

LETTER TO THE EDITOR

A Simple Explanation for the Large and Widely Differing Time Exponent of the Initial Response of *Limulus* Photoreceptors

Dear Sir:

Recently, Payne and Fein (1986) have reported measurements of the initial current response of *Limulus* ventral photoreceptors to bright flashes of light, both in the dark-adapted (DA) and in the light-adapted (LA) state of the cell. The authors have fitted their results by writing the response current in the form

$$J(t) = J_{\text{sat}} \frac{Y(t)}{\sigma + Y(t)} \quad (1)$$

where $Y(t)$ is the time course of the concentration level of transmitter molecules that cause the light-sensitive channels to open. The formation of transmitter molecules, Y , was modeled by two parallel visual cascades that interact nonlinearly in such a way that $Y(t)$ turned out to behave as

$$Y(t) = g(N)t^n \quad (2)$$

where N is the effective number of absorbed photons from the flash. The kinetics of the two cascades and their nonlinear interaction was chosen such that the exponent n and the function $g(N)$ of Eq. 2 became different for the DA and LA states of the cell, respectively. The fit of Eqs. 1 and 2 to the experimental curves of the initial response yielded

$$\begin{aligned} \text{DA: } g(N) &\sim N^4, & n &\approx 17 \\ \text{LA: } g(N) &\sim N, & n &\approx 5 \end{aligned} \quad (3)$$

The point that we would like to make in this comment is that the fitting results of Eq. 3 may be understood in a much simpler way and independently of any detailed transduction model. To this purpose, we adopt a hypothesis that was suggested for the first time by Goldring and Lisman (1983), namely that the transduction process starts with some number of nonamplifying steps. Goldring and Lisman observed that in the Fuortes-Hodgkin model of transduction (1964) the ratio $t_{\text{lat}}/t_{\text{D}}$ of the latency t_{lat} and the duration t_{D} of quantum bumps became much too small as compared with the experimental result if the phototransduction chain was assumed to amplify from the very beginning at its head end. One of us (Schnakenberg, 1989) has generalized this hypothesis to a much broader class of cascade models and has identified further experimental evidence supporting this hypothesis.

A number of steps without or with only very low amplification at the beginning of the transduction chain will show up as a latency t_{lat} such that after a stimulus flash at

time $t = 0$ the transmitter level $Y(t)$ is expected to behave as

$$Y(t) = \begin{cases} 0 & \text{for } 0 \leq t \leq t_{\text{lat}} \\ g(N)(t - t_{\text{lat}})^m & \text{for } t_{\text{lat}} \leq t \end{cases} \quad (4)$$

instead of Eq. 2. The exponent m is determined by the number of amplifying steps that follow the latency steps in the phototransduction chain.

If single photons initiate a single chain each, the latency t_{lat} will fluctuate from event to event, which is observed in quantum bump experiments. For bright flashes of light, a large number of initiated chains will compete for the shortest latency. This explains why latency decreases with increasing stimulus intensity.

It is also well known that the latency depends on the light adaptation state of the cell, namely long latencies for DA and short latencies for LA. We shall come back to this point below.

Let us now present the main point of our comment. We have fitted a curve of Eq. 2 for $Y(t)$ as used by Payne and Fein (1986), i.e., a power law $\sim t^n$ beginning at $t = 0$, to the experimentally expected behavior of $Y(t)$ as given in Eq. 4. To this purpose, we have minimized the integrated square deviations of $Y(t)$ from Eqs. 2 and 4 within a time interval $0 \leq t \leq t_{\text{fit}}$ on a computer to find the best fit for the exponent n of Eq. 2 for a given value of the exponent m in Eq. 4. The fitting results depend on the exponent m and even more sensitively on the ratio $q = t_{\text{lat}}/t_{\text{fit}}$. Our point is that even for rather modest values of the exponent m , e.g., $m = 2, 3$, or 4 , we may obtain results for the exponent n up to $n = 50$! A selection of our fitting results is shown in Table I.

Let us choose a fixed fitting time interval t_{fit} both for DA and LA from Payne's and Fein's measurements: $t_{\text{fit}} \approx 100$ ms. Since t_{lat} is known to be short in LA and large in DA, we expect a small value of q in LA and a large value (but of course still $q < 1$) in DA. This then explains at least qualitatively why one should find small exponents n in LA and rather high exponents n in DA.

The form of $Y(t)$ which we suggest for the time course of the transmitter level in Eq. 4 means a separation of the processes of latency and amplification. There are five experimental observations that argue in favor of this suggestion: (a) Latency and bump size (amplitude or current integral) are not correlated at a constant state of adaptation (Stieve and Bruns, 1983; Keiper et al., 1984; Schnakenberg et al.,

TABLE I

	$m = 2$	$m = 3$	$m = 4$
$q = 0.4$	4	6	7
$q = 0.5$	5	7	9
$q = 0.6$	7	9	12
$q = 0.7$	9	13	16
$q = 0.8$	14	19	24
$q = 0.9$	30	40	50

Results for the exponent n in Eq. 2 from a fit of $Y(t)$ of Eq. 2 to $Y(t)$ of Eq. 4 for various values of the exponent m of Eq. 4 and of $q = t_{\text{lat}}/t_{\text{fit}}$.

1986; Stieve, 1986). (b) Latency and slope of the bump rise are not correlated at a constant state of adaptation (Keiper et al., 1984; Stieve, 1986). (c) Latency and bump size are influenced differently by the mutation *norp A* in *Drosophila* (Pak et al., 1976). (d) The temperature dependence of bump latency has a coefficient Q_{10} of ~ 4 as compared with the Q_{10} of bump amplitude and duration of ~ 2.5 (Adolph, 1968; Srebro and Behbehani, 1972; Wong et al., 1980). (e) Facilitation by a weak conditioning flash enhances the bump size and all other bump parameters opposite to the changes of light adaptation, whereas the bump latency is shortened as by light adaptation (Stieve, 1986).

We plan to generalize our analysis to include the variation of t_{lat} with the stimulus intensity, which would lead to a variation of the fitting exponent n with the stimulus intensity. Such a variation may be picked out of Payne's and Fein's (1986) curves. A direct interpretation of Payne's and Fein's results in terms of our hypothesis as given in Eq. 4 is difficult since Payne and Fein present their results for the initial response currents $J(t)$ in a double log-plot as functions of $\log(t)$, whereas we need double log-plots as functions of $\log(t - t_{\text{lat}})$.

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P. KRAEMER
R. LEDERHOFER
J. SCHNAKENBERG
Institut für Theoretische Physik,
H. STIEVE
Institut für Biologie II,
Rheinisch-Westfälische
Technische Hochschule Aachen,
D-5100 Aachen,
Federal Republic of Germany