MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Physics Department

Physics 8.044 Spring Term 2008

Human Vision

In 1942, S. Hecht, S. Shlaer, and M. Pirenne (HSP) published an article ["Energy Quanta and Vision", S. Hecht, S. Shlaer, and M. Pirenne, *Journal of General Physiology* **25**, 819 (1942)] in which they investigated the detectability of light at the threshold of human vision. Their work is discussed in detail in the excellent textbook *Physics With Illustrative Examples From Medicine and Biology: STATISTICAL PHYSICS* by George B. Benedek and Felix M. H. Villars [Springer-Verlag, 2000]. This discussion is taken from that book.

HSP found that the eye integrates for about 0.1 s and the response is determined by the number of photons that arrive in that time. They applied 1 ms flashes of light to a dark-adapted carrot-fed eye so that the light would fall on the most sensitive part of the retina, and measured the probability the light would be detected as a function of the number of photons incident on the cornea. Here is a table of their results.

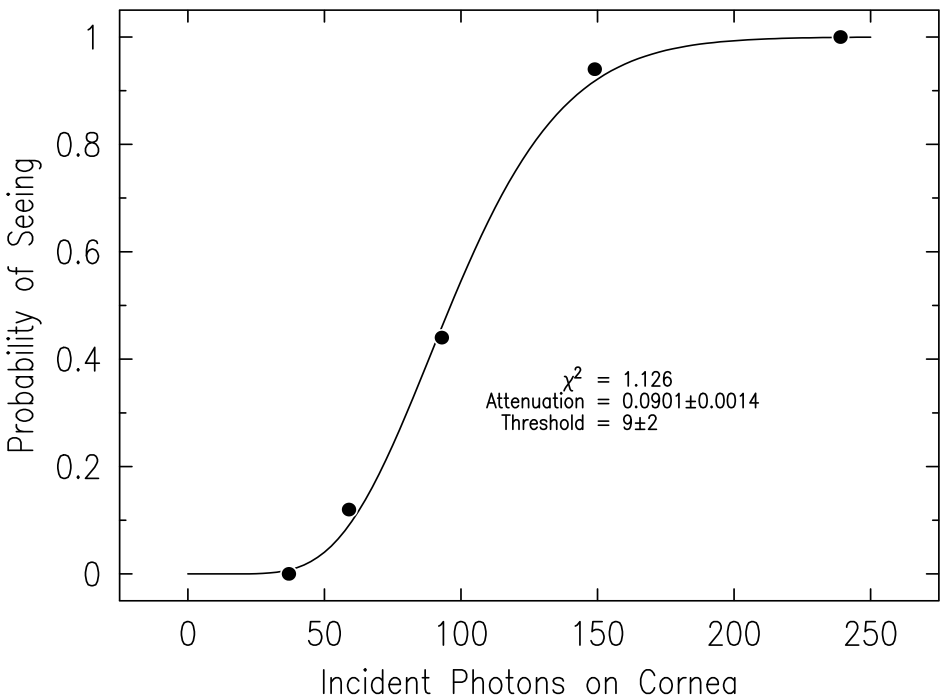
n	$p(n)$
37	0.00
59	0.12
93	0.44
149	0.94
239	1.00

Not all of the light incident on the cornea reaches the retina; HSP estimated that about 50% of it does. Then, not all of the light that reaches the retina triggers a conformation change of a rhodopsin molecule—the process that initiates the visual detection process. They estimated about 20% of the photons at the retina triggered rhodopsin. They went on to estimate how many rhodopsin molecules must be triggered in order that the light pulse will be detected. We can analyze the process using Poisson statistics, just as you did in a homework problem for a photomultiplier tube.

HSP analyzed their results assuming that if n photons arrived at the cornea cn of them would be absorbed in the retina and excite the conformational change in rhodopsin. They also assumed that the light would be seen if at least m_0 rhodopsin molecules were excited. If n photons reach the cornea, the mean number that excite rhodopsin will be cn; if the excitation of rhodopsin obeys Poisson statistics, then the probability of seeing them will be

$$p(n) = \sum_{m=m_0}^{\infty} \frac{(cn)^m}{m!} e^{-cn} = 1 - \sum_{m=0}^{m_0-1} \frac{(cn)^m}{m!} e^{-cn} .$$

This provides a probability of seeing function with two adjustable parameters: the fraction of incident photons that excite rhodopsin, c, and the threshold for detection, m_0.



Here is a graph of the data in the table of the previous page along with the parameters $c = 0.0901 \pm 0.0014$ and $m_0 = 9 \pm 2$ that provide the best fit to them.

The result for c is consistent with the HSP estimate that 10% of the photons incident on the cornea excited rhodopsin molecules in the retina, and the fit also shows that about 9 molecules must be excited in order for the light to be detected. The human eye, at its best, can detect a rather small number of photons and the process appears to follow Poisson statistics.

That explains, for example, why we cannot see stars during the day and why we look look at movies in darkened theaters. It is because the shot noise from the background light masks the signal we would like to see. If you want to make estimates of signal to noise ratios, as in the homework problem for the phototube, take the integration time of the eye to be about 0.1 s.

There is a lot more discussion of this in the book by Benedek and Villars.