

# Adaptive Motion Detectors Inspired By Insect Vision

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## Introduction

Inventions such as miniature unmanned aerial vehicles would extend our capabilities in a variety of areas and are a major focus of active research. Before their promise can be reached, however, significant challenges in guidance and control, flight mechanisms, and energy storage must be overcome. Engineers and scientists are turning to animals, particularly insects, for inspiration about how evolution has solved these problems. Our group believes that understanding the visual system of the fly will provide solutions for building a small and efficient visual system suited for real-time flight control. We are therefore investigating the algorithms used in visual motion detection and course stabilization implemented in neural hardware by the fly and translating the concepts into software and analog, “neuromorphic” VLSI electronic implementations. The present work shows that flies implement an adaptive contrast gain control on visual signals before performing motion detection, resulting in neural responses that signal velocity largely independently of overall contrast in the visual input. Additionally, we describe a circuit that implements a proposed mechanism of adaptive contrast gain control based on our neurobiological findings.

The spatiotemporal pattern of light an observer sees while moving, called optical flow, can be used to estimate self-motion and thus guide flight. In flies, a prominent class of cells, the wide-field movement detecting neurons of the lobula plate, are sensitive to movement over a large portion of the visual world and have been shown to be involved in optomotor stabilization (Hausen and Wehrhahn 1983, Hausen and Wehrhahn 1990). These cells have been suggested to respond selectively to the pattern of optic flow induced by particular forms of self-motion. For example, one group of these wide-field movement detectors, the HS cells (“horizontal sensitive”) have response properties suggesting selectivity for yaw-induced visual motion (Krapp et al., 1998). Thus, a prevailing hypothesis is that the HS cells stabilize against yaw rotation through selectively responding to yaw-induced optic flow and causing a compensatory turning response via outputs to the central brain and motor control system. In a similar manner, the VS cells (“vertical sensitive”) are postulated to stabilize against roll and pitch rotations.

The large receptive fields of the wide-field movement detectors are thought to arise through a non-linear spatial integration of many elementary motion detectors, or EMDs

(Borst et al., 1995). By understanding the computational principles employed by the EMDs we aim to produce an array of electronic EMDs on the focal plane of an integrated vision chip (Shoemaker et al., 2001). Additionally, the outputs of this array could be spatially integrated to mimic the responses of HS and VS cells and could potentially be used to stabilize a hovering aircraft against unwanted rotations.

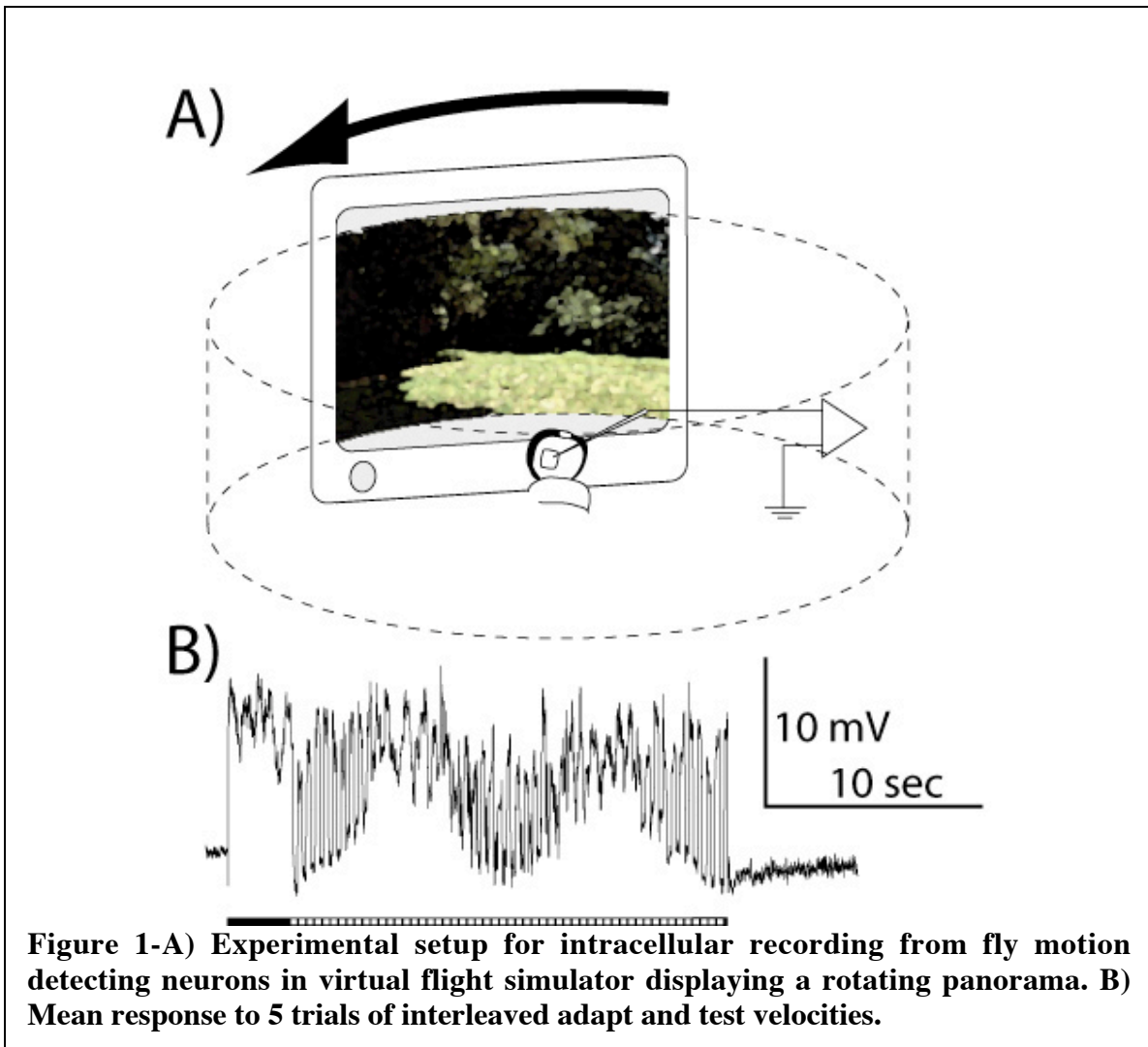
The most successful family of computational models to describe the EMDs is based on the Hassenstein-Reichardt correlator model (Hassenstein and Reichardt, 1956, rev. Reichardt 1961). In the “half-correlator”, two nearby spatial luminance signals (from adjacent photoreceptors, for example) are multiplied after passing through asymmetric delay filters. In this way, a directionally selective response is generated, but suffers from sensitivity to non-motion induced overall changes in illumination. To eliminate this non-motion component, a mirror symmetric half-correlator (delays switched) is subtracted from the output of the first half-correlator to produce a final, motion sensitive output. While decades of work supports the correlator model as a useful predictor of biological motion detector responses, the original form can be significantly improved when predicting responses to motion. For example, spatial and temporal prefiltering, saturation of neural elements (compressive non-linearities), and spatial integration with output of other EMDs have all been used to more accurately predict the responses of HS cells (Dror et al., 2001).

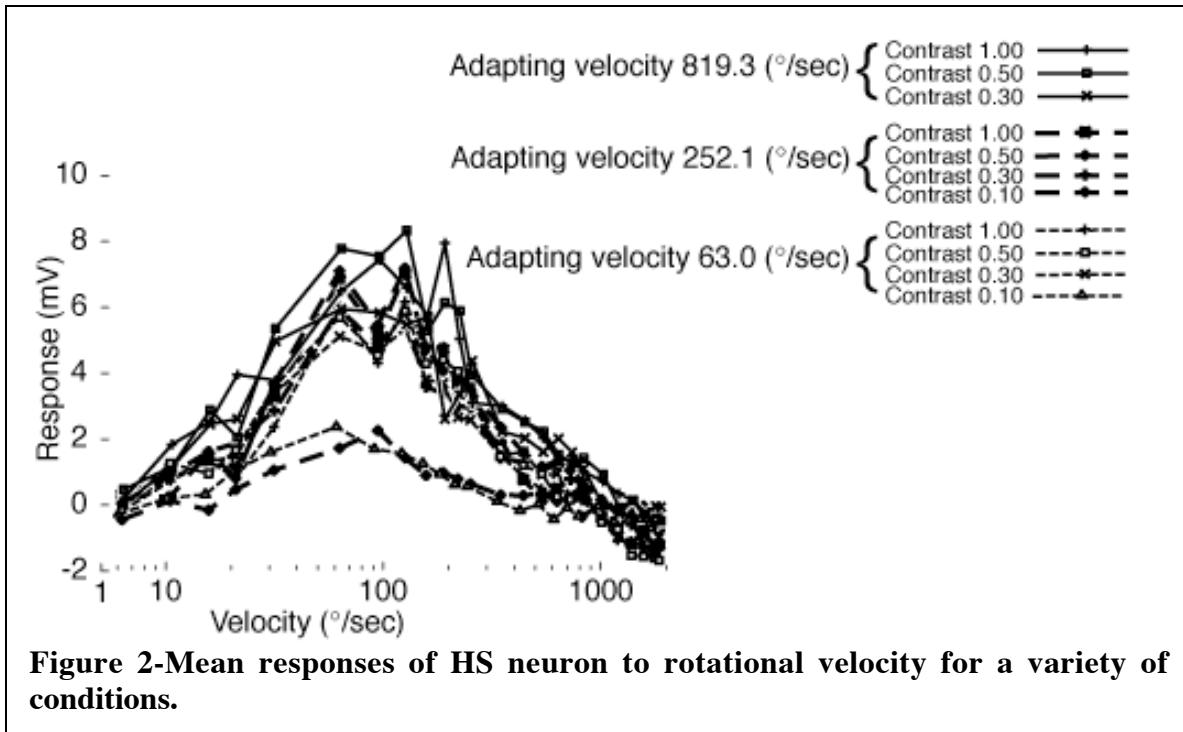
## **Adaptive gain control prior to motion detecting neurons**

A striking phenomenon observed in the responses of wide field movement detectors but not predicted by the original correlator model is adaptation, which was first described in the 1980s (Maddess and Laughlin, 1985, de Ruyter van Steveninck et al., 1986, Borst and Egelhaaf, 1987). Recent work shows that adaptation consists of a direction insensitive contrast gain reduction and a direction selective hyperpolarization (Harris et al., 2000). Functionally, it is not clear how these adaptive mechanisms affect the behavior of biological movement detectors in real-world situations, so we have performed experiments to measure the response of HS cells in a novel virtual reality flight simulator programmed using the Vision Egg software library developed in our laboratory (Figure 1A). Intracellular electrophysiological recordings were made from restrained hoverflies viewing a CRT subtending ~100 degrees. Panoramic scenes obtained from natural habitats were perspective-distorted, temporally anti-aliased (motion blurred), and updated at 200 frames per second to simulate yaw rotation induced optic flow. After a prolonged (3s) initial adaptation period, 200ms bursts of test speeds were interleaved with further 200 ms adapting periods. Test speeds were monotonically increasing to the maximum velocity tested and then decreased in order to maximize and measure any potential hysteresis, which was found to be minimal. Velocity-response curves were obtained at various combinations of contrast, adapting velocity, and initial phase.

HS cells responded to rotational motion across 3 decades of stimulus velocity, peaking at 100 degrees per second (Figure 2). The shape and magnitude of motion-adapted velocity tuning curves are very similar over a large range of adapting speeds. Additionally, global image contrast can be reduced to less than 30% of the original value before responses to velocity become weak and differ significantly from responses measured at higher contrasts. Fluctuations in the response appear to be noise in individual trials (Figure 1-B), but repeated stimulation shows much of this variability to be image feature dependent and can be reduced by signal-averaging trials in which the animal is stimulated with the same velocity waveform starting at different initial angular positions (as measured in Figure 2).

Our results suggest a functional role for the contrast gain reduction component of motion adaptation described by Harris et al., 2000. As the data presented here suggest, HS cells provide reliable estimates of velocity in natural conditions, despite variability in global image contrast. This “velocity constancy” may be functionally important for the fly, which uses the output of these cells for optomotor stabilization. We propose this velocity





**Figure 2-Mean responses of HS neuron to rotational velocity for a variety of conditions.**

constancy results from an adaptive contrast gain reduction in motion detector inputs.

The greatest remaining source of “noise” in the response results from the spatial structure of the stimulus. Since our display stimulates only a subset of the large receptive fields of these cells, it is likely that such pattern-induced response variability is reduced during natural behavior due to stimulation of the entire receptive field. Additionally, the simultaneous activity of other wide-field motion detecting neurons, including those with contralateral receptive fields, may combine downstream to create a signal with less variability.

**Biomimetic implementation of adaptive motion detection**

As the basis for a neuromorphic analog VLSI vision chip containing of an array of on-focal-plane EMDs, we are creating biologically inspired EMDs in silicon with adaptive properties similar to those we propose in fly motion detectors. There have been other efforts to create biologically inspired correlator-type EMDs in silicon (Delbrück, 1993, Harrison and Koch, 1998, Harrison and Koch, 2000). One implementation (Liu, 1996) implemented an adaptive model based on varying the delay filter time course suggested to occur in fly motion detectors (Clifford and Langley, 1996), but subsequently challenged on the basis of further experiments (Harris et al., 1999).

We have proposed a circuit for implementation in silicon based on a model of the adaptive contrast gain control found in fly movement detectors (Shoemaker et al., 2001). In this circuit, contrast gain control occurs via attenuation of the inputs to the correlation mechanism based on feed-forward mechanism. A copy of the un-attenuated inputs to the correlator is rectified and low pass filtered to produce a normalization signal which may normalize the inputs to the correlation mechanism via shunting inhibition. This

normalization is gated via a binary (on-off) feedback circuit computed from a copy of the EMD output which is rectified, low pass filtered, and compared against a reference signal. Implementation of such an algorithm in analog VLSI using the traditional CMOS process has many potential difficulties, such as junction leakage currents, transistor mismatches, and noise when operating in subthreshold mode. For these reasons, we are also pursuing an implementation using the Silicon-On-Sapphire (SOS) process. In this process, a thin film of silicon a high-dielectric layer is etched away to produce electrically isolated transistors. Features such as the long time constants required by the correlator mechanism are difficult to implement in CMOS, and may be more suitable for production with SOS process.

## Summary

Motion adaptation is an important component of the response of fly wide-field motion detectors. There are two components to motion adaptation in these cells, a contrast gain reduction and a hyperpolarizing offset (Harris et al., 2000). We show that a functional consequence of motion adaptation is a velocity-response relationship which is largely insensitive to overall contrast and stimulus history. We are building an analog neuromorphic VLSI implementation of adaptive EMDs which exhibits this same “velocity constancy”.

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