UNITS AND DEFINITIONS

Photometric Units

1 lumen of green light	$=$	1.5×10^{-3} watt
	$=$	4×10^{15} photons/sec
1 lumen of white light	$\doteq$	4×10^{-3} watt
	$\doteq$	10^{16} photons/sec

Incident Illumination

1 lumen/m^2	$\equiv$	1 lux $\equiv$ 1 meter-candle
1 lumen/ft^2	$\equiv$	1 foot-candle $\doteq$ 10 lux

Surface Brightness

1 lumen/ft^2 falling on a 100% reflecting and perfectly-diffusing surface yields a surface brightness of 1 foot-lambert. Similarly, 1 lumen/cm^2 yields a surface brightness of 1 lambert.

1 foot-lambert $\doteq$ 1 millilambert

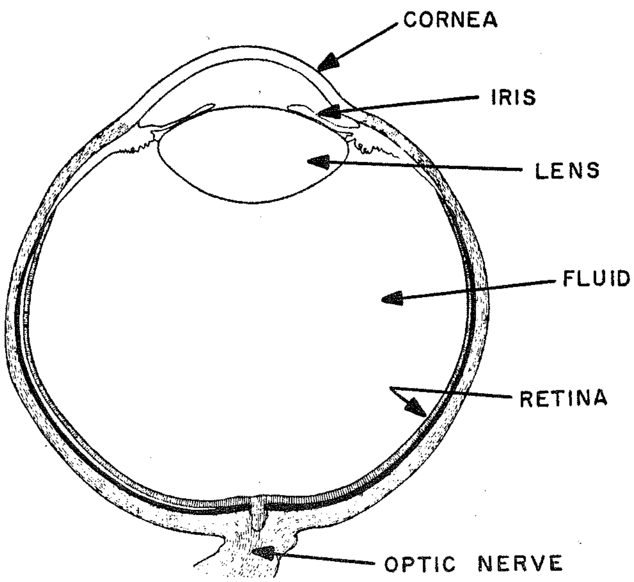


Fig. 2.1. Outline of the human eye.

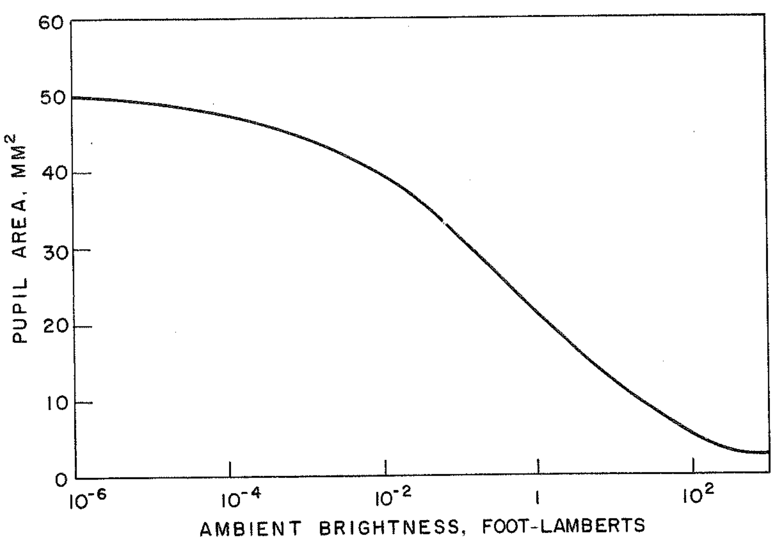


Fig. 2.2. Plot of pupil opening as a function of ambient brightness.

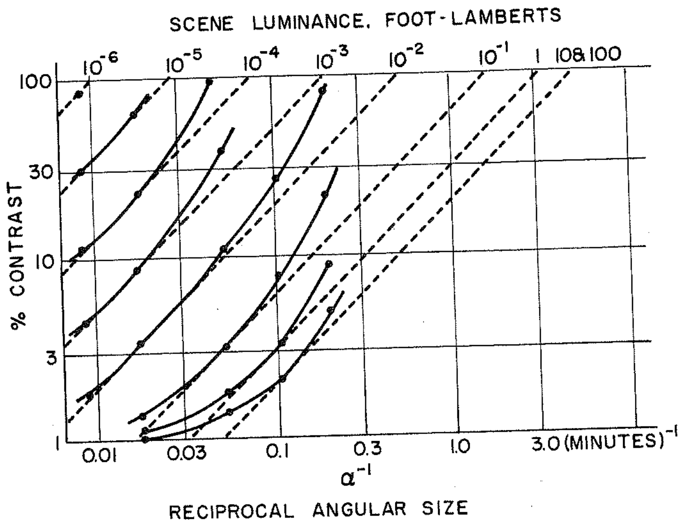


Fig. 2.3. Visual performance data as measured by Blackwell.(B-3)

resolution at 1–2 minutes of arc. In the latter case, the finite size of rods and cones set the geometric limit to resolution.

Figure 2.4 is a plot of similar and earlier data by Conner and Ganoung (1935)(C-2) and Cobb and Moss (1928).(C-1) A comparison of Figs. 2.3 and 2.4 shows substantial agreement. One notable difference is that Blackwell's data show no improvement in going from 10 to 100 foot-lamberts, whereas the data of Cobb and Moss do.

In both Figs. 2.3 and 2.4, 45° lines represent the performances to be expected if the performance were noise limited as shown by Eq. (1.2). The data in Fig. 2.4 follow the noise-limited 45° slopes moderately well. The data in Fig. 2.3 are somewhat bowed and only tangent to the 45° slopes in a finite range. The departures in Fig. 2.3 from the 45° slopes can be ascribed to the admixture of limitations other than photon noise.

2.4. Quantum Efficiency of Human Vision

The data in Figs. 2.3 and 2.4 need to be converted into photons/ cm^2 at the retina in order to make an estimate of the quantum

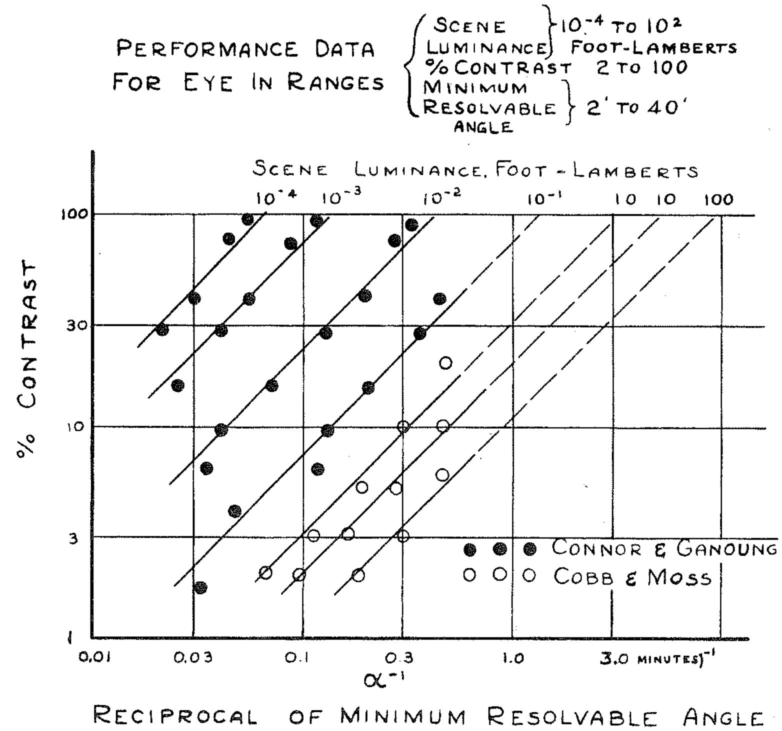


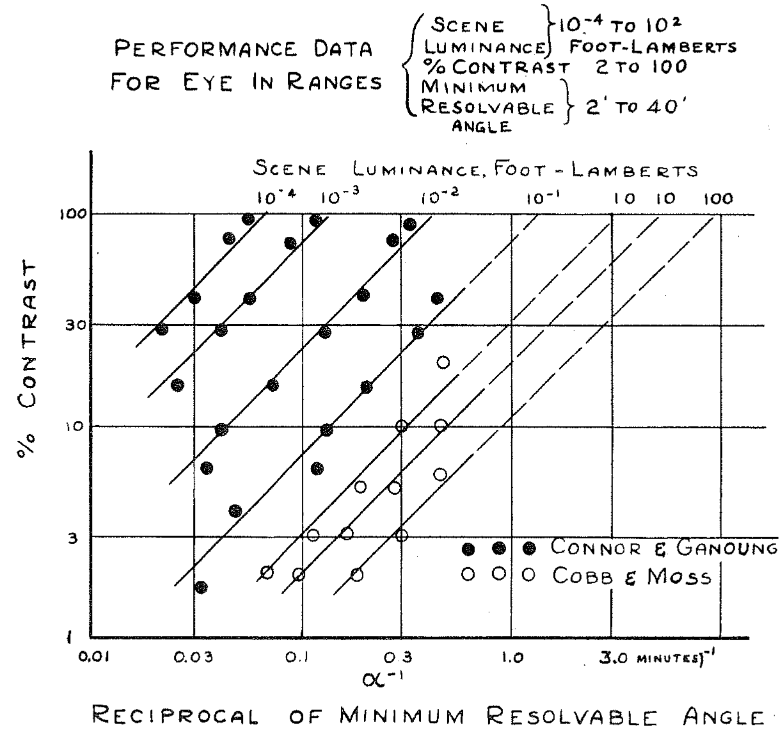
Fig. 2.4. Visual performance data as measured by Cobb and Moss[(C-1)] and by Connor and Ganoung.[(C-2)]

efficiency of the eye. To do so we have assumed a storage time of 0.2 sec, a lens transmission of 0.5, and a range of pupil openings given by Reeve's data in Fig. 2.2. Once having made the conversion, the photon density at the retina is inserted into Eq. (1.3) in the form

$$C^2 d^2 \theta n = k^2 = 25$$

where θ is the quantum yield of the eye (quantum efficiency $\equiv 100 \times \theta\,\%$). The value of k, the threshold signal-to-noise ratio, is taken to be 5.

Figure 2.5 shows the quantum efficiency of the eye, computed from Blackwell's data, as a function of ambient brightness. The most striking aspect of these results is the relatively small variation of quantum efficiency in the span of 8 orders of magnitude of light



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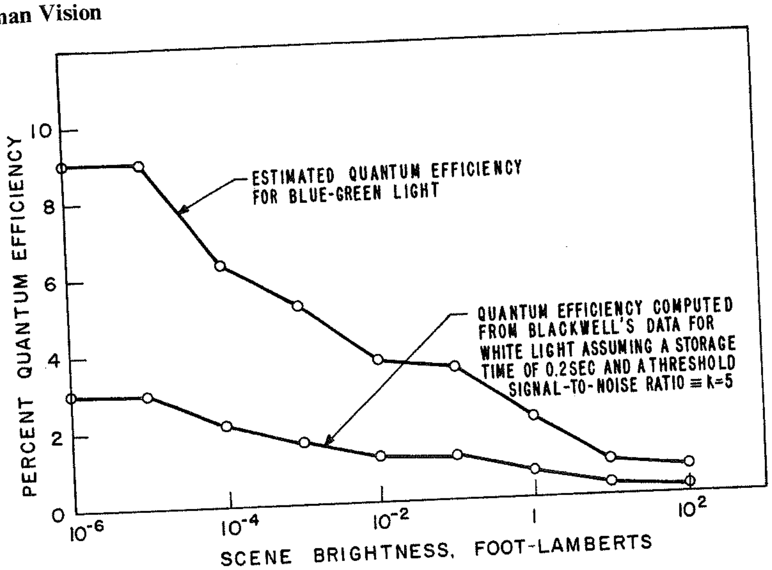
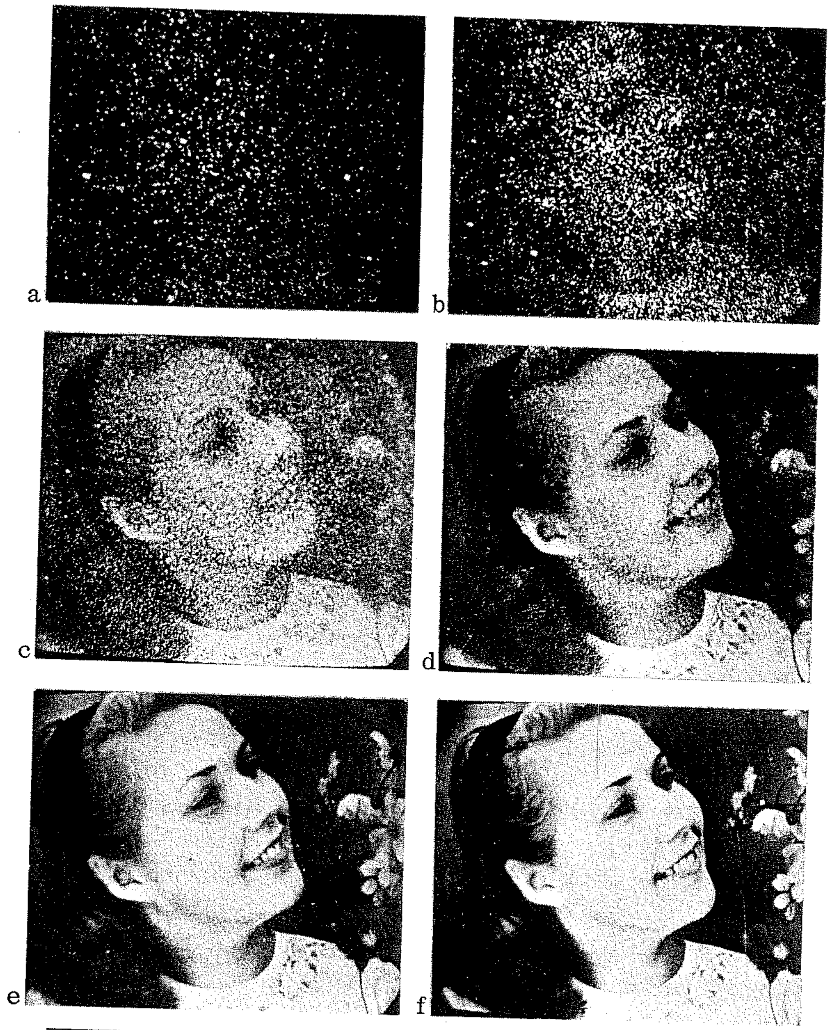


Fig. 2.5. Quantum efficiency of the eye as a function of ambient brightness. The values for gree-blue light at the peak of visual sensitivity are taken to be three times larger than for white light. The quantum efficiencies at the retina should be about twice the values plotted above. The sum of the photons incident on both eyes was used in computing the quantum efficiency.

intensity. The quantum efficiency starts at 3% at extreme low lights near absolute threshold (approximately 10^{-7} foot-lambert) and declines slowly to about $\frac{1}{2}$% at 100 foot-lamberts. It is true, on the one hand, that this is a tenfold variation in quantum efficiency. On the other hand, it must be compared with a 1000- or 10,000-fold variation in quantum efficiency which was invoked in the earlier literature to account for the phenomenon of dark adaptation. We will return to this point in more detail below. In the meantime, it is well to recognize that even this tenfold variation may considerably overstate the facts. In deducing the tenfold variation we have assumed a constant exposure time and a constant k factor. There is some evidence that the exposure time may be a factor of 2 larger at low lights than at high lights. If so, the variation of quantum efficiency would then be reduced to only fivefold. It is further likely that the k factor is smaller at low lights than at high lights. This variation in k (or, rather, k^2) could easily introduce another



Picture	Number of photons	High-light brightness, foot-lamberts
a	3×10^{3}	10^{-6}
b	1.2×10^{4}	4×10^{-6}
c	9.3×10^{4}	3×10^{-5}
d	7.6×10^{5}	2.5×10^{-4}
e	3.6×10^{6}	1.2×10^{-3}
f	2.8×10^{7}	9.5×10^{-3}

Fig. 2.6. Series of pictures used in evaluating the quantum efficiency of the eye.(R-4)