.

(B) Illustration of ON/OFF extraction by the preprocessing stage depicted in (A). Upper-left panel shows example input consisting of a 1 s ON step and a 1 s OFF step. Lower-left panel illustrates resulting signal (black line) after adding up the high-pass filtered stimulus ($\tau = 250$ ms) and a 10% fraction of the unfiltered stimulus. Dashed lines represent threshold of the ON (red) and OFF (blue) rectifier. Right panels show ON and OFF components extracted by the two rectifiers.

(C) Simulated responses of the 2-Quadrant-Detector to apparent motion stimuli. The model exhibits responses similar to the experimental results (compare to Figures 2B and 2C): for stimulus sequences of the same sign (ON-ON, OFF-OFF, red traces for PD, blue traces for ND), the response difference (PD response minus ND response, black traces) is positive; for stimulus sequences of opposite sign (ON-OFF, OFF-ON), the response difference is negative. Until the appearance of the second stimulus, the ND response (blue) is identical to the PD response and, therefore, covered by the red trace.

(D) Normalized steady-state response of an array of standard Reichardt Detectors (blue) and 2-Quadrant-Detectors (red) to a moving sine grating (spatial wavelength $\lambda = 20°$) as a function of the contrast frequency of a stimulus. The contrast frequency refers to the angular stimulus velocity, divided by the spatial wavelength of the grating.

(E) Responses of a spatially integrated array of detectors to the onset of constant grating motion (spatial wavelength $\lambda = 20°$; stimulus velocity $v = 100°/s$) under two conditions: in one case the grating was visible before the onset of motion (red trace); in the other case the grating was invisible before motion onset (black trace). The detector array exhibits strong oscillations if the grating was visible before motion onset. These oscillations are much weaker if a uniform illumination was shown before the grating started moving.

(F) Responses of a spatially integrated array of standard Reichardt Detectors (blue) and 2-Quadrant-Detectors (red) to a sine grating (spatial wavelength $\lambda = 20°$), moving according to a random velocity profile (low-pass filtered with $\tau = 500$ ms) for 10 s. The response of the 2-Quadrant-Detector (red) is largely identical to the response of the Reichardt Detector (blue); therefore, the blue trace is largely covered by the red trace.

with a 1 s interstimulus interval (compare Figures 2B and 2C, first and second row, with Figure 4C, first and second row): for sequences along the PD (red traces), the response to the second stimulus was larger than the response to the first one; for sequences along the ND (blue traces), the response to the second stimulus was smaller than the response to the first one. Therefore, the difference between the PD and the ND response (black traces) was always positive. However, despite lacking specific ON-OFF and OFF-ON subunits, this model also exhibited responses to stimulus sequences of opposite sign (ON-OFF, OFF-ON, Figure 4C, third and fourth row): For sequences along the PD (red traces), the response to the second stimulus was smaller than the response to the first one; for sequences along the ND (blue traces), the response to the second stimulus was larger than the response to the first one. Therefore, the difference between the PD and the ND response (black traces)

was always negative. Thus, the model also reproduced the PD-ND inversion mentioned above. While the simulation results constitute a good qualitative fit, there are quantitative differences between the measurements depicted in Figures 2B and 2C and the simulations in Figure 4C, such as stronger ND responses and different decay time constants. We believe that these shortcomings mainly stem from two deliberate choices: (1) the intentional simplicity of our model that, for instance, is incapable of reproducing the complex temporal responses of lamina monopolar cells to brightness steps; and (2) the choice of a single parameter set for fitting responses of two different fly species (extracellular H1 recordings in *Calliphora* and whole-cell patch-clamp recordings in *Drosophila*). In addition, strong negative input cannot be observed in extracellular recordings of a spiking cell because firing rates can only decrease to 0 Hz.

These results demonstrate that the responses of a 2-Quadrant-Detector, equipped with experimentally justified stimulus preprocessing stages, can be reconciled with the experimental results to apparent motion stimuli shown in Figure 2. However, the question arises as to whether this model is also able to reproduce experimentally confirmed response characteristics of the original Reichardt Detector to other stimuli. We investigated this point by comparing the responses of the 2-Quadrant-Model with the Reichardt Detector to stimuli where the outputs of a large array of motion detectors are spatially integrated. In particular, it has been shown that for moving sine gratings, steady-state responses of lobula plate tangential cells exhibit an optimum that depends on the contrast frequency of the stimulus (angular velocity divided by the spatial wavelength). To this end, we simulated an array of 200 motion detectors, either Reichardt Detectors (Figure 1A) or 2-Quadrant-Detectors (Figure 4A), and determined their spatially integrated responses to sine gratings (wavelength $\lambda = 20^{\circ}$) moving at various velocities. For both models, the input was preprocessed by the identical high-pass/DC filter combination. We observed a high degree of similarity between the two models in their steady-state response amplitude: the response is maximum at a certain contrast frequency and declines for frequencies beyond that point (Figure 4D). The only difference between the model responses consists of a slightly reduced ND response amplitude of the 2-Quadrant-Detector as compared to the Reichardt Detector. Next, we tested a more subtle response characteristic of the Reichardt Detector, the so-called ''afterimage effect'' (Maddess, 1986; Harris and O'Carroll, 2002; Reisenman et al., 2003; Joesch et al., 2008): The oscillatory component of motion detectors at the motion onset of a sine grating depends on whether a static grating or a uniform gray area is presented prior to motion onset. As reported before for fly lobula plate tangential cells (Reisenman et al., 2003) and the original Reichardt Detector (Borst et al., 2003), the 2-Quadrant-Detector exhibits strong initial oscillations when confronted with a standing grating before motion onset but only slight modulations when a gray field was presented instead (Figure 4E). We then compared the dynamic response properties of the two models by stimulating the detector array with a moving sine grating following a pseudorandom velocity profile (Figure 4F). Both types of models reveal an almost identical response. This degree of similarity is particularly remarkable regarding the complexity of the stimulus.

Experimental Evidence for a 2-Quadrant-Detector

The simulations presented so far show that a slightly modified 2-Quadrant-Detector, albeit lacking specific subunits for correlating ON and OFF inputs, reproduces the experimentally observed PD-ND inversion for ON-OFF and OFF-ON apparent motion stimuli. However, demonstrating that specific subunits processing ON-OFF and OFF-ON stimuli are not necessary does not allow for excluding them. To ultimately distinguish between the two models, we were guided by the notion that the PD-ND inversion depends on the DC component and is largely independent of the interstimulus interval. Therefore, we chose an apparent motion stimulus that emphasizes the delay-and-correlate mechanism while removing the impact of the DC component. To this end, we performed simulations and experiments with sequences of two short brightness pulses (duration 16 ms) instead of brightness steps, separated by 25 ms (simulations and *Calliphora*) or 48 ms (*Drosophila*), as depicted in Figure 5A for an ON-ON PD sequence. Indeed, comparing the simulated responses of an array of 4-Quadrant-Detectors (Figure 5B) with those of a 2-Quadrant-Detector (Figure 5C) reveals that the PD-ND inversion for ON-OFF and OFF-ON pulse sequences is a distinguishing feature of the 4-Quadrant-Detector (Figure 5B, third and fourth row). In contrast, a 2-Quadrant-Detector, lacking specific subunits for correlating ON and OFF stimuli, exhibits only slight differences between the PD and ND response (Figure 5C, third and fourth row).

Performing the corresponding experiments in *Calliphora* reveals strong directionally selective responses for ON-ON and OFF-OFF stimuli (Figure 5D, first and second row; n = 10 flies), as predicted by both models—subtracting the ND from the PD response gives a clearly positive signal. Most importantly, there is no PD-ND inversion for ON-OFF and OFF-ON stimuli (Figure 5D, third and fourth row). In contrast, we even observe a slight increase in firing rate in response to these mixed stimuli. Furthermore, we found very similar response characteristics in *Drosophila* (Figure 5E)—a strong degree of direction selectivity for ON-ON and OFF-OFF pulse sequences, but no significant difference between PD and ND stimulation with ON-OFF and OFF-ON sequences. In contrast to the brightness step experiments, we observed much smaller responses to OFF pulses than to ON pulses in *Drosophila*, to an extent that forced us to change the amplitude of the ON and OFF luminance steps to make OFF responses visible. This might reflect different response amplitudes in photoreceptor cells or lamina monopolar cells in response to brightness pulses in the two species, or biophysical differences in the implementation of the rectification stages for extracting ON and OFF components. The results in Figures 5D and 5E clearly refute the 4-Quadrant-Detector as the model underlying motion detection but offer strong support for a 2-Quadrant-Detector as proposed here.

DISCUSSION

Recent experiments demonstrated that flies split the photoreceptor output signal into its ON and OFF components, leading to the idea that these components are processed by parallel motion detector subunits. The goal of our study was to develop and fortify a new model for the fly elementary motion detector

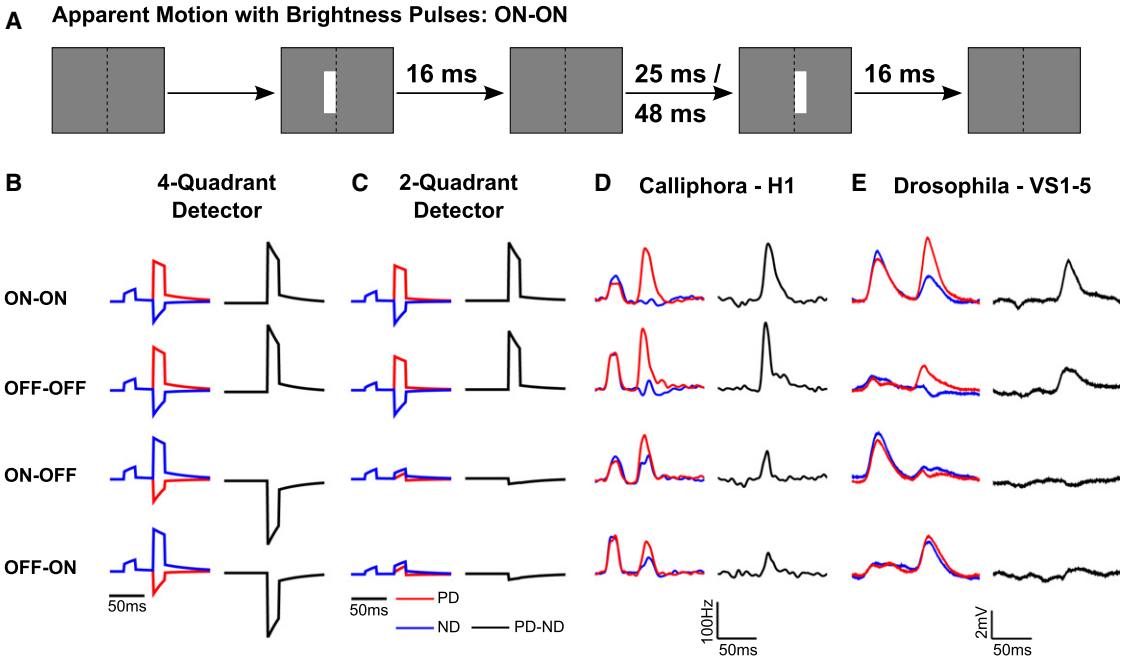

Figure 5. Model and Experimental Responses to Apparent Motion Stimuli Consisting of Two Short Brightness Pulses

Simulations of a 4-Quadrant-Detector, a 2-Quadrant-Detector, and corresponding measurements in *Calliphora* and *Drosophila* for apparent motion stimuli consisting of two brightness pulses (each lasting for 16 ms), separated by an interstimulus interval of 25 ms (simulations, *Calliphora*) or 48 ms (*Drosophila*). For both models the same parameter set as in Figure 4 was used.

(A) Illustration of an ON-ON PD brightness pulse sequence. Each pulse lasted for 16 ms, and the interpulse interval was 25 ms for *Calliphora* and 48 ms for *Drosophila*.

(B) Simulated responses of the 4-Quadrant-Detector to sequences of brightness pulses. For stimulus sequences of the same sign (ON-ON, OFF-OFF, red traces for PD, blue traces for ND), the response difference (PD response minus ND response, black traces) is positive. For stimulus sequences of opposite sign (ON-OFF, OFF-ON), the response difference is negative with approximately the same amplitude as for ON-ON and OFF-OFF sequences.

(C) Simulated responses of the 2-Quadrant-Detector. For ON-ON and OFF-OFF sequences, the response difference is again positive; for ON-OFF and OFF-ON sequences, the response difference is relatively small.

(D) Responses of the H1 neuron in *Calliphora* (average from ten flies). As predicted by both detector types, the response difference to stimulus sequences of same sign is strong, positive, and very stable (first and second row; mean responses from ten flies). In contrast, the response differences to stimulus sequences of different sign (ON-OFF, OFF-ON; third and fourth row) are rather small and highly variable across flies.

(E) Responses of VS cells in *Drosophila* (average from six flies). Responses to ON-ON and OFF-OFF stimuli again give rise to strongly direction-selective responses, while there is no significant difference between PD and ND stimulation with ON-OFF or OFF-ON pulse sequences. These results contradict a 4-Quadrant-Detector scheme underlying motion detection where these stimuli should give a clearly negative response difference. The slight positive response difference in the results from *Calliphora* can be explained by adjusting the input filter parameters of the 2-Quadrant-Detector to result in a more biphasic response of the input stage to brightness pulses.

that takes these new findings into account. This model should have an internal structure in accordance with these recent results but also fit the previously reported input-output behavior of the classical Reichardt model. The most basic question that arises after the finding that input is split into ON and OFF components is whether there exist four or two detector subunits in parallel. A model with four subunits, one for each combination of input signs (ON-ON, OFF-OFF, ON-OFF, OFF-ON) and, therefore, termed 4-Quadrant-Detector, leads to the same input-output behavior as the original Reichardt Detector (it is mathematically identical). In contrast, a basic 2-Quadrant-Detector as depicted in Figure 1B processes inputs of the same sign (ON-ON, OFF-OFF) only. The obvious way to discriminate between these two alternatives is to apply apparent motion stimuli, consisting of sequences of distinct ON and OFF brightness steps, while recording from large output neurons of the visual system. In agreement with previous results (Egelhaaf and Borst, 1992), we found consistent and significant responses to sequences consisting of signals of same (ON-ON, OFF-OFF) as well as to opposite sign (ON-OFF, OFF-ON) in two fly species, *Calliphora* and *Drosophila*. This effect has also been observed in neurons of the wallaby nucleus of the optic tract (Ibbotson and Clifford, 2001) and in human psychophysics (Anstis, 1970). While this would readily lead us to exclude the 2-Quadrant-Detector model, the distinct nature of the neural substrate postsynaptic to the L1 and L2 cells suggests the existence of two rather than four different subunits (Bausenwein and Fischbach, 1992; Bausenwein et al., 1992). This made us reconsider how a 2-Quadrant-Detector could be reconciled with the responses to input sequences of opposite sign.

We found that introducing a DC component passing through the initial filter stage, in addition to the high-pass filtered signal,

is largely sufficient to account for these response properties in the 2-Quadrant-Detector. We provide an experimental justification for this assumption by demonstrating that even for interstimulus intervals of 10 s, a strong directionally selective response in lobula plate tangential cells is obtained. Purely high-pass-filtering the input, in contrast, would remove information about the absolute luminance after some 100 ms. In addition, the low-pass filter time constant has been estimated to lie between 5 and 50 ms (Guo and Reichardt, 1987; Egelhaaf and Reichardt, 1987; Dror et al., 2001; Borst et al., 2003; Lindemann et al., 2005; Spavieri et al., 2010). Thus, this filter is incapable of storing the luminance information over a time period that exceeds its time constant by almost three orders of magnitude. Assuming that some fraction of the ongoing luminance, rather than only its time derivative, is represented at the input of the rectifiers leads to a "bleed-through" of ON signals into the OFF pathway and vice versa. Indeed, when optically recording the calcium changes at the axon terminals of L2 cells, which represent input lines to the OFF pathway, a small but consistent decrease of calcium concentration was found in response to ON stimuli, in addition to the large increase in calcium in response to OFF stimuli (Reiff et al., 2010). Adjusting the parameters of the 2-Quadrant-Detector to account for the responses to apparent motion leads to a model that, with the same parameter settings, also accounts for the response properties of the original Reichardt Detector that have been investigated and tested in fly lobula plate tangential cells in the past.

A closer investigation of why an array of 2-Quadrant-Detectors is able to exhibit the PD-ND inversion for ON-OFF and OFF-ON apparent motion step stimuli revealed that reproducing these results requires a certain DC component in the input signal. At the same time, this effect is largely independent of the actual interstimulus interval. A conclusive test for the existence of separate ON-OFF and OFF-ON subunits is therefore to remove this tonic input and reduce the interstimulus interval by displaying apparent motion stimuli consisting of two temporally nonoverlapping brightness pulses, separated by a short delay. For these kinds of stimuli, the two models discussed here predict very different responses. While the 4-Quadrant-Detector produces strongly direction-selective but inverted responses for ON-OFF and OFF-ON stimuli, the 2-Quadrant-Detector responds to such pulse sequences with only negligible amplitude. Our experiments on *Calliphora* and *Drosophila* revealed that the responses to these stimuli cannot be reconciled with a 4-Quadrant-Detector but rather match the characteristics of a 2-Quadrant-Detector. We therefore conclude that the fly motion detection circuit is comprised of two parallel, noninteracting subunits for detecting ON and OFF motion.

The responses to ON-OFF and OFF-ON pulse sequences measured in *Calliphora* are not in perfect agreement with the predictions of a 2-Quadrant-Detector. However, the experimental data varied strongly across flies. The peak subtracted firing rate for ON-OFF sequences was 78 ± 76 Hz (mean ± standard deviation across ten flies); for OFF-ON sequences, it amounted to 56 ± 50 Hz. We suspect this effect to arise from the biphasic responses of L1 and L2 to brightness pulses (van Hateren, 1992). Indeed, the positivity of the subtracted responses to ON-OFF and OFF-ON sequences can be reproduced in simulations by halving the input filter time constants and DC fraction to give a more biphasic filter response to pulses (data not shown).

An important implication of splitting visual input into ON and OFF components is that the subsequent motion detection circuit now is confronted with nonnegative signals only. This significantly facilitates the implementation of the nonlinear operation inherent to motion detection (Poggio and Reichardt, 1973), as specified by the multiplication in the Reichardt Detector. Independently of the exact kind of nonlinearity actually used in motion detection, it is required to give a positive output for two positive (excitatory) as well as for two negative (inhibitory) inputs. Performing such an operation within one neuron is biophysically implausible. In contrast, splitting the inputs into nonnegative signals (ON and OFF) allows for a neural implementation of the nonlinearity that operates on two nonnegative inputs, only. This unit is replicated for the different signal components with a final stage that combines the outputs.

Nonetheless, splitting of the input does not answer the question of what exact kind of nonlinearity is used, and many ideas have been put forward in the literature to this end (Grzywacz and Koch, 1987; Gabbiani et al., 2002; Hausselt et al., 2007; Enciso et al., 2010). One possibility of approximating a multiplicative interaction is the so-called log-exp-transform, where the two factors are preprocessed by a saturating, e.g., logarithmic function, and their sum is fed through an exponential nonlinearity. This mechanism has been experimentally confirmed in an identified neuron of the locust involved in collision avoidance (Gabbiani et al., 2002). Another possibility consists of a tonic voltage gradient along the dendrite together with a high voltage-activated calcium current, giving rise to a supra-linear relationship between any two inputs along the dendrite, which has been tested in the starburst amacrine cells of the rabbit retina (Hausselt et al., 2007). What exact mechanism is implemented in the neurons presynaptic to the fly lobula plate tangential cells can only be answered by experimental investigation of the respective cells.

A further interesting question concerns the separation of the input into its ON and OFF components. In their dendrites, both L1 and L2 depolarize in response to OFF stimulation and hyperpolarize in response to ON stimulation. Expressing a genetically encoded calcium indicator in L2 neurons, Reiff et al. (2010) have shown that the extraction of the OFF component occurs in the axon terminals of L2. Given that blocking synaptic output of L1 removes lobula plate tangential cell responses to moving ON edges, which are encoded by L1 dendritic hyperpolarizations, we suggest that the ON component is extracted via a tonically active, inhibitory synapse from L1 onto downstream neurons.

Along this way, the results presented above mark an important step by presenting unambiguous evidence for the existence of two, not four, separate motion detectors acting in parallel on appropriately processed input signals. This should facilitate the identification of the corresponding neurons in the fly optic lobe.

EXPERIMENTAL PROCEDURES

Electrophysiology in *Calliphora*

We recorded extracellular spike trains from the motion-sensitive neuron H1 in 3- to 12-day-old blow flies (*Calliphora vicina*). Flies were fixed with wax, the

head capsule was opened, and air sacks and fat tissue were removed. The head was then aligned to the frontal pseudo-pupils. H1 activity was recorded with a tungsten electrode inserted into the left lobula plate, amplified, band-pass filtered, and recorded at a sampling frequency of 10 kHz. Spikes were detected offline with a threshold operation. The traces depicted in this work were generated by averaging over trials and convolving the result with a Gaussian filter (standard deviation of 5 ms).

The visual stimulus was presented on a CRT monitor (M21LMAX; Image Systems Corp., Minnetonka, MN, USA) updated at 240 Hz. For OFF, intermediate, and ON brightness values, we used 1 cd/m^2, 14 cd/m^2, and 57 cd/m^2; the intermediate luminance was chosen such that ON and OFF stimuli yielded responses of similar amplitudes. The horizontal angular extent of one stripe was set to 3°, the vertical extent amounted to 40°.

Electrophysiology in *Drosophila*

We used female wild-type Canton-S experimental flies, 1–2 days after eclosion, raised on standard cornmeal-agar medium with a 12 hr light/12 hr dark cycle, 25°C, and 60% humidity. Patch-clamp recordings were performed as described in Joesch et al. (2008). VS-cell somata covered by ringer solution (Wilson et al., 2004) were approached with a patch electrode filled with a red fluorescent dye (intracellular solution as in Joesch et al. [2008]). Recordings were established under visual control using a 40× water-immersion objective (LumplanF; Olympus), a Zeiss Microscope (Axiotech vario 100; Zeiss, Oberkochen, Germany), and illumination (100 W fluorescence lamp, hot mirror, neutral density filter OD 0.3; all from Zeiss, Germany). To enhance tissue contrast, we used two polarization filters, one located as an excitation filter and the other as an emission filter, with slight deviation on their polarization plane. For eye protection, we additionally used a 420 nm LP filter on the light path.

Visual stimuli were delivered using a custom-built light-emitting diode (LED) arena (Reiser and Dickinson, 2008; Joesch et al., 2008; Schnell et al., 2010). Horizontal stripes were presented in the front of the fly's visual field. For the results depicted in Figures 2 and 3, we used stripes covering the complete arena in the horizontal plane and 10° in elevation (either from 0° to +10° or −10° in elevation). The vertical angular extent of the stripe was set to match twice the inter-ommatidial distance. The luminance values used for OFF, intermediate, and ON stimuli were 0 cd/m^2, 16 cd/m^2, and 64 cd/m^2, respectively. For the brightness pulse experiments shown in Figure 5, we used two stripes of 5° each in elevation, covered the contralateral side, and set the luminance values for OFF, intermediate, and ON stimuli to 0 cd/m^2, 48 cd/m^2, and 74 cd/m^2, respectively. The intermediate luminance was increased to give a stronger response amplitude to OFF brightness pulses.

Computer Simulations

The model was simulated using the parameters described in the Results section with a time step of 1 ms. For Figures 4C, 5B, and 5C, we used five individual but identical detectors: one observing both stripes, two observing the environment and one of the two stripes, and two detectors observing only one stripe. The latter two are necessary to approximate the comparatively strong responses to the appearance of the first stripe especially in *Drosophila*, where the slit width was set to approximately twice the inter-ommatidial distance. The parameters of the model (high-pass filter time constant, DC fraction, clip point for the OFF rectification, low-pass filter time constant, synaptic imbalance) were fitted to simultaneously match the results shown in Figures 2B and 2C. The parameter search was performed with a novel online technique. A MIDI controller was connected to the computer performing the simulation, and the positions of its control elements (sliders and knobs) were readout by MATLAB using a custom middle-ware layer written in the Java programming language (Oracle Corporation). These positions were then used to adjust the unknown parameters manually. The simulation was executed in a loop, repeatedly drawing the newest results on screen, while continuously adjusting the parameters based on the input from the MIDI controller. This technique will be described in more detail in a follow-up publication. Our aim was to find a parameter set that matches both the results from *Calliphora* and *Drosophila* in qualitative terms. The search for parameters of the input stage mimicking L1 and L2 was mainly unconstrained and aimed at properly reproducing the apparent motion results given that relatively little is known about the synaptic output of these cells. Our main considerations for the DC component, the time constant, and the threshold were the data published in Laughlin et al. (1987) and Reiff et al. (2010). At the output level of the circuit, we did not use a conductance-based model but subtracted the responses of the two half-detectors in a weighted manner to mimic excitatory and inhibitory synaptic transmission. It is commonly assumed that the excitatory half-detector provides stronger input, possibly due to an asymmetry of the synaptic reversal potentials (about $E_{inh} = -80$ mV, $E_{exc} = 0$ mV) relative to the resting membrane potential of lobula plate tangential cells (between −40 and −50 mV). We therefore used a factor g to weight the output of the inhibitory half-detector before subtracting it from the excitatory half-detector. During parameter search, the factor g was constrained by taking the assumed synaptic reversal potentials and the resting potential into account, as well as a previously used value of g = 0.89 in Egelhaaf et al. (1989). The parameter set found for the apparent motion experiments in Figures 2B and 2C was then used for the simulation results shown in Figures 4D–4F and Figures 5B and 5C as well. In Figures 4D–4F, we simulated 200 identical motion detectors homogeneously covering one period of the moving sine wave grating (wavelength $\lambda = 20°$). The amplitude of the stimuli ranged from 0.1 (OFF; sine grating minimum value) to 0.5 (ON; sine grating maximum value), with an intermediate luminance of 0.3.

ACKNOWLEDGMENTS

We thank Mark Huebener for critically reading the manuscript, Juergen Haag and Franz Weber for discussions, and Renate Gleich, Christian Theile, and Wolfgang Essbauer for technical assistance.

Accepted: March 22, 2011
Published: June 22, 2011

REFERENCES

Anstis, S.M. (1970). Phi movement as a subtraction process. Vision Res. *10*, 1411–1430.

Bausenwein, B., and Fischbach, K.F. (1992). Activity labeling patterns in the medulla of *Drosophila melanogaster* caused by motion stimuli. Cell Tissue Res. *270*, 25–35.

Bausenwein, B., Dittrich, A.P., and Fischbach, K.F. (1992). The optic lobe of *Drosophila melanogaster*. II. Sorting of retinotopic pathways in the medulla. Cell Tissue Res. *267*, 17–28.

Bialek, W., Rieke, F., de Ruyter van Steveninck, R.R., and Warland, D. (1991). Reading a neural code. Science *252*, 1854–1857.

Borst, A. (2009). *Drosophila*'s view on insect vision. Curr. Biol. *19*, R36–R47.

Borst, A., Reisenman, C., and Haag, J. (2003). Adaptation of response transients in fly motion vision. II: model studies. Vision Res. *43*, 1309–1322.

Borst, A., Haag, J., and Reiff, D.F. (2010). Fly motion vision. Annu. Rev. Neurosci. *33*, 49–70.

Chiappe, M.E., Seelig, J.D., Reiser, M.B., and Jayaraman, V. (2010). Walking modulates speed sensitivity in *Drosophila* motion vision. Curr. Biol. *20*, 1470–1475.

Dror, R.O., O'Carroll, D.C., and Laughlin, S.B. (2001). Accuracy of velocity estimation by Reichardt correlators. J. Opt. Soc. Am. A Opt. Image Sci. Vis. *18*, 241–252.

Egelhaaf, M., and Borst, A. (1992). Are there separate ON and OFF channels in fly motion vision? Vis. Neurosci. *8*, 151–164.

Egelhaaf, M., and Reichardt, W. (1987). Dynamic response properties of movement detectors - Theoretical analysis and electrophysiological investigation in the visual system of the fly. Biol. Cybern. *56*, 69–87.

Egelhaaf, M., Borst, A., and Reichardt, W. (1989). Computational structure of a biological motion-detection system as revealed by local detector analysis in the fly's nervous system. J. Opt. Soc. Am. A *6*, 1070–1087.

Enciso, G.A., Rempe, M., Dmitriev, A.V., Gavrikov, K.E., Terman, D., and Mangel, S.C. (2010). A model of direction selectivity in the starburst amacrine cell network. J. Comput. Neurosci. *28*, 567–578.

Fairhall, A.L., Lewen, G.D., Bialek, W., and de Ruyter Van Steveninck, R.R. (2001). Efficiency and ambiguity in an adaptive neural code. Nature *412*, 787–792.

Franceschini, N., Riehle, A., and Le Nestour, A. (1989). Directionally selective motion detection by insect neurons. In Facets of Vision, D.G. Stavenga and R.C. Hardie, eds. (Berlin: Springer), pp. 360–390.

Gabbiani, F., Krapp, H.G., Koch, C., and Laurent, G. (2002). Multiplicative computation in a visual neuron sensitive to looming. Nature *420*, 320–324.

Gengs, C., Leung, H.T., Skingsley, D.R., Iovchev, M.I., Yin, Z., Semenov, E.P., Burg, M.G., Hardie, R.C., and Pak, W.L. (2002). The target of *Drosophila* photoreceptor synaptic transmission is a histamine-gated chloride channel encoded by ort (hclA). J. Biol. Chem. *277*, 42113–42120.

Götz, K.G. (1964). Optomotorische Untersuchung des visuellen Systems einiger Augenmutanten der Fruchtfliege *Drosophila*. Kybernetik *2*, 77–92.

Grzywacz, N.M., and Koch, C. (1987). Functional properties of models for direction selectivity in the retina. Synapse *1*, 417–434.

Guo, A., and Reichardt, W. (1987). An estimation of the time constant of movement detectors. Naturwissenschaften *74*, 91–92.

Hardie, R.C. (1989). A histamine-activated chloride channel involved in neurotransmission at a photoreceptor synapse. Nature *339*, 704–706.

Harris, R.A., and O'Carroll, D.C. (2002). Afterimages in fly motion vision. Vision Res. *42*, 1701–1714.

Hassenstein, B., and Reichardt, W. (1956). Systemtheoretische Analyse der Zeit, Reihenfolgen und Vorzeichenauswertung bei der Bewegungsperzeption des Rüsselkäfers *Chlorophanus*. Z. Naturforsch. *11b*, 513–524.

Hausselt, S.E., Euler, T., Detwiler, P.B., and Denk, W. (2007). A dendrite-autonomous mechanism for direction selectivity in retinal starburst amacrine cells. PLoS Biol. *5*, e185.

Hengstenberg, R. (1982). Common visual response properties of giant vertical cells in the lobula plate of the blowfly *Calliphora*. J. Comp. Physiol. *149*, 179–193.

Ibbotson, M.R., and Clifford, C.W. (2001). Interactions between ON and OFF signals in directional motion detectors feeding the not of the wallaby. J. Neurophysiol. *86*, 997–1005.

Joesch, M., Plett, J., Borst, A., and Reiff, D.F. (2008). Response properties of motion-sensitive visual interneurons in the lobula plate of *Drosophila melanogaster*. Curr. Biol. *18*, 368–374.

Joesch, M., Schnell, B., Raghu, S.V., Reiff, D.F., and Borst, A. (2010). ON and OFF pathways in *Drosophila* motion vision. Nature *468*, 300–304.

Katsov, A.Y., and Clandinin, T.R. (2008). Motion processing streams in *Drosophila* are behaviorally specialized. Neuron *59*, 322–335.

Laughlin, S.B., and Hardie, R.C. (1978). Common strategies for light adaptation in the peripheral visual systems of fly and dragonfly. J. Comp. Physiol. A Neuroethol. Sens. Neural Behav. Physiol. *128*, 319–340.

Laughlin, S.B., Howard, J., and Blakeslee, B. (1987). Synaptic limitations to contrast coding in the retina of the blowfly *Calliphora*. Proc. R. Soc. Lond. B Biol. Sci. *231*, 437–467.

Lindemann, J.P., Kern, R., van Hateren, J.H., Ritter, H., and Egelhaaf, M. (2005). On the computations analyzing natural optic flow: quantitative model analysis of the blowfly motion vision pathway. J. Neurosci. *25*, 6435–6448.

Maddess, T. (1986). Afterimage-like effects in the motion-sensitive neuron H-1. Proc. R. Soc. Lond. B Biol. Sci. *228*, 433–459.

Maimon, G., Straw, A.D., and Dickinson, M.H. (2010). Active flight increases the gain of visual motion processing in *Drosophila*. Nat. Neurosci. *13*, 393–399.

Poggio, T., and Reichardt, W. (1973). Considerations on models of movement detection. Kybernetik *13*, 223–227.

Ramachandran, V.S., and Anstis, S.M. (1986). The perception of apparent motion. Sci. Am. *254*, 102–109.

Reichardt, W. (1961). Autocorrelation, a principle for the evaluation of sensory information by the central nervous system. In Sensory Communication, W.A. Rosenblith, ed. (New York: MIT Press and John Wiley and Sons), pp. 303–317.

Reiff, D.F., Plett, J., Mank, M., Griesbeck, O., and Borst, A. (2010). Visualizing retinotopic half-wave rectified input to the motion detection circuitry of *Drosophila*. Nat. Neurosci. *13*, 973–978.

Reisenman, C., Haag, J., and Borst, A. (2003). Adaptation of response transients in fly motion vision. I: experiments. Vision Res. *43*, 1291–1307.

Reiser, M.B., and Dickinson, M.H. (2008). A modular display system for insect behavioral neuroscience. J. Neurosci. Methods *167*, 127–139.

Riehle, A., and Franceschini, N. (1984). Motion detection in flies: parametric control over ON-OFF pathways. Exp. Brain Res. *54*, 390–394.

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). Dissection of the peripheral motion channel in the visual system of *Drosophila melanogaster*. Neuron *56*, 155–170.

Schnell, B., Joesch, M., Forstner, F., Raghu, S.V., Otsuna, H., Ito, K., Borst, A., and Reiff, D.F. (2010). Processing of horizontal optic flow in three visual interneurons of the *Drosophila* brain. J. Neurophysiol. *103*, 1646–1657.

Single, S., and Borst, A. (1998). Dendritic integration and its role in computing image velocity. Science *281*, 1848–1850.

Spavieri, D.L., Jr., Eichner, H., and Borst, A. (2010). Coding efficiency of fly motion processing is set by firing rate, not firing precision. PLoS Comput. Biol. *6*, e1000860.

van Hateren, J.H. (1992). Real and optimal neural images in early vision. Nature *360*, 68–70.

Wilson, R.I., Turner, G.C., and Laurent, G. (2004). Transformation of olfactory representations in the *Drosophila* antennal lobe. Science *303*, 366–370.