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## Retinal Noise and Absolute Threshold

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It is shown that the absorption of one quantum can excite a rod in the human retina, but that at least two, and probably many more, excited rods are needed to give a sensation of light. It is suggested that noise in the optic pathway limits its sensitivity, and this idea is subjected to an experimental test. The hypothesis is then formulated quantitatively, and shown to be able to account for the above experiment, and also the disagreement in the literature between those who believe that the absorption of two quanta can cause a sensation, and those who believe that 5 or more are required. The formulation of the hypothesis is used to calculate the maximum allowable noise (expressed as a number  $x$  of random, independent events confusable with the absorption of a quantum of light) in the optic pathway for the absorption of various fractions of the total number of quanta incident at the cornea.

### INTRODUCTION

THE value of the absolute threshold of the human eye has been known for some time, but two recent advances in this field have emphasized the difficulty of arguing quantitatively from this value to the underlying mechanisms. Firstly, it is now known that rods contain more rhodopsin than was previously thought (Denton and Wyllie,<sup>1</sup> Hagins and Rushton,<sup>2</sup> Rushton<sup>3</sup>), and therefore more quanta are absorbed from a threshold flash; secondly, the quantum efficiency of bleaching of rhodopsin turns out to be  $\frac{1}{2}$  instead of 1 both *in vitro* (Collins and Morton,<sup>4</sup> Wald, Durell, and St. George<sup>5</sup>), and in the intact rod (Hagins<sup>6</sup>). If bleaching is the prerequisite for seeing, these two discoveries work in opposite directions, and it might be that the estimated number of quanta effective in excitation from a threshold flash was more or less unchanged. In this paper some of the facts and theories of the mechanisms responsible for absolute threshold are briefly reviewed, and it is shown that they lead to the idea that spurious excitations, or retinal noise, are another important factor determining the value of absolute threshold. This is supported by an experimental observation and by arguments from the literature.

### More Than One Quantum Needed

It is known that the human eye can, under optimal conditions, detect about 100 quanta falling on the cornea, and the attractively simple hypothesis was advanced by de Vries,<sup>7(a)</sup> refuted convincingly by

Pirenne,<sup>7(b)</sup> and put forward again by Weale,<sup>8</sup> that a flash of light is detected when one of these quanta succeeds in activating one rod. This must be rejected for the following reasons.

(a) The best estimates of rhodopsin concentration in the human retina show that at least 3.5% (Crescitelli and Dartnall<sup>9</sup>) and possibly as much as 20% (Rushton<sup>3</sup> and Campbell and Rushton<sup>10</sup>) of light incident on the retina is absorbed. De Vries<sup>7(a)</sup> was aware that more than one quantum was absorbed from a threshold flash, but accepted the argument of Granit, Holmberg, and Zewi<sup>11</sup> that only light absorbed by rhodopsin at the surface of the rod was effective in exciting it; the following arguments, which are indirect, therefore become important.

(b) If a sensation of light resulted from absorption of a single quantum, the threshold quantity of light would not depend in any way on area or duration of the stimulus, since these factors would not affect the number of quanta that were, on the average, absorbed. Experiment shows that this prediction is false.

(c) The frequency-of-seeing curve obtained by measuring the probability of seeing a flash of light as a function of its intensity, may be regarded as a measure of the statistical variability of the threshold process, and all who have used this method agree that the variability is less than would result from a one-quantum threshold. This provides a convincing refutation of the hypothesis because the variability results from the unpredictability of quantum absorption, and thus represents the lower limit of variability of the chain of reactions ending in the sensation of light. Later steps in the chain could only increase the variability, unless they were themselves related to the absorption of quanta, which would be in conflict with the original

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<sup>1</sup> E. J. Denton and J. H. Wyllie, *J. Physiol.* **127**, 81-89 (1955).

<sup>2</sup> W. A. Hagins and W. A. H. Rushton, *J. Physiol.* **120**, 61P (1953).

<sup>3</sup> W. A. H. Rushton, the density of rhodopsin in a human rod is about 0.12; personal communication (1955).

<sup>4</sup> F. D. Collins and R. A. Morton, *Biochem J.* **47**, 3-24 (1950).

<sup>5</sup> Wald, Durell, and St. George, *Science* **111**, 179-181 (1950).

<sup>6</sup> W. A. Hagins, *J. Physiol.* **128**, 22-23P (1955).

<sup>7</sup> (a) H. L. de Vries, *Physica* **10**, 553-564 (1943). (b) M. H. Pirenne, "Quantum physics of vision: theoretical discussion," in

*Progress in Biophysics*, edited by J. A. V. Butler and J. T. Randall (Pergamon Press, 1951, London), Vol. 2, pp. 193-223.

<sup>8</sup> R. A. Weale, *Physiol. Rev.* **35**, 233-246 (1955).

<sup>9</sup> F. Crescitelli and H. J. A. Dartnall, *Nature* **172**, 195-197 (1953).

<sup>10</sup> F. W. Campbell and W. A. H. Rushton, *J. Physiol.* **130**, 131-147 (1955).

<sup>11</sup> Granit, Holmberg, and Zewi, *J. Physiol.* **94**, 430-440 (1938).

hypothesis (Pirenne and Marriott<sup>12</sup>). Hecht, Shlaer, and Pirenne<sup>13</sup> originally used this method to confirm their conclusion that 5 to 14 quanta were absorbed from a threshold flash; the measured variability actually corresponded to that expected if threshold required the coincident absorption of 5 to 8 quanta. On the other hand, van der Velden<sup>14</sup> and Bouman and van der Velden<sup>15</sup> found variability corresponding to twofold coincidence, and obtained additional evidence in support of a 2 quantum threshold from the dependence of threshold on area and duration of the stimulus, by a continuation of the argument indicated under (b) above. The disagreement between these two groups will be discussed later but both of them came to the conclusion that a single quantum can excite a rod; let us first examine this conclusion.

### One Quantum Excites a Rod

Hecht, Shlaer, and Pirenne<sup>13</sup> rejected the idea that a "double hit"—two quanta absorbed by a single rod—was required to excite on the grounds that the calculated chance of a double absorption was lower than the observed frequency of seeing. Their calculation gives a rather unconvincing result even if one uses their original estimate of the rhodopsin concentration in the human retina; if modern estimates are used their argument is further weakened. However, the conditions of their threshold determinations favored double hits, as the geometric image of their stimulus covered only some 300 rods, and if the calculation is repeated using a figure obtained by Denton and Pirenne<sup>16</sup> the original argument stands firmly on its feet. Denton and Pirenne found a threshold (50% seen) of 280 quanta (measured at the cornea) for a stimulus flash 2.83 degrees in diameter, and therefore covering over 70 000 rods. Even if 20% of the quanta are absorbed the chance of one or more rods absorbing two or more quanta is under 0.03. Two more arguments can be leveled against the double-hit hypothesis. Firstly, like Bouman and van der Velden's<sup>15</sup> two-quantum hypothesis, it leads to Piper's law (threshold intensity proportional to square root of area) for the dependence of threshold on area of stimulus, but, unlike the two-quantum hypothesis, it predicts that this should hold down to the smallest areas resolvable by the optics of the eye; in fact the law breaks down for areas which are almost certainly resolvable, and the failure to find Piper's law when recording from ganglion cells in the retina

and using microscope optics (Barlow<sup>17</sup>) should dispel any remaining doubts. Secondly, Brindley<sup>18</sup> showed rigorously that, if threshold depended on a twofold coincidence occurring somewhere in the stimulation area, there was a lower limit to the variability of the threshold, and the frequency-of-seeing curves, as normally plotted, could not be steeper than this limiting case; some experimental curves obtained with short, small, stimulus flashes are steeper (Hecht, Shlaer, and Pirenne<sup>13</sup>; this paper), and the double hit idea is therefore ruled out as an explanation of threshold, at least for the conditions under which these curves were obtained.

### Two or More Excited Rods Needed for Threshold

One must accept the conclusion that the absorption of a single quantum *can* excite a rod, and, for the reasons given in refuting de Vries' and Weale's one-quantum hypothesis, one must also accept the conclusion that a threshold flash which is seen *does* cause two or more rods to be excited. Apparently, the limit to the sensitivity of vision does not lie in the rods but at a later point in the nervous pathway leading to consciousness. It would be surprising if there were no explanation for the failure to detect a single excited rod, and the performance of light-sensitive physical instruments may provide a clue; here it is not the difficulty of amplifying weak signals that limits the sensitivity, but the difficulty of distinguishing a weak signal from the background of spurious signals, or "noise," which occurs without any light signal at all. Hecht<sup>18(a)</sup> and Pirenne<sup>18(b)</sup> have considered this possibility, and Rose,<sup>19</sup> Gregory and Cane,<sup>20</sup> and Tanner and Swets,<sup>21</sup> have all argued in favor of the view that human thresholds should be treated as signal/noise discrimination problems. It has also been shown that in the cat, the species closest to man for which reliable evidence is available, the optic nerve carries an extremely irregular succession of impulses to the nervous system even after complete dark adaptation, and at a time when its sensitivity approaches that of the human (Granit<sup>22</sup> and Barlow, FitzHugh, and Kuffler<sup>23,24</sup>).

The matter may be approached from quite a different point of view. Anybody who has worked with living materials is likely to agree that they may show great inconstancy in their responses to fixed stimuli, and it

<sup>17</sup> H. B. Barlow, *J. Physiol.* **119**, 69–87 (1953).

<sup>18</sup> G. S. Brindley, *Proc. Phys. Soc. (London)* **B67**, 673–676 (1954).

<sup>18</sup> (a) S. Hecht, "Energy and vision," in *Science in Progress*, (Yale University Press, New Haven, 1945), Ser. 4, pp. 75–97. (b) M. H. Pirenne, *Biol. Revs. Cambridge Phil Soc.* (to be published).

<sup>19</sup> A. Rose, *J. Opt. Soc. Am.* **38**, 196–208 (1948).

<sup>20</sup> R. L. Gregory and V. Cane, *Nature* (to be published).

<sup>21</sup> W. P. Tanner and J. A. Swets, "Human use of information. I. Signal detection for the case of the signal known exactly," *Trans. Inst. Radio Engrs. PGIT* **4**, pp. 213–221 (1954).

<sup>22</sup> R. Granit, *Acta Physiol. Scand.* **1**, 370–379 (1941).

<sup>23</sup> Barlow, FitzHugh, and Kuffler, *J. Physiol.* **125**, 28–29P (1954).

<sup>24</sup> Barlow, FitzHugh, and Kuffler (to be published).

<sup>12</sup> M. H. Pirenne and F. H. C. Marriott, *J. Opt. Soc. Am.* **45**, 909–912 (1955).

<sup>13</sup> Hecht, Shlaer, and Pirenne, *J. Gen. Physiol.* **25**, 819–840 (1942).

<sup>14</sup> H. A. van der Velden, *Physica* **11**, 179–189 (1944); *Ophthalmologica* **111**, 321–331 (1946).

<sup>15</sup> M. A. Bouman and H. A. van der Velden, *J. Opt. Soc. Am.* **37**, 908–919 (1947).

<sup>16</sup> E. J. Denton and M. H. Pirenne, *J. Physiol.* **123**, 417–442 (1954).

must have come as a great surprise when Hecht *et al.*, showed that a large part of the inconstancy of response to a threshold flash of light could result from quantum fluctuations in the stimulus. The residual variability could be explained by "noise" entering the system anywhere between the stimulus and the final response, but if this noise is to set a limit to sensitivity it must enter the system before the level at which the threshold decision is made: this is the possibility which is pursued in this paper. Since the level of the threshold decision is not known, there is a strong case for considering first the effects of noise acting at the earliest possible point in the system—that is, to consider the effects of the rhodopsin molecule undergoing spontaneously the same reaction that occurs when it absorbs a quantum of light. Denton and Pirenne<sup>6</sup> have already considered this possibility and give figures for the highest rate for this reaction consistent with the known low values of absolute threshold. They were, however, mainly interested in showing that the rate of this reaction *in vivo* must be very much lower than it is *in vitro*, and they did not exclude the occurrence of the reaction altogether.

The idea that sensitivity is limited by background noise implies that the threshold can only be lowered at the cost of a decrease in the reliability of the response, and an experimental test of this prediction will now be given. The problem will then be formulated quantitatively in a way that is biased in favor of the specific assumption that noise results from the thermal decomposition of rhodopsin. This assumption may well be wrong; noise might be nervous in origin, and it may also enter the system after the threshold decision is made, but these possibilities would be hard to investigate without first having explored the effect of noise acting at the earliest possible level in the visual pathway.

#### TEST OF NOISE HYPOTHESIS

The hypothesis to be examined is that events occur in the retina, or later in the pathway, which cannot be distinguished from the events which occur when light falls on the rods and a quantum is absorbed. A single such event might occur frequently without light; a coincidence of two occasionally; a high order of coincidence only very rarely. A subject can only say that he "sees" a flash of light when a large number of events occur simultaneously, because if he "saw" when a smaller number occurred he would "see" when there was no stimulus—that is, he would be unreliable and give a large number of false positives. If this is the correct interpretation of threshold it follows that the reliability of the response will affect the value of the threshold. Figure 1 shows the result of an experiment designed to test this. The subject was looking at flashes of light under conditions similar to those used by Hecht *et al.*<sup>13</sup> and van der Velden<sup>14</sup> (40 or more minutes dark adaptation, flash 20 degrees nasal to fixation point,

stimulus duration 2.4 msec, diam 7.5 min of arc, light beam 2.1 mm diameter entering center of natural pupil, narrow band at 495 m $\mu$ , subject operates shutter himself). He signaled when he saw the flash for each of the 100 presentations at each of the five intensities, which occurred in a random sequence. The fractions of "seen" flashes form the right hand set of points (dots) in Fig. 1. In addition, he was encouraged to signal "possible" when he believed that there was a flash, but was not quite sure; these "possibles," added to the "seens," are also plotted and form the left-hand set of points (crosses). The threshold for "possible" is lower than for "seen," but a measure of the change in reliability of response was also needed, so 300 flashes of zero intensity were mixed in with the stimulus flashes, and the results for these form the left-hand points of each group. The subject never gave a "seen" response to these blanks, but gave three (1%) "possibles."

Since the threshold is defined as the intensity of flash which the subject says he sees on 50% of occasions, a subject can always lower his threshold by guessing; he would only have to convert, at random, some of his "no" answers to "possible." If he did this, "possibles" would tend to be a constant fraction of "no's," and would therefore occur most frequently in response to a blank. Though some subjects may guess like this, it does not provide the explanation for the result of this experiment; on decreasing the stimulus from a threshold level to zero the "possible" responses decreased from 23% to 1%, whereas "no" increased from 49% to 99%. A similar result is usually obtained if a subject is allowed to report "possibles."

In the experiment a lowering of the threshold by 25% to include "possibles" had the effect of introducing 1% of false positive responses. This would only have happened if the threshold for "seen" had already been close to the level at which false positives occur, and the result therefore seems to show, rather directly, that

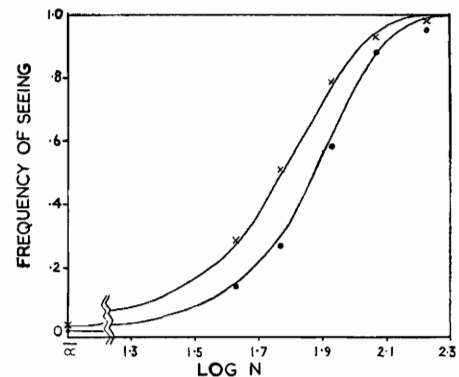


FIG. 1. Frequency of "seen" (dots) and "possible or seen" (crosses) responses of one subject plotted against log (number of quanta at the cornea). Theoretical curves are from Molina's tabulation of Eq. (1) with  $a = n + x = 0.13N + 8.9$  for both curves,  $c = 19$  for "seen,"  $c = 17$  for "possible or seen."

the normal threshold is set as low as is compatible with a reliable response. Theories which neglect noise, or introduce it after the threshold criterion has been applied to the sensory message, might account for "seen" and "possible" responses having different thresholds, but they would have difficulty in accounting for the appearance of false responses with use of the lower threshold criterion.

QUANTITATIVE FORMULATION

In order to make quantitative predictions from the noise hypothesis, it is necessary to make specific assumptions about its statistical nature. Since the noise events are supposed to be indistinguishable by the C.N.S. from the events resulting from the absorption of a quantum of light, it is both reasonable and convenient to assume that both types of event have the same type of statistical distribution. The absorption of a quantum of light is an event which is only predictable on the average; a single absorption can only be described by stating a probability which is fixed by the physical conditions under which the absorption takes place. This probability is quite independent of the number of similar events in the past or the neighboring retina, and therefore the number of events in a given retinal area and time follows the Poisson distribution as shown in detail by Pirenne.<sup>7(b)</sup> If the same is true of the events caused by "noise," it follows that the total number of events of both kinds also follows a Poisson distribution. This remains true whatever the relative number of "signal" and "noise" events. It may be pointed out that, if any other distribution of noise was considered, then the occurrence of a light stimulus would change the type of distribution, as well as the mean number, and this, besides complicating the mathematics, would give a secondary clue as to the presence of the light. Moreover, the assumption is reasonable if one has in mind the spontaneous breakdown of visual purple as a source of the noise, and it should in any case be adequate to describe the amount of noise to a first approximation, even if the distribution is different.

The Poisson distribution is not particularly convenient to deal with, but fortunately, the values have been tabulated by Molina<sup>25</sup> over a wide range. Hecht, Shlaer, and Pirenne, and Bouman and van der Velden assumed that the average number of events was proportional to the intensity of flash; thus, if the cumulative Poisson curves were plotted out with log (average number) as abscissa, and the experimentally determined frequencies of seeing plotted with log (intensity of flash) as abscissa, the best fitting value for the threshold number of events could be determined by simply sliding the theoretical curves over the experimental points. In the case considered here the fitting

is more difficult because noise events are contributing to the average, which is therefore no longer directly proportional to the light intensity. Curve fitting would be an excessively tedious business if the parameters were to be found by trial and error; a method of deriving them from the slope of the experimental curve close to threshold, the threshold value itself, and the frequency of false positives is given below. The approximations involved lead to errors if the number of independent events involved is small; this is not important here because, having found possible parameters, the numerical values are obtained from Molina's tables, and it is these values which are used to plot the theoretical curves of Figs. 1 and 2.

- Let  $N$  = average number of quanta at cornea from a flash.
- $n$  = average number of independent events (rod excitations) resulting from the stimulus flash.
- $x$  = average number of noise events confusable with the stimulus events.
- $a = n + x$  = total average of events.
- $c$  = the number of events which must be equalled or exceeded to get a response.
- $Pa(c)$  = probability of  $c$  or more events occurring if the average number is  $a$ .

$$Pa(c) = \sum_{y=c}^{\infty} \frac{a^y e^{-a}}{y!} \tag{1}$$

The experimental curves are plotted with  $\log N$  as abscissa:

$$\log N = \log(a - x) - \log(n/N)$$

so the values of Eq. (1) must be plotted with  $\log(a - x) - \log(n/N)$  as abscissa for comparison with experiment. There are three parameters ( $x$ ,  $n/N$ , and  $c$ ) to be found, and the three experimental values used are the slope close to threshold, the threshold itself, and the frequency of false positive responses.

Differentiating Eq. (1) with respect to  $a$  gives

$$\frac{dPa(c)}{da} = \frac{e^{-a} a^{c-1}}{(c-1)!}$$

from which

$$\frac{dPa(c)}{d(\log N)} = \frac{dPa(c)}{d(\log n)} = \frac{dPa(c)}{da} \times \frac{da}{d(\log n)} = \frac{e^{-a} a^{c-1}}{(c-1)!} \times \frac{n}{\log e}$$

Applying Stirling's approximation for  $c!$ , and saying that, at threshold,  $a = n + x \doteq c$  yields

$$\frac{dPa(c)}{d(\log N)} \times (2\pi)^{\frac{1}{2}} \log e = \frac{c-x}{(c)^{\frac{1}{2}}} \tag{2}$$

But  $x$  and  $c$  are also related by Eq. (1) when  $a = x$ , and  $Px(c)$  is the frequency of false responses. Hence, in theory, one can obtain a unique set of parameters.

<sup>25</sup> E. C. Molina, *Poisson's Exponential Binomial Limit* (D. Van Nostrand Company, Inc., New York, 1942).

TABLE I. Best fitting parameters for fitting "possible or seen" response of Fig. 1, with upper and lower limits (see text).

|              | Both responses |     | Possible or seen |         | Seen only |         |
|--------------|----------------|-----|------------------|---------|-----------|---------|
|              | $n/N$          | $x$ | $c$              | False + | $c$       | False + |
| Upper limit  | 0.31           | 66  | 84               | 0.018   | 90        | 0.003   |
| Best fitting | 0.14           | 8.9 | 17               | 0.010   | 19        | 0.002   |
| Lower limit  | 0.10           | 3.1 | 9                | 0.005   | 11        | 0.0004  |

The parameters for the curve for "possible or seen" response in Fig. 1 were obtained in this way; there is good agreement with the experimental points, and by changing  $c$  alone the curve was shifted to the right and fitted the curve for seen. But in practice, the frequency of false responses cannot be obtained with great accuracy and Table I shows three allowable sets of values of  $n/N$ ,  $x$ ,  $c$  for "seen,"  $c$  for "possible or seen," and the predicted false positives for each response. The middle are the best-fitting values used in Fig. 1; the upper set is so chosen that, if  $n/N$  was as low as this, 1% or more false "possibles" would have been obtained in 20% of experiments; the lower so that, if  $n/N$  had been as high as this, 1% or less false "possibles" would have been obtained in 20% of experiments. It will be seen that the allowable range of values is large, and the experiment is not easily made more precise. Nor can one get any quantitative help by fitting the "seen" frequencies of seeing; the predicted slope of the curve if shifted to the right by the amount observed is not measurably different for the three cases of Table I, any one of which would fit the experimental points, and in each case the predicted false "seens" are too low to measure (i.e., the most likely frequency is 0/300, in agreement with observation). The conclusion is that the experiment is not precise enough to determine the theoretical parameters accurately, and they must be determined by other methods. But it does limit the possible values, and it will be seen that the introduction of one additional parameter—the noise level  $x$ —allows the fitting of two frequency of seeing curves from the same subject, and also accounts for the number of false positives.

**Multiquantumites and Two-Quantumites**

The disagreement between Hecht, Shlaer, and Pirenne,<sup>13</sup> who found frequency-of-seeing curves characteristic of a fivefold to eightfold coincidence, and Bouman and van der Velden,<sup>15</sup> who claimed that they were characteristic of a twofold coincidence, might result from a different standard of reliability being demanded of the subjects of the two sets of experiments. If so, their response should yield curves differing from each other in the same way as those of Fig. 1. Figure 2 is a replot of points from these two papers fitted by curves obtained assuming a noise level of 8.9 for both subjects. If correct, it would follow that the subject of Hecht *et al.* gave 0.038% of false positives, van der

Velden's 3.83%; neither figure is unduly high, and the difference is possibly related to the great emphasis on reliability of Hecht *et al.* It will be seen that the curve for the subject of Hecht *et al.* is one of the same family as the pair in Fig. 1; that is, both  $n/N$  and  $x$  are the same, only  $c$  is changed. To fit van der Velden's points it was necessary to choose the unlikely value of 0.9 for  $n/N$ ; this results from his equally unlikely threshold value of 6.1 quanta at the cornea.

**Quantitative Predictions**

Hecht, Shlaer, and Pirenne's<sup>13</sup> data on absolute threshold appear to be the most reliable that we have, and it is therefore worth making calculations from them; the data of Fig. 1 would give similar results. The average threshold (50% seeing) was 112 quanta at the cornea for the three subjects whose frequency-of-seeing curves are published, and the average of the best-fitting cumulative Poisson curves was 6. Taking these values, and using Eq. (2) etc., one obtains Table II, showing the value of  $x$  corresponding to different values of  $n/N$ , the fraction of quanta incident at the cornea which excite rods. Two points should be noticed: firstly, that  $x$  increases very rapidly as  $n/N$  increases; secondly, that the value of  $x$  represents the greatest amount of noise that the visual system could have, and still give frequency of seeing curves of the observed steepness; if any particular source of noise is considered it must have a value lower than this. Hence, the value of  $x$  indicates, for example, the maximum permissible spontaneous breakdown rate of rhodopsin in a manner simulating the reactions occurring as a result of light. This is a possible source of noise, and the final column of Table II gives the calculated minimum half-life of a rhodopsin molecule for each of the postulated concentrations.

Denton and Pirenne<sup>16</sup> give an estimated upper limit of 44.4 spontaneous breakdowns of rhodopsin per summation area and time, based on Graham and

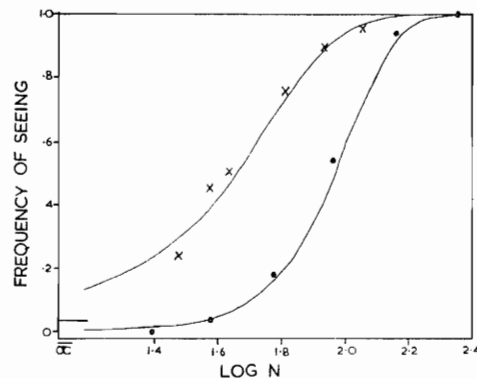


FIG. 2. Data from Hecht *et al.* (dots) and van der Velden (crosses) fitted by theoretical curves obtained from Molina's tables with  $a=n+x=0.13N+8.9$ ,  $c=21$  (Hecht *et al.*);  $a=0.9N+8.9$ ,  $c=15$  (van der Velden).

Margaria's<sup>26</sup> data for temporal and area summation, a figure of 0.1 for  $n/N$ , and the assumption that the number of quanta required for threshold is as low as possible compatible with reliability. The figures of Table II are of the same order of magnitude as theirs, and both imply a high order of stability for rhodopsin *in vivo*. Lythgoe and Quilliam<sup>27</sup> studied the thermal decomposition of rhodopsin solutions and showed that it was probably a first-order reaction with products of decomposition similar to the products of bleaching by light. They found an activation energy for the reaction of 44 000 cal/g mole, which corresponds to one quantum of 6500 Å radiation per chromophore. Since the products are the same, and since it requires practically the whole energy of a visible light quantum to activate the reaction, it is highly probable that the thermal reaction is the same as the bleaching reaction, and if this is so rods must be excited thermally in the way demanded by the theory developed here. Denton and Pirenne have pointed out that the actual rate of the reaction *in vitro* is very much higher than that needed by the theory, and there must be factors which enormously increase the stability of the molecule *in vivo*. Nevertheless, the fact that the bleaching reaction does occur thermally adds some plausibility to the suggestion that this may be the source of spurious rod excitations which make it necessary for many rods to be activated before a flash of light can be detected with a high degree of reliability.

#### CONCLUSIONS

The idea that noise in the optic pathway is a limiting factor in the sensitivity of the eye to light (a) is *a priori* likely in view of its sensitivity; (b) is supported

<sup>26</sup> C. H. Graham and R. Margaria, *Am. J. Physiol.* **113**, 299-305 (1935).

<sup>27</sup> R. J. Lythgoe and J. P. Quilliam, *J. Physiol.* **93**, 24-38 (1938).

TABLE II. Allowable noise levels for various fractions of quanta at the cornea exciting rods.<sup>a</sup>

| Fraction exciting $n/N$ | Allowable noise $x$ | Calculated chromophores per rod $\times 10^{-7}$ | Minimum half-life in years |
|-------------------------|---------------------|--|----------------------------|
| 0.054                   | 0                   | 2.5  | Infinite                   |
| 0.075                   | 3.4                 | 3.5  | 257                        |
| 0.10                    | 9.7                 | 4.8  | 124                        |
| 0.15                    | 23.5                | 7.7  | 82                         |
| 0.20                    | 61                  | 10.9   | 45                         |
| 0.30                    | 154                 | 19.3   | 31                         |

<sup>a</sup> Calculations are based on the following assumptions: Decadic molar extinction of rhodopsin in rods = 60 900 cm<sup>2</sup> [G. Wald and P. K. Brown, *J. Gen. Physiol.* **37**, 189-200 (1953) and W. J. Schmidt, *Kolloidzshr.* **85**, 137-148 (1938)]; cross section of rod  $5.25 \times 10^{-8}$  sq cm; rods receive 0.7 of light reaching the retina; 0.75 of light at cornea reaches the retina; quantum efficiency of rod excitation = 1; summation area = 1 sq deg (covers 12 000 rods); summation time = 0.1 sec (Graham and Margaria, see reference 26); noise only confused with stimulus if it occurs in the same summation area and time that is, or would have been, occupied by the stimulus.

by the finding of noisy signals in the optic nerves of animals; (c) explains why the coincident absorption of more than two quanta is necessary for vision; (d) explains, quantitatively, why threshold is lowered by lowering the reliability of the responses, and why this is accompanied by a flattening of the frequency of seeing curve; and (e) accounts for the long-standing disagreement between Hecht, Shlaer, and Pirenne<sup>13</sup> and Bouman and van der Velden.<sup>15</sup>

Its importance does not rest here; the idea can easily be extended to cover other visual data, such as the area threshold relation, and the differential threshold; the square root relationships that are known to hold here certainly suggest a signal/noise discrimination.

Finally, determination of the noise level would allow one to give a lower limit to  $n/N$ , the fraction of quanta incident on the cornea which are effective in exciting rods; comparison with the fraction of quanta absorbed by rhodopsin would then give a lower limit to the quantum efficiency of rod excitation.



