Encoder Adaptation Modulates the Visual Responses of Crayfish Interneurons

Raymon M. Glantz and John P. Schroeter
Dept. Biochemistry and Cell Biology
Rice University, Houston Tx

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Correspondence to:
Raymon M. Glantz
Friday Harbor Laboratory
620 University Rd
Friday Harbor WA 98250
phone (360) 378 - 4271
correspondence email rmg@bioc.rice.edu
Abstract and Summary

The responses of sustaining and dimming fibers were characterized by the time varying firing rates elicited by extrinsic current and flashes of light. These data were simulated by an adaptive integrate-and-fire model. A post-impulse shunt conductance simulated spike-frequency adaptation. The correlation between observed and model current-elicited impulse rates were 0.94 to 0.98. But for a difference in input resistance (both measured and simulated), the voltage to impulse encoders of the two cell groups are similar and exhibit comparable degrees of spike-frequency adaptation (40 to 45%). The encoder model derived from current-elicited responses (with fixed parameters) was used to simulate visual responses elicited by light flashes. These simulations included a synaptic current derived from the time course of the postsynaptic potential (PSP). The sustaining fiber visual response consists of a large excitatory PSP and high frequency transient burst which adapts (by about 80%) to a low frequency plateau discharge. The simulations indicate that spike-frequency adaptation has no effect on the transient discharge but reduces the plateau firing rate by about 60%. Encoder adaptation enhances the sustaining fiber response to the time derivative of the stimulus. In dimming fibers, the light flash elicits an inhibitory PSP which interrupts the ‘dark discharge’ and an OFF response following the end of the flash. The simulations indicate that spike-frequency adaptation reduces the firing rate of both the dark discharge and the OFF response. Thus the model suggests that different effects of encoder adaptation on the two cell types arise from the same encoder mechanisms but with different actions determined by differences in impulse rate and the time course of the discharge.
A critical feature of many sensory systems is the capacity to detect change in the environment. This capacity is expressed in a disproportionately higher neuronal sensitivity to fast temporal variations in stimuli. In visual systems it is well established that light adaptation in photoreceptors and the properties of the peripheral lateral inhibitory network contribute to the response adaptation observed in higher order cells (Naka and Nye, 1970; Sakai, 1992; Glantz and Bartels, 1994). In several systems, the firing rate of higher order visual neurons appears to be linearly related to the magnitude of the suprathreshold post-synaptic potential (PSP) (Korenberg et al, 1989; Sakai, 1992; Carandini and Ferster, 2000). Thus the firing rate may be controlled by the dynamics of the afferent pathways which generate the PSP.

In crayfish visual interneurons (i.e sustaining fibers and dimming fibers, Kirk et al, 1983; Pfeiffer and Glantz, 1989; Glantz et al, 1995) and a number of other interneurons (Fohlmeister et al, 1977; Powers and Binder, 1996; Poliakov et al, 1997; Galarreta and Hestrin, 2001) the time course of the discharge may be quite distinct from that of the PSP and the discharge may exhibit a higher temporal frequency response than the PSP (Knight et al, 1970; Glantz et al, 1995; French et al, 2001). Following an illumination increment (or decrement for dimming fibers), response adaptation in the sustaining fiber PSP is on the order of 15 to 50% while the concurrent sustaining fiber discharge may decline by up to 95 or even 100%. The difference may reflect the impulse threshold, the properties of the spike generating mechanism (i.e. the voltage to impulse encoder) (Mainen and Sejnowski, 1995; Wang, 1998; Kretzberg et al, 2001), dynamic properties of the synaptic current (Dobrunz et al, 1997), voltage-dependent conductances in the dendrites (Magee et al, 1998) or some combination of these. A substantial body of theoretical work suggests that self-inhibition (Knight et al, 1970; Fohlmeister et al, 1977) or spike-frequency adaptation (Wang, 1998; Ermentrout, 1998; Liu and Wang, 2001; Benda and Herz, 2003) may contribute to the time-dependent decline of the sustaining fiber visually-elicited step response. The extent of that contribution however is not accessible to simple inspection because the adaptation is dynamically determined by the recent history of impulse activity (Liu and Wang, 2001; Benda and Herz, 2003). Furthermore encoder adaptation may be based upon any of several
ionic channels (Sah, 1996; Schwarz et al, 1997; Benda and Herz, 2003) with different dependence upon voltage, intracellular [Ca²⁺] or the recent history of impulse activity. Variations in channel distribution can produce substantial differences in the time course of the discharge (Wang and McKinnon, 1995) among otherwise similar cells.

Sustaining fibers have several features that can facilitate the analysis of integrative mechanisms. Dendritic recordings (Kirk et al, 1983; Waldrop and Glantz, 1985) reveal PSPs of up to 40 mV associated with impulses of only 5 to 10 mV. Thus the PSPs can be separated from the spike trains (French et al, 2001) while preserving most of the details of the time-varying membrane potential. Furthermore, the impulses appear to be passively conducted from the spike initiating zone (where the action potential amplitude is 70 to 80 mV) to the dendritic tree. Tetrodotoxin (TTX) blocks the sustaining fiber action potential but has no observable influence on the magnitude or time course of the PSP (Waldrop and Glantz, 1985). In the presence of TTX the current-voltage functions principally reveal a leakage conductance. This implies that the voltage-dependent conductances are not present in high density in the dendrite. If voltage-dependent dendritic currents are minimal, the relationship between the PSP and the firing rate is principally governed by the time course of the synaptic current and the dynamical properties of the spike generating mechanism. Here we formulate a minimal adaptive integrate-and-fire model that uses synaptic currents to generate impulses at rates controlled by spike-frequency adaptation (Koch, 1999; Liu and Wang, 2001). The analysis and model are implemented for two cell classes (sustaining fibers and dimming fibers) arising in the crayfish second optic neuropile. The cells have complementary visual responses (ON vs OFF discharges) but discharge at substantially different rates.

Extrinsic current was used to characterize impulse generation (i.e. the voltage to impulse encoders). We found that spike-frequency adaptation diminished the current-elicited firing rate by 35 to 45% in 50 to 200 ms in both cell classes. The time varying firing rates were simulated by an adaptive integrate-and-fire encoder model. Spike-frequency adaptation was simulated by a shunting conductance. For each cell, the same
model with fixed parameters and supplemented by a model of the synaptic current was then used to describe the visually elicited response. Because the simulated visual responses contain the adaptive characteristics of the encoder, they provide a theoretical measure of the influence of encoder adaptation on the visually elicited discharge. The simulations indicate that spike-frequency adaptation contributes to the time-dependent decline of the sustaining fiber visually elicited discharge and it influences both the dark discharge and decremental responses of dimming fibers.

Methods

The Physiological Preparation

Adult crayfish, *Pacifastacus leniusculus*, of both sexes were prepared as in (Glantz et al., 1995). The eyestalks were cemented into their sockets with cyanoacrylate adhesive and chilled to 8°C. The haemolymph was replaced with oxygenated crayfish saline buffered with 5.0 mM Hepes at pH 7.5. During the experiments, the animal was clamped in a lucite chamber and submerged in buffered saline which was continuously oxygenated and slowly warmed to 15°C. The optic lobe was exposed by removal of the dorsal eyestalk cuticle and the optic neuropile was visualized by removing portions of an overlying sheath. The results are based upon studies of 48 neurons in 34 animals. Twenty nine of these neurons met several constraints and they are the focus of this report. These 29 cells exhibited repeatable responses to both current and light and they were differentially responsive to a range of stimulus magnitudes. Furthermore, in each of these cells the PSPs were large enough so that the PSP time course could be extracted (see below) from the complex physiological waveform which also included action potentials.

Recording and Data Acquisition

Sustaining and dimming fibers were impaled in the second-optic neuropile (medulla externa) with sharp micropipettes filled with 3.0 M K+-acetate. Electrodes had 80 to 100 Mohm resistances and 0.2 to 0.4 ms time constants (after capacity compensation). Signals were led to an Axoclamp (Axon Instruments, Foster City, CA) IB amplifier. The neurons were identified by their location and their characteristic responses to a
flash of light. The voltage, current and stimulus signals (see below) were digitized at 1000 Hz/channel with a National Instruments (Austin, Tx) A/D card running under a Pentium computer and LABVIEW software.

**Visual Stimuli**

Light flashes were produced with a green (\(\lambda = 532\) nM) solid state laser diode (MWK Industries, Pomona, CA) with maximum intensity of 1.2 mW/mm\(^2\) at the eye. The laser beam was positioned with galvanometer mirrors. Stimulus intensity was controlled with a neutral density wedge with optical density spanning 6.0 log\(_{10}\) units and with the optical density increasing by a factor of 10 over each 2.5 cm of wedge length. The laser diode was operated with a relay circuit and pulse generator. Contrast flashes were derived from a Hitachi display oscilloscope driven by a Picasso Image Synthesizer (Innesfree, Cambridge, U.K.). A stimulus patch subtending 10-20E degrees was superposed on a background subtending a 120E on a side. Stimulus flashes were of 0.5 to 1.0 s duration presented at 0.2 Hz or 5.0 s duration presented once per 30 s. The 5.0 s stimuli were used in the earliest studies to determine the time course of adaptation. Since most cells approach steady-state in 0.5 to 1.0 s, about 90% of the data were obtained with the shorter flashes.

**Current Injection Protocols**

Impulse trains were elicited with rectangular pulses of 0.02 to 4.5 nA. The pulses were 0.5 to 4.0 s duration and delivered at a repetition rate of 0.2 to 0.05 Hz. The magnitudes and durations were set to generate a wide range of impulse rates, and of sufficient duration to measure the spike frequency adaptation. To minimize long-term or cumulative adaptation the current pulses were delivered in blocks of 10 to 20 stimuli separated by 30 to 60 s. Test pulses of fixed magnitude were inserted throughout the stimulus sequence to assess nonstationarity. The injected currents were monitored at a port on the Axoclamp IB amplifier.

**Computational Methods**

**Spike train isolation**

The light- and current-elicited impulse trains were separated from the PSP or slowly varying
potential by wavelet denoising (Johnson et al, 2000). In this non-linear method, the wavelet transform was computed using the Daubechies-6 (Daubechies, 1994) wavelet. Wavelet coefficients less than an adjustable threshold were set to zero, and the result was inverse transformed to give the raw spike train.

PSP extraction

For the light-elicited responses, the PSP was separated from the superposed spike train by digital subtraction of the previously identified spikes (French et al, 2001). The binarized spike train (a train of ones and zeros) produced by wavelet denoising was first used to locate the spike positions. The spike foot was then found using the known spike width, adjusted for PSP-dependent variations. The spike was removed from the baseline potential by interpolation. This method yielded a potential comparable to that in the raw data, and, except for the small regions spanned by the spike foot, the high frequency membrane noise was left intact. A possible difficulty is that some of the spike foot is inevitably included in the voltage record. To evaluate this artifact we hyperpolarized cells with sufficient current to block impulse generation during the light response and then compared the time course of the PSP isolated by hyperpolarization (as in Fig. 1B, continuous trace) to those derived by spike subtraction (as in Fig. 1B, broken trace) from responses elicited at rest potential shown in Fig. 1A. In general we found that with intradendritic recordings the PSPs were large (up to 35 mV) and the impulses small (5 to 10 mV), and the averaged PSP isolated by subtraction was nearly indistinguishable from that isolated by hyperpolarization. Conversely, recordings nearer the spike initiating zone exhibited 40 to 80 mV impulses superposed on 2 to 5 mV PSPs. Four of the 21 sustaining fibers and 6 of 18 dimming fibers had these features. In these cells the PSPs isolated by spike subtraction contained large artifacts and the data could not be used to compute the synaptic currents in the second phase of this study.

Specification of the Stimulus

For the current injection experiments, a square-wave current trajectory was obtained by appropriate scaling of the voltage representation of the stimulus. For light-elicited responses, the input to the model was
the current derived from the PSP with Eq. 3. Because the simulations are sensitive to the recent history of activity (e.g. impulses), computations initiated at the start of a stimulus sequence can generate large artifacts. To avoid these artifacts, the beginning of each data set was lengthened by two stimuli and associated with two average responses for model input and these stimulus-response pairs were discarded at the end of the computation.

Characterization of the Response for Model and Data

The response of the cell and of the model were expressed as a time varying impulse rate or post stimulus time histogram (PSTH). The impulse rate at a particular point in time, \( t_i \), was calculated as the inverse of the time between the binarized spikes surrounding \( t_i \). The PSTH was calculated using fixed width bins (10 ms) distributed over the duration of one data sample and smoothed by a moving window average of 2-4 neighboring bins.

Adaptive Leaky Integrate-and-Fire Model

The adaptive leaky integrate-and-fire encoder is given by:

\[
I_e + I_s + I_b = \left( \tau_m/R_{in} \right) \frac{dV}{dt} + \left( G_{\text{adapt}} + 1/R_{in} \right) V \tag{1}
\]

where \( I_e \) is the extrinsic current, \( I_s \) is the synaptic current (set to 0 for noise-free extrinsic current studies), \( I_b \) is a steady background current that drives spontaneous impulse activity, \( V \) is the membrane potential above resting potential (\( V_{\text{rest}} = 0 \)), \( \tau_m \) is the membrane time constant, and \( R_{in} \) is the input resistance. When \( V \) reaches the impulse threshold, \( V_{\text{th}} \), an impulse is produced and \( V \) is set to \( V_{\text{rest}} \). \( G_{\text{adapt}} \) is the post-impulse conductance (the adaptive mechanism) which is initially zero and incremented after each impulse by \( G_{\text{inc}} \). \( G_{\text{adapt}} \) then decays exponentially with time constant \( \tau_{\text{adapt}} \):

\[
\frac{dG_{\text{adapt}}}{dt} = -\frac{G_{\text{adapt}}}{\tau_{\text{adapt}}} \tag{2}
\]

\( G_{\text{adapt}} \) is a shunting conductance (Koch, 1999). It gates the currents of Eq. 1 but it is not specifically linked to a potassium equilibrium potential.

Previous studies (Fohlmeister and Miller, 1997; Liu and Wang, 2001) indicate that an adaptive
mechanism based upon a calcium-activated potassium conductance will be delayed due to the time required for Ca$^{2+}$ to accumulate in the cytoplasm. Furthermore, we found that the hyperpolarizing after-potential associated with each impulse typically required about 20 ms to attain maximum amplitude. We simulated this delay by requiring a succession of two impulses above a specified impulse rate threshold for activation of $G_{\text{adapt}}$ following onset of a current pulse or light flash. The threshold rate was set just below the peak rate of the smallest transient response in each series.

The impulse rate is also constrained by the refractory period, $t_{\text{ref}}$. $V$ is held at $V_{\text{rest}}$ following each impulse at $t_i$ so long as $t - t_i < t_{\text{ref}}$.

**Currents Derived from the Membrane Potential or PSP**

The extracted potential provided the basis for computing the synaptic current, by assuming that the potential is constrained by the same variables that define the encoder. Thus $I_s$ is given by,

$$I_s = (\tau_m / R_{in} k_s) \frac{dV}{dt} + (V G_s(V) / k_s)$$

Here, the synaptic conductance $G_s(V)$ was previously shown to be a fixed sigmoidal function of the instantaneous synaptic potential ($V$) (Waldrop and Glantz, 1985). As the potential varies from 0 to 40 mV, $G_s$ normalized by the resting input conductance, $G_{in} (R_{in}^{-1})$, varies from 0 to 1.5. $G_s$ acts in parallel with $G_{in}$. $k_s$ represents the ratio between the synaptic resistance and the input resistance, $R_{in}$ at the spike initiating zone, and $\tau_m$ is the membrane time constant. For the visual stimuli, $I_s$ was calculated from the PSP using Eq. 3 for input to Eqs. 1 and 2.

**Optimization of Model Parameters**

Equations 1 and 2 specify a seven-parameter ($I_{b}, G_{inc}, \tau_{\text{adapt}}, V_{th}, t_{\text{ref}}, \tau_m, R_{in}$) model which generates firing times given the extrinsic ($I_e$) and synaptic ($I_s$) currents. To describe the response to current stimuli $I_s$ is set to zero. To describe the response to light flashes, $I_e$ is set to zero and $I_s$ is calculated from Eq. 3.
In this case, the model has eight parameters, including the resistance ratio, $k_r$. In practice the refractory period ($t_{ref}$) was fixed to a value slightly smaller than the shortest interspike interval (4 or 5 ms) and was not varied during optimization. For each cell, an optimum fit of the model response to the observed response was discovered for the current step stimuli. The parameters so determined were used to describe the model response to light flashes, varying only the background current $I_b$ and the resistance ratio $k_r$. It was necessary to vary $I_b$ between the two simulations because the background discharge often varied between sets of measurements and was usually suppressed by repeated flashes of light.

To find the best fit of model responses to stimulus-elicited responses, the step current input or the extracted PSP input was discretized with a time interval of 0.5 ms (one half the digitization interval). This time step reduced aliasing artifacts to a few percent, and allowed reasonably rapid calculation times. Selection of optimum parameters for the fit was performed using the Nelder-Mead methods in the MATLAB optimization toolkit. Software was produced in house to start the optimization from a particular set of parameters and to specify the parameter dimensions used. Discovery of the true optimum was difficult due to the "stair-step" nature of the optimization surface, which in some cases had many non-minimal but relatively flat regions. These regions were avoided by requiring the optimizer to restart many times at regions distant from an apparent minimum. The best fitting parameters found by this procedure were taken to be the true optimum.

The fit of the model to the data was evaluated by the root mean square error (RMSE) and the linear correlation coefficient. The RMSE = $\sqrt[3]{\frac{\sum (F_d - F_m)^2}{n}}$ where $F_d$ is the observed instantaneous impulse rate, $F_m$ is the model instantaneous rate and $n$ is the number of data points in the optimized data set. Optimization was always performed on a family of responses (5 to 13) associated with variations in extrinsic current. The tabulated results indicate the RMSE normalized by the average standard deviation (SD) of the measured data set.
Results

Our current injection studies were carried out on 21 sustaining fibers and 18 dimming fibers. Our overall strategy had two phases. In the first we characterized the spike generator by analysis of the time-varying discharge elicited by current pulses and simulation of the discharge by Eqs. 1 and 2. The optimized model provided good approximations of the peak and steady-state firing rates and the magnitude of spike-frequency adaptation in every neuron. In the second phase, we examined the visual responses of 29 of the same neurons and simulated these responses as an interaction between the synaptic current (derived from the PSP) and the identical model (same parameter values) derived from responses elicited by extrinsic current.

The Sustaining Fiber’s Current-elicited Discharge

At suprathreshold currents, the characteristic response pattern consists of a brief high frequency transient followed by adaptation to a lower frequency plateau rate (as in Fig. 2 A-D). Adaptation reduces the firing rate by about 40% as described below. The peak transient rate (estimated from the first one or two interspike intervals as in the firing rate functions of Fig. 2 E-H) is occasionally quite variable (average coefficient of variation (CV) is 0.18) while the plateau discharge is both regular and less variable (CV is 0.11) as shown by the shaded areas (±1.0 S.D.) of Fig. 2 E-H. The average CV for the whole population was 0.06 for the transient and 0.08 for the plateau discharge. In spontaneously active neurons, the termination of the current pulse is typically associated with a hyperpolarization and silent period in the discharge of up to several hundred ms duration as in Fig. 2 A-D. Similar responses in other cells have been attributed to the cumulative effects of a slow hyperpolarizing after-potential (Wang and McKinnon, 1995; Schwarz et al, 1997). We estimated the speed of adaptation by fitting a single exponential (by least squares) or the sum of two exponentials to the firing rate functions between the peak and the end of the plateau. At peak firing rates less than 25 imp/s, the firing rates of nearly all cells decline as a single exponential with a time constant ($\tau_a$) of 100 to 250 ms. For about half the cells the same holds for rates up to 60 imp/s and the time constants were weakly dependent (correlation coefficient ($r = 0.55$) upon the inverse of the peak impulse rate (data
not shown). At the highest firing rates, adaptation evolves in two stages (as in Fig 2 G and H and Fig. 3F-H for dimming fibers) as previously described in other neurons (Sawczuk et al, 1995; Wang, 1998). The initial phase is rapid ($\tau_{a1} = 21.7 \pm 11.1$ ms) and accounts for 70% of the total adaptation. In the second stage $\tau_{a2}$ is 100 to 300 ms. The two time constants were relatively insensitive to the peak impulse rate but the component of adaptation associated with $\tau_{a1}$ increased as the peak firing rate increased.

Simulation of the Sustaining Fiber Response to Extrinsic Current

The firing rates simulated by the adaptive integrate-and-fire model are shown by the continuous line superposed on the shaded areas of Fig. 2 E-H. The model captures the principal features of the observed response including i) the timing of the peak impulse rate; ii) the current-dependence of both the peak and plateau firing rates (details in Fig. 4); and iii) the suppression of the discharge following the termination of the current pulse. The correlation between the measured and simulated instantaneous firing rates (elicited by 7 current magnitudes) was 0.96 (the RMSE/SD was 0.91SDs Table 1, column 1). Similar results were obtained for a population of 17 sustaining fibers (Table 1, column 2). We estimated the temporal accuracy of the model by comparing the observed and simulated latencies to 90% of the maximum impulse rate. For the cell described in Fig. 2; at the lowest 3 current magnitudes the model latencies deviated from observed values by 6 to 22 ms. At the higher currents tested the average deviation was less than 1.0 ms. For the population as a whole the average deviation at the highest currents was 4.8 ± 3.6 ms. It is possible that the underlying mechanisms of $G_{\text{adapt}}$ ($G_{\text{inc}}$ and $\tau_{\text{adapt}}$) might vary systematically with the firing rate. We examined this possibility by optimizing the model, one response at a time, for each response in a series. We found no evidence for systematic variations. In general, $G_{\text{inc}}$ and $\tau_{\text{adapt}}$ optimized for single responses, fell within a few percent of the values obtained for the entire response population. This result implies that wide variations in the magnitude of adaptation can be produced by variations in the current-elicited firing rate and an invariant adaptive mechanism.

For the entire sustaining fiber data set, the simulated $\tau_{\text{adapt}}$ was $99 \pm 77$ ms and it provided a
reasonable estimate of the time course of adaptation in most responses. The responses which exhibited two
decay time constants during adaptation were also approximated by $\tau_{\text{adapt}}$ (as determined in the optimization
routine) and these simulations were less precise. For these data the simulated responses generally decayed
more slowly than the observed responses as shown in the dimming fiber response in Fig. 3H and the
discrepancy contributed to the RMSE. The optimized value of $\tau_{\text{adapt}}$ was typically between $\tau_{a1}$ and $\tau_{a2}$.

We also found that $\tau_{\text{adapt}}$ is similar to the decay time constant of the hyperpolarizing after-potential
(as in Table 1). The significance of this similarity is that $\tau_{\text{adapt}}$ is the theoretical decay time constant of the
post-impulse conductance and this time constant should be reflected in the time course of the hyperpolarizing
after-potential.

*The Dimming Fiber Current-Elicited Response*

Dimming fibers are characterized by an OFF response following a decrement in illumination and
inhibition of a tonic discharge following an increment of illumination. The dimming fiber current-elicited
discharge, shown in Fig. 3 A-D, is similar to that of sustaining fibers with a short latency transient discharge
followed by rapid adaptation to a lower frequency plateau rate. The speed of the initial phase of adaptation
can be ascertained from the firing rate plots in Fig. 3 E-H. At the highest currents (as in Fig. 3H) the peak
rate persists for no more than two interspike intervals.

*Simulation of the Dimming Fiber Response to Extrinsic Current*

The integrate-and-fire simulation of the dimming fiber discharge was comparable to that for
sustaining fibers. The model response (as in Fig. 3 E-H, solid line through the shaded area) captured the
timing of the peak rate and provided good approximations of the transient and plateau firing rates. The model
parameters for dimming fiber simulations (Table 1, columns 4 and 5) were generally similar to those of the
sustaining fiber simulation but for the input resistance (Table 1, $R_{in}$) which was 100 to 200% larger for the
dimming fibers. For the cell described in Fig. 3, we simulated the responses to 9 current magnitudes (model
parameters in Table 1, column 4) and the correlation between observed and model responses was 0.98 (RMSE
as noted in Methods, the optimization surface has a ‘stair-step’ nature which implies that changes in one parameter (e.g. $V_{th}$) if accompanied by changes in other parameters (e.g. $I_b$, $R_{in}$) may produce no change in the RMSE. In this respect any particular model (i.e. a specific set of parameter values) should be viewed as a global description (Goldman et al, 2001). Although the model approximates the behavior of the neuron (in a least squares sense), the particular parameter values of the model are only meaningful in the context of the entire set.

It is significant however that the fit of the model to the data is not equally sensitive to variations in the several parameters. We determined the percent change in each of the parameters that is necessary to increase the RMSE by 50%. The relative sensitivities (inversely related to the percent change) were; $V_{th}$ (11%) > $R_{in}$ (16%) > $\tau_{adapt}$ (18%) > $G_{inc}$ (20%) >> $I_b$ (46%) > $\tau_m$ (50%) >> $t_{ref}$ (82%). The sensitivity analysis also revealed that reductions of parameter values were generally more effective than increases \textit{vis a vis} an increase in the RMSE. Furthermore, the relative significance of a parameter can vary between cells and different parameters typically influence different aspects of the response. Thus the sensitivity to variations in $\tau_{adapt}$ is high in strongly adapting cells and low in weakly adapting cells. The peak firing rate is sensitive to $V_{th}$ and $R_{in}$ but relatively insensitive to $G_{inc}$ and $\tau_{adapt}$. The reverse holds for the simulation of spike-frequency adaptation. If two variables are changed simultaneously such that the changes have opposing effects on the firing rate (e.g. a reduction in $V_{th}$ and a reduction in $R_{in}$) it requires about twice as large a percentage change (compared to single variable changes) to produce the same increase in RMSE.

To measure the robustness of the model we determined the extent to which variations of the entire set of parameters could compensate for a large change in any one of them (e.g. $V_{th}$). We reduced one parameter value sufficiently to increase the RMSE by 50% and optimized the remaining six parameters to minimize RMSE. Invariably, the RMSE of the new parameter set was within 1-2% of the original minimum.
If the initial condition involved two parameters jointly offset (by 20 to 40%) to produce a 50% increase in RMSE, optimization of the 5 remaining parameters could reduce the RMSE to within 10% of the original value. These results imply that the ability of the model to describe the neural responses as defined by the RMSE is a robust feature of the structure of the model and not a reflection of particular parameter values.

**Predictive Power of the Integrate-and-Fire Model**

When spike trains are elicited by ramp or sinusoidal currents the timing of the response (data not shown) is sensitive to the slope or frequency as well as the magnitude of the current trajectory (Knight et al, 1970; Fohlmeister et al, 1977). Small deviations in the timing of simulated responses can produce large increases in the RMSE compared to model descriptions of the responses to current pulses. When the parameters of Eqs. 1 and 2 are optimized for these responses, the RMSE is typically 20 to 30% larger than that for comparable current pulse responses. We examined the predictive power of the model for different current waveforms in 19 cells. In each case the model was optimized for responses to current pulses and we determined the RMSE of the model (with fixed parameters) for a population of responses to sine wave currents of varied frequency or ramp currents with varied depolarizing slope. The RMSE for the pulse-elicited responses was equivalent to about 0.68 SDs relative to the measured responses. In 10 of the 19 cases, the RMSE of the simulated ramp- or sine wave-elicited response was about 20 to 30% larger than that for the pulse responses. For these cells, the model derived for the responses to current pulses was about as good as an unconstrained simulation of the same data. In another four cells the principle deviation was a shift in the level of spontaneous activity between the two stimulus protocols. For these cells an adjustment of I_b brought the RMSE of the simulation to within 20 to 30% of that for the pulse responses. For the remaining five cells the RMSE of the model response was about 200% larger than that for the pulse-elicited responses. The principle source of the discrepancy was an apparent reduction in the neuron’s sensitivity to current when subjected to continuous sinusoidal current. The sensitivity shift may indicate a nonstationarity in the spike generator. Alternatively, the reduced sensitivity may reflect the activation of a slow and persistent form of
spike-frequency adaptation (Sawczuk et al, 1995) elicited by the continuous impulse activity during sine wave stimulation.

*Frequency - Current (F-I) Functions*

The f - I functions are an important feature of the voltage to impulse encoder and also provide useful estimates of spike frequency adaptation. The open circles in Fig. 4A indicate the peak firing rates vs. extrinsic current and the squares are the steady-state rates for the sustaining fiber responses shown in Fig. 2. The vertical lines are ± 1.0 standard deviation (SD). Similarly, the circles and squares in Fig. 4B are peak and steady-state rates vs. current for the dimming fiber in Fig. 3. A common feature of f - I functions that is not shown in Fig. 4 is a relatively steep rise in the transient impulse rate between 0 and threshold current (Ermentrout, 1998). This initial segment is better described by $f \propto \sqrt{I}$ (Ermentrout, 1998) rather than $f \propto I$. To examine the generality of this description we computed the best linear fit (in a least squares sense) for $f = m_1 I + b_1$ and the best linear fit to the square root of the current ($f = m_2 \sqrt{I} + b_2$) for the transient impulse rates of each of 37 cells. When the results are evaluated by the correlation between observed and computed firing rates, the accuracy of the linear and square root models were indistinguishable for most cells. Thus the average correlation between observed and computed peak rates was 0.946 ± 0.041 (SD) for the linear model and 0.933 ± 0.060 (SD) for the square root model. In most instances the correlation coefficient was 0.94 to 0.99 but the averages are diminished by one or two more variable cells. For the plateau firing rates the f - I relationship was approximately linear in all cells (Fig. 4A and B).

For a linear regression, the slope of the least-square function provides an estimate of the encoder’s sensitivity to current (imp/s/nA) and the difference between the regression slopes for peak transient responses (Fig. 4A and B, solid lines) and steady-state responses (Fig. 4A and B, broken lines) is a measure of spike frequency adaptation. For the sustaining fiber described in Fig. 4A the adaptation calculated by this method is 37% while for the dimming fiber (Fig. 4B) it is 41%. Similar results were obtained for the two cell
populations. The average adaptations were 42.5 ± 16.4% for sustaining fibers and 45.1 ± 17.3% for dimming fibers.

In general the simulated peak and steady-state firing rates (Fig. 4A and B, Xs and ∆s respectively) closely approximated the observed rates. The correlations between observed and model peak and steady-state rates were about 0.95 and the regression slopes varied between 0.9 and 1.0. Furthermore the spike-frequency adaptation of the simulated discharge (derived from the slopes of the f - I functions, 38% to 42%) was similar to that of the neuronal responses (43 to 45%). Thus estimates of spike-frequency adaptation from f - I functions suggest 40 to 45% decline in rate between the peak and steady-state discharge.

The magnitude of the observed adaptation (i.e. the change in impulse rate from peak to steady-state, ∆F) is related to the peak impulse rate (Fp). The relationship is approximately linear and the regression slope ∆F/Fp provides an alternate estimate of spike frequency adaptation. For sustaining fibers, the two measures (f - I slopes and ∆F/Fp) yielded similar results (i.e. ~40% adaptation). For dimming fibers, ∆F/Fp appears to exhibit a somewhat larger (53.6 % )adaptation, but the difference is well within 1.0 S.D. of the estimate derived from the f - I functions. It is possible, however, that when a population of adaptation measurements is scaled by the peak firing rate (and independent of the particular cell of origin) it may vary from that scaled by current and evaluated on a cell by cell basis. We have more confidence in estimates of adaptation based upon the f - I functions because each measurement is based on the responses to 6 to 10 stimuli and the regression slopes were typically associated with high correlation coefficients.

**Interspike Intervals**

The interspike interval (ISI) statistics of the current-elicited responses exhibit a predictable relation to the stimulus current. At the lowest suprathreshold currents the discharge is irregular. Spontaneous fluctuations in membrane current and ion channel noise (White et al, 2000) contribute to the variability of the firing pattern. At rates below 10 imp/s the CV of the ISIs is about 0.6. As the current increases the firing pattern becomes more regular. At the highest currents, the mean ISI of the plateau discharge is 20 to 40 ms
and the average CV is about 0.2. The serial correlation of successive ISIs has particular relevance for cells exhibiting spike-frequency adaptation. Wang (1998) has shown (in numerical simulation) that steady-state responses with mean ISI near or just larger than $\tau_{\text{adapt}}$ should exhibit a small (~0.2) negative serial correlation due to the operation of the adaptive mechanism. Much of our data was not appropriate for these measurements because the firing rates were too high or the responses did not quite reach steady-state (and thus contain a positive bias in the serial correlation). In general we found that the serial correlations were close to zero (between ±0.05) in most responses at constant mean rates exceeding 20 imp/s and negative serial correlations exceeding -0.1 were not observed in these conditions. However, at lower firing rates of 5 to 12 imp/s, 10 of 13 cells exhibited significant (p < .05) serial correlation coefficients of -0.17 to -0.5 as shown in Fig. 5.

**Sustaining Fiber Visual Response**

Sustaining fiber excitation by an increment of illumination entails a rapid depolarization (the initial phase of the PSP) accompanied by a transient discharge as in Fig. 6A (solid trace). The PSP then declines toward a plateau phase and the time course of the decay can vary from less than 100 ms to 0.5 s. The decay phase is often associated with a silent period in the discharge, while the plateau phase elicits a sustained discharge. Variations in stimulus intensity or contrast may be expressed in the response latency, the transient or plateau response phases or all three. For the cell shown in Fig. 6, the transient phase of the PSP and the peak firing rate were nearly independent of stimulus intensity but the response latency, the PSP plateau and the sustained discharge all varied systematically with light intensity.

The firing rate functions in Fig. 6 E-H indicate that the adaptation of the light-elicited response can be both profound (approaching 100% in Fig.6E) and rapid (time constant of about 50 ms). These features are characteristic of most cells. The average response adaptation was 72±18% (N = 102) and the adaptation time constant was about 50 ms.

The firing rate variability (shaded areas in Fig. 6E-H are ±1.0 SD of the mean rate) was typically
about 20% (CV = 0.2) of the mean instantaneous rate throughout the response. Because the firing rate functions are derived from the reciprocal of the interspike intervals, a CV of 0.2 for a peak rate of 100 imp/s implies that the interspike intervals at the peak of the transient discharge are about 10.0 ± 2.0 ms.

Simulation of the Sustaining Fiber Light Response

The simulation of the visual response (Fig. 6, E-H, solid line superposed over shaded areas) is based upon a current derived from the PSP (Fig. 6A -D, dotted traces, inward currents are positive), and the parameters of the adaptive integrate and fire model derived from the responses to extrinsic current injection (Table 1, column 1 for the cell shown in Fig. 6). The correlation between observed and simulated impulse rates for this cell is \( r = 0.95 \) (for 6 stimulus intensities, RMSE = 0.84 SDs). For the whole sustaining fiber population (17 cells, 6 or 7 light-elicited responses/cell) the average \( r = 0.91 ± 0.04 \) and the average RMSE was 0.89 SDs.

The performance of the model can be appreciated by examining some of the details in Fig. 6D and H. In this response the PSP declines from its peak by 16% in 90 ms and the concurrent firing rate declines by 85%. Underlying the change in firing rate is a steep change in synaptic current (dotted trace in Fig. 6D) as \( \frac{dV}{dt} \) goes from positive to negative and the similarly steep initial phase of spike-frequency adaptation. The model simulates this rate change with high fidelity as shown in Fig. 6H.

Because the firing rate function is in part derived from the time course of the PSP, an examination of the degree of linearity between the PSP and firing rate provides a useful framework to evaluate the model. The cross-correlation function estimates the linear relationship between the PSPs and firing rate functions. For the cell shown in Fig. 6, the cross-correlation function (not shown) exhibited maximum intensity at a time lag of 5 ms (i.e. within one interspike interval at peak rate) and a correlation coefficient \( (r) \) of 0.72 at that time lag. This implies that the linear relationship between the PSP and the firing rate describes about 52% \( (0.72^2) \) of the variance in firing rate. Conversely, the optimized model describes 90% of firing rate variance. The PSP vs firing rate correlations were similar for the entire sustaining fiber population \( (r = 0.725 ± 0.195, \)
We also examined a more complex model, in which the firing rate, \( F = k_1(V-V_{th}) + k_2(dV/dt) \) (Stein, 1980; Poliakov et al., 1997), more closely reflects the synaptic current. Though the results were a little better than those obtained with cross-correlation (\( r = 0.8 \) for observed vs computed firing rates), they were substantially inferior to the nonlinear adaptive model.

The transient peak discharge is the most difficult to simulate because it is strongly influenced by variations in capacitative currents associated with fluctuations in the rising and decay phases of the peak of the PSP (as in Fig. 6 A-D dotted traces). Errors of 10-20% in the computed peak rates are not uncommon as shown in Fig. 8A (solid line). Conversely the plateau discharge is largely governed by a slowly varying potential (with minimal capacitative current) and the computed rates more faithfully reflect the observed response as shown in Fig. 8A (broken line). For the entire sustaining fiber population the correlations between observed and model peak and plateau firing rates were 0.91 and 0.95 respectively.

There are two variants of the sustaining fiber response to a light flash that are not represented in Fig. 6. In one, the transient discharge is followed by a silent period of 100 to 150 ms before the onset of the plateau phase. In the second, there is no plateau discharge. Both of these response variants are well described by the model. The strong adaptations are associated with large values of \( G_{inc} \) or \( \tau_{adapt} \).

**The Dimming Fiber Visual Response**

Dimming fibers respond to a flash of light with an inhibitory post-synaptic potential (IPSP) and cessation of the dark discharge, as in Fig. 7A-D (solid traces). At the lowest intensities, the IPSP decays and the discharge resumes during the light flash (as in Fig. 7A). At higher light intensities (as in Fig 7B - D) the discharge is totally inhibited by the IPSP. At the termination of the flash there is a rapid repolarization toward the “dark” potential. The repolarization is followed by a delayed depolarizing overshoot (typically of 5 to 10 mV) accompanied by the OFF discharge. Thus dimming fiber impulse trains exhibit three distinct phases; the dark discharge (typically 5 to 10 imp/s), the inhibited phase associated with increments of light
(typically 0 to 3 imp/s) and the transient OFF response at the end of the light flash (peak rates up to 50 imp/s). In addition to the reversal of the sign of the light response, dimming fibers differ from sustaining fibers in three other respects: i) they generally exhibit higher firing rates in the dark and much lower transient impulse rates; ii) the OFF transient in both potential and impulse rates is slower, and iii) the dimming fiber input resistance is 2 to 3 times that of sustaining fibers (Table 1).

*Simulation of the Dimming Fiber Light Response*

Because dimming fiber potentials vary more slowly, the variable capacitative currents (as in Fig. 7A-D, dotted traces) are smaller and the simulations of the peak rates have higher fidelity. This can be seen in the model firing rate functions of Fig. 7E-H (dark traces superposed on shadowed areas) and in Figs 8B. Although the dark discharge is variable (shaded area of Fig. 7E-H, first 200 ms) due to spontaneous fluctuations in membrane potential (i.e. PSPs), the model provided a good approximation of these rates in most cells (as in Fig. 8). The firing rates shown in Fig. 8B (broken line) are typical of the impulse rates of dimming fibers during the interval between the OFF response and the beginning of the steady dark discharge. Most of the failures in model performance were associated with cells firing at rates below 5.0 imp/s. In these conditions spontaneous fluctuations in membrane current are substantial compared to the light-elicited currents.

*Adaptation of the Visual Response*

The magnitude of adaptation in sustaining fibers (i.e. the change in impulse rate from peak to plateau, ∆F) is linearly related to the peak impulse rate in both the neuronal and model responses (r = 0.95 and 0.98 respectively) and ∆F is about 82% of the peak rate. In simulated responses the average adaptation is 84% of the peak rate.

Our model focuses on three factors which predict a decline in firing rate between the peak transient rate (Fₚ) and the plateau discharge: i) the time course of the PSP; ii) the contributions of capacitative currents, which are much larger during the transient discharge; and iii) spike frequency adaptation. We will assume
that these three factors are additive.

The current injection studies indicate that the measured encoder’s output declines by about 40% under conditions in which spike frequency adaptation is the exclusive basis of the decline in rate. We can estimate the contribution of spike frequency adaptation to the decline of the visual response firing rate by computing the model response with adaptation removed ($G_{\text{adapt}} = 0$), as shown in Fig. 9A (dotted trace). Removing $G_{\text{adapt}}$ from this simulation has very little influence on the peak rate but it doubles the plateau rate at 1.0 second post-stimulus onset. The average effect for 17 sustaining fibers is a 121 ± 75% increase in the plateau rate and on average $G_{\text{adapt}}$ is responsible for 38% of the adaptation of the model light response.

A second source of light response adaptation is the decline of the PSP from peak ($V_p$) to plateau ($V_{ss}$). We can estimate the magnitude of this contribution ($\Delta F_{\text{psp}}$) assuming that the decline in impulse rate is linearly proportional to the decline of the PSP normalized to the model peak impulse rate, $F_{pm}$. That is, $\Delta F_{\text{psp}} = F_{pm} (V_p - V_{ss})/V_p$. The contribution of $G_{\text{adapt}}$ to adaptation of the model light response ($\Delta F_g$) is derived from the difference between the plateau impulse rates with and without $G_{\text{adapt}}$. The sum of $\Delta F_{\text{psp}}$ and $\Delta F_g$ provide an estimate of total adaptation ($F_a$) (as in Fig. 9C) which omits only the contribution of the capacitative current. The high correlation (and regression slope) between $F_a$ and model adaptation implies that $G_{\text{adapt}}$ and the adaptation of the PSP are jointly responsible for most of the adaptation of the model’s visual response. The assumed linearity and additivity however, may be contrary to the operation of the neuronal encoder.

In dimming fibers, the OFF response also exhibits adaptation. Though not shown by the cell in Fig. 7, the dimming fiber OFF discharge typically decays more rapidly than the corresponding PSP. The magnitude of the firing rate adaptation is a function of the peak impulse rate as in sustaining fibers. Removing $G_{\text{adapt}}$ from the dimming fiber model increases all of the rates by 120 to 150%, as shown in Fig. 9B. This result implies that a major effect of spike frequency adaptation is to control the impulse rates at all frequencies exceeding about $\tau_{\text{adapt}}^{-1}$. Because the dimming fiber OFF response typically evolves more slowly than the sustaining fiber ON response, there is sufficient time for encoder adaptation to control the OFF
response. In exceptionally fast dimming fibers, the OFF response resembles the sustaining fiber ON response and removing $G_{\text{adapt}}$ from the model produces results similar to that in Fig. 9A, i.e. no influence on the transient but a large increase in the plateau phase of the OFF response.

**Discussion**

But for a difference in input resistance, the sustaining and dimming fiber voltage-to-impulse encoders are very similar. The magnitude of spike-frequency adaptation is similar in both cell classes, as is the firing rate dependence of adaptation. In both cell types the observed adaptation time constant is long (100-300 ms) at low firing rates and this is preceded by a more rapid phase ($\tau_{a1}$ of about 22 ms) at higher impulse rates. The main consequence of the difference in $R_{\text{in}}$ (and a small difference in $V_{\text{th}}$) is that the dimming fiber firing rate is three to four times more sensitive to current than that of sustaining fibers. The magnitude and speed of spike-frequency adaptation that we observe is within the ranges of values previously noted in both crayfish (Fohlmeister et al, 1977) and mammalian neurons (Sawczuk et al, 1995; Schneider, 2003). Furthermore, there is extensive evidence that encoder adaptation may exhibit several phases operating over different time scales (Fohlmeister et al, 1977; Sawczuk et al, 1995; Sah,1996; Schwarz et al,1997; Schneider,2003) and based upon different ionic mechanisms (Schwarz et al,1997; Benda and Herz, 2003).

The adaptive integrate-and-fire model approximates the principal features of the encoders in both cell types, including the timing of the peak discharge, the f-I functions, the magnitude of adaptation and the dependence of adaptation upon the peak firing rate. Furthermore the simulations incorporate input resistances and membrane time constants that are not far removed from the measured values for the two cell populations as shown in Table 1. Although we have no direct evidence that the spike-frequency adaptation we observe is connected to the time course of the hyperpolarizing after-potential (AHP) (Table 1, observed $\tau_{\text{adapt}}$) such an association has been noted previously (Sawczuk et al., 1995) and the relationship is also suggested by numerical simulations (Fohlmeister and Miller, 1997; Wang, 1998; Liu and Wang , 2001). We interpret the similarity between $\tau_{\text{adapt}}$ and the decay time constant of AHP as further support of this relationship. A key
feature of the simulated adaptation is contained in \(G_{inc}\) (Eq. 3, Table 1) which stipulates that following each action potential the input resistance declines by about 61% in sustaining fibers and by about 66% in dimming fibers. Though seemingly large, these decrements are smaller than those in some mammalian neurons (Schwarz et al, 1997). The conductance increase implies that currents just above threshold at rest potential will be substantially below threshold for some fraction of \(\tau_{adapt}\). If two spikes occur in rapid succession \(G_{adapt}\) is augmented and the stimulus current will be below threshold for a longer interval. This is consistent with Wang’s (1998) explanation of the patternning of impulse trains (and the negative serial correlation) by spike-frequency adaptation.

The adaptive model as formulated here has several limitations. The first (noted above) is that the simulation is prone to error when the mean ISI is substantially less than \(\tau_{adapt}\). A second is that at the highest impulse rates, the neurons adapt in two phases (with \(\tau_{a1}\) and \(\tau_{a2}\)) while the model contains only one adaptation time constant. As a consequence, the simulated response often exhibits a decay time constant that is between \(\tau_{a1}\) and \(\tau_{a2}\). A third limitation arises from our decision to model encoder adaptation with a shunting conductance \(G_{adapt}\) rather than a potassium current \([G_{adapt}(V - V_k)]\). This approach is consistent with measurements indicating that \(G_{adapt}\) is the controlling variable during the ISI (Fohlmeister and Miller, 1997; Schwarz et al 1997). If the hyperpolarizing current is substantial however then the optimized model will exaggerate the magnitude of \(G_{adapt}\) to compensate for the absence of the current.

Many neurons exhibit spike-frequency adaptation derived from \(Ca^{2+}\) currents associated with the impulse and \(Ca^{2+}\)-dependent \(K^+\) currents associated with the hyperpolarizing after-potential (Wang and McKinnon, 1995; Fohlmeister and Miller 1997; Wang, 1998; Liu and Wang, 2001; Benda and Herz, 2003). In several of these neurons, the adaptation \(F_{adapt}\), expressed as a percent change in the peak rate \(F_p\), is proportional to \(F_p\) and inversely related to the adaptation time constant, \(\tau_{adapt}\) (Wang, 1998). In sustaining and dimming fibers the absolute magnitude of the rate change \(\Delta F\) is related to \(F_p\) but \(F_{adapt}\) (as a percent change) varies very little. The high correlations between \(\Delta F\) and \(F_p\) and the slopes of the f-I functions (Fig. 4) all
support this relationship. Our results do however support the contention that the speed of adaptation is related to \( F_{pt} \), but the relationship is not monotonic. The quantitative relationship is complicated by the fact that high firing rates are associated with two phases of adaptation. The two time constants might imply a role for two ionic mechanisms or the same mechanism (e.g. \( g_{k(Ca)} \)) regulated by a two phase process (e.g. regulation of \([Ca^+]_a\)).

An important difference between the current- and light-elicited response, is that the latter is driven by a synaptic current, \( I_s \). \( I_s \) varies substantially during the stimulus period and also introduces variance between trials of the same stimulus. Thus the sustaining fiber visual response exhibits greater adaptation and the CV is 3 to 4 times that of the current-elicited response. Our simulations indicate that the adaptation of \( I_s \) plays a major role in the adaptation of the visual response.

When the influence of spike-frequency adaptation is evaluated for the sustaining and dimming fiber visual responses, the results appear to be quite distinct. In order to interpret our findings, it is essential to make two assertions explicit. The first is that the model produces a good approximation of the visual response. The second is that spike-frequency adaptation operates (at least in part) by increasing the input conductance of the spike generator. If these assertions are valid, then the effect of setting \( G_{adap} \) to zero in the simulation is equivalent to eliciting the visual response following a selective pharmacological block of the spike-frequency adaptation mechanism (Wang and McKinnon, 1995; Fohlmeister and Miller, 1997; Schwarz et al, 1997). The results suggest that spike-frequency adaptation has little or no influence on the sustaining fiber dark discharge (mean ISI \( > \tau_{adap} \)) or on the peak incremental impulse rate (which evolves too quickly). Encoder adaptation reduces the model firing rate during the simulated plateau phase by about 60%. By reducing the plateau impulse rate, encoder adaptation enhances the response to the temporal derivative of the stimulus. In simulated dimming fibers both the dark discharge and the peak of the off response are substantially diminished by encoder adaptation. Since the operational features of the encoders are much the same in the two cell types we can infer that the different effects of adaptation are due to the differences in
the time course and firing rates between the two cell classes.

The above results are related to two broader aspects of visual neuron function. Because the sustaining fiber’s transient discharge is tightly coupled to the onset of local increments in illumination, the firing rate is particularly sensitive to visual motion (Glantz et al, 1995). As a complex scene traverses the sustaining fiber receptive field, the passage of each element of positive contrast is reflected in a distinct burst (Miller et al, 2003). The bursts are separated by silent periods which are in part due to spike-frequency adaptation. The structure of the sustaining and dimming fiber discharges also have a bearing on crayfish behavior. These interneurons are connected to optomotor neurons (Glantz et al, 1984; Okada and Yamaguchi, 1989) and participate in the control of ocular reflexes (Miller et al, 2002, 2003). Both the motoneurons and the behavior exhibit strong transient and weaker steady-state responses following rapid shifts in the distribution of illumination in the dorsal visual field. Our results suggest that spike-frequency adaptation may participate in this behavioral bias.
Acknowledgments

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Table 1. Parameters of the Adaptive Integrate and Model

<table>
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<tr>
<th></th>
<th>SusF #1</th>
<th>SusFs</th>
<th>Observed</th>
<th>DimF</th>
<th>DimFs</th>
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<td>DimF</td>
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Abbreviations: SusF #1 indicates the sustaining fiber shown in Figs. 2, 4 and 6. DimF #1 indicates the dimming fiber shown in Figs. 3, 4 and 7. The columns labeled SusFs and DimFs refer to the whole population of each of the two cells types. RMSE/SD is the root mean square error normalized by the average standard deviation of the firing rate. For the first row (N), the first entry is the number of cells, the parentheses contain the typical number of extrinsic current magnitudes per cell. The columns labeled Observed contain directly measured values derived from the cells in the adjacent columns. * The observed values in the $\tau_{adapt}$ row indicate the decay time constant of the hyperpolarizing after potential. In the row headings (first column) (I) or (L) indicates values for the current or light models respectively, when they differed. Errors are ± 1.0 SD.
Figure Legends

Fig. 1. Comparison of sustaining fiber PSPs derived by spike subtraction and isolated by hyperpolarization.  A. Response to an 0.5 s flash at log intensity -3.5.  B. Isolated PSPs. Broken line is the average of 16 PSPs following spike subtraction. The continuous line is the average of six responses to the same stimulus and in the presence of a -1.8 nA hyperpolarizing current. Note that the hyperpolarization produced an increase in PSP amplitude.

Fig. 2. Sustaining fiber current-elicited and simulated impulse trains.  A-D. Samples of responses to the indicated 0.5 s current pulses. Stimulus timing is indicated by the bar at the bottom of each panel E-H. Average firing rate versus time for the current magnitudes in the adjacent panels. Shaded areas indicate ±1.0 S.D. of the instantaneous firing rate. Each function is the average of 10 responses. Solid line superposed on firing rate functions is the model response for the same currents.  Model parameters in Table 1, column 2.

Fig. 3. Dimming fiber current-elicited and simulated impulse trains.  A-D. Samples of responses to the indicated current magnitudes for 1.0 s current pulses. Lower traces indicate stimulus timing.  E-H. Average firing rate versus time for the current magnitudes indicated in the adjacent panels. Shaded areas indicate ±1.0 S.D. of the instantaneous firing rate. The solid line superposed on the shaded areas are the model responses for the same currents.  Model parameters in Table 1, column 4.

Fig. 4. Comparison of neuronal and model frequency vs current functions.  A. Peak (circles ○) and steady-state (squares □) firing rates vs. current magnitude for the sustaining fiber described in Fig. 2. The vertical bars indicate ±1.0 S.D. of the mean rate. Model peak and steady-state rates are indicated by Xs and triangles Δs respectively. Solid and broken lines are the least square linear regression functions for current vs peak and steady-state rates respectively. The correlation coefficient (r) and regression slopes (m) are 0.95 and 20.3 imp/s/nA for the peak rate.
and 0.96 and 11.8 imp/s/nA for the plateau response. B. As in panel A for the dimming fiber described in Fig. 3, r and m are 0.97 and 83.0 imp/s/nA for the peak rate and 0.99 and 48.6 imp/s/nA for the plateau rates.

**Fig. 5.** The steady-state discharge pattern is modified by spike-frequency adaptation. Serial correlation coefficient of successive ISIs vs the mean current-elicited firing rate. The correlations were measured during the plateau discharge of responses to 4.0 s current pulses, 10 repetitions per current magnitude. Arrow indicates \( \tau_{\text{adapt}} \). * significant correlations (p<.05).

**Fig. 6.** Sustaining fiber responses and simulated firing rates to light flashes. A-D. Samples of responses (solid lines) to 4 light intensities indicated by log attenuation in each panel. The dotted lines indicate the synaptic currents computed by Eq. 3 for each voltage response and are referenced to the right-hand ordinate. As required by Eq. 1 we use the convention that inward currents are positive. Lower traces indicate stimulus timing. E-H. Average firing rate vs. time for responses to same stimuli used in the adjacent panels. Shaded areas are ±1.0 S.D. of the instantaneous firing rate. N=15 responses/panel. Solid line is the model rate based upon parameters in Table 1, first column 1, and the synaptic currents shown in the adjacent panels. Lower traces indicate stimulus timing.

**Fig. 7.** A-D. Samples of dimming fiber responses and model firing rates to light flashes of varied intensity. The voltage responses (solid lines) are from the same cell shown in Fig. 3. Log of stimulus intensities are indicated above each trace. The dotted lines indicate the synaptic currents computed by Eq. 3 from each voltage response and are referenced to the right hand ordinate. The outward currents are negative as required by Eq. 1. Stimulus timing is indicated by the bar at the bottom of each panel. E-H. Dimming fiber firing rates vs. time for same stimuli as in adjacent panels. Shaded areas are ±1.0 S.D. of the mean instantaneous rates. Solid lines superposed on shaded areas are model rates computed with model parameters in Table 1, column 4 and currents shown in the adjacent panels. Lower trace indicates stimulus timing.
**Fig. 8.** A. Sustaining fiber peak (circles ○) and steady-state (squares □) light-elicited impulse rates vs. log stimulus intensity. Data from cell shown in Fig. 6. Vertical bars are ±1.0 S.D. Solid and broken lines are peak and steady-state model rates respectively. B. Dimming fiber peak (circles ○) and steady-state (squares □) impulse rates vs. log stimulus intensity. Data is from same cell shown in Fig. 7. Solid and broken lines are model peak and steady-state rates respectively.

**Fig. 9.** Influence of spike-frequency adaptation on the time course of the sustaining and dimming fiber light-elicited responses. A. Sustaining fiber response (thin solid line), model sustaining fiber response (dash-dot line) and model response with $G_{adap} = 0$ (dotted line). Model parameters in Table 1, column 1. B. Dimming fiber light responses as in panel A. Model parameters in Table 1, column 4. C. Model adaptation in sustaining fibers as a function of $F_a$ which is the sum of adaptations produced by $G_{adap} (\Delta F_g)$ and the adaptation of the PSP ($\Delta F_{PSP}$).
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Fig. 5
Fig. 6
Fig. 8
Fig. 9