The Sensitivity Performance of the Human Eye on an Absolute Scale*

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An absolute scale of performance is set up in terms of the performance of an ideal picture pickup device, that is, one limited only by random fluctuations in the primary photo process. Only one parameter, the quantum efficiency of the primary photo process, locates position on this scale. The characteristic equation for the performance of an ideal device has the form

$$BC^2\alpha^2 = \text{constant}$$

where B is the luminance of the scene, and C and α are respectively the threshold contrast and angular size of a test object in the scene. This ideal type of performance is shown to be satisfied by a simple experimental television pickup arrangement. By means of the arrangement, two parameters, storage time of the eye and threshold signal-to-noise ratio are determined to be 0.2 seconds and five respectively. Published data on the performance of the eye are compared with ideal performance. In the ranges of $B(10^{-6}$ to 10^2 footlamberts), $C(2$ to 100 percent) and $\alpha(2'$ to $100')$, the performance of the eye may be matched by an ideal device having a quantum efficiency of 5 percent at low lights and 0.5 percent at high lights. This is of considerable technical importance in simplifying the analysis of problems involving comparisons of the performance of the eye and man-made devices. To the extent that independent measurements of the quantum efficiency of the eye confirm the values (0.5 percent to 5.0 percent), the performance of the eye is limited by fluctuations in the primary photo process. To the same extent, other mechanisms for describing the eye that do not take these fluctuations into account are ruled out. It is argued that the phenomenon of dark adaptation can be ascribed only in small part to the primary photo-process and must be mainly controlled by a variable gain mechanism located between the primary photo-process and the nerve fibers carrying pulses to the brain.

INTRODUCTION

THE designer of picture pickup devices such as television pickup tubes, photographic film and electron image tubes is faced steadily with the problem of comparing the performance of these devices with the performance of the human eye. This is especially true for comparisons of sensitivity. Neither television pickup tubes nor photographic film match the ability of the eye to record pictures at very low scene luminances. Film ceases to record at a scene luminance of a few footlamberts, and present television pickup tubes at a few tenths of a footlambert. (Lens diameters and exposure times are assumed equal to those of the eye.) The eye, however, still transmits a picture at 10^{-6} footlambert. This is a striking discrepancy, especially when it is known that eye, film and pickup tube each require about the same number of incident quanta to generate a visual act. By visual act is meant a threshold visual sensation for the eye, the rendering of a photographic grain developable in film or the release of a photo-electron in a television pickup tube. This number of incident quanta is in the neighborhood of 100. The sources of this discrepancy will be discussed later. For the present, the discrepancy is introduced and emphasized for the following reason. Since television pickup tubes and photographic film are already limited in their performance by more or less fundamental statistical fluctuations (noise currents in pickup tubes and graininess in film) and since the low light performance of the eye so far outstrips that of pickup tubes and film, it is not unreasonable to inquire whether the performance of the eye also is limited by statistical fluctuations.

The purpose of this paper is, in fact, to lay out clearly the absolute limitations to the visual process that are imposed by fluctuation theory and to compare the actual performance of the eye with these limitations. The gap, if there is one, between the performance to be expected from fluctuation theory and the actual performance of the eye is a measure of the "logical space" within which one may introduce special mechanisms, other than fluctuations, to determine its performance. These special mechanisms can only contract the limits already set by fluctuation theory. This point is especially important because it restricts the freedom with which one can introduce such assumptions as: (1) rods or cones

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with variable thresholds of excitation, (2) an absorption coefficient for the retina that varies with scene luminance or (3) photo-chemical reaction rate equations with arbitrary coefficients.

The following discussion begins with a description of ideal performance, that is, performance limited only by statistical fluctuations in the absorption of light quanta. Next an experimental realization of ideal performance is introduced in the form of a special television pickup arrangement. The performance data for the eye is then compared with ideal performance and finally some implications of this comparison are discussed.

It must be emphasized that this discussion is concerned primarily with the low light end of the light range over which the eye operates. It is here that fluctuation limitations would be expected to be the dominant factor. At very high lights other limitations set in, as for example, the finite structure of the retinal mosaic, or the limited traffic carrying capacity of the optic nerve fibers. Important as these factors are for a complete understanding of the eye, they do not constitute, as do statistical fluctuations, an absolute limit to the possible performance of the visual process. They are the particular boundary conditions pertaining to the eye, which, in another device or in an "improved eye," might take on other values. The light range considered here is still the larger part of the total light range of the eye, namely, from 10^{-6} to 10^{2} footlamberts. The excluded range is 10^{2} to 10^{4} footlamberts.

Also the discussion is confined, except for a few remarks on color, to the sensitivity performance of the eye for white (as opposed to colored) test patterns.

PERFORMANCE OF AN IDEAL PICTURE PICKUP DEVICE

An ideal picture pickup device is defined to be one whose performance is limited by random fluctuations in the absorption of light quanta in the primary photo-process. Each absorbed quantum is assumed to be observable in the sense that it may be counted in the final picture. From well known statistical relations, an average absorption of N quanta will have associated with it deviations from the average whose root mean square value is $N^{\frac{1}{2}}$. These deviations are a measure of the accuracy with which the average number N may be determined. They also control the smallest change in N that may be detected. Thus if this smallest change is denoted by ΔN:

$$\Delta N \sim N^{\frac{1}{2}} \tag{1}$$

or

$$\Delta N = kN^{\frac{1}{2}} \tag{1a}$$

where k is a constant to be determined experimentally. k is called the threshold signal-to-noise ratio.

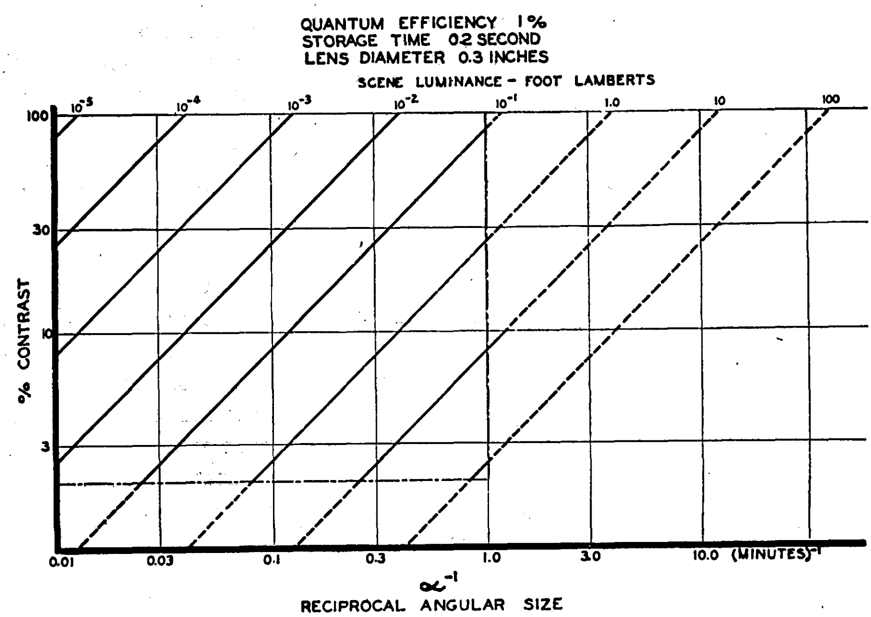


FIG. 1. Performance of ideal pickup device. The experimentally determined value, 5, of threshold signal-to-noise ratio was used to compute these curves.

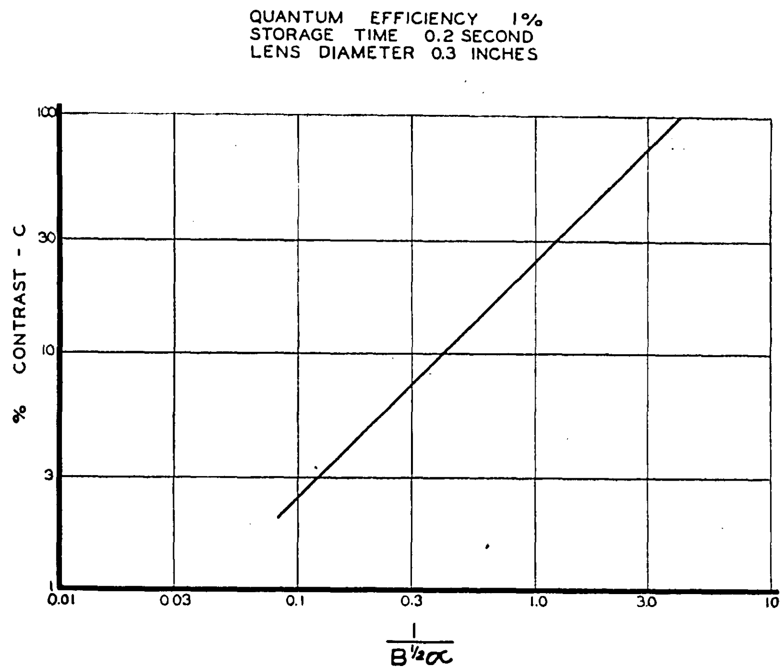


FIG. 2. Performance curve for ideal pickup device. A reduced plot of the curves in Fig. 1.

Let the average number of quanta, N, be absorbed in an element of area of side length, h, and in the exposure time of the pick-up device. Then N/h^2 is proportional to the luminance of the original scene and ΔN to the threshold change in luminance and we may write

$$\text{scene luminance} \equiv B \sim (N/h^2), \tag{2}$$

$$\begin{aligned}\text{threshold contrast} &\equiv C = \Delta B/B \times 100\% \\ &= \Delta N/N \times 100\% \sim 1/N^{\frac{1}{2}}.\end{aligned} \tag{3}$$

Combining Eqs. (2) and (3) we get:

$$B \sim 1/C^2h^2, \tag{4}$$

$$B \sim 1/C^2\alpha^2, \tag{4a}$$

or

$$B = \text{constant } (1/C^2\alpha^2), \tag{4b}$$

where α is the angle subtended by h at the lens. Equation (4b) is the characteristic equation for the performance of an ideal picture pickup device. It is based on the simplest and most general assumptions regarding the visual process. Since no special mechanism has been called upon, it applies equally well to chemical, electrical or biological processes of vision. The constant factor includes among other constants, the storage time, quantum efficiency and optical parameters of the particular device. When two ideal devices are compared for performance under equivalent conditions, the only distinguishing parameter is their respective quantum efficiencies.

Equation 4b provides the threshold value of any one of the variables when the other two are arbitrarily specified. Thus Fig. 1 shows a plot on a log–log scale of threshold contrast as a function of visual angle for various fixed values of the scene luminance. In Fig. 2, threshold contrast is plotted as a function of $1/(B^{\frac{1}{2}}\alpha)$ and, as expected from Eq. (4b), all of the performance data of Fig. 1 collapse into a single straight line. The location of this line determines the constant in Eq. (4b) and from this constant the quantum efficiency of the device may be computed (see Eq. 5).

It should be clear that there is nothing in the fluctuation theory used to derive Eq. (4b) that would prevent the lines in Fig. 1 from being extended indefinitely to the right toward small angles or indefinitely downward toward low contrasts. It should also be clear, on the other hand, that any actual physical device will impose such limitations. The smallest angle that can be resolved may be limited either by structure in the surface on which the optical image is focused or eventually by diffraction effects in the optical focus itself. Also any actual physical device cannot generate arbitrarily high signals as would be required if the lines in Fig. 1 were extended to arbitrarily small contrasts. Both these limitations have no necessary connection with fluctuation theory and serve merely to define the boundaries within which such a theory may be applied. Such boundaries may be shown, for example, as in Fig. 1 by the two dash-dot lines. The lines represent asymptotic values approached by an actual device under high light conditions. For this reason, data plotted for an actual device would be expected to bend away from their theoretically straight lines as they approach the dash-dot boundaries.

The complete characteristic equation with the constant factor written out is

$$B=5(k^2/D^2t\theta)(1/\alpha^2C^2)\times 10^{-3}\text{ footlambert,} \quad (5)$$

where the symbols have these meanings and units:

- k—threshold signal-to-noise ratio [see Eq. (1a)]
- D—diameter of the lens (inches)
- t—exposure time (seconds)
- θ—quantum yield ($\theta=1$ means 100 percent quantum efficiency)
- α—angular size of the test object in minutes of arc
- C—percent contrast of the test object [i.e., $C=(\Delta B/B)\times 100$ percent]

The constant factor is derived as follows. In place of Eq. (2) we write (see Fig. 3):

$$N=\theta N_0 t l^2 \sin^2\phi, \quad (6)$$

where N_0 is the total number of quanta emitted per ft.^{2} of the scene per second according to a Lambert distribution. Now since

$$l \doteqdot (d/F)h, \quad \text{and} \quad \sin\phi \doteqdot D/2d,$$

we can write

$$N=\tfrac{1}{4}\theta N_0 t D^2(h^2/F^2)=1.4\theta N_0 t D^2\alpha^2\times 10^{-10}, \quad (7)$$

where α is expressed in minutes of arc and D in inches. Using the equivalence, one lumen of white light $=1.3\times 10^{16}$ quanta per second,

$$N_0/1.3\times 10^{16}=B\text{ footlamberts}$$
$$N=2\theta BtD^2\alpha^2\times 10^6,$$

and

$$B=5(N/D^2t\theta\alpha^2)\times 10^{-7}\text{ footlambert.} \quad (8)$$

From Eqs. (3) and (1a) we get:

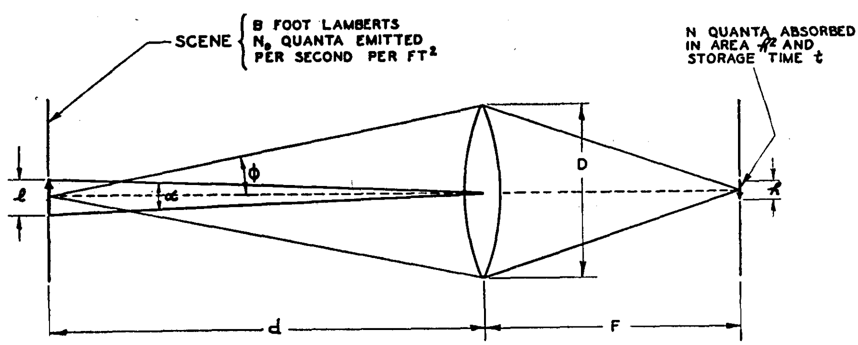
$$C=100k/N^{\frac{1}{2}}. \quad (9)$$

Combining Eq. (8) and (9) we get:

$$B=5(k^2/D^2t\theta)(1/\alpha^2C^2)\times 10^{-3}\text{ footlambert} \quad (10)$$

The factor k in Eq. (5) is of special interest because its value has frequently been assumed to be unity. That is, the statement is made that a threshold signal is one that is just equal to the r.m.s. noise.** Some estimates made recently by the writer[3] and based on observations on photographic film and on television pictures lay in the

FIG. 3.



** Such an assumption, for example, was made by the writer (reference 1) and also by H. De Vries (reference 2).

[1] A. Rose, "The relative sensitivities of television pickup tubes, photographic film and the human eye," Proc. I.R.E. 30, 295 (1942).

[2] H. DeVries, "The quantum character of light and its bearing upon threshold of vision, the differential sensitivity and visual acuity of the eye," Physica 10, 553 (1943).

[3] A. Rose, "A unified approach to the performance of photographic film, television pickup tubes and the human eye," J.S.M.P.E. 47, 273 (1946).

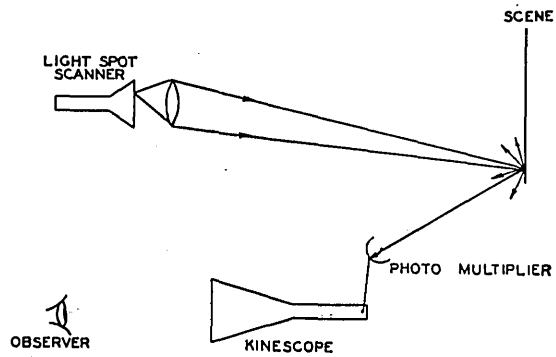


FIG. 4. Television pickup arrangement using a light spot scanner.

range of 3 to 7. Additional and more direct evidence is given in the next section that the value of k is not unity but is in the neighborhood of 5.

AN EXPERIMENTAL APPROACH TO AN IDEAL PICTURE PICKUP DEVICE

One of the oldest means of generating television pictures is the so-called light spot scanning arrangement in which the subject to be transmitted is scanned by a small sharply focused spot of light. The variable amount of light reflected from the subject is picked up by a photocell and these variations translated into beam current variations in a kinescope whose beam scans a fluorescent screen in synchronism with the first light spot. The arrangement is shown in Fig. 4. Recent developments in luminescent materials and photo multipliers have brought renewed interest in the arrangement for certain types of pick-ups.[4] On the one hand, it is especially simple and free from the spurious signals usually found in pickup tubes. On the other hand, it is limited in application to those scenes that may be conveniently illuminated by a scanning light spot. Its particular virtue for the present discussion is that it offers a close approximation to the performance to be expected from an ideal picture pickup device. The photo-cathode of the electron multiplier represents at once both the lens opening and primary photo surface of the usual pickup device. The gain in the multiplier section is sufficient to make each photo electron, liberated from the photo-cathode, visible on the kinescope screen as a discrete speck of light. That is, each quantum usefully absorbed at the primary photo-surface can be counted in the final picture. The exposure time of the system is the exposure time of the final observer (human or instrumental) that looks at the reproduced picture on the kinescope.

The special test pattern used as subject or scene for the light spot scanner is shown in Fig. 5. This test pattern is in fact a materialization of the theoretical curves in Fig. 1. The disks along any row decrease in diameter by a factor of two for each step. The disks in any column have the same diameter but vary in contrast stepwise by a factor of two. If this pattern is reproduced by a pickup device performing in accordance with Fig. 1, all of the disks to the upper left of some 45° diagonal should be visible and all of those to the lower right should not. As the illumination is increased, the diagonal demarcation between visibility and invisibility should move to the right and in particular should move from one diagonal of disks to the next for a factor of four increase in illumination.

The series of pictures shown in Fig. 6 is a series of timed exposures of the picture reproduced on the kinescope as the light spot from another cathode ray tube scanned the test pattern. For experimental convenience, the exposure time, rather than the scene luminance, was increased, since, according to Eq. (5), it is only the product Bt that is significant. The first pictures in the series show what is transmitted at exceed-

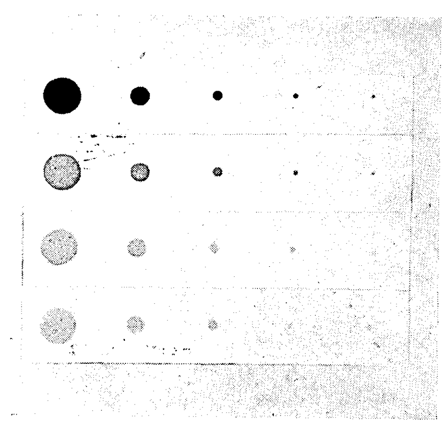


FIG. 5. Photograph of test pattern used as subject for the light spot scanner.

[4] G. C. Sziklai, R. C. Ballard and A. C. Schroeder, "An experimental simultaneous color television system, Part II: Pickup equipment," Proc. I.R.E. 35, 862 (1947).

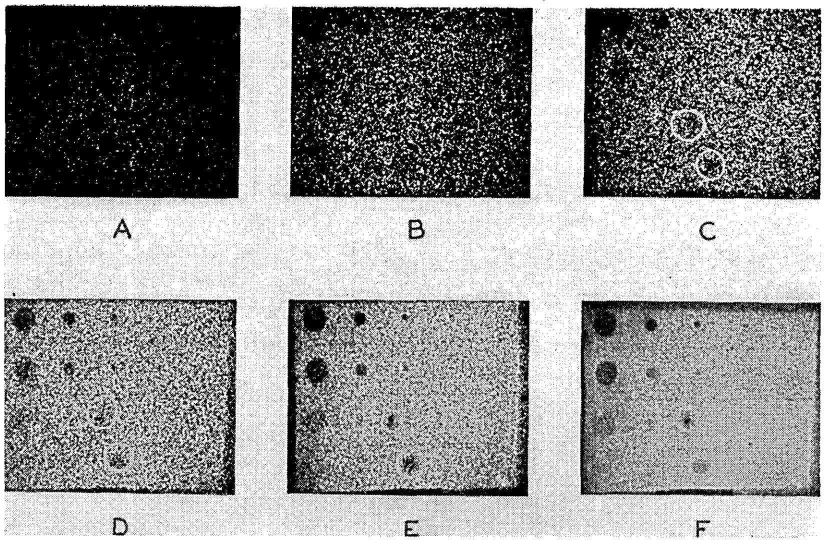


FIG. 6. Series of timed exposures of the test pattern shown in Fig. 5 as transmitted by the television pickup arrangement shown in Fig. 4. The exposure times, starting with Fig. 6a, are $\frac{1}{16}$, $\frac{1}{4}$, 1, 4, 16 and 64 seconds respectively. These exposures were chosen so that the diagonal demarcation between visibility and invisibility fell to the right of rather than on a particular diagonal of discs. Thus the smallest visible black dots are somewhat above threshold visibility. To get a short decay time, the ultraviolet emission from a special zinc-oxide phosphor scanner was used.† Two obvious blemishes that were not apparent under visible light, and have no connection with the test, are marked off by circles in Figs. 6c, d, e, and f.

ingly low scene luminance. In fact the number of "quanta" per unit area may easily be counted. As the scene luminance is increased, more and more of the pattern becomes visible.

Equation (5) and Figure 1 are quantitatively borne out by these pictures in two important respects. First, the demarcation between visibility and invisibility is, with good approximation, a diagonal. That is, the threshold contrast varies as the reciprocal angle of the test object. Second, the demarcation shifts by one diagonal for a factor of four change in scene luminance. That is, the threshold scene luminance varies as the square of the reciprocal contrast or as the square of the reciprocal angle. While the precision of the separate pictures is not high, the precision of the series is, since there are no significant cumulative or progressive departures in the large range of scene luminance covered.

† This was suggested to the writer by O. H. Schade of the RCA Victor Division, Harrison, N. J. See also R. E. Shrader and H. W. Leverenz "Cathodoluminescence Emission Spectra of Zinc-Oxide Phosphors," to be published in an early issue of the Journal of the Optical Society of America.

The series of pictures in Fig. 6 also establishes the values of two of the parameters in Eq. (5), namely the threshold signal-to-noise ratio (k) and the exposure or storage time (t) of the eye. The threshold signal-to-noise ratio has this meaning. Take the smallest black (not grey) disk that may be seen in any one of the pictures. Transpose the outline of the disk to the neighboring white background. Count the average number of "quanta" (specks of light) within this outline. The average number of "quanta" is the signal associated with the black disk; the square root of the average number is the root mean square fluctuation,*** and the ratio of signal to r.m.s. fluctuation, also the square root of the average number, is the threshold signal-to-noise ratio. A similar operation can be carried out for any of the grey dots to obtain the same value of k. The results of this operation are that k lies in the neighborhood of 5. A more precise value of k depends on a more precise operation for determining the threshold visibility of any one of the black disks. A more pre-

*** This has been roughly verified by actual counts taken on Fig. 6a.

cise value for k would, however, not depart significantly from the one given here. This is based on the fact that the range from substantial certainty of not seeing to substantial certainty of seeing is covered by a factor of four in scene luminance. This corresponds to a factor of two in the range of k values that might be selected. The interesting fact is that the threshold signal-to-noise ratio is not unity as is usually assumed but more nearly five.

The storage time of the eye is usually taken to be about 0.2 seconds. The series of photographs in Fig. 6 confirmed that choice if confirmation were needed. The visual impression of the kinescope picture matched within a factor of two the photographic exposure for 0.25 second.

To summarize this section, the series of pictures in Fig. 6 form a simple, quantitative representation of the operation of an ideal picture pick-up device.

COMPARISON OF THE PERFORMANCE OF THE HUMAN EYE WITH IDEAL PERFORMANCE

Experimental data for the human eye relating scene luminance, contrast and visual angle have been scarce. The writer[3] has already made use of the data of Connor and Ganoung[5] and of Cobb and Moss[6] to cover the range from 10^{-4} to 10^{2} footlamberts. These data are reproduced in Figs. 7 and 8 and are to be compared with Figs. 1 and 2. As in the previous use of the data, values of α less than two minutes of arc and values of contrast less than two percent were omitted. These points are close to the absolute cut-offs of $\frac{1}{2}$ minute of arc and $\frac{1}{2}$ percent contrast set by other than fluctuation limitations and would be expected to depart from the theoretical curves of Fig. 1.

Recently a more complete and thorough investigation of visual performance has appeared by Blackwell.[7] The points in Figs. 9 and 10 were computed from Blackwell's data for grey disks on a white background. In order to plot both Figs. 8 and 10, Reeves'[8] data on pupil diameter versus scene luminance were used.

In Fig. 7, the data have been approximated by lines of 45° slope in accordance with Eq. (4b). The fit is close enough to be significant. The same degree of fit is not, however, present in Black-

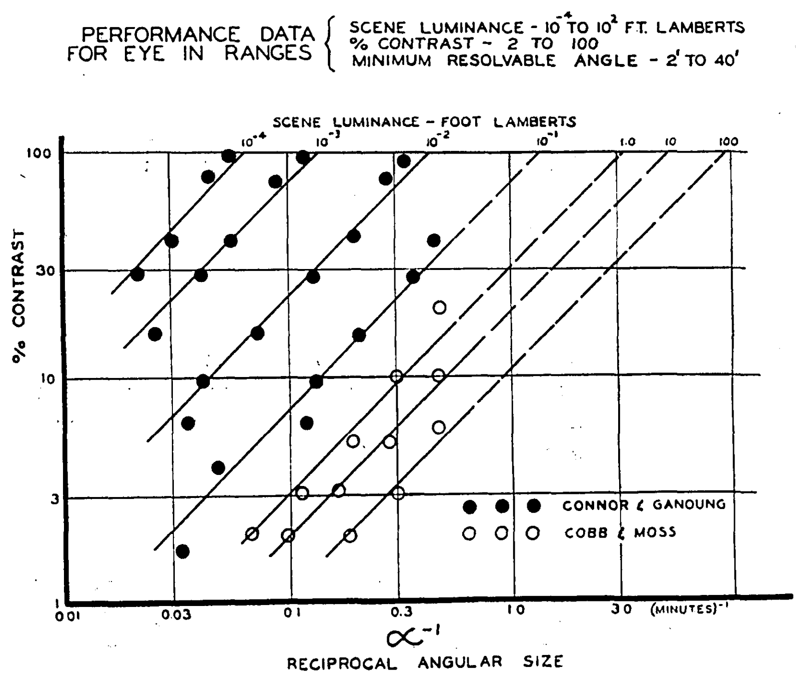


FIG. 7. The solid lines with 45° slope are approximations to the experimental data by ideal performance curves.

[5] J. P. Connor and R. E. Ganoung, "An experimental determination of visual thresholds at low values of illumination," J. Opt. Soc. Am. 25, 287 (1935).
[6] P. W. Cobb and F. K. Moss, "The four variables of visual threshold," J. Frank. Inst. 205, 831 (1928).
[7] H. R. Blackwell, "Contrast thresholds of the human eye," J. Opt. Soc. Am. 36, 624 (1946).
[8] P. Reeves, "The response of the average pupil to various intensities of light," J. Opt. Soc. Am. 4, 35 (1920).

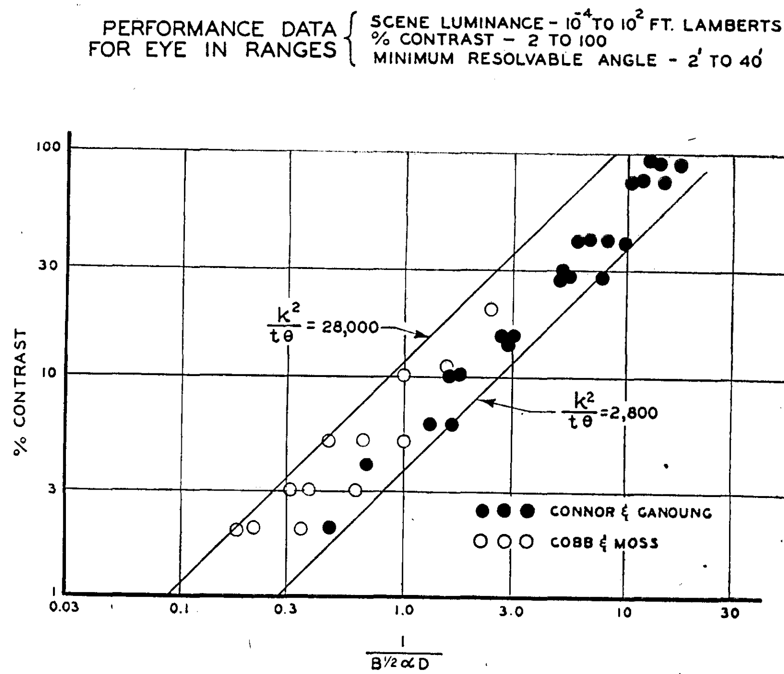


FIG. 8. A reduced plot of the data in Fig. 7. The two solid lines are computed from Eq. 5 for an ideal device

well's data in Fig. 9. Here the 45° lines are drawn tangent to the best performance at each value of scene luminance. The data in each case curve away from the straight lines. The degree of fit is still, however, sufficiently good for many engineering purposes. It is also sufficiently good to draw significant conclusions regarding the mechanism of the eye, as will be discussed below. In comparing Figs. 7 and 9 with Fig. 1 it is to be noted that the correction for the variation in pupil diameter has not yet been introduced. Such correction is introduced in Figs. 8 and 10.

In Figs. 8 and 10 the data are re-plotted as in Fig. 2. If the quantum efficiency, exposure time and threshold signal-to-noise ratio of the eye were invariant with scene luminance, and if the performance of the eye were limited by fluctuations in the absorption of light quanta, the data in Figs. 8 and 10 should all lie along a single straight line. The fact that the data do not lie along a single straight line but have some spread is a measure of the departure from one or more of the above conditions. Before discussing these departures it is well to note that Blackwell's data are substantially contained between the same two straight lines as are the data of Connor and Ganoung and Cobb and Moss.

The two straight lines that bracket the data both in Fig. 8 and in Fig. 10 are labelled $k^2/t\theta = 2800$ and $k^2/t\theta = 28{,}000$. Equation (5) was used to compute these values. The significance of these lines may be indicated as follows. If one arbitrarily assumed that k and t were invariant with scene luminance and that the performance of the eye were limited by fluctuations and took for k and t the values 5 and 0.20 respectively, then one would conclude that all of the data contained within these lines could be represented by an ideal picture pickup device having a quantum efficiency between 0.5 and 5 percent. On the one hand, this is a large spread in quantum efficiency; on the other hand, even this large spread severely limits the choice of mechanisms used to explain the phenomenon of dark adaptation, the latter covering a range of "apparent sensitivities" of over a thousand to one.

If, now, k and t instead of being assumed constant, were allowed to vary with scene luminance, their most reasonable direction of variation would be such as to reduce the range of variation of θ, the quantum efficiency. So also, if mechanisms other than fluctuations in the absorption of light quanta are used to describe the performance of the eye, these mechanisms, because they would be introduced at the high light end, would tend to reduce the range of variation of θ.

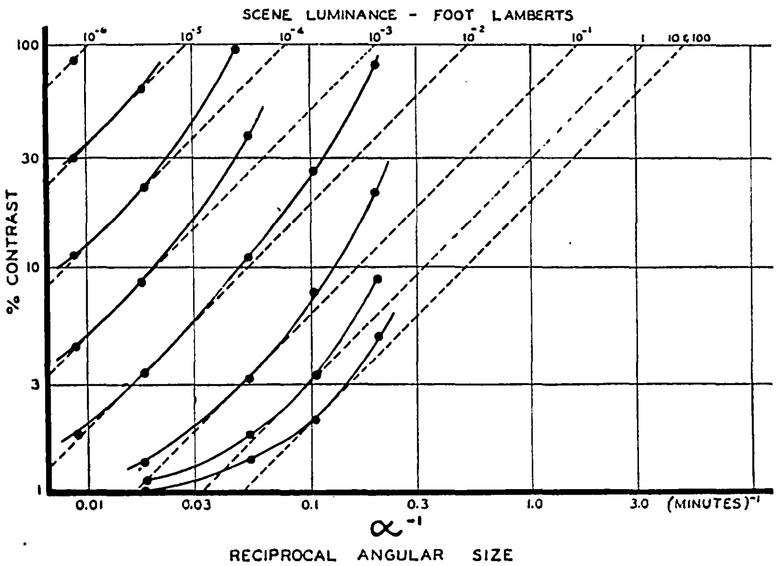


FIG. 9. Performance data for eye (computed from Blackwell). The dotted lines with 45° slope are ideal performance curves drawn tangent to the best observed performance at each value of scene luminance.

In brief, a factor of ten represents the maximum variation that the quantum efficiency of the eye undergoes in the range of 10^{-6} to 10^{2} footlamberts.

GENERAL DISCUSSION

A. Problems of Engineering Importance

The fact that the bulk of the performance data of the eye can be simply summarized by the performance of an ideal picture pickup device operating with a quantum efficiency of 5 percent at low lights and 0.5 percent at high lights is of considerable technical convenience. The ranges of the three parameters are:

scene luminance	10^{-6} to 10^{+2} footlamberts
percent contrast	2 to 100
visual angle	2′ to 100′

The types of problems that are clarified by this approach are: specification of the performance of television pickup tubes that are designed to replace the human eye; estimate of the factor by which pick-up tubes should exceed the eye in performance when the reproduced picture is viewed at a higher luminance than the original scene; estimate of the maximum gain in intelligence that may be obtained by any picture pickup device interposed between the eye and the scene; the setting up of criteria for the visibility of noise in a television picture or of graininess in photographic film; and finally, the ordering of the performance of present television pickup tubes and film relative to that of the eye. Two of these problems will be discussed briefly.

If the eye may be treated as an ideal pickup device, the criterion of threshold noise visibility is simple. It is that the signal-to-noise ratio associated with an element of area of the retina be approximately equal to the signal-to-noise ratio associated with the same element of area in the original scene in which noise is to be observed. Thus, in a series of tests in which pictures similar to those in Fig. 6 were directly viewed on a kinescope, it was found that the noise in these pictures could be reduced to threshold visibility by interposing a neutral filter between the eye and the kinescope. The transmission of the neutral filter was such that, at threshold, the number of white specks per unit area per unit time on the kinescope face was approximately equal to the number of light quanta absorbed by the retina from the same area per unit time. A quantum efficiency of 0.5 percent was used for this computation. It is probably more significant to apply the same type of analysis to data already published, as for example, in the paper by Jones and Higgins[9] on the graininess of photographic film. Table I, column 1 shows the values of signal-to-noise ratio measured by Jones and Higgins for several widely different types of film and for a test area 40 microns in diameter on the film. In

[9] L. A. Jones and G. C. Higgins, "Photographic granularity and graininess," J. Opt. Soc. Am. 36, 203 (1946).

column 2 are given the computed values of signal-to-noise ratio for the same test area at the retina under what they call threshold conditions for seeing graininess. To compute column 2, a quantum efficiency of 0.5 percent was assumed for the eye as well as a pupil diameter of 4 millimeters and a storage time of 0.2 second.

The large discrepancy between the low light performance of the eye and that of present television pickup tubes and photographic film was referred to at the beginning of this paper. Its origin is this. The eye appears to act like an ideal device over a large range of scene luminances. That is, as the scene luminance is decreased the signal received by the retina falls linearly while the noise associated with the signal falls as the square root of the scene luminance. And these relations hold even down to 10^{-6} footlambert. The same relations hold for pickup tubes and film but usually only over the relatively narrow light ranges in which they are normally used. In these ranges, they act like ideal devices with a quantum efficiency about the same as that of the eye. As the scene luminance is lowered, however, various sources of fixed noise (invariant with scene luminance) dominate and obscure the picture. These sources of noise include the noise in a television amplifier, the shot noise in a scanning beam, and the fog in photographic film. None of these sources represent absolute limits to the performance of pickup tubes or film since designs are conceivable in which these sources of noise are absent and only the intrinsic noise in the primary photo process is present. They do, however, represent present and, it is hoped, transient limitations. A further handicap to the performance of film at low illuminations is the fact that more than one absorbed quantum is needed to make a grain developable. When the incident concentration of quanta falls below the concentration of grains, the picture disappears as if by a "clipping" action. In brief, photographic film would satisfy ideal performance even, or especially, at arbitrarily low scene luminances if (a) fog were absent and (b) a single absorbed quantum were sufficient to make a grain developable. Film could then *count* each absorbed quantum.

TABLE I.

Film	Signal-to-noise ratio of 40-micron-diameter disk on film. (From Jones and Higgins.[9]) Density of film ≑0.4	Signal-to-noise ratio of image of 40 micron diameter disk at retina. Computed for 0.5 percent quantum efficiency and 0.2 seconds storage time.
Tri-X	11	13
Super XX	23	22
Pan X	36	39
Fine grain	77	58

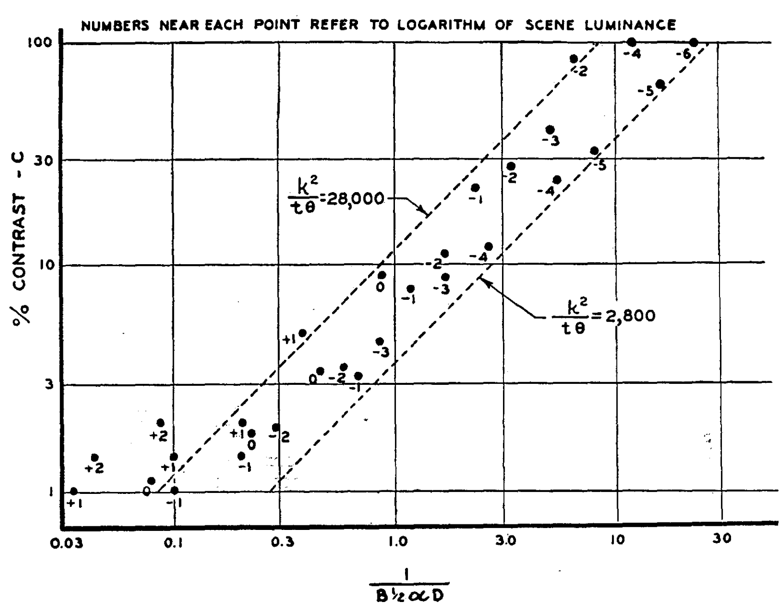


FIG. 10. A reduced plot of the data in Fig. 9. The two dotted lines are the same as the two solid lines in Fig. 8.

B. Dark Adaptation and Related Phenomena

The outstanding feature of dark adaptation is well known. Immediately after exposure to a luminance of about 100 footlamberts, the lowest luminance the eye can detect is over 1000 times larger than the luminance it can detect after extended dark adaptation. The significant question here, that bears on the mechanism of the eye, is, "Is the sensitivity, that is, quantum efficiency, of the dark adapted eye over a thousand times greater than that of the light adapted eye?**** The answer, from Figs. 8 and 10, is definitely in the negative and with a large factor of safety. From these figures, at most a factor of ten can be ascribed to change in quantum efficiency. The rest, except for some contribution of pupil opening, must come from another mechanism. And a reasonable mechanism to postulate is a gain control mechanism located between the primary photo process at the retina and the nerve fibers that carry the impulses to the brain. A gain mechanism, minus the idea of control or variability, is not at all *ad hoc*. It is needed to raise the energy level of the absorbed quanta to the energy level of their corresponding nerve pulses. To add variability to the gain mechanism is indeed a minor assumption and one that can readily account for the large range of dark adaptation.† From necessarily subjective evidence, the gain control appears to be automatically set so that noise is near the threshold of visibility. At very low lights, around 10^{-4} footlambert, "noise" appears to be more easily visible than at moderate lights around one footlambert. The writer has been most impressed by the appearance of noise in dimly lit scenes after the thorough dark accommodation that comes from several hours of sleeping in a dark room. Since these conditions are not the normal ones for making reliable observations, the reference must be regarded as one of interest but not of evidence.

At the risk of being repetitive, the conclusions of this section may be stated in another way. Photo-chemical mechanisms that are confined to the primary photo-process at the retina cannot account for more than a few percent of the total range of dark adaptation. By primary photo process is meant the process in which the incident light quanta are absorbed. The *products* of the primary photo process may however be transmitted to the nerve fibers with variable efficiency consistent with the variable gain mechanism already discussed. Thus the assumption of a variable concentration of active material whose absorption of incident light quanta is correspondingly variable, or the assumption of rods and cones with a variable threshold of excitation can be expected at most to play only a minor role in dark adaptation.

It is interesting to record here a possible but less certain application of the gain control mechanism. At high lights, luminosity, visual acuity[12] and contrast discrimination are substantially the same for red and blue illumination having the same luminance. At very low lights, less than 10^{-3} footlambert, luminosity, visual acuity[12] and contrast discrimination under red light rapidly approach zero while under blue light, significantly finite values are maintained. In the intermediate range of 10^{-3} to 1 foot lambert, the range of present interest, the luminosity of red light drops below that of blue light while acuity[12] and contrast discrimination[13] remain substantially the same for the two colors. A formal explanation of the observations in the intermediate light range follows immediately if one allows fluctuations in the primary photo process to determine visual acuity and contrast discrimination. Then, if the gain control is set high enough so that these fluctuations are apparent to the brain, all possible intelligence is thereby transmitted to the brain

**** If one takes, for example, Hecht's (reference 10) assumption that threshold visibility corresponds to a fixed amount of sensitive material decomposed by the incident threshold light, then since the threshold light intensity changes by a factor of 10^4 (see Fig. 3 of Hecht's paper, "Rod portion of the 'blue' curve"), from low to high adaptation light intensities, the quantum efficiency must also change by this factor.

[10] S. Hecht, "The instantaneous visual thresholds after light adaptation," Proc. Nat. Acad. Sci. **23**, 227 (1937).

† Parallels to the idea of a variable gain element are common in electron tubes. In the image orthicon (reference 11), for example, an electron multiplier acts as the variable gain element that raises the level of signal and noise coming out of the tube above the noise level of the amplifier to which the tube is connected.

[11] A. Rose, P. K. Weimer, and H. B. Law, "The image orthicon, a sensitive television pickup tube," Proc. I.R.E. **34**, 424 (1946).

[12] S. Shlaer, E. L. Smith and A. M. Chase, "Visual acuity and illumination in different spectral regions," J. Gen. Physiol. **25**, 553 (1942).

[13] M. Luckiesh and A. H. Taylor, "Tungsten, mercury and sodium illuminants at low brightness levels," J. Opt. Soc. Am. **28**, 237 (1938).

and variations of the gain setting vary luminosity but not acuity or discrimination. According to this argument, the gain for red light is less than that for blue light in the intermediate light range.

C. Other Mechanisms

It was stated earlier in this paper that the departure of the actual performance of the eye from that to be expected from an ideal device was a measure of the "logical space" within which one could introduce mechanisms, other than fluctuations in the primary photo process, to determine the performance of the eye. Such other mechanisms would, of course, lead to lower performance than would fluctuations in the primary photo process alone. What is important, then, is to get an estimate of the extent of this "logical space."

To clarify the problem, reference is made to Figs. 8 or 10. If independent measurements of k, t, and θ verify that $k^2/t\theta$ is 2,800 at low lights and 28,000 at high lights as shown in these figures, then, except for minor departures, the actual performance of the eye matches the performance expected from an ideal device and the "logical space" is substantially absent. The inquiry then leads to what is known of k, t, and θ separately.

The threshold signal-to-noise ratio, k, was taken from Fig. 6. Its value, 5, is primarily a low light value in that it applies to the condition that noise is easily visible. If noise is not easily visible, as at higher lights, an increase in k can be invoked. But such an increase is in the direction already noted in Figs. 8 and 10 and would only relieve the quantum efficiency (θ) of the necessity of varying from low to high lights.

The storage time (t) was also observed from Fig. 6 and the original kinescope pictures to be about 0.25 second. This value applies to the intermediate light range. At very low lights, if one takes the constant in the often quoted law of Blondel and Rey, the storage time is still about 0.2 second. Finally, the data of Cobb and Moss in the range of 1 to 100 footlamberts was taken for an exposure time of 0.18 second and match the data of Connor and Ganoung fairly well, the latter having been taken for an observation time of one second. All of this points to a storage time of 0.2 second independent of scene luminance. Langmuir and Westendorp[14] confirm this constancy except for a suggestion of a longer storage time near absolute threshold.

In spite of all of these independent sources of evidence pointing to a storage time of 0.2 second, there is still some uncertainty. The uncertainty comes from not having good data on how well the memory process can extend the physical storage time to times longer than 0.2 second. Such extension would of course vary with the observer and improve with training. Some remarks and data in Blackwell's paper suggest that memory may extend the effective storage time up to seconds. The most that may be said for the data quoted in the present paper, with the exception of the Cobb and Moss data, is that the effective storage time may be anywhere between the physical storage time of 0.2 second and the actual observation time of one second.

Independent measurements of quantum efficiency at low lights bracket the value of 5 percent used in this paper. Hecht,[15] by a statistical analysis of threshold measurements, consistently arrives at about 5 percent. Brumberg, Vavilov and Sverdlov,[16] by a similar experiment, arrive at values from about 5 to 25 percent. Both Hecht and Brumberg's measurements are for blue light in the neighborhood of maximum visual response. They should be divided by a factor of about three to reduce them to white light for comparison with the value of 5 percent already noted in this paper. At high lights, the writer knows of no independent measurements of quantum efficiency.

To summarize the discussion thus far, independent measurements of k, t, and θ agree well with the low light value of $k^2/t\theta$ in Figs. 8 and 10. At high lights there is uncertainty both about k and θ. If k increases or θ decreases, the high light value of $k^2/t\theta$ in Figs. 8 and 10 might be independently verified. In that event little room is left for mechanisms other than fluctuations in

[14] I. Langmuir and W. F. Westendorp, "A study of light signals in aviation and navigation," Physics **1**, 273 (1931).
[15] S. Hecht, "The quantum relations of vision," J. Opt. Soc. Am. **32**, 42 (1942).
[16] E. M. Brumberg, S. I. Vavilov and Z. M. Sverdlov, "Visual measurements of quantum fluctuations," J. Phys. U.S.S.R. **7**, 1 (1943).

the primary photo process to determine the acuity and contrast discrimination of the eye. If, however, k and θ are independent of scene luminance, as much as a factor of ten in performance can be ascribed to the limitations imposed by other mechanisms.

There remains the departures from straight lines noted in Fig. 9. Since, at a fixed scene luminance, k, θ, and t should remain constant these could not account for such departures. It is rather more likely that the departures represent optical defects in the sense that, as the scene luminance is lowered, the eye combines signals from neighboring rods and cones to form larger picture elements. These larger picture elements, if they are of the same order as the smallest resolvable black disks, would limit acuity in the same way that the separate cones set a final limit to acuity. That the eye combines signals from neighboring rods and cones is a consequence of the fact that more than one absorbed quantum is needed to generate a visual sensation (see also Hecht[15]). Objective measurements by Hartline[17] on the frog's eye also point to such a combining process.

[17] H. K. Hartline, "Nerve messages in the fibers of the visual pathway," J. Opt. Soc. Am. **30**, 239 (1940).

SUMMARY

The performance of the eye over the bulk of its operating range may be matched by an ideal picture pickup device having a storage time of 0.2 second and a quantum efficiency of 5 percent at low lights decreasing to 0.5 percent at high lights. For many engineering problems in which the performance of the eye must be quantitatively compared with the performance of man-made pickup systems, the substitution of an equivalent ideal device for the eye considerably simplifies the analysis. The match between the eye and an ideal device also provides at minimum a good first approximation to an understanding of the performance of the eye in terms of fluctuations in the primary photo process. Depending mostly on how well further independent measurements of the quantum efficiency of the eye agree with the quantum efficiencies deduced in this paper, the analysis of performance in terms of fluctuations may be appreciably better than a first approximation.

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