Adapting Bump Model for
Ventral Photoreceptors of *Limulus*

FULTON WONG, BRUCE W. KNIGHT, and FREDERICK A. DODGE
From The Rockefeller University, New York 10021

ABSTRACT  Light-evoked current fluctuations have been recorded from ventral photoreceptors of *Limulus* for light intensity from threshold up to 10^6 times threshold. These data are analyzed in terms of the adapting bump noise model, which postulates that (a) the response to light is a summation of bumps; and (b) the average size of bump decreases with light intensity, and this is the major mechanism of light adaptation. It is shown here that this model can account for the data well. Furthermore, the model provides a convenient framework to characterize, in terms of bump parameters, the effects of calcium ions, which are known to affect photoreceptor functions. From responses to very dim light, it is found that the average impulse response (average of a large number of responses to dim flashes) can be predicted from knowledge of both the noise characteristics under steady light and the dispersion of latencies of individual bumps. Over the range of light intensities studied, it is shown that (a) the bump rate increases in strict proportionality to light intensity, up to ~10^6 bumps per second; and (b) the bump height decreases approximately as the −0.7 power of light intensity; at rates >10^6 bumps per second, the conductance change associated with the single bump seems to reach a minimum value of ~10^-11 reciprocal ohms; (c) from the lowest to the highest light intensity, the bump duration decreases approximately by a factor of 2, and the time scale of the dispersion of latencies of individual bumps decreases approximately by a factor of 3; (d) removal of calcium ions from the bath lengthens the latency process and causes an increase in bump height but appears to have no effect on either the bump rate or the bump duration.

INTRODUCTION
In the studies reported here, we have tested the basic postulates of the adapting bump model with data obtained from the ventral photoreceptor cells of *Limulus*. As described in previous papers (see, for example, Wong and Knight, 1980), these postulates are: (a) the generator potential (or underlying conductance change) is a summation of bumps; and (b) the average size of bump decreases with light intensity and this is the major mechanism of light adaptation. These postulates seem to be very reasonable because records at different light intensities show that bumps fuse together to form the light response (Fig. 1), and the “noisiness” of the response in the steady state
decreases with increasing light intensity, which suggests that at high light intensities, the size of the individual bump becomes smaller than in dim light.

The ventral photoreceptor cells of Limulus provide a good working model for the study of bumps because many pieces of important information about the phototransduction process have already been gathered from studies performed on these cells. The basic physiological properties of these cells have been studied by Millecchia and Mauro (1969a, b). The effects of intracellular iontophoretic injection of various ions and buffers, particularly calcium ions and calcium buffers, on the light response have been studied extensively by Lisman and Brown (1972, 1975) and Fein and Lisman (1975). The effects of local adaptation and local desensitization have been studied by Fein and Charlton (1975) and Fein and Lisman (1975). Properties of these cells in an organ culture medium have been studied by Bayer and Barlow (1978). Recently, the possible role of cyclic nucleotides in phototransduction has been studied by Corson et al. (1979). Because it is generally accepted that the bumps are fundamental to the underlying mechanisms of phototransduction, it seems desirable to have a model, such as the adapting bump model, that can provide a framework for analysis and facilitate the interpretation of this vast amount of information.

The bumps of Limulus ventral photoreceptors, recorded as voltage changes or as current changes under voltage-clamp conditions, have a high signal-to-noise ratio that makes them attractive for quantitative studies (Fig. 1). However, in order to analyze the light-induced conductance changes in the ventral photoreceptor, it is necessary to use the voltage-clamp technique because of the highly nonlinear voltage-dependent permeability changes of this cell membrane (Millecchia and Mauro, 1969b; Pepose and Lisman, 1978). Moreover, we have found that the conductance time course of individual bumps in these cells is briefer than the membrane time constant. By use of the voltage-clamp technique, the time course of the light-sensitive processes can be studied in isolation because the observed light-induced current is directly proportional to the conductance change and independent of the membrane time constant.

To analyze the data in terms of the adapting bump model, we have performed the following studies:

(a) We have tested the hypothesis that the dynamics of the response to light is determined by the dispersion of latencies of individual bumps and by the bump shape. As described in Wong et al. (1980), a simple shot noise model predicts the relation

\[ |\tilde{F}(f)|^2 = |\tilde{D}(f)|^2 \cdot |\tilde{B}(f)|^2 \]  

(1)

where \( \tilde{F}(f) \) is the conductance transfer function, \( \tilde{D}(t) \) is the dispersion of latencies, \( \tilde{B}(t) \) is the bump shape, and the tilde indicates Fourier transformation of the respective functions of time. The three quantities in Eq. 1 were measured independently at low light intensities and thus the relation was tested.

(b) We have measured the parameters of the adapting bump model as functions of ambient light intensity. The major parameters were found to be
the bump height, bump duration, and rate of occurrence. The adapting bump model assumes that the response to dim light is a summation of large bumps, and the response to bright light is a summation of many smaller bumps. Such an assumption makes definite predictions as to the functional dependence of the bump parameters on light intensity. Based on the shot noise model, the bump parameters can be determined as functions of light intensity. Thus, the predictions of the model can be tested. (The correlation factor, $\psi$, described in Wong and Knight [1980] is found to be very close to unity for all light intensities studied. The implications of this observation will be discussed later in this paper.)

(c) Because it is known that the reduction of extracellular calcium ions can lead to an enhanced photoresponse (Millecchia and Mauro, 1969a), attempts were also made in these studies to relate the effects of calcium ions to the bump parameters.

**THEORY**

Based on the model postulates of the photoresponse described in the previous section, we can analyze the current noise records (Fig. 1) to extract the underlying parameters of rate $\lambda$, height $h$, and duration $T$. We emphasize that this analysis, like those reported previously (Dodge et al., 1968; Wong et al., 1980; Wong and Knight, 1980), is restricted to the response during the steady state. The dynamic properties which account for the shape of the transient (Fig. 1) are outside the scope of the present analysis (see Discussion). If $g(t)$, the current noise signal, is composed of superimposed bumps of a common shape $B(t)$ (zero for $t < 0$) that occur independently at a mean rate $\lambda$ and the distribution of occurrence in time follows Poisson statistics (Yeandle and Speigler, 1973), Campbell’s theorem states that:

$$\text{mean } (g) = \lambda \int_0^\infty dt \ B(t),$$

and

$$\text{variance } (g) = \lambda \int_0^\infty dt \ B^2(t).$$

With definitions for bump height and bump duration as

$$h = \frac{\int_0^\infty dt \ B^2(t)}{\int_0^\infty dt \ B(t)},$$

$$T = \frac{\left\{ \int_0^\infty dt \ B(t) \right\}^2}{\int_0^\infty dt \ B^2(t)},$$
Campbell's theorem takes the simple form

\[
\text{mean } (g) = \lambda h T, \quad (6)
\]

\[
\text{variance } (g) = \lambda h^2 T. \quad (7)
\]

(See also Knight, 1972; Wong and Knight, 1980; and the Discussion of this paper). Provided that the duration \( T \) can be estimated independently from the noise signal, and mean \( (g) \) and variance \( (g) \) can be measured directly

---

**Figure 1.** Current responses to steps of light at different light intensities. The membrane voltage is maintained at the resting potential \((-52 \text{ mV})\) of the cell. At low light, the bumps are seen as discrete events. At higher light intensities, the responses appear to be a summation of bumps. The mean of the steady state response increases as the 0.3 power of light intensity and the amplitude of the noise in the steady state decreases with increasing light intensity. These observations are qualitatively consistent with the notion that in bright light, the response is a summation of many small bumps. (The truncation of the peaks during the transient response was caused by saturation of the recording amplifiers.)
Adapting Bump Model for Limulus Ventral Photoreceptors

(Wong et al., 1980), Eqs. 6 and 7 can be solved for the underlying rate $\lambda$ and bump height $h$.

If $g(t)$ is composed of uncorrelated (independent) bumps, the shape $B(t)$ is related to the power spectrum $S(f)$ (the expected squared Fourier coefficients of the frequency components) of the noisy signal $g(t)$. As shown earlier (Wong et al., 1980),

$$S(f) = \lambda |\tilde{B}(f)|^2,$$

where $\tilde{B}(f)$ is the Fourier transform of $B(t)$. With $B(t)$, the duration parameter $T$ can be calculated according to Eq. 5.

A major theoretical task in applying a shot noise model to the adapting bump process is to account for the correlation of the underlying bumps. The simple shot noise model from which Campbell’s theorem is derived requires uncorrelated bumps. However, the adapting feature of the adapting bump model implies that the sizes of later bumps are reduced because of the occurrences of earlier bumps. Therefore, the bumps cannot be uncorrelated. Wong and Knight (1980) argued on dimensional grounds that the correlative effect of adaptation amends Campbell’s theorem by a single multiplicative factor, i.e., the expression for variance is changed from Eq. 7 to

$$\text{variance } (g_c) = \psi \lambda h^2 T,$$

where the subscript $c$ indicates that $g_c(t)$ is composed of correlated bumps and $\psi$ is a real number without physical dimension, characteristic of the processes that underlie the noise. For example, $\psi$ takes the value unity if the bumps are uncorrelated and thus Eq. 9 would reduce to Eq. 7. For the adapting bump process where the occurrence of a bump reduces the sizes of subsequent bumps, $\psi$ is expected to be less than unity. The appropriate equations (omitting the subscript $c$) for $h$ and $\lambda$ then are

$$h = \frac{\text{variance } (g)}{\psi \text{ mean } (g)},$$

$$\lambda = \frac{\psi \{\text{mean } (g)\}^2}{T \text{ variance } (g)}.$$  

It was also shown in Wong and Knight (1980) that $\psi$ can be estimated from the power spectrum of the noise data. The most attractive feature of this approach is that the effect of correlation (adaptation) on the bump parameters duration $T$, height $h$, and rate $\lambda$ can be accounted for without specification of detailed mechanisms of adaptation.

In the analysis of data obtained from the eccentric cells of Limulus (Wong and Knight, 1980), it was noted that whatever the actual mechanisms of adaptation (correlation of the bumps) may be, the observable effect on the power spectrum is a depression in the low-frequency region. The extent of this

* If the shot noise is composed of two or more sizes of bumps, the height $h$ and the rate $\lambda$ so calculated must be regarded as “effective” values referring to a comparison shot noise with a single bump type of intermediate size, which size is easily calculated by following the classic treatment of Rice (1944).
effect depends on the characteristic time scale of the correlation. For the eccentric cells, frequency components below ~3 Hz are observed to be affected at high light intensities (Fig. 2a). In the time domain, this effect of adaptation is manifested as a characteristic undershoot of the response to a brief flash superimposed upon a bright steady light. Such an example is shown in Fig. 2b. After the initial rise, the flash-response swings below the steady baseline value and returns to baseline from below. Because the individual bumps are believed to be monophasic (no undershoot), these observations are interpreted to indicate that "adaptation" has occurred. The time course of the undershoot in the flash-response as well as the suppression of the low-frequency components of the power spectrum sets the value of the time scale of this fast adaptation process (correlation). For the eccentric cells, the time scale of bump duration and of adaptation are similar but also sufficiently different to enable
the estimation of the bump duration as well as the factor \( \psi \) at high light intensities.

In the case of the ventral photoreceptors, it is observed that the shape of the power spectrum can be fit by a monotonic function, even at high light intensities. That is, there is no obvious suppression of the low-frequency components of the power spectrum (compare Figs. 2a and c; see also Wong, 1978). In the time domain, the response to a brief flash superimposed upon a bright steady light shows no undershoot (Fig. 2d). When compared with their counterparts derived from the eccentric cells (Figs. 2a and b), observations made on the ventral photoreceptors (Figs. 2c and d) seem to indicate that the time scale of this fast adaptation (for the ventral photoreceptors) is very different compared with the time scale of the bump duration. According to the arguments presented earlier, this implies that the steady state variance of the noisy signal is only minimally affected by this fast adaptation, which in turn implies that \( \psi \), the factor that characterizes the correlation and appears in Eq. 9, is essentially equal to unity for all light intensities. The full implication of the above-mentioned observation will be commented on in the Discussion. Meanwhile, this observation renders the data analysis simple because, at least procedurally, the steady state data can be treated as though they were derived from the superposition of "uncorrelated" bumps.

**METHODS**

**Biological Preparation**

The morphology of the ventral photoreceptor and the methods for its isolation have been described in Clark et al. (1969). The lateral olfactory nerves were first dissected out of the animal. The blood vessel that surrounded the nerve was removed. The connective tissue that remained on the cells was digested with 1% pronase (Calbiochem-Behring Corp., San Diego, CA) in buffered seawater (pH 7.3) for 45 s. After treatment with pronase, the nerve was washed five times before it was mounted in a small plastic chamber and bathed in artificial seawater. The artificial seawater contained various salts: 435 mM NaCl, 10 mM KCl, 10 mM CaCl₂, 20 mM MgCl₂, and 25 mM MgSO₄. The pH of this solution was adjusted to 7.3 by buffering with Tris (hydroxymethyl) aminomethane. The solution in the recording chamber could be exchanged rapidly by means of a simple perfusion system. Experiments described in this report were performed at room temperature, 19–22°C.

**Stimulus Control**

The light source (glow modulator tubes, R1131C; GTE Sylvania Inc., Stamford, CT) and the method to turn the stimulus on and off have been described previously (Wong et al., 1980). For the present studies, two such light sources were used, each controlled independently. The outputs of these two sources were combined by a Y-fiber optic bundle (American Optical, Buffalo, NY). This optic bundle has two inputs and one output. The individual fibers are mixed so that the output gives a uniform illumination even when only one input receives light. Light from the glow tubes was guided inside a shielded cage and the image of the tip of the optic bundle was focused on the preparation. The intensity of each light source was attenuated separately by means of neutral density filters. The unattenuated light intensity from one light source at the
level of the preparation was $\sim 10^{12}$ photons/cm$^2$·s when measured at 520 nm over a 100-nm bandwidth.

**Recording Instruments and Technique**

The responses of the photoreceptor to light were measured by means of the classical two-electrode voltage-clamp technique. Two glass capillary microelectrodes were inserted into the cell soma. The microelectrodes were filled with 3 M KCl (DC resistance 15–20 MΩ) and each one was connected to an Ag-AgCl electrode, which was connected to a high input-impedance amplifier, and the membrane potential was measured with respect to the bathing solution. The bath potential was held at virtual ground by an operational amplifier that was arranged as a current-to-voltage converter. The current flow, which is proportional to the membrane conductance change, across the membrane of the cell to ground was measured with this current-to-voltage converter through an Ag-AgCl electrode ($R = 5$ kΩ) connected with the bath via an agar salt bridge. The capacitative coupling between the two microelectrodes was reduced by a copper shield around the microelectrode that was used to pass current, and by use of only a minimum level of the solution that bathed the cell.

Large and isolated cells that lay on the nerve were selected for impalement. The cells reported here had membrane resting potentials that ranged from −40 to −65 mV. When both microelectrodes had entered the same cell and both had recorded the same resting potential, the cell was allowed to dark adapt. After $\sim 10$ min of dark adaptation, bumps began to appear, either spontaneously or in response to very dim light. If both microelectrodes recorded the same voltage fluctuations, as shown in Fig. 3, one of the microelectrodes was connected to the clamp amplifier and the command voltage was set at the resting potential of the cell. The light-induced changes of membrane conductance were determined from the current, which was supplied by the clamping amplifier at the level necessary to keep the membrane potential equal to the controlling voltage.

![Open Circuit and Voltage Clamp](image)

**Figure 3.** Experimental procedure used to ascertain the proper application of the voltage-clamp technique. When both microelectrodes had entered the same cell and both recorded the same resting potential, the cell was allowed to dark adapt. When bumps began to appear, both microelectrodes recorded the same voltage fluctuations. When one of the microelectrodes was connected to the clamp amplifier and the command voltage was set at the resting potential, the light-induced current responses could be recorded. Under voltage clamp, the membrane potential was observed to remain constant throughout the experiment.
The two-electrode voltage-clamp technique (see, for example, Millecchia and Mauro, 1969b) is thought to be applicable in studies of the ventral photoreceptor cells. It has been shown that there is no significant spatial nonuniformity of intracellular voltage in the soma of these cells (Brown et al., 1979). In the studies reported here, we have taken the following precautions to ensure the proper application of voltage clamp. (a) Only isolated cells found scattered along the lateral olfactory nerve are studied. (b) The two microelectrodes are spaced as far apart as possible within a single cell. (c) Cells are rejected unless the two microelectrodes record the same resting potential (to within 1 mV), the same response amplitude (to within 1 mV) to bright light and completely correlated fluctuations (bumps) to very dim light. (d) The voltage-clamp circuit used is tested to be adequate by noting that for a 10-mV step change in command voltage, the membrane potential follows in <50 µs and that during a steady state response to light (current amplitude <5 nA), the membrane potential is never observed to deviate from the command. Only during the transient response to very bright light (amplitude >100 nA) is the membrane potential observed to deviate slightly from command (by <5 mV).

Data Collection

In these experiments, the stimulus control and data collection were achieved by programming a PDP 8/e computer (Digital Equipment Corp., Maynard, MA). For the present study, responses to brief flashes and to steady light were recorded for analysis. Before data were sampled and stored by the computer, the signal was routinely filtered by analogue and digital filters. These procedures were necessary because under voltage clamp, the current measured by the current-to-voltage converter contained a major component of high-frequency noise. The major portion of this additional noise originated in the microelectrodes and in the recording amplifiers. The high-frequency components of this instrumental noise were amplified by the feedback circuit inherent in the voltage-clamp technique. In the present analysis, the major frequency components of interest in the biological signal lie below 20 Hz. Thus, the high-frequency instrumental noise was filtered out with a four-pole, Bessel (linear phase approximation) low-pass filter. The filter has a half-power point at 70 Hz and a final cutoff slope of 80 db/decade. To minimize the problem of aliasing in the determination of power spectra, the high-frequency noise was further reduced by the use of a digital filter: the computer sampled the signal at 156-µs intervals and the average of 64 such consecutive samples was stored on a magnetic disk. In essence, this procedure corresponded to a relatively slow sampling rate of 100.16 Hz. However, this method is effective in avoiding the problem of aliasing.

For the verification of Eq. 1, the dispersion of latencies of the individual bumps in dim light was estimated from the latencies of the first occurrences in response to very dim flashes. Details of this method and its validity have been described in Srebro and Yeandle (1970) and Wong et al. (1980). This method was chosen because it allowed the efficient estimation of \( D(t) \). Routinely, sequences of pulses 1 ms in duration and at 8-s intervals were sent by the computer to activate the glow tube driver. This caused the glow tube to give a sequence of flashes 1 ms in duration. The intensity of the flashes was adjusted so that between two to three bumps were elicited per flash on the average. The computer sampled and stored the flash responses as 2-s-long records. The flash occurred in the middle of the record so that the first second contained information about the baseline value as well as the spontaneous occurrences of bumps, the rest of the record contained the flash response. Usually, 240 records were used to determine \( D(t) \). Samples of the responses to dim flashes are shown in Fig. 4. For the purpose of illustration, the records shown in Fig. 4 were responses to a train of flashes.
given at one flash per second. The intensity of the flash was adjusted so that each flash elicited about three bumps on the average. Before these records were taken, the photoreceptor was dark-adapted for 20 min. (In this state of dark adaptation, a few bumps were seen to occur spontaneously, ~1 bump per 10 s. The arrows in Fig. 4 point at spontaneous bumps.) The multiplex feature of these responses to dim flashes indicates the importance of the dispersion of latencies in the determination of the dynamic response of the photoreceptor, as discussed in later sections. The 240 records used to determine \( D(t) \) in dim light can also be averaged to obtain the averaged impulse response from which the transfer function can be obtained by a Fourier transformation (see Data Analysis and Results).

The procedure to collect steady state data for the estimation of the bump shape and other bump parameters was the same for all light intensities. Stimulus sequences were presented in runs. Each run contained 5–10 episodes. Each episode was 60 s long for the \(-5\) and \(-4\) log light intensities; 90 s long for the \(-3\) and \(-2\) log light intensities; and 120 s long for the \(-1\) and 0 log light intensities. The stimulus in each episode was a step 30 s long. The reason for the increases in episode length with increasing light intensity was to allow enough time between two stimuli for the cells to dark adapt. The episode length appropriate for a particular light intensity was determined by the shortest time needed for dark adaptation after a stimulus at that light intensity so that the response to the next stimulus of equal intensity would have the same amplitude as the previous one. If the dark interval between stimuli was long enough, the order of the light intensities would not introduce any bias to the analysis. It should also be pointed out that in order to compare the values of bump parameters obtained at different light intensities, it was necessary to maintain the cell at the same adaptation level throughout the entire experiment. The particular choices of episode length cited for the various light intensities appeared to be appropriate for these requirements.

In these studies, the transfer function was determined from the impulse response (averaged response to brief flashes superimposed on a background light) by a Fourier transformation. The method of determining the transfer function from measurement
of the impulse response is found to be more convenient than the alternative method using measurements of the response to sinusoidal flicker (Wong et al., 1980). The procedure for collecting data for the estimation of the impulse response was similar to that used for steady state data. The background stimulus in each episode was also a 30-s-long step. Superimposed on this were pulses of 10 ms duration, given at a repetition rate of 1 pulse/s during the last 20 s of the step. The step was produced by one of the glow tubes, whereas the pulses were produced by the second glow tube. The intensities of the flashes were adjusted so that in each episode, the total number of photons delivered by the flashes would not exceed 10% of the number of photons delivered in the steady state over the time span of the episode. (Usually the fraction was ~5%).

### DATA ANALYSIS AND RESULTS

#### Verification of Eq. 1

Following the procedure described in detail previously (Wong et al., 1980) and in this paper, it was found that the dispersion of latencies, \( D(t) \), in dim light can be fit by a gamma distribution

\[
\Gamma(t; n, \tau) = \frac{1}{n!\tau} (t/\tau)^{n-1} e^{-t/\tau}
\]

with an offset from \( t = 0 \). Eq. 12 describes a two-parameter family of curves. By varying \( n \) and \( \tau \), a family of similar curves can be generated. Once values for \( n \) and \( \tau \) are determined, these two parameters characterize the shape of the distribution. For the experiment that provided the data used in Fig. 5, the values for \( n \) and \( \tau \) were found to be 3 and 22.1 ms, respectively. (Pooled results from all the cells studied will be presented in the next section.)

Because the dynamic response of the photoreceptor can be analyzed as a linear system (Pinter, 1966; Dodge et al., 1968), the transfer function can be obtained as the Fourier transform of the impulse response. In dim light, the average impulse response was constructed as the average of the 240 records used to determine \( D(t) \). Examples of the responses to dim flashes are shown in Fig. 4. As mentioned earlier, the multipeak feature (the occurrences of the bumps caused by a flash are well dispersed in time) of these responses to dim flashes (1 ms in duration) indicates that the dispersion of latencies could play a significant role in determining the dynamics of the response of these photoreceptors to light. For instance, the “duration” of the impulse response used in Fig. 5 was found to be 160 ms, whereas the average duration of the individual bumps (see below) was found to be only 71 ms.

As mentioned earlier, the bump shape can be estimated from the steady state data (the power spectrum). The procedure described below for obtaining the bump shape and hence the bump duration is applicable to data obtained at all light intensities (see Theory). To calculate the power spectrum, only the last 20 s of the response to the 30-s step of light were used. This procedure was followed to ensure that the response had reached the steady state. From each 20-s record, 14 overlapping data segments, each of 2.56 s were formed (see Welch, 1967, for details of the method). Fourier coefficients were calculated by a fast Fourier transform algorithm (Cooley and Tukey, 1965). In each run with 10 episodes, 140 spectra were averaged to obtain the power spectrum with no further “smoothing.” Examples of the power spectrum (normalized to an arbitrary value of area under the curve), calculated for very low light intensity, are shown in Fig. 6. It was noted that the power spectrum, and thus
$|\tilde{B}(f)|^2$, can be fit well by a curve of the form

$$
|\tilde{\Gamma}(f)|^2 = \frac{1}{(1 + 4\pi^2 f^2 \tau^2)^{n+1}}.
$$

(13)

Discussion about the use of this functional form can be found in Wong and Knight (1980). Fitting the power spectrum with the form in Eq. 13 is equivalent to assuming that the bump shape is well fit by a gamma distribution (Fig. 6). It can be shown easily that $\tilde{\Gamma}(f)$ is the Fourier transform of $\Gamma(t; n, \tau)$, Eq. 12, and from $\tilde{\Gamma}(f)$, Eq. 13 can be derived. With the values of $n$ and $\tau$ that gave the best fit, the bump shape and the bump duration were determined (Wong and Knight, 1980). An algorithm was devised to obtain the best fit. The expression on the right-hand side of Eq. 13 was fit to an experimental power spectrum by choosing values of $\tau$ and of integer $n$, which minimized the quantity $\langle (\text{measured value} - \text{value of fit})^2 \rangle$, where the average was taken over all the frequency values up to 20 Hz. The frequency cutoff was chosen at 20 Hz because >80% of the signal power from the cell lies below that frequency, whereas the signal at higher frequencies can be contaminated by instrument noise. To make certain that the fitting procedure did not introduce any trend with respect to frequency in the residual errors, the difference between the theoretical curve and the data was calculated for each frequency component. The slope of the straight line that best fit these points in the least-square sense was then calculated. It was found

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Verification of Eq. 1. The quantities $|\tilde{F}(f)|^2$, $|\tilde{D}(f)|^2$, and $|\tilde{B}(f)|^2$ were measured from the same cell at light intensities that caused an average of 2 bumps/s in the steady state. All the curves shown here are normalized to the same area. The horizontal scale is frequency in 0.39 Hz per bin and the vertical scale is in arbitrary units. It can be seen that the curve that corresponds to $|\tilde{D}(f)|^2$ lies closer to $|\tilde{F}(f)|^2$ than does $|\tilde{B}(f)|^2$. This implies that the dynamic response of the cell is determined mainly by the dispersion of latencies (see text). As shown in the upper right-hand frame of this figure, the curve corresponding to $|\tilde{D}(f)|^2|\tilde{B}(f)|^2$ agrees well with the one corresponding to $|\tilde{F}(f)|^2$, which indicates that the theory is verified.
that in general, when the optimum combination of values for \( n \) and \( \tau \) was found, the slope of this line would be very close to zero. This indicated that the algorithm had introduced no detectable bias in favor of fitting any particular frequency range. To illustrate this procedure, the power spectrum used in Fig. 5 is shown in Fig. 6. The steady state data used to calculate the power spectrum represented the response to very dim steady light. The stimulus intensity was adjusted so that on the average, the bump rate was 0.7 bump/s. It can be seen in Fig. 6 that the theoretical curve fits the data very well. The inset shows a straight line of slope zero and the points that represent the difference between the theoretical curve and the data at each frequency component. The values of \( n \) and \( \tau \) for the theoretical curve are \( n = 2 \) and \( \tau = 13.4 \) ms. From these values of \( n \) and \( \tau \), the bump duration was calculated by the formula (as discussed by Wong and Knight, 1980)

\[
T = \tau \cdot \frac{(n!)^{2}2^{n+1}}{(2n)!}
\]

(14)
to be 71.4 ms. The deduced bump shape is also shown in Fig. 6.
With the independently measured quantities, $|\tilde{D}(f)|^2$, $|\tilde{A}(f)|^2$ and $|\tilde{B}(f)|^2$, Eq. 1 can be tested. In Fig. 5, the three quantities were measured from the same cell at the average light intensity which caused about 0.7 bump/s in the steady state. All the curves shown in Fig. 5 were normalized to the same area. It can be seen that the curve that corresponds to $|\tilde{B}(f)|^2$ lies closer to $|\tilde{A}(f)|^2$ than does $|\tilde{B}(f)|^2$. This implies that the dynamic response of the cell is determined to a large extent by the dispersion of latencies. (Recall the observation made in dim light, Fig. 4.) The upper right-hand frame shows the comparison of $|\tilde{A}(f)|^2$ to $|\tilde{D}(f)|^2$. It can be seen that the prediction according to Eq. 1 is verified.

**Parameters of the Model as Functions of Light Intensity**

It is clear from results such as shown in Figs. 4 and 5 that the dispersion of latencies of individual bumps could play an important role in phototransduction. Although the occurrences of bumps overlap in time so that the distribution of latencies cannot be measured directly except under conditions where on the average less than one bump is elicited per flash, an efficient method has been devised to estimate this distribution, the dispersion, from the distribution of first occurrences (Srebro and Yeandle, 1970; Wong et al., 1980). Furthermore, it appears that the dispersion can be fit by a gamma distribution, Eq. 12, with an offset from $t = 0$. For the six cells studied, in the course of this project, the parameters of the distribution that fit gave $n = 3$, whereas $\tau$ ranged from 21 to 36 ms. The offset of the gamma distribution from $t = 0$ was 95.8 ± 24.2 ms. The mean time determined by the distribution $D(t)$ as measured from the time of the flash was found to be 212 ± 56.0 ms, whereas the width, defined as twice the root of the variance, was found to be 117 ± 32.3 ms.

For light intensities above the lowest level used, the dispersion $D(t)$ can no longer be estimated from the distribution of first occurrences because the variability of the delay is very small under such conditions. However, noting that the time scale (e.g., the duration or the time course) of the impulse response obtained with a background light is significantly longer than that of the bump duration, it is clear that in high light intensities the effects of dispersion remain, albeit less in magnitude. Given that at low light, the difference (or discrepancy) between the bump shape and the transfer function can be accounted for by the dispersion (Fig. 5), it is reasonable to assume that at high light, the difference is also caused by dispersion (Wong et al., 1980). Therefore, the dispersion at high light is characterized by a gamma distribution with the same shape ($n = 3$) but a smaller value of $\tau$ is chosen to fit the data to account for the difference between the transfer function and the bump shape. The transfer function is obtained by a Fourier transformation of the average impulse response, average of 200–400 responses to flashes as described in Data Collection. Shown in the uppermost frame of Fig. 7 is the dispersion width, $D_w$, defined as twice the root of the variance of the dispersion for four different light intensities. It is observed that $D_w$ decreases monotonically with increasing light intensity. Over the range of light intensities studied, $D_w$ has decreased by a factor of 2.6 from the lowest to the highest.

The estimation of the bump shape from steady state data has been described
in detail for data obtained at low light (see Verification of Eq. 1). It was found that for all the cells studied (seven for the bump shape in dim light), the power spectrum can be fit to the functional form by the parameters $n = 2$ and $\tau$ ranging from 11 to 14 ms. The duration calculated for the seven cells is 67.6 ± 8.3 ms. For high light intensities, the procedure to obtain the bump shape and hence the bump duration is the same as that for low light except the slow trends in the data were removed from each data segment before the calculation of the Fourier coefficients. Values of $n$ and $\tau$ that gave the best fit for each

![Graph showing the relationship between duration ($D_w$), time ($T$), height ($h$), and lambda ($\lambda$) with respect to log intensity.](image)
power spectrum were used to calculate the duration. (It was observed consistently that power spectra obtained at high light intensities can better be fit with \( n < 2 \). We refer the reader to Wong, 1978, for a detailed discussion.) In Fig. 7, it is shown that the duration has decreased by a factor of 2 over the range of light intensity studied. This observation is consistently made for all the cells studied. However, for some of the cells, the functional dependence of the bump duration on intermediate intensities (e.g., about \(-3\) and \(-2\) log units) was observed to be different from that shown in Fig. 7. In those cases, the duration did not decrease smoothly although over the entire range, the duration has decreased by a factor of about 2. (This apparently complex functional dependence of bump duration on light intensity is caused by the mathematical definition of \( T \) in Eq. 5 rather than to the physiology of the cells. This is best understood by noting in Eq. 14 that \( T \) is dependent on both \( n \) and \( \tau \): linear in \( \tau \) but not in \( n \). This implies that \( T \) is sensitive to the shape factor \( n \). However, the change in shape is so small that this slight complication does not affect the rest of this analysis in any significant manner.)

Once the parameter duration \( T \) is determined, the parameters height \( h \) and rate \( \lambda \) can be calculated from the mean and the variance of the steady state response by using Eqs. 6 and 7. As mentioned previously in this analysis, only the last 20 s of the response to the 30-s step of light were used in these calculations. To calculate the mean, the time average of the response was first made. Then the baseline (the value for the current before the light was turned on) was subtracted from the average to obtain the mean. Usually the baseline was very close to zero. However, occasionally spontaneous bumps would occur just before the onset of light, which caused the baseline to deviate from zero. To avoid such contaminations, a procedure was adopted to eliminate the effects of spontaneous bumps. The computer was programmed to search for large spurious deviations from zero in the response during a 3-s period just before the onset of light. Any large nonzero values were removed from the record. The rest of the record was then time-averaged to obtain the baseline. This routine was found to be effective in removing the spontaneous bumps from the record and returned a baseline value very close to zero each time. For very bright light intensities, such as those above the \(-1\) log unit used to obtain samples shown in Fig. 1, it was seen that the response did not return to baseline (current \( \approx 0 \)) immediately at the cessation of the stimulus (Fig. 1). This might indicate that during the response to light, some other processes, such as an electrogenic pump, might contribute a small current to the response. The source of this current is not known. However, to account for its effect on the estimation of the mean, the average response was first measured from the baseline before the onset of the light stimulus as described and then measured from the value shortly (\( \sim 1 \) s) after the cessation of the light stimulus. The average of these two numbers was taken to be the mean of the response. The variance was either calculated from data after the slow trends had been removed (by subtracting a straight line from the data segments) or was calculated by integration from the area under the curve that best fitted the power spectrum from which the duration was estimated. The variance calculated this way agrees well (within 5%) with the value calculated from data...
directly. However, the values calculated from the method of integration were used because it reduced the residual error introduced by the removal of slow trends.

With the values of mean, variance and duration, Eqs. 6 and 7 were solved for \( h \) and \( \lambda \). As shown in Fig. 7, over the range of light intensity studied, the height of the bumps was found to decrease approximately as the \(-0.7\) power of light intensity, whereas the rate was found to increase in strict proportionality to light intensity. These observations were replicated in four cells studied throughout this project.

**Effects of External Calcium Ions**

In an experiment similar to those above, the effects upon the bump parameters of removing the external Ca\(^{++}\) were studied. This was achieved by a perfusion system. After data were obtained in normal Ca\(^{++}\) solution, a solution that contained no Ca\(^{++}\) was put into the bath from one side, while the fluid level of the bath was maintained by drawing off the excess solution with an aspirator from another side. The new solution flowed through the bath for 3 min, which corresponded to about five complete exchanges of solution in the bath. Within 5 min after the flow was stopped, it was observed that the amplitude of the bumps that occurred spontaneously became larger (Fig. 8), as has been observed by other workers (Millecchia and Mauro, 1969a).

![Graphs showing effects of external calcium ions](image)

**Figure 8.** Effects of lowering external calcium ions. In dim light (-5 log), it can be seen that the amplitude of the bumps has increased, although it could not easily be determined by eye the effects on the bump shape and rate. In bright light (-3 log), lowering external calcium ions caused the transient response, the steady state response, and the noise superimposed on the steady response to increase.

After the cell was dark adapted for another 5 min, the standard sequence of stimulation and data collection was initiated. Responses to steps of light and responses to flashes superimposed on the steps were recorded. The steady state parameters rate, height, and duration were deduced from the steady state responses to steps of light, and the dispersion of latencies was deduced...
from the impulse response and the power spectrum by the method described earlier in this paper. After data were collected in zero Ca++, normal seawater was reintroduced. The cell recovered to its normal responses in ~10 min.

Fig. 9 shows the results of this experiment. Data were obtained at -5 and -3 log light intensities in the zero Ca**+ solution. It can be seen that the rate was not affected by the change in Ca**+ concentration. In both normal and zero Ca**+ solution, the rate increased in strict proportionality to light intensity. In normal Ca**+, the height decreased as the -0.7 power of light intensity. In the zero Ca**+ solution, the height decreased in the same way with light intensity, whereas the amplitude of the bumps increased by a factor of 2. The durations were not at all affected by Ca**+. The time scale of the dispersion process was found to have increased by 30% at -5 log and 15% at -3 log.

-3 log light intensities in the zero Ca**+ solution. It can be seen that the rate was not affected by the change in Ca**+ concentration. In both normal and zero Ca**+ solution, the rate increased in strict proportionality to light intensity, the calculated points virtually superimpose those for normal calcium. In normal Ca**+, the height decreased as the -0.7 power of light intensity. For the two light intensities at which data were taken with zero Ca**+ solution, the height decreased according to the same power law with light intensity; however, the amplitudes of the bumps were increased by a factor of 2. The
durations were not affected at all by Ca++. The time scale of the dispersion process was increased in zero Ca++ by 30% at -5 log and by 15% at -3 log. Not only were the durations unaffected by lowering Ca++, the bump shapes were also unaffected. Fig. 10 is a log-log plot of the power spectra obtained at

![Log-log plot of the power spectra obtained at -5 and -3 log light intensities, in normal and zero-calcium. These curves are derived from the same cell that provided the data shown in Fig. 9. In normal calcium (the closed symbols), the effects of high light intensity (light adaptation) are to decrease the noise variance as well as to change the shape of the curve, shifting the high-frequency cutoff to the right. This implies that the bumps become smaller and briefer in bright light. (Although the vertical scale is in arbitrary units, the relative positions of the two curves [with closed symbols] have been preserved in this plot.) In zero calcium (the open symbols), the noise variance has increased. To highlight the effects of zero calcium on the shapes of the curves, the power spectra obtained in zero calcium are shifted along the vertical axis to coincide with their counterparts in normal calcium. It can be seen that lowering calcium has not affected the shapes of the curves. This implies that in zero calcium, the amplitudes of the bumps have increased but the shapes have not changed. However, the effects of light adaptation on the shape of the curves remain in zero calcium. ](image-url)
DISCUSSION

This study indicates that Eq. 1 can account for the data well and thus supports the idea that the dynamics of the photoreceptor's response to light is determined by the dispersion of latencies and by the bump shape. On the assumption that the response of the photoreceptor is a summation of bumps, our results indicate that over a range of 5 log units in light intensity, the rate of occurrence is strictly proportional to light intensity, whereas the size of individual bumps decreases with increasing light intensity. The height was shown to decrease with the \(-0.7\) power of light intensity. This result agrees well with the observation that in the steady state the mean response increases with the \(0.3\) power of light intensity (Fig. 1). (This follows because the steady state response is equal to \(\lambda \cdot h \cdot T\). \(\lambda\) increases strictly proportionally to light intensity and \(T\) decreases only slightly: a factor of 2 over a 5 log unit increase in light intensity.) The results of this analysis also account for the longstanding observation that the time scale of the photoreceptor's response shortens as a result of light adaptation: the shortening of the time scale of the response can be attributed to the shortening of the time scales of the latency process as well as the time scale of the bump process. Thus, the adapting bump model, which is based on a few simple assumptions, is able to account for a number of general observations in both lateral eye and ventral photoreceptors of Limulus in a consistent manner.

There are two observations that indicate that the adapting bump process may not apply in some circumstances. The first one is the observation that after treatments that abolish the receptor response reversibly, such as anoxia, the cell may recover to its original sensitivity to light, but frequently, the response is no longer "bumpy," which indicates that under such circumstances the response may no longer be a summation of bumps that adapt as a function of light intensity. The second observation is the enhancement effect observed by Fein and Charlton (1977a). These authors observed that the incremental response to a brief test flash superimposed on a bright background light could be larger than the incremental response to the same flash without the background light if the test flash is given during the transient of the response to the background light. This observation indicates that the simple adapting bump mechanism may not apply during the transient of the response to a bright light. However, Fein and Charlton (1977a) also pointed out that the enhancement effect is observable only during the transient. During the steady state, data from similar experiments indicate that adaptation rather than enhancement is taking place.

The two examples cited above should not be taken as contradictions to the adapting bump model because the first example may indicate abnormal physiology when those particular cells recover from treatments that might have damaged them. Because the enhancement effect described in the second example is restricted only to the transient, whereas our analysis applies only
during the steady state, there is no fundamental contradiction between the two sets of observations. What occurs in the photoreceptor during the transient of the response to a step of (bright) light is more complicated than what occurs in the steady state. Apart from such restrictions the adapting bump model seems to be a good working hypothesis for the study of mechanisms of phototransduction. The assumptions of the model are relatively simple and the model accounts for a variety of observations in a consistent manner. In fact, the adapting bump model provides us with a framework to ask specific questions about the underlying mechanisms of phototransduction. For example, the notion that the transduction process can be divided into a latency process and a bump process is clearly demonstrated in the analysis of the adapting bump model (see also Wong et al., 1980). Such a result from our analysis adds much refinement to the simple cascading mechanism implied in the Fuortes and Hodgkin (1964) and Borsellino and Fuortes (1968) models. One can now ask questions about the underlying mechanisms of the latency process and the bump process separately. Along this line of thinking, the adapting bump model has created a new avenue for the study of phototransduction: the study of bump parameters. The fact that different manipulations, such as temperature (Wong et al., 1980), light intensity, and external calcium ions, are shown to affect the individual parameters differently is a strong indication that the parameters probably represent different components of the underlying mechanisms of phototransduction. Furthermore, these components can be manipulated separately.

The latency is the delay between the absorption of a photon and the appearance of the response. The latency (and the dispersion of latencies) is shown to have strong dependence on temperature, adaptation, and external calcium ions. This makes simple diffusion an unlikely explanation for the delay. The current thinking about the underlying mechanisms of the latency process is that after the absorption of a photon, some chemical reactions take place. The end result of these reactions is the initiation of a bump. The chemical reactions are not yet identified and the mechanisms of bump initiation are not known. In locust retinula cells, “light-induced dark bumps” have been observed to occur 15-20 min after the stimulus has terminated (Tsukahara and Horridge, 1977). It is currently believed that an “internal transmitter” mediates between the absorption of a photon and the initiation of a bump. Although the identity of this alleged internal transmitter is not known, it probably is the end product of the chemical reactions.

It is consistently observed that in very dim light the bump shape can be fit by Eq. 13 with \( n = 2 \) and \( \tau \) ranging from 11 to 14 ms. In a broad sense, this result implies that the bump process is consistent with three exponential delays, each with a time constant of 11-14 ms. The exact nature of these exponential processes is not known. However, the following argument might give some insight into this issue. The parameter bump height was shown to decrease approximately as the \(-0.7\) power of light intensity. For the ventral photoreceptors, the reversal potential for the light-induced current was consistently found to be around +15 mV (Millecchia and Mauro, 1969b). Taking this value for the equilibrium potential of the cells studied, and \(-50\) mV for
the resting potential, the conductance change caused by a single bump at 0 log light intensity can be calculated to be $\sim 10^{-11}$ reciprocal ohms. This value is close to the value of the conductance of a single ionic channel found in biological membranes (Anderson and Stevens, 1973; Conti et al., 1976). This value for the average conductance of a bump seems to be a lower limit: in one experiment, which introduced a light >100 times the 0 log light intensity, the calculated value was still $\sim 10^{-11}$ reciprocal ohms (Wong, 1978). This implies that at very high intensity, each bump corresponds to one or a few ionic channels. Assuming that a bump occurring at 0 log light intensity consists of a single channel, a bump occurring in very dim light would consist of $\sim 10^3$ channels. (The bump size $h \cdot T$ has decreased by about a factor of $10^3$ over the range of light intensities as shown in Fig. 7.) In other words, the bump process can be thought of as the concerted action of $\sim 10^3$ channels. If these channels are similar in property to other membrane ionic channels, one of the three exponential processes can be attributed to the stochastic opening time of these channels (Anderson and Stevens, 1973). The other two exponential processes are probably related to the correlation of the $10^3$ channels in a bump (Wong, 1978).

If a bump indeed consists of individual ionic channels, the simplest mechanism for adaptation of bump size would be the reduction of the number of channels associated with a single bump. This notion is supported informally by the observation that in fitting the bump shape over the range of light intensity studied, the choice of value for $n$ in Eq. 13 to give the best fit goes from $n = 2$ (three exponential processes) in dim light to $n = 1$ (two exponential processes) at moderate light intensities and finally to $n = 0$ (1 exponential process) at the brightest light (see also Wong, 1978). This observation is consistent with the idea of reduction of the number of channels associated with a single bump because as the number decreases, the shape (power spectrum) should approach closer to a single exponential process. Further biophysical analysis similar to those described in this paper should be useful in testing this idea quantitatively.

The interpretation of the rate process in a physiological context may also provide us with insights into the mechanisms of excitation and adaptation. Wong and Knight (1980) propose that the photoreceptor membrane may be organized by patches into "functional blocks" of single channels, which respond with near unanimity (if they respond at all) to initiate a bump. The average size (number of channels) of the individual blocks adjusts with adaptation, being largest (containing $\sim 10^3$ channels) in the dark and smallest (containing maybe one channel) in the most light-adapted state. This notion is strongly supported by our observation that the adaptation factor $\psi$ stays close to unity throughout the entire range of light intensity studied. In other words, it seems that in response to a bright step, the cell membrane quickly adjusts itself to provide more blocks of fewer channels. Furthermore, this adjustment seems to be completed during the transient. This readjustment according to adaptation is the reason the bumps behave almost like independent events during the steady state. This adjustment process should be directly
related to the rate parameter. In fact, the value for the rate at each light intensity should be closely related to the number of functional blocks at each light intensity. This observation limits the possible mechanisms of excitation and adaptation. Obviously, more biophysical analysis along the lines mentioned in this discussion would be needed to test the hypotheses suggested.

The ability to manipulate the ionic composition of the cell's environment supports this biophysical approach. For example, the prevailing hypothesis concerning the role of the divalent cations Ca++, in adaptation of invertebrate photoreceptors, is that light somehow causes an increase in intracellular free Ca++ concentration and that this reduces the sensitivity of the photoreceptor to light (Lisman and Brown, 1972). This hypothesis, and a sequence of experiments that followed it (Lisman and Brown, 1975; Fein and Lisman, 1975; Brown and Blinks, 1974; Fein and Charlton, 1977b), stemmed from the observation that if the Ca++ concentration in the bathing medium is lowered, then the size of the photoresponse increases (Millecchia and Mauro, 1969a). It had not been clear whether the size of the bumps or the rate of occurrence of the bumps is affected by low Ca++. The results shown in Fig. 9 indicate that the height of the bumps is increased by the removal of external Ca++ but the rate and the duration of the bumps are not affected. Also, the removal of external Ca++ increases the time scale of the latency process, which is in agreement with the results obtained at low light and reported by Lisman (1976) and Martinez and Srebro (1976).

According to the hypothesis we described earlier about the mechanisms of the bump process, the observations that the height of the bumps is increased while the shape remains unaffected (Fig. 10) by removing external Ca++ implies that the conductance of individual conducting channels would have to increase. For example, Ca++ may modify the selectivity of the individual ionic channels. Such speculations can be subjected to experimental verification and results should have significant implications about the nature of the channels and the role of Ca++. Furthermore, because similar experiments can be performed by altering internal Ca++, it would be possible also to characterize the effects of intracellular Ca++ in terms of bump parameters.

In conclusion, although the response of the ventral eye of Limulus to light is different in several respects from the response of the lateral eye, a quantitative and consistent accounting for the ventral eye's response dynamics is furnished by the adapting bump model. Data analyzed by this model indicate that under dark adaptation the photoresponse is composed of "bumps," each of which consists of the coordinated opening of \( \sim 10^3 \) membrane channels that have \( \sim 10^{-11} \) reciprocal ohms conductance each, whereas light adaptation reduces the number of channels represented by a single bump, eventually down to a single channel at the brightest light. The adapting bump model leads to a separation of the photoresponse into several component effects and shows that low calcium increases bump size and dispersion of latencies but does not affect bump shape or rate of occurrence.

The authors wish to thank Ms. Emily Preslar, Ms. Sharon Silverman, and Ms. Su-jen Wong for typing the many drafts of this manuscript and assisting with the illustrations.
This work was supported in part by National Institutes of Health grants EY-0188 and EY-1428. F. W. was supported by a graduate fellowship from The Rockefeller University. This work formed part of a dissertation submitted by F. W. to The Rockefeller University in partial fulfillment of the requirements for a PhD degree. Some of the results have appeared previously in abstract form (Wong, F., and B. Knight. 1977. The adapting bump model for Limulus ventral photoreceptors. [Abstr.] Assoc. Res. Vision and Ophthalmol. Annu. Meeting, 1977, p. 119. [Suppl. Invest. Ophthalmol.]).

Received for publication 29 October 1980 and in revised form 25 February 1982.

REFERENCES

Anderson, C. R., and C. F. Stevens. 1973. Voltage clamp analysis of acetylcholine produced end-plate current fluctuations at frog neuromuscular junction. J. Physiol. (Lond.). 235:655–691.

Bayer, D. S., and R. B. Barlow, Jr. 1978. Limulus ventral eye. Physiological properties of photoreceptor cells in an organ culture medium. J. Gen. Physiol. 72:539–563.

Borsellino, A., and M. G. F. Fuortes. 1968. Responses to single photons in visual cells of Limulus. J. Physiol. (Lond.). 196:507–539.

Brown, J. E., and J. R. Blinks. 1974. Changes in intracellular free calcium during illumination of invertebrate photoreceptors: detection with aequorin. J. Gen. Physiol. 64:643–665.

Brown, J. E., H. D. Harary, and A. Waggoner. 1979. Isopotentiality and an optical determination of series resistance in Limulus ventral photoreceptors. J. Physiol. (Lond.). 296:357–372.

Clark, A. W., R. Millecchia, and A. Mauro. 1969. The ventral photoreceptor cells of Limulus. I. The microanatomy. J. Gen. Physiol. 54:289–309.

Conti, F., B. Hille, B. Neumcke, W. Nonner, and R. Stämpfli. 1976. Measurement of the conductance of the sodium channel from current fluctuations at the node of Ranvier. J. Physiol. (Lond.). 262:699–727.

Cooley, J. W., and J. W. Tukey. 1965. An algorithm for the machine calculation of Fourier series. Math. Computation. 19:297–301.

Corson, D. W., A. Fein, and J. Schmidt. 1979. Two effects of phosphodiesterase inhibitors on Limulus ventral photoreceptors. Brain Res. 176:365–368.

Dodge, F. A., B. W. Knight, and J. Toyoda. 1968. Voltage noise in Limulus visual cells. Science (Wash. D. C.). 160:88–90.

Fein, A., and J. S. Charlton. 1975. Local adaptation in the ventral photoreceptors of Limulus. J. Gen. Physiol. 66:823–836.

Fein, A., and J. S. Charlton. 1977a. Enhancement and phototransduction in the ventral eye of Limulus. J. Gen. Physiol. 69:553–569.

Fein, A., and J. S. Charlton. 1977b. A quantitative comparison of the effects of intracellular calcium injection and light adaptation in the photoreceptors of Limulus ventral photoreceptors. J. Gen. Physiol. 70:591–600.

Fein, A., and J. Lisman. 1975. Localized desensitization of Limulus photoreceptors produced by light or intracellular calcium ion injection. Science (Wash. D. C.). 187:1094–1096.

Fuortes, M. G. F., and A. L. Hodgkin. 1964. Changes in time scale and sensitivity in the ommatidia of Limulus. J. Physiol. (Lond.). 172:239–263.

Knight, B. W. 1972. Some point processes in motor and sensory neurophysiology. In Stochastic Point Processes: Statistical Analysis, Theory and Applications. P. A. W. Lewis, editor. John Wiley & Sons, Inc., New York.
Lisman, J. E. 1976. Effects of removing extracellular Ca\(^{2+}\) on excitation and adaptation in Limulus photoreceptors. *Biophys. J.* 16:1331–1335.

Lisman, J. E., and J. E. Brown. 1972. The effects of intracellular iontophoretic injection of calcium and sodium ions on the light response of Limulus ventral photoreceptors. *J. Gen. Physiol.* 59:701–719.

Lisman, J. E., and J. E. Brown. 1975. Effects of intracellular injection of calcium buffers on light adaptation in Limulus ventral photoreceptors. *J. Gen. Physiol.* 66:489–506.

Martinez, J. M., and R. Srebro. 1976. Calcium and control of discrete wave latency in the ventral photoreceptor of Limulus. *J. Physiol.* (Lond.) 261:535–562.

Millechcia, R., and A. Mauro. 1969a. The ventral photoreceptor cells of Limulus. II. The basic photoresponse. *J. Gen. Physiol.* 54:310–330.

Millechcia, R., and A. Mauro. 1969b. The ventral photoreceptor cells of Limulus. III. A voltage-clamp study. *J. Gen. Physiol.* 54:331–351.

Pepe, J. S., and J. E. Lisman. 1978. Voltage-sensitive potassium channels in Limulus ventral photoreceptors. *J. Gen. Physiol.* 71:101–120.

Pinter, R. B. 1966. Sinusoidal and delta function responses of visual cells of the Limulus eye. *J. Gen. Physiol.* 49:656–693.

Rice, S. O. 1944. Mathematical analysis of random noise. *Bell. Tel. Syst. J.* 23:282–332.

Srebro, R., and S. Yeandle. 1970. Stochastic properties of discrete waves of the Limulus photoreceptor. *J. Gen. Physiol.* 56:751–767.

Tsukahara, Y., and G. A. Horridge. 1977. Miniature potentials, light adaptation and afterpotentials in locust retinula cells. *J. Exp. Biol.* 68:137–149.

Welch, P. D. 1967. The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. *IEEE Trans. Audio Electroacoustics.* AV-15:70–73.

Wong, F. 1978. Nature of light-induced conductance changes in ventral photoreceptors of Limulus. *Nature (Lond).* 276:75–79.

Wong, F., and B. W. Knight. 1980. The adapting-bump model for eccentric cells of Limulus. *J. Gen. Physiol.* 76:539–557.

Wong, F., B. W. Knight, and F. A. Dodge. 1980. Dispersion of latencies and the adapting-bump model on photoreceptors of Limulus. *J. Gen. Physiol.* 76:517–537.

Yeandle, S., and J. B. Spiegel. 1973. Light-evoked and spontaneous discrete waves in the ventral nerve photoreceptor of Limulus. *J. Gen. Physiol.* 61:552–571.