Light-induced Reduction in Excitation Efficiency in the *trp* Mutant of *Drosophila*

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ABSTRACT In the transient receptor potential (*trp*) mutant of *Drosophila*, the receptor potential appears almost normal in response to a flash but quickly decays to baseline during prolonged illumination. Photometric and early receptor potential measurements of the pigment suggest that the pigment is normal and that the decay of the *trp* response during illumination does not arise from a reduction in the available photopigment molecules. However, there is reduction in pigment concentration with age. Light adaptation cannot account for the decay of the *trp* response during illumination: in normal *Drosophila* a dim background light shortens the latency and rise time of the response and also shifts the intensity response function (V-log I curve) to higher levels of light intensity with relatively little reduction in the maximal amplitude (V_max) of response. In the *trp* mutant, a dim background light or short, strong adapting light paradoxically lengthens the latency and rise time of the response and substantially reduces V_max without a pronounced shift of the V-log I curve along the I axis. The effects of adapting light on the latency and V-log I curve seen in *trp* are associated with a reduction in effective stimulus intensity (reduction in excitation efficiency) rather than with light adaptation. Removing extracellular Ca^{2+} reduces light adaptation in normal *Drosophila*, as evidenced by the appearance of "square" responses to strong illumination. In the *trp* mutant, removing extracellular Ca^{2+} does not prevent the decay of the response during illumination.

INTRODUCTION

Phototransduction is a complex, multi-stage process that is difficult to analyze. One of the more hopeful approaches is to study the effect of single gene mutation on the process. Several *Drosophila* mutants in which phototransduction is abnormal have been isolated and described (for review see Pak, 1979). At the present time it is not clear in any of the available phototransduction mutants what mechanism is responsible for the defect in the receptor potential. Therefore a detailed study on the characteristics of the available mutants seems highly desirable.

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One of the most interesting phototransduction mutants is the transient receptor potential (trp) mutant. Ultrastructural study of the mutant eye indicated that the mutant eye is normal at eclosion but shows shrinkage of the rhabdomeres and small areas of vesiculation in the rhabdomeres by 5 d of age, and yet at 4 wk deterioration has not progressed extensively (Cosens and Perry, 1972). The receptor potential of the trp mutant, which appears normal in response to a short stimulus (Minke, 1977), quickly decays close to baseline during prolonged illumination (Cosens and Manning, 1969; Minke et al., 1975). The receptor potential of invertebrate photoreceptors in response to strong light stimulus also shows a decay of the response from the initial transient to a lower steady-state level. This decay of the response can be explained, at least partially, by light adaptation (Wong, 1978). Therefore an unusually strong light adaptation could account for the mutant phenotype.

Light adaptation in invertebrate photoreceptors has known effects on several parameters of the receptor potential: it decreases the sensitivity and amplitude of the response (Fuortes and Hodgkin, 1964), reduces the noise superimposed on the response (Dodge et al., 1968; Wu and Pak, 1978; Wong, 1978), and decreases the response latency and rise time (Fuortes and Hodgkin, 1964; Millecchia and Mauro, 1969). An increase in intracellular free Ca\(^{2+}\) is known to mimic the above effects of light adaptation in invertebrates (Lisman and Brown, 1972a and b, 1975; Brown and Lisman, 1975; Muijser, 1979; Tsukahara, 1980; Fein and Charlton, 1977). Previous studies have already suggested that there is neither a pronounced reduction in the size of the quantum bumps (Minke et al., 1975), nor a pronounced shift of the intensity-response function to higher levels of light intensities in the trp mutant during continuous dim illumination (Minke and Armon, 1980). Shot noise analysis has suggested that the decay of the trp receptor potential during illumination arises primarily from a reduction in the quantum efficiency for induction of quantum bumps (Minke et al., 1975) that sum to produce the receptor potential (Dodge et al., 1968; Wu and Pak, 1978; Wong, 1978).

The main aim of this work is to examine in detail whether either a decrease in the available photopigment molecules or light adaptation can account for the decay of the trp response to baseline during illumination. Therefore, I measured in the mutant and normal fly the intensity-response function during background light, the effect of strong illumination and dim background light on the latency and rise time of the response, and the effect of removing extracellular Ca\(^{2+}\) ions on the decay of the trp response during illumination. In addition, the visual pigment of the trp mutant was measured photometrically and electrophysiologically under various conditions.

**MATERIALS AND METHODS**

*Intracellular Recordings*

Intracellular recordings were made in vivo in both the white-eyed trp mutant of *Drosophila* and normal* white-eyed *Drosophila* at 1–4 d of age (at 19°C). The details of

* I call a fly normal when its photoreceptor characteristics are indistinguishable from those of wild-type fly.
the intracellular recording technique are described elsewhere (Wu and Pak, 1975). 2 M KCl-filled micropipettes of 100–160 MΩ resistance were used. The electrodes were lowered into the fly retina via a cut in the eye that was covered by *Drosophila* Ringer's solution (Ikeda and Kaplan, 1970). The stimulating and recording systems have been described elsewhere (Minke and Kirschfeld, 1979). For adapting lights we used a Xenon light source (XBO, 150 W Osram, München, Federal Republic of Germany) that had 521-nm green interference filters (Schott-Dopal, Mainz, Federal Republic of Germany), a KG1 heat filter, and quartz neutral density filters (Melles Griot, Arnhem, Netherlands, and Massy Cedex, France) in its light path. The unattenuated intensity of the 521-nm green adapting light was $1.24 \times 10^{15}$ photons cm$^{-2}$ s$^{-1}$. We also used this light source with the 521-nm green filter replaced by a yellow OG 515 edge filter (Schott-Dopal). The effective intensity of this yellow light for generation of the receptor potential was equivalent to $6.2 \times 10^{15}$ photons cm$^{-2}$ s$^{-1}$ of 521 nm light since it had to be attenuated by a factor of $\sim 5$ in order to give a similar peak amplitude of receptor potential as the unattenuated 521-nm green light.

For test flashes a photographic flash (Braun, type F900, Frankfurt, Federal Republic of Germany) filtered by a yellow OG 515 Schott edge filter and attenuated by quartz neutral density filters (mto, Massy Cedex, France) was used. The unattenuated energy of the yellow flash when using the 583-nm interference filter (Schott-Dopal) and KG1 heat filter was $2.8 \times 10^{13}$ photons·cm$^{-2}$. The efficiency of the yellow flash without the 583-nm filter was equivalent to $4.4 \times 10^{15}$ photons·cm$^{-2}$ of 583-nm light since it had to be attenuated by 2.2 log units in order to give a similar peak amplitude of receptor potential as the unattenuated 583-nm monochromatic flash. Fast responses were either directly photographed from the oscilloscope traces or recorded on a fast time scale using the memory of an averaging computer (NIC-527; Nicolet Instrument Corp., Madison, Wis.) and later transferred to an X-Y plotter (Hewlett-Packard, Inc., Frankfurt, Federal Republic of Germany). The responses were also recorded on a pen recorder at a slower time scale (Gould Inc., Cleveland, Ohio).

**Early Receptor Potential (ERP) Measurements**

The ERP of the fly can be recorded as a fast corneal-negative potential that appears in the initial part of the electroretinogram (ERG) and arises from selective activation of fly metarhodopsin ($M$) (Pak and Lidington, 1974; Stephenson and Pak, 1980; Minke and Kirschfeld, 1980). This corneal-negative ERP, called the $M_1$ phase, elicits in the second-order neurons a much larger, corneal-positive potential, known as the $M_2$ (see Fig. 4, right side). The $M$ potential was used in this work to monitor the relative concentration of the visual pigment. It was elicited by a strong orange flash originating from a photographic strobe flash (Strobonar 65C, Honeywell, Inc., Denver, Colo.) filtered by a broad-band orange filter (Corning CS 3–67; Corning Glass Works, Corning, N. Y.) and a KG1 heat filter. Three orange flashes were required to put the pigment system in photoequilibrium. The $M$ potential is observed only after pigments are shifted to the $M$ state by blue light (Pak and Lidington, 1974). For blue and orange adaptation, I used a 12-V quartz iodide lamp in conjunction with 480- and 600-nm Baird Atomic interference filters (Baird Atomic Inc., Bedford, Mass.) and Balzer neutral density filters (Balzers Aktiengesellschaft, Furstentum, Lichtenstein). A maximal intensity blue or orange adapting light of $\sim 5$ s duration was required to put the pigment system in photoequilibrium.

**Microspectrophotometric Measurements**

The microspectrophotometric measurements were made on a modified Cary model 14 spectrophotometer (Ostroy et al., 1974; Ostroy, 1978). For these measurements single flies were placed on ice, their heads were removed, and the sample beam of the
spectrophotometer was focused on one of the eyes (using 580-nm light). An initial spectrum was then taken. The eye was then illuminated for 5 min with saturating light from an 80-W fiber optic illuminator (type II-80; American Optical) containing two heat filters and a broad-band 455-nm interference filter in its light path (Balzer K2). Another spectrum was then taken. After completion of the spectrum, a 5-min illumination with orange light was carried out using a broad-band 600-nm interference filter (Balzer K5). A third spectrum was then taken. This was followed by a second blue illumination, a fourth spectrum, another orange illumination, and a fifth and final spectrum. Difference spectra were obtained by taking the difference between each of the succeeding spectra, resulting in four difference spectra corresponding to the rhodopsin<sub>480</sub> to metarhodopsin<sub>580</sub> transition or its reversal (see Fig. 5).

**Fast Perfusion Experiments**

The perfusion experiments were performed according to the method developed by Wilcox (1980). Flies were initially prepared in the same way described above for intracellular recordings. A second cut, in the neck, separated the sectioned head from the body. The head was then placed in a perfusion chamber constructed from a strip of magnetic rubber in which was cut a double-tapered slot as wide in the middle as the fly's head. This magnetic strip was attached to a coverslip using high vacuum silicon grease, forming a perfusion chamber with a total volume of 30 μl. The perfusate was saturated with oxygen by bubbling O<sub>2</sub> through the saline reservoir at 1 liter per minute for 10 min before an experiment. Saline flowed into one side of the chamber via a 23-gauge hypodermic needle and was vacuumed off from the other side by a 21-gauge needle. The rate of saline flow was 3 ml/min (~100 chamber volume changes per minute). The composition of the control saline was based mainly on the concentration of *Drosophila* haemolymph determined by Larrivee et al. (1978). The solutions were osmotically balanced with sucrose to 435 mosmol (Larrivee et al., 1978). The composition of the solutions used in my experiments is presented in Table I in millimolar concentrations.

| Solutions | KCl | NaCl | CaCl<sub>2</sub> | Sucrose | NTA | MgCl<sub>2</sub> |
|-----------|-----|------|-----------------|---------|-----|-----------------|
| Control   | 10  | 120  | 2               | 148     | —   | 2               |
| Low Ca<sup>2+</sup> | 10  | 120  | 0.2             | 148     | 5   | 2               |

All solutions contained 5 mM glucose, 20 mM trehalose, and 5 mM HEPES buffer and were adjusted to pH 7.0 with NaOH. The low Ca<sup>2+</sup> solution was used only in the experiments presented in Fig. 12. Extracellular recordings were performed by measuring the potential difference between a broken pipette filled with control saline and placed in the retina and an agar-2 M KCl salt bridge placed in the chamber. The light stimuli used in the perfusion experiments were generated by an Osram XBO 150W Xenon lamp with Bausch and Lomb power supply and reached the preparation through a Bausch and Lomb High Intensity Monochromator (Bausch and Lomb, Inc., Rochester, N. Y). The intensity of the unattenuated light beam at the level of the preparation was 1.5 × 10<sup>18</sup> photons·cm<sup>-2</sup>·s<sup>-1</sup> at 520 nm.

**Effect of Perfusion on the ERG Waveform**

The waveform of the ERG recorded in the fly eye differs from that of the intracellularly recorded receptor potential mainly in two aspects: (a) the existence of "on" and "off"
transients in the ERG arising from the second-order neurons (Goldsmit and Bernard, 1974; see also Fig. 4); (b) the appearance of slow components in the ERG that distort the receptor component. A recent study conducted in the drone retina (Coles and Tsacopoulos, 1979) indicated that during light response there is an increase in K⁺ concentration in the extracellular space, which depolarizes the pigment cells surrounding the photoreceptors. This relatively slow depolarization slowly disappears after the K ions are absorbed by the pigment cells. It seems that a similar mechanism exists in Drosophila.

A detailed study concerning the origin of the various components of the ERG is outside the scope of this study. A few points that are somewhat relevant to this study are discussed below.

Fig. 1 shows the ERG waveforms of a normal fly to a green light pulse at the beginning of perfusion (upper trace) and after 15 min of perfusion (lower trace). A

![Figure 1](image)

**Figure 1.** The effect of perfusion on the ERG waveform. The figure shows ERG waveforms of a normal fly to 550 nm green light attenuated by 1.0 log unit, at the beginning of the perfusion (upper trace) and after 15 min of perfusion (lower trace). The typical ERG response with small “on” and “off” transients and slow rise and decay times changes to a response without the “transients” and the slow component after 15 min of perfusion. This response has the shape of the intracellularly recorded receptor potential.

typical ERG waveform with small “on” and “off” transients and slow rise and decay times (upper trace) changes to a response without the “transients” and the slow component after 15 min of perfusion. The latter response is a “mirror” image of the intracellularly recorded receptor potential. It was furthermore found by intracellular recordings from unidentified cells, presumably pigment cells, that a slow photoresponse, observed at the beginning of the perfusion, disappeared later on during perfusion. The disappearance of the “transients” may arise from a reduction in the electrical resistance of the basement membrane (see Shaw, 1975). The disappearance of the slow component can be explained by assuming that the superfusion buffers the extracellular space of the retina, thus preventing the accumulation of K⁺ during light response. It therefore eliminates the depolarization of the pigment cells that otherwise would distort the receptor component in the ERG.
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The change in the ERG waveform of Fig. 1 was used as a convenient measure of the efficiency of perfusion. In the case of Drosophila heads that were sectioned only slightly, or in the case of relatively large Musca heads, it sometimes took more than 30 min for the ERG to change from the upper shape of Fig. 1 to the lower shape.

The ERG could be recorded in the perfusion systems for at least several hours with only a small reduction in the response amplitude. Therefore, in the control solutions the viability of the preparation was not a limiting factor.

RESULTS

Decay of the \textit{trp} Response during Various Light Intensities

The decay rate of the \textit{trp} response during illumination is an important parameter that characterizes the receptor potential of the \textit{trp}. The decay rate and the final steady-state level attained varied among different flies. The mutants could be classified roughly into two groups: (a) those with relatively slow decay to a non-zero steady state (Minke et al., 1975; Fig. 8A) and (b) those with fast decay to a zero steady state (Fig. 2). Fig. 2 illustrates typical responses of the \textit{trp} mutant to increasing intensities of light stimuli. At the dimmest light stimulus (bottom trace) the response did not decay to baseline even after prolonged illumination (of more than 1 min). However, at higher intensities the response decayed to baseline during prolonged illumination. At the highest intensity (top trace), a small steady-state response reappeared but with a reduced noise level as compared with the bottom traces. This small steady state could arise from some damage to the cell. The figure shows that the rate of decay of the \textit{trp} response during illumination is strongly dependent on stimulus intensity and it approaches a maximum limiting value at higher levels of light intensities.

The decay of the receptor potential of the \textit{trp} mutant may arise from an increase in conductance to ions like Cl$^-$ and K$^+$, which have a negative equilibrium potential. Fig. 3 presents bridge measurements made in a photoreceptor of the \textit{trp} mutant. After illumination the bridge shows a conductance increase which then decreases roughly in parallel with the decrease in voltage. The figure thus suggests that the decay of the \textit{trp} response during illumination does not arise from conductance increase to such ions as Cl$^-$ or K$^+$ but rather from a conductance decrease to Na$^+$ ions.

Decay of the \textit{trp} Response during Various Amounts of Rhodopsin Activation

Cosens and Manning (1969) and Cosens (1971) suggested that the decay of the \textit{trp} response during illumination arises from a reduction in the amount of available pigment molecules during illumination, whereas Minke et al. (1975) suggested reduction in quantum efficiency without specifying a mechanism. To test Cosens’ hypothesis, I measured in the orange-adapted (for 30 s) \textit{trp} fly the ERG response to increasing intensities of blue light (Fig. 4, left). The orange adaptation before each trace put all the pigment in the rhodopsin (\textit{R}) state and the following blue pulses shifted increasing amounts of pigment molecules to the metarhodopsin (\textit{M}) state. Relative amounts of pigment
**FIGURE 2.** The dependence of the decay time of the *trp* response on the intensity of the light stimulus. At very dim light the response does not decay to the baseline (bottom trace). At slightly higher light intensities the decay time becomes shorter with increasing light intensity, and at higher light intensities (upper two traces) the decay time approaches a minimum limiting value. All responses were recorded intracellularly from the same cell, which was stimulated by 524-nm monochromatic green light (Schott-Depal filter) arising from the XBO light source.
shifted to the metarhodopsin state by 60-s blue pulses of varying intensity were monitored by the amplitude of the $M$ potential (see Materials and Methods) in response to a strong orange test flash (Fig. 4, right).

The figure shows that at relative intensity of $-2.5$ the $trp$ response decayed to a steady-state baseline within $\sim 10$ s. The $M$ potential arising from 60 s blue adaptation of the same intensity (Fig. 4, upper right trace) had a very small amplitude relative to the maximal amplitude obtained when $\sim 80\%$ of pigment conversion occurred when a saturating amount of blue light was given (Hamdorf, 1979) (bottom right trace). Since the receptor component of the ERG is distorted by a nonreceptor slow response (see Fig. 1), the receptor component in the ERG of Fig. 4 most likely reaches baseline three to five times faster than actually observed in the figure. The figure therefore shows that the $trp$ response decays close to baseline even when negligible amounts of pigment are activated.

**FIGURE 3.** The decay of the $trp$ response is accompanied by a conductance decrease. The figure shows intracellular bridge measurements made in the $trp$ mutant before and during 524-nm green light attenuated by 2.0 log units. The bridge, which was balanced in the dark, shows during light an initial conductance increase that then decreases roughly in parallel with the decrease in voltage.

**Dependence of Pigment Concentration on the Age of the $trp$ Flies**

An ultrastructural study of the $trp$ retina has shown some degeneration with age (Cosens and Perry, 1972). This degeneration may suggest that the visual pigment in the $trp$ mutant is defective. Therefore I measured photometrically and by the ERP the relative concentration of visual pigment at different ages of the $trp$ mutant as a possible monitor for the degeneration. These measurements could also be used to determine whether the pigment system of the mutant is normal.

Fig. 5 shows an example of difference spectra measured from the whole eye of white-eyed $trp$ flies of ages of 4, 8, and 16 d (see Materials and Methods) raised at 24°C. The difference spectrum of the 4-d-old fly is normal (see Ostroy et al., 1974; Ostroy, 1978). The 455-nm adapting blue light causes an absorbance decrease in the blue due to a decrease in $R$ concentration and an increase in absorbance in the orange due to an increase in $M$ concentration. A symmetrical difference spectrum was obtained after 600-nm adaptation.
The standard errors in the figure were calculated from four consecutive measurements made on the same fly.

At age of 8 d there was a reduction in the amount of absorbance change (middle curve). At 16 d of age the absorbance change of the particular fly presented in the figure was below the resolution of this method. Although I found a normal concentration of photopigment in all flies tested at the age of 1–4 d, the decrease in pigment concentration with age was variable among individual trp flies. In some flies the concentration of the pigment, as assayed photometrically or by the M potential, showed normal concentration at 8 d.
and sometimes close to normal even at 16 d. By the age of 32 d, however, M-potential measurements showed without exception (22 flies) either a reduced concentration or no detectable pigment concentration at all.

Fig. 6 summarizes the age-dependent reduction in pigment concentration of the trp mutant as measured photometrically at 580 nm (squares) or electrophysiologically with the ERP (M1 phase; circles) in a paradigm similar to that of Fig. 4 (bottom right trace). The large standard errors at ages 8 and 16 d are due to the fact that some flies had normal or close to normal concentrations of pigment.

**Effect of Light Adaptation**

It is possible that the decay of the trp response during illumination arises from unusually strong light adaptation. Therefore the effect of continuous dim background light and strong adapting light on the trp response was compared with that of normal fly.
Fig. 7 demonstrates similarities between the receptor potential of the dark-adapted trp mutant (A) and that of the dark-adapted normal fly (F) and differences between their receptor potentials when background light is applied.

**Effects on the Latency**

The figure shows that the dark-adapted responses of the mutant (A) and the normal fly (F) to short test flashes are qualitatively similar. In both cases the latency and rise time of the response decrease when...
FIGURE 7. A comparison between the intracellularly recorded receptor potentials of trp mutant and normal Drosophila photoreceptors to stimuli of different intensities. With increasing light intensity, the latency and the rise time in the dark-adapted photoreceptors of the trp mutant (A) and normal Drosophila (F) decrease. Dim green (521 nm) background lights of variable intensities lead to a reduction in the receptor potential amplitude. This reduction in amplitude is accompanied by an increase in latency in the mutant fly (B), but by a decrease in latency in the normal fly (G). The constant test flashes (OG 515 edge filter) used were obtained by attenuating the light source having an intensity of $4.4 \times 10^{16}$ photons·cm$^{-2}$ per flash (at 580 nm) by 1.0 and 3.0 log units for the mutant and normal fly, respectively. Tracings of the dark-adapted responses of the same cells are also shown in B and G for comparison. The bottom response in B was averaged (eight times). The response of the same cells to the onset of the background lights used in light adaptation protocol of B and G also illustrate the difference between the mutant and the normal fly (C-E, H-I).
the intensity of the test flash increases. However, in the mutant the sensitivity to light is lower, and the latency and rise time are longer. A striking difference between the mutant and the normal photoreceptor was revealed when constant flashes of relative intensity of −1.0 and −3.0 for the mutant (B) and normal fly (G), respectively, were superimposed on dim green background adapting lights. The figure shows that in the normal fly the latency and rise time of the light-adapted responses are slightly shorter than the dark-adapted response (the response to relative intensity −3.0 in F is redrawn as −∞ in G). In contrast, in the mutant (Fig. 7B) the effect of similar background illumination was a pronounced slowing in the rate of rise and an increase in the latency of the responses (the response to −1.0 in A is redrawn as −∞ in B). In addition, in contrast to the normal fly, a relatively small increase in background light (by 0.4 log unit) caused a dramatic decrease in the amplitude of the response in spite of the fact that the test flash was more intense for trp. Similar results were obtained from all 18 cells recorded from 9 different trp flies and 7 different normal flies.

Fig. 7C–E, H, and I show in slower time scale initial portions of the receptor potentials of the mutant (C–E) and normal photoreceptors (H and I) evoked in response to the different levels of background illumination used to obtain traces B and G.

The increase in latency and rise time of the trp response obtained during dim background light could also be obtained in the trp eye, which was stimulated in the dark shortly after prolonged intense illumination (Fig. 8). The extracellular measurements illustrated in Fig. 8 were obtained by repeatedly presenting to the eye pairs of strong green (550 nm) pulses: a 10-s adapting pulse and a shorter test pulse of the same intensity. The dark interval between the two pulses was varied between 0 and 3 min. After the second test pulse the eye was dark adapted for 3 min before another pair of pulses was given. The measurements were performed in a perfused preparation to preserve the undistorted waveshape of the trp receptor potential. Sample recordings are presented in Fig. 8 which show that the trp response recovers to ~90% of the initial amplitude within ~1 min. Responses similar to those of Fig. 8A were also recorded (from other flies) on a fast sweep speed in Fig. 8B where they were compared with responses of normal fly obtained in a similar paradigm of stimulation. The fast measurements showed an increased latency and rise time of the trp responses to the second pulse (upper two traces in Fig. 8B, left) whenever the responses had not fully recovered. In contrast, in the normal fly (Fig. 8B, right) the latency and rise time became shorter in response to a test light presented shortly after a prolonged adapting light of the same light intensity.

**Similarities between the Responses of trp and Normal Drosophila**

Figs. 9 and 10 present results that raise the possibility that the differences between the trp mutant and the normal fly are basically quantitative and not qualitative. These figures show that some important features of the mutant response can also be observed in the normal fly under bright illumination. Fig. 9 (A and B) demonstrates that with a strong background light that
saturates the steady-state phase of the receptor potential, a pronounced response still can be observed when a bright test light is superimposed on the strong background light. However, the response to the test light decays to the steady-state baseline during illumination. Many seconds were required for the steady-state response to recover after the test light was turned off. The figure furthermore shows that when the intensity of the background light is slightly increased (Fig. 9B), the decay to baseline becomes faster. Qualitatively similar results are obtained in the trp mutant when no, or dim, background light is used (Fig. 9, bottom).

![Figure 8A. The dark recovery of the trp response after illumination. A sample of extracellularly recorded responses from a superfused fly to pairs of monochromatic 550-nm light stimuli of the same relative light intensity (~1.0 log) with variable dark intervals. The dark intervals between the pairs were 3 min.](image)

Fig. 10 demonstrates that with the bright background light that would saturate the steady-state response of a normal fly, a superimposed test flash elicits a response with an increased latency and rise time (Fig. 10, bottom traces) as compared with the dark-adapted responses (largest responses). When the background light intensity is below saturation (middle traces), the latency is shorter than that of the dark-adapted responses.

Since damaged cells tend to show increased latency and rise time, only stable recordings that gave reproducible responses (like those of Fig. 10) were used in this study.
Effect on the Intensity-Response Function

A shift in the intensity-response function is a very sensitive indication of light adaptation in photoreceptors. Fig. 11 illustrates the effect of dim background light on the intensity-response function ($V$-log $I$ curves, $V$ being the amplitude of the voltage response and $I$ light intensity) of the trp mutant as compared with normal Drosophila. The relative peak response amplitude (intracellular recordings) is plotted against relative light intensity for dark-adapted (upper curve) and light-adapted (lower curves) photoreceptors. Whereas the dark-adapted responses of both normal (circles) and mutant (squares) flies show very similar $V$-log-$I$ curves, the effect of background light is very different in

\[ V/V_{\text{max}} = \frac{I^n}{I^n + \sigma^n} \]  

where $V$ is the peak response amplitude at a given stimulus intensity $I$, $V_{\text{max}}$ is the maximum response amplitude, and $\sigma$ is the value of the intensity that evokes a half-maximum response amplitude (Naka and Rushton, 1966). The exponent $n$ usually has a value of 0.5–0.6 for intracellularly recorded responses. Fig. 11 demonstrates that the effect of background light on the mutant is mainly to reduce $V_{\text{max}}$ with only a relatively small shift in $\sigma$, whereas in the
normal fly $\sigma$ is significantly shifted to higher levels of light intensities. In the lower curves of Fig. 11 only incremental responses are plotted. However, if the steady-state response of the normal fly is added to the incremental responses of normal fly, then no reduction in $V_{\text{max}}$ is observed. In the mutant, on the

![Graph](attachment:graph.png)

**Figure 9.** The decay of the response to the base-line during dim illumination in the trp mutant (test lights, 524 nm; adapting light, 521 nm, right column) can also be observed in the incremental responses of the normal fly when the background and test light intensities are increased (left column). The figure also shows that the amplitude and decay time of the decaying response during a constant light pulse (of two different intensities in the mutant, traces C and E) are reduced in the normal fly when the intensity of the background is increased (B), or in the mutant when dim background light is applied (D and F).
other hand, the voltage of the steady-state response was negligible; therefore, the reduction in $V_{\text{max}}$ is very pronounced even if the steady-state responses are added.

**Effect of Removing Extracellular Ca$^{2+}$**

Several studies on invertebrates photoreceptors have indicated that lowering intracellular free Ca$^{2+}$ concentration by injection of EGTA buffer into the cell prevents the typical effect of light adaptation on the receptor response (Lisman and Brown, 1975; Muijser, 1979; Tsukahara, 1980). In the case of the *Limulus*

Relative Intensity of Background Light

$$\log I$$

Figure 10. Effects similar to those of dim background lights on the shape of the response of the mutant, namely, an increase in latency and rise time, can also be obtained in normal flies when bright saturating background lights are used. The figure shows that the above effect can be observed only at background light intensities that saturate the steady-state phase (smallest responses: $-0.6$) but not at a lower intensity levels (middle responses: $-2.6, -1.6$). The largest two responses, measured intracellularly at the beginning (left) and end of the experiment (right), are responses to the same constant test flash when no background light was present. The similarity between the dark adapted responses indicates that the effect of the background light is reversible and reproducible. The constant test flash was the maximum-intensity yellow flash (515 edge filter) used in Fig. 7. All the responses are from the same cell. The middle and bottom responses are superimposed on the same base-line of the dark adapted responses for comparison.

ventral eye, however, light adaptation during prolonged intense illumination could not be eliminated by removing extracellular Ca$^{2+}$ (Lisman, 1976) since part of the intracellular increase in Ca$^{2+}$ level during illumination apparently arose from intracellular stores (Brown and Blinks, 1974; Lisman, 1976). Fig. 12 (bottom traces) shows that in normal *Drosophila*, reducing extracellular Ca$^{2+}$ by nitritolriacetiacid-Ca$^{2+}$ (NTA-Ca$^{2+}$) buffer to $\sim 10^{-7}$ M for 10 min does not change the waveform of the receptor potential in a manner similar to that obtained by intracellular injection of EGTA into the photoreceptors of *Calliphora* (Muijser, 1979). Namely, the low extracellular Ca$^{2+}$ concentration
prevents the typical decay of the transient to the lower steady-state level, and a square-shaped response appears in response to a strong stimulus. The normal shape of response (with reduced amplitude) recovers in ~12 min after the low Ca\(^{2+}\) solution is changed to normal saline. Similar results were obtained in six other normal flies perfused with NTA-Ca\(^{2+}\) buffer and two others perfused

![Graph showing intensity-response functions measured intracellularly from a single normal (○) and a single trp photoreceptor (■). All the points were measured at the peak of the receptor potential in response to increasing intensities of 524-nm green light pulses. The upper curve was measured in dark-adapted cells and the other two curves were measured from theincremented responses during 521-nm background lights of various intensities as indicated. The smooth curves were calculated using the hyperbolic function \( V/V_{\text{max}} = \frac{I^n}{I^n + \sigma^a} \) with \( n = 0.6 \) and \( \sigma = -3.7 \) for the upper curve, \( n = 0.6 \) and \( \sigma = -3.0 \) for the lower trp curve, and \( n = 0.75 \) and \( \sigma = -2.2 \) for the light-adapted normal fly.]

**Figure 11.** Intensity-response functions measured intracellularly from a single normal (○) and a single trp photoreceptor (■). All the points were measured at the peak of the receptor potential in response to increasing intensities of 524-nm green light pulses. The upper curve was measured in dark-adapted cells and the other two curves were measured from the incremented responses during 521-nm background lights of various intensities as indicated. The smooth curves were calculated using the hyperbolic function \( V/V_{\text{max}} = \frac{I^n}{I^n + \sigma^a} \) with \( n = 0.6 \) and \( \sigma = -3.7 \) for the upper curve, \( n = 0.6 \) and \( \sigma = -3.0 \) for the lower trp curve, and \( n = 0.75 \) and \( \sigma = -2.2 \) for the light-adapted normal fly.
with 5 mM EGTA-0.2 Ca\(^{+2}\) buffer for 7 min. In the experiments with EGTA the reversibility of the response was poor. Therefore I adopted the NTA buffer for my experiments. Fig. 12 (upper three traces of the middle column) shows that removing extracellular Ca\(^{+2}\) from the perfusate of the trp eye for 10 min (middle column) does not prevent the decay of the response during illumination. The effects of the low Ca\(^{+2}\) medium on the trp response were: (a) to slow down the initial fast decay ("nose") observed in normal saline (left and right column), (b) to increase the amplitude of the response (mainly at low light intensities), and (c) to enhance the low steady-state response. About 10 min after the solution was changed back to control the original waveform of the trp responses returned but with a reduced amplitude (Fig. 12, right column). Experiments similar to those of Fig. 12 were performed on 11 other trp flies and similar results were obtained.
DISCUSSION

The complexity of the phototransduction process on one hand and the
discovery of specific light-induced activation of several enzymes on the other
(see reviews by Bownds, 1980; Pober and Bitensky, 1979) calls now more than
ever before for the use of phototransduction-defective mutants. The trp
mutation may provide such a useful mutant. What can be the nature of the
defect of the trp mutant?

A Structural Defect?
The ultrastructure study (Cosens and Perry, 1972) showed normal structure
of the trp photoreceptors until a few days after eclosion, whereas the receptor
potential is always abnormal from eclosion (B. Minke, unpublished observa-
tions). Therefore the partial degeneration that appears after 5 d of age is most
likely a secondary effect of the mutation. The degeneration of trp with age as
observed either in the ultrastructural study or by my pigment concentration
measurements (Figs. 5 and 6) consistently shows a different pattern of degen-
eration than that observed in another hereditary degenerative mutant of
Drosophila, rdgB. In the rdgB mutant (Harris and Stark, 1977) the degeneration
of R1-6 photoreceptors in light dark cycle is completed in less than 5 d. The
trp mutant in this respect is more similar to several of the norpA carrying more
severe alleles of the norpA gene. These show only partial degeneration with age
(Ostroy, 1978).

A Defect in the Visual Pigment?
At an age of less than 5 d after eclosion I found no indication of any
abnormality in the trp photopigment. The difference spectrum of the pigment
is normal (Ostroy et al., 1974), the waveform of the M1 potential, which is the
ERP of the fly (Stephenson and Pak, 1980; Minke and Kirschfeld, 1980), is
normal, and the photoconvertibility of the pigment between the R and M
states is also normal. Even at a later age the only difference between the
mutant and normal fly is a reduction in the total pigment content.

The fact that the trp phenotype is fully expressed even when only a very
small amount of pigment (relative to the total pigment content) is activated
(Fig. 4) indicates that the decay of the response does not arise from a reduction
in the amount of available photopigment molecules during illumination.

The dark recovery time of the trp response after illumination (in the range
of 2 min) is much too slow to fit with any photometrically observed pigment
transitions of the fly (faster than 100 μs; Kirschfeld et al., 1978). By assuming
that the ERP reflects linearly pigment transitions (Stephenson and Pak, 1980),
the shape of the ERP (M1 potential) of the trp mutant suggests that the
pigment transitions in the mutant are very similar to those of the normal fly
(Minke and Kirschfeld, 1980; Stephenson and Pak, 1980).

Therefore it seems quite safe to conclude that a defect in the visual pigment
is not a major cause for the trp phenotype.
Can one attribute the decay of the \( trp \) response during illumination to an unusually strong effect of light adaptation? A failure of the intracellular mechanisms to reduce the increased level of intracellular free \( Ca^{2+} \) back to the dark level fast enough during and after illumination could account for the \( trp \) phenotype. Several lines of evidence, however, indicate that the above mechanism is very unlikely: (a) there is little or no reduction in the calculated size of the quantum bumps in the steady-state response of the \( trp \) mutant to strong light as compared with weak light* (Minke et al., 1975), unlike in normal fly (see below). The results presented in Figs. 7, 8, and 11 are consistent with the shot noise analysis done on \( trp \). (b) The intensity-response functions (Fig. 11) show that the effect of background light on the \( V\log I \) curve of the \( trp \) mutant (solid squares) is very different from the effect on that of normal fly (open circles) (for more details see Minke and Armon, 1980). In the normal fly the main expression of light adaptation, caused by a dim background, is a shift in the \( V\log I \) curve to higher levels of light intensities (shift in \( \sigma \), Eq. 1). In the \( trp \) mutant there is very little shift in \( \sigma \) but instead a large reduction in \( V_{max} \). (c) Shortening of the response latency and rise time is another expression of light adaptation that is caused by dim background light and strong adapting light in normal \emph{Drosophila} (Figs. 7 and 8) as in other invertebrates (Fuortes and Hodgkin, 1964; Millecchia and Mauro, 1969). In contrast, in the \( trp \) mutant latency and rise time are \textit{increased} either during dim background light (Fig. 7) or during the recovery of the response in the dark after strong, long adapting light (Fig. 8 B). These phenomena observed in the \( trp \) fly during background light and after a strong, long light are most likely associated with a reduction in the effective intensity of the light stimulus because they can qualitatively be mimicked by reducing the stimulus intensity. All the above phenomena do not seem to arise from light adaptation. Following the term proposed by Rodieck (1973), I call this effect a reduction in excitation efficiency.

The final evidence that the \( trp \) phenotype is not due to an unusually strong light adaptation comes from the effect of reducing extracellular \( Ca^{2+} \) concentration. The appearance of a square-shaped response to strong stimulus in the normal fly when extracellular \( Ca^{2+} \) concentration is lowered suggests that the NTA-Ca\(^{2+}\) buffer prevents a large increase in intracellular free \( Ca^{2+} \) concentration during illumination, because very similar square responses were obtained by intracellular injection of EGTA (Muijser, 1979) into the photoreceptor of the blowfly. The fact that a very low extracellular \( Ca^{2+} \) concentration does not prevent the pronounced decay of the \( trp \) response during stimulation strongly suggests that “light adaptation” induced by an increase in intracellular \( Ca^{2+} \) does not cause the decay of the \( trp \) response during illumination. However, there are two effects of the low \( Ca^{2+} \) level on the \( trp \) response: (a)

* The noise level during the steady-state phase can only be observed in those \( trp \) flies where the response does not decay to zero baseline.
the low steady-state level in response to strong stimulus became more pronounced, and (b) a slowing down of the initial fast decay of the response was observed. These phenomena suggest that some suppression of the trp response during continuous strong illumination does arise from a small increase in intracellular free Ca\(^{2+}\). This conclusion fits nicely with recent observations on pigment migration in the trp mutant (Zuidervaart et al., 1979; Lo and Pak, 1981). These studies showed that pigment migration in the trp mutant during light does not proceed fully to the light-adapted position but instead returns to the dark-adapted position during a stimulus. In wild type Drosophila the pigment granules stay in the light-adapted position as long as the light is on. The correlation between pigment migration and increase in intracellular free Ca\(^{2+}\) was demonstrated recently by Kirschfeld and Vogt (1980) in Musca. They could prevent pigment migration during strong light by reducing extracellular Ca\(^{2+}\) concentration with 50 mM EGTA.

**Similarities between the Responses of the trp and Normal Drosophila**

Figs. 9 and 10 show that several phenomena observed in the trp fly when either no background or a dim background light is applied can also be observed in normal Drosophila when strong background light is used. Namely, (a) there is an increase in latency and in rise time in response to a strong test flash superimposed on a strong background light, as previously reported in other species (turtle, Baylor and Hodgkin, 1974; Limulus ventral eye, Stieve et al., 1978); (b) the response to a long, strong light pulse superimposed on a strong background light decays back to baseline; and (c) when the intensity of a strong background light is increased, the response to a constant light pulse decays faster. These similarities might be explained by using the results of shot noise analysis obtained in the Limulus ventral eye by Wong (1978) and in normal Drosophila by Wu and Pak (1978). The above studies indicate that the calculated rate of occurrence of the quantum bumps increases linearly with increasing light intensities in a range of four to five log units above threshold while their calculated size decreases. Accordingly, in this light intensity range the decay of the receptor potential from transient to steady-state level can be accounted for by a reduction in the effective size of the quantum bumps. However, at higher light intensities the derived size of the quantum bumps tends to reach a minimum while the rate of occurrence tends to saturate due to a reduction in quantum efficiency. It is unlikely that this reduction in quantum efficiency arises from reduction in the available rhodopsin molecules. Because the transient response and the increase in latency are also observed in normal Drosophila at saturating levels of illumination, it might be possible that the reduction in excitation efficiency observed in the trp mutant during dim background light occurs in normal Drosophila at high background light due to a similar mechanism. If this is the case, then the trp mutation narrows the range in which bump production can linearly follow the absorption of photons. This defect may arise from a temporary shortage in some critical factor that has to be replenished with time. In the trp mutant, for example, a defective protein that normally has to interact with another protein at a certain speed
may be responsible for that temporary shortage. In normal Drosophila the concentration of the hypothetical critical substance becomes a limiting factor only at the very bright light intensities.

In summary, all the results are consistent with the hypothesis that in the trp mutant the decay of the response during illumination arises neither from a reduction in the available photopigment molecules nor from light adaptation, but rather from light-induced reduction in excitation efficiency, which arises from a defect in an intermediate stage of phototransduction. The effects of various agents and of other phototransduction mutations (in combination with the trp mutation) on the rate of decay of the trp response during light and on the recovery of the response in the dark are presently under investigation. The ability to modify the above parameters might prove to be very useful in understanding the nature of the trp defect and therefore of some of the intermediate steps in phototransduction.

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REFERENCES

BAYLOR, D. A., and A. L. HODGKIN. 1974. Changes in the time scale and sensitivity in turtle photoreceptors. J. Physiol (Lond.). 242:729-756.

BOWNDS, M. D. 1980. Biochemical steps in visual transduction: role for nucleotides and calcium ions. Photochem. Photobiol. 32:487-490.

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., and J. E. LISMAN. 1975. Intracellular Ca modulates both sensitivity and time scale in Limulus ventral photoreceptors. Nature (Lond.). 258:252-254.

COLES, J. A., and M. TSACOPOULOS. 1979. Potassium activity in photoreceptors, glial cells and extracellular space in the drone retina: changes during photostimulation. J. Physiol. (Lond.). 290:525-549.

COSENS, D. J. 1971. Blindness in a Drosophila mutant. J. Insect Physiol. 17:285-302.

COSENS, D. J., and A. MANNING. 1969. Abnormal electroretinogram from a Drosophila mutant. Nature (Lond.). 224:285-287.

COSENS, D. J., and M. M. PERRY. 1972. The fine structure of the eye of a visual mutant A-Type, of Drosophila melanogaster. J. Insect Physiol. 18:1773-1786.

DOODGE, F. A., JR., B. W. KNIGHT, and J. TOYODA. 1968. Voltage noise in Limulus visual cells. Science ( Wash. D. C.). 160:88-90.
calcium injection and light adaptation on the photoresponse of the Limulus ventral photoreceptors. J. Gen. Physiol. 70:591–600.

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

Goldschmidt, T. H., and G. H. Bernard. 1974. The visual system of insects. In Physiology of Insects. Academic Press, Inc., New York. 2nd edition. 2:165–272.

Hamdorf, K. 1979. The physiology of invertebrate visual pigment. In Handbook of Sensory Physiology, Vol. VII/6A. H. Autrum, editor. Springer-Verlag, Berlin. 145–224.

Harris, W. A., and W. S. Stark. 1977. Hereditary retinal degeneration in Drosophila melanogaster: a mutant defect associated with the phototransduction process. J. Gen. Physiol. 69:261–291.

Ikeda, K., and W. D. Kaplan. 1970. Patterned neural activity of a mutant Drosophila melanogaster. Proc. Natl. Acad. Sci. U.S.A. 66:765–772.

Kirschfeld, K., R. Feiler, and B. Minke. 1978. The kinetics of formation of metarhodopsin in intact photoreceptors of the fly. Z. Naturforsch. Teil. C. Biochem. Biophys. Biol. Virol. 33c:1009–1010.

Kirschfeld, K., and K. Voigt. 1980. Calcium ions and pigment migration in fly photoreceptors. Naturwissenschaften. 67:S516.

Larrivee, D., M. Wilcox, and W. L. Pak. 1978. Ionic analysis of Drosophila melanogaster haemolymph: its relation to the ionic dependence of the receptor potential. Assoc. Res. Vis. Ophthalmol. 239.

Lisman, J. E., 1976. Effects of removing extracellular Ca++ on excitation and adaptation in Limulus ventral photoreceptors. Biophys. J. 16:1331–1333.

Lisman, J. E., and J. E. Brown. 1972a. The effect of intracellular Ca++ on the light response and light adaptation on Limulus ventral photoreceptors. In The Visual System: Neurophysiology, Biophysics and Their Clinical Application. G. B. Arden, editor. Plenum Publishing Corp., New York. 23–33.

Lisman, J. E., and J. E. Brown. 1972b. The effect 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.

Lo, Mei-Ven C., and W. L. Pak. 1981. Light-induced pigment granule migration in the retinular cells of Drosophila melanogaster: comparison of wild type with ERG-defective mutant. J. Gen. Physiol. 77:155–175.

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

Minke, B., and E. Armon. 1980. Intermediate processes in phototransduction: a study in Drosophila mutants. Photochem. Photobiol. 32:553–562.

Minke, B. 1977. Drosophila mutant with a transducer defect. Biophys. Struct. Mech. 3:59–63.

Minke, B., and K. Kirschfeld. 1979. The contribution of a sensitizing pigment to the photosensitivity spectra of fly rhodopsin and metarhodopsin. J. Gen. Physiol. 73:517–540.

Minke, B., and K. Kirschfeld. 1980. Fast electrical potential arising from activation of metarhodopsin in the fly. J. Gen. Physiol. 75:381–402.

Minke, B., C.-F., Wu, and W. L. Pak. 1975. Induction of photoreceptor voltage noise in the dark in Drosophila mutant. Nature (Lond.). 258:84–87.

Mujster, H. 1979. The receptor potential of retinular cells of the blowfly Calliphora: the role of sodium, potassium and calcium ions. J. Comp. Physiol. 132:87–95.
BARUCH MINKE  Reducution in Drosophila trp Mutant Excitation Efficiency

NAKA, K. I., and W. A. H. RUSHTON. 1966. S-potentials from color units in the retina of fish (Cyprinidae). J. Physiol. (Lond.). 185:536–555.

OSTROV, S. E. 1978. Characteristics of Drosophila rhodopsin in wild-type and norpA vision transduction mutant. J. Gen. Physiol. 72:717–732.

OSTROV, S. E., M. WILSON, and W. L. PAK. 1974. Drosophila rhodopsin: photochemistry extraction and differences in the norpA<sup>PI2</sup> phototransduction mutant. Biochem. Biophys. Res. Commun. 59:960–966.

PAK, W. L. 1979. Study of photoreceptor function using Drosophila mutants. In Neurogenetics: Genetic Approaches to the Nervous System. X. Breakefield, editor. Elsevier North-Holland, New York.

PAK, W. L., and K. J. LIDINGTON. 1974. Fast electrical potential from a long-lived long-wavelength photoprodocr of fly visual pigment. J. Gen. Physiol. 63:740–756.

POBER, Y. S., and M. W. BITENSKY. 1979. Light-regulated enzymes of vertebrate retinal rods. In Advances in Cyclic Nucleotide Research. P. Greengard and G. A. Robison, editors. Raven Press, New York. 2:265–301.

RODIECK, R. W. 1973. In The Vertebrate Retina. W. H. Freeman & Co., San Francisco. 266.

SHAW, S. R. 1975. Retinal resistance barriers and electrical lateral inhibition. Nature (Lond.). 255:480–483.

STEPHENSON, R., and W. L. PAK. 1980. Heterogenic components of a fast electrical potential in Drosophila compound eye and their relation to visual pigment photoconversion. J. Gen. Physiol. 75:353–379.

STIEVE, H., M. BURN, M. PFLEAUM, and H. GAUBE. 1978. The effect of lowering the extracellular calcium concentration on the light response of dark- and light-adapted ventral nerve photoreceptors of Limulus. KFA-Intern. Bericht. 1–54.

TSUKAHARA, Y. 1980. Effect of intracellular injection of EGTA and tetraethylammonium chloride on the receptor potential of locust photoreceptors. Photochem. Photobiol. 32:509–514.

WILCOX, M. 1980. Ionic mechanism of the receptor potential in the photoreceptor of wild type and mutant Drosophila. Ph.D. Thesis. Purdue University, West Lafayette, Indiana.

WONG, F. 1978. Nature of light-induced conductance changes in ventral photoreceptors of Limulus. Nature (Lond.). 276:76–79.

WU, C.-F., and W. L. PAK. 1975. Quantal basis of photoreceptor spectral sensitivity of Drosophila melanogaster. J. Gen. Physiol. 66:149–168.

WU, C.-F., and W. L. PAK. 1978. Light-induced voltage noise in the photoreceptor of Drosophila melanogaster. J. Gen. Physiol. 71:249–268.

ZUIDERVAART, H., D. G. STAVENGA, W. S. STARK, and G. D. BERNARD. 1979. Pupillary responses revealing receptor characteristics in wild-type and mutant Drosophila. Soc. Neurosci. Abstracts. 5:814.