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A METHOD OF DETERMINING THE OVERALL QUANTUM EFFICIENCY OF VISUAL DISCRIMINATIONS

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The present literature on quantum efficiency is confusing and contains contradictions partly because definitions of efficiency have differed, partly because false assumptions about the working of the eye have been implicit in the method of calculation used, and partly because the experimental results chosen for the calculations were obtained under different conditions. The present paper defines overall quantum efficiency, reviews the literature leading up to the present work, points out the difficulties that have arisen, and describes a new method for determining the efficiency that is simpler and more accurate than previous methods. The range of application and significance of quantum efficiency as a measure of visual performance are discussed. In the following paper (Barlow, 1962) some results obtained with the method will be presented.

Definition. The overall quantum efficiency (F) of vision is most simply defined as the following ratio:

$$F = \frac{\text{Least quantity of light theoretically required for performing a task}}{\text{Least quantity required in practice for performing that same task}}.$$

The basic idea, due originally to Rose (1942), is to compare the performance of a human subject with that of an ideal device in which all the light entering the eye is correctly focused on the retina, all of it is absorbed by the receptor cells, all the quantal absorptions are correctly signalled centrally, and in which the central mechanisms process the resulting information optimally for the performance of whatever task is required. Such an ideal device will perform the task optimally, but not absolutely correctly; quantal fluctuations lead to random scatter in the numbers of quanta absorbed in the various parts of the retinal image, and even with ideal central processing this scatter must occasionally lead to the incorrect performance of the task. Such errors will occur more often if the light entering the device is reduced by a neutral filter, for this decreases the average number of quantal absorptions, and thereby increases the relative magnitude of the quantum fluctuations. Now imagine a human subject and such an ideal device performing the same task: with no filter in front of it, the ideal device will of course perform better, but by interposing the appropriate filter its performance can be reduced until it matches that achieved by the subject. The fraction of light transmitted by this filter is then equal to the overall quantum efficiency, F, as defined above. Of course the ideal device does not exist, so that in practice one substitutes performance figures calculated theoretically.

Historical background. Quantum efficiency was proposed by Rose (1942) as an absolute measure of performance of an optical task and was later applied by him to the human eye (Rose, 1948). Two facts seemed to emerge at once from the use of this measure: first, the efficiency appeared to be remarkably high, suggesting that little loss of efficiency occurred except from the absorption of light in the optic media, and the failure to absorb all of it in the receptor cells of the retina: and secondly this high efficiency was thought to be maintained under a great diversity of working conditions of the eye. At this stage it seemed possible that much of the empirical psychophysical data on the visual performance could be summarized by the single statement that the quantum efficiency was high and almost constant (as de Vries had suggested in 1943), but in fact both these early results have proved misleading. Aguilar & Stiles (1954) made a critical estimate of efficiency under conditions where Rose thought it was high, and obtained a lower value which decreased rapidly with increasing background intensity. Barlow (1958) showed that the range of conditions for constant quantum efficiency was very restricted; there is, for instance, no range of values of background intensity, and area and duration of an added increment, over which the values of threshold are consistent with the quantum efficiency for detection of the increment remaining invariant. Clark Jones (1957, 1959), pursuing Rose's line of thought, has obtained lower values of quantum efficiency, and has shown up more variation with variation of the experimental parameters.

Necessary precautions. The most troublesome disagreement in the past has been about the limitations to be accepted for the 'ideal detector'. The tendency has been to assume that the eye functions in a particular way, and then to impose the equivalent limitation on the ideal device. For instance, Rose (1948) assumed a constant figure of 0·2 sec for the summation time of the eye, and calculated the number of quanta required by an ideal device which was exposed to the test field for a single 0·2 sec exposure. That this is incorrect is easily seen when it is pointed out that a human subject's performance would, in many of the test situations, have been seriously impaired if he had been exposed to it for 0·2 sec instead of the much longer observation periods allowed. Complete summation may be limited to this time but incomplete summation certainly occurs over longer periods. Clark Jones (1957) made similar assumptions, and in his latest calculations (Clark Jones, 1959) he has compared the performance of an ideal device using the light entering one eye with the actual performance of subjects who used both eyes. Again, the one-eyed performance would have been worse than the two-eyed, and his calculated figures for quantum efficiency are therefore too high.

Disagreements of this sort can be avoided if these two rules are followed when calculating the ideal performance:

(1) No limitations are to be imposed upon the ideal detector except those that incontrovertibly apply to the eye—e.g. the finite pupil area.

(2) The task for which the calculation is made must be exactly the same as the task performed by the subject.

Detective efficiency and the false-positive rate. The visual task performed in all the above cases was the detection of a stimulus just sufficient to give rise to a sensation, and Clark Jones therefore talks of the *detective* quantum efficiency. Now to calculate a theoretical minimum signal for any response one needs to know both the probability that the signal, if present, will give the response, and the probability that the same response will be given in the absence of the signal. The importance of specifying the first when stating a threshold value is of course recognized, but there are difficulties with the second. This may be partly because people are unwilling to admit the unreliability of their own sensations, or because they are unwilling to quibble about the exact significance of a sensation when there is such complete consensus of opinion about the verbal meaning of 'seeing a light'. But there is also a genuine technical difficulty in specifying reliability numerically. The probability of 'seeing' a zero stimulus is certainly low, and the number of occasions upon which it occurs in any reasonably designed experiment is consequently small. Hence the accuracy of any estimate of the probability is very poor. This statistical problem is one which the method of estimating F described in this paper was designed to overcome.

Fitting frequency-of-seeing curves. While this work on detective quantum efficiency was being done, Hecht, Shlaer & Pirenne (1942), van der Velden (1944), Bouman & van der Velden (1947), Baumgardt (1948) and others were using an alternative method of calculating the smallest quantity of light theoretically required (see review by Pirenne, 1956). This was first used as an independent check on direct estimates of the number of quanta absorbed from a threshold flash of light, though it really only sets a lower limit to this figure. The principle is to match an experimentally determined frequency-of-seeing curve with a theoretical curve calculated for an ideal detector that responds when the number of quanta absorbed equals or exceeds a certain critical value. If a fit is obtained for a critical number equal to, say, 5, then one can conclude that the average number of quanta that are required to cause a reported sensation is not less than 5. The quantum efficiency is easily derived by dividing the critical number by the average number of quanta which must be delivered to the eye to produce a response, though the above workers have not made this calculation.

Quantum efficiency for discriminating two intensities. The first object of this paper is to describe a simplified method of determining the quantum efficiency. This is derived from the use by Hecht *et al.* (1942) of frequency-of-seeing curves, but employs only two intensities of stimulus; it thus makes the calculations easier. All the required quantities are measured in the actual experimental situation, and the sampling error of the estimate can be calculated together with the estimate itself. The task the subject performs for this 'two-point method' is not restricted to the detection of the presence or absence of a stimulus and it would not be accurate to describe it as a measure of *detective* quantum efficiency. Since the subject's task is to discriminate between two added stimuli of different intensities, it should be called the *discriminative* quantum efficiency. In the special case where one stimulus is of zero intensity, and the other is just threshold, discriminative and detective quantum efficiencies are identical, but the two-point discriminative method can be applied in different conditions; for instance, both stimuli can be supra-threshold, the subject distinguishing them by the brightness of the sensation.

The two-point method

Apparatus is arranged to give two alternative stimuli, S_1 the brighter of the pair, and S_2 the dimmer. The stimuli may be of any area, duration, and location in the visual field, and may appear on a background of any intensity. It is important, however, that the pair should only differ from each other in intensity, that subsidiary clues aiding their differentiation (e.g. clicks, sequences) should be rigorously eliminated, and that the subject should have adequate experience, in advance of the test, of both classes of stimuli. When he has this experience he is presented with one of the pair selected at random, and his task is to classify it as brighter or dimmer. The four possible combinations of stimulus and response are counted separately, so the quantities known for each of the stimuli S_1 and S_2 are: M, the average numbers of quanta delivered to the eye from the stimuli, together with any quanta entering the eye from the background during the stimulus and from the area covered by the stimulus;* n, the

* The justification for adding in these background quanta is that no ideal device could exclude them, and the increased fluctuation they bring with them. On the other hand, quanta from outside the area and period of time occupied by the stimulus can be excluded if, as is here assumed to be the case, the detector knows the time and position of occurrence of the stimulus, and its area and duration.

numbers of stimuli delivered; and P, the proportions classed as 'brighter.' The problem is to calculate m_1 and m_2, the smallest numbers of quanta bearing the same ratio to each other as M_1 and M_2 that would enable the unknown signals to be discriminated to the extent indicated by the values of P_1, P_2.

Consider a device that classes a stimulus as brighter if the number of quanta absorbed equals or exceeds a critical number c, dimmer if it does not. The proportions, P, classed as brighter for varying average numbers of quanta absorbed, m, are given by the cumulative Poisson formula, and if these proportions are to match those achieved by the human subject, then

$$P_1 = \mathrm{e}^{-m_1} \sum_{r=c}^{\infty} \frac{m_1^r}{r!} \quad \text{and} \quad P_2 = \mathrm{e}^{-m_2} \sum_{r=c}^{\infty} \frac{m_2^r}{r!}.$$

The ratio $m_1 : m_2$ is known, since it is equal to that of the stimuli $M_1 : M_2$, and in principle one can determine the two unknowns (c and either m_1 or m_2) from these two equations. The following theoretical section derives an approximate method for doing this. In outline, the family of curves representing P as a function of m for varying c (Fig. 1, top) is converted into a set of parallel straight lines (Fig. 1, bottom) by use of appropriate transformations for ordinate and abscissa. Putting a neutral filter in front of the ideal device described by this set of lines would have the effect of reducing the slope of all of them equally. It is an easy matter to calculate what value of neutral filter would reduce the slope to the value represented by the line joining the two experimental points, P_1M_1 and P_2M_2, plotted on these transformed co-ordinates. The transmission of this neutral filter is then the quantum efficiency corresponding to the experimental performance.

THEORY

The derivation of the formulae for F and for the sampling error of F are the main contributions of the present paper, but it is clearly not necessary to follow this through in detail in order to understand the principle of the method. Figure 2 is the result of calculations showing that the sampling error of the two-point method is least when P_1 and P_2 are about 95 and 5 %, and that it is then considerably more accurate than other methods of determining F. Apart from this, the next section of general interest is the Discussion.

Notation

M_1 = average number of quanta entering the eye during the exposure of the brighter stimulus (S_1) from the stimulus and from the background over the area covered by that stimulus.

M_2 = same for dimmer stimulus (S_2).

n_1, n_2 = number of presentations of S_1, S_2.

$P_1 = r_1/n_1$ proportion of S_1 classified (correctly) as brighter.

$P_2 = r_2/n_2$ proportion of S_2 classified (incorrectly) as brighter.

m_1, m_2 = smallest average numbers of quanta absorbed from the M_1, M_2, which will allow P_1 and P_2 to be as high and low (respectively) as observed.

c = number of quanta absorbed which, if exceeded or equalled, leads to classifying as brighter by ideal device.

Y_1, Y_2 = probits corresponding to P_1, P_2; $P = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{Y-5} e^{-\frac{1}{2}u^2}\,du$.

w_1, w_2 = weighting coefficient corresponding to P_1, P_2; $w = \frac{(dP/dY)^2}{P(1-P)}$.

$V_{(Y_1)}$, etc. = variance of estimate of Y_1, etc.

$S_{(Y_1-Y_2)}$, etc. = estimate of standard deviation of $Y_1 - Y_2$, etc.

$F = m_1/M_1 = m_2/M_2$ = overall quantum efficiency = smallest fraction of incident quanta which must necessarily be absorbed in order to obtain P_1 and P_2.

Problem

To calculate F and $S_{(F)}$ from experimentally obtained values of P_1, P_2, M_1, M_2 and n_1, n_2.

The treatment of the cumulative Poisson curves to yield approximations to which the experimental data can be fitted is shown in Fig. 1. First a function of m is chosen for the abscissa which converts the family of cumulative Poisson curves into a family that are almost the same shape and almost parallel to each other (i.e. superposable by lateral displacement). $\sqrt{m}$ does this, as shown in Fig. 1 (top and middle), and it has the additional advantage of removing some of the skewness, so that the following transformation is more effective. Secondly, in place of the probability P, which is the ordinate in Fig. 1 (top and middle), the probit Y is used. The probit of a probability P is Y where

$$P = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{Y-5} e^{-\frac{1}{2}u^2}\,du.$$

This transformation converts the integral of a normal distribution into a straight line whose slope is the reciprocal of the standard deviation of that distribution. It is extensively used in the statistical analysis of dosage–response relations (Finney, 1947), but it is historically interesting that, according to Finney, the method was originated by Fechner for the treatment of psychophysical results similar to those considered in this paper.

An ideal detector with criterion c would give the curves of Fig. 1 (middle). These are not integrals of normal distributions, hence they are not converted into exactly straight lines by the probit transformation. It will be seen from Fig. 1 (bottom) that the lines are straight where c is large, but where it is small they are slightly convex to the left. For $c = 12$ or more, a straight line with the equation

$$Y = 5+2(m^{\frac{1}{2}}-c^{\frac{1}{2}})$$

is practically coincident with the transformed cumulative Poisson. The errors that may result from using the above straight lines as approximations when c is less than 12 are considered in a later section.

From the definition of quantum efficiency, F is m/M. Substituting for m in the straight-line approximation above, and eliminating c, one has

$$Y_1-Y_2 = 2(F^{\frac{1}{2}}M_1^{\frac{1}{2}}-F^{\frac{1}{2}}M_2^{\frac{1}{2}}),\quad F = \frac{1}{4}\left(\frac{Y_1-Y_2}{M_1^{\frac{1}{2}}-M_2^{\frac{1}{2}}}\right)^2. \tag{1}$$

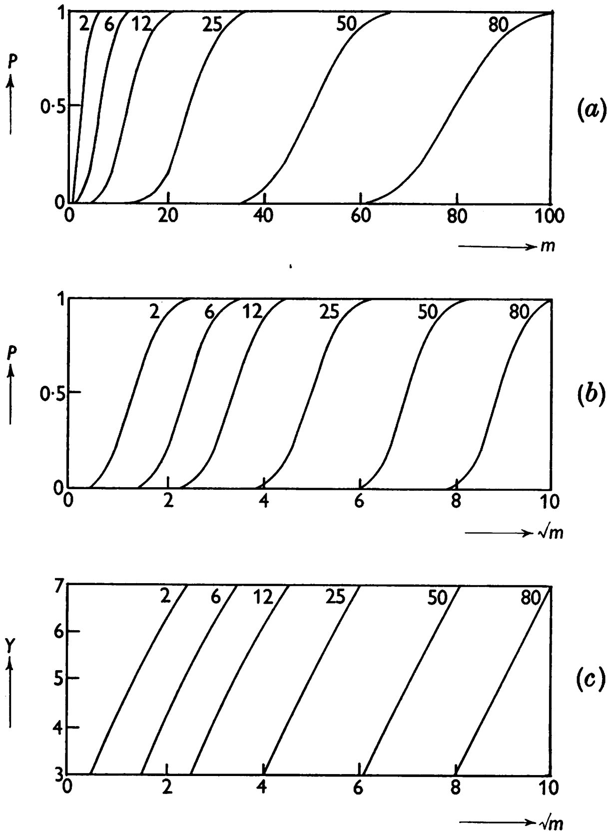

Fig. 1. Transformations of ordinates and abscissae to produce a set of almost parallel, almost straight, lines from cumulative Poisson curves. (a) Top; ordinates, the probability P, and abscissa m, the average number of quanta absorbed. (b) Middle; P and $\sqrt{m}$. (c) Lower; Y, the probit transformation of P (see text), and $\sqrt{m}$. The number on each curve indicates the values of c.

Criterion and discriminant level

The ideal detector has a criterion c, and the 'discriminant level' is defined as c/F. It is the stimulus intensity that is classified as 'brighter' on 50 % of occasions.

It is given by

$$\frac{c}{F} = \left[M_2^{\frac{1}{2}}\left(\frac{Y_1-5}{Y_1-Y_2}\right)-M_1^{\frac{1}{2}}\left(\frac{Y_2-5}{Y_1-Y_2}\right)\right]^2.$$

It should be noted that the choice of discriminant level is, within limits, left to the subject, and the ideal detector is then matched to this choice. This step makes it unnecessary to have any knowledge of the rewards and penalties associated with each possible outcome of the task in calculating the optimum performance. Presumably one might deduce something about a subject's impression of this pay-off matrix from his choice of discriminant level, but this has not been attempted.

Variation of criterion

To derive the theoretical curves it was assumed that c was constant, and one might question whether this is necessarily so in the ideal device. If the experiment is suitably designed, there will be no means of telling whether S_1 or S_2 is presented except by the number of quanta absorbed; hence if c does change, the distribution of its values will be the same, on average, for S_1 and S_2. In such a situation the curve relating probabilities of exceeding c to $\sqrt{m}$ would be a weighted mean of several of the curves of Fig. 1 (*b*), and at all values of ordinate it would have a slope less than those curves. The reduction of slope would persist after the probit transformation. This justifies the intuitive feeling that fluctuations of threshold criterion must cause a loss of quantum efficiency.

Sampling error of estimates

For the estimate of F to be accurate all the quantities in the above equation must be accurately known. M_1 and M_2 are fixed by ordinary physical calibrations. Y_1 and Y_2 are derived from P_1 and P_2, the proportions of the two stimuli classed as brighter, and as they are estimates of true probabilities obtained from a limited number of trials they are subject to sampling error. The effect of this on the estimate of F can be calculated as follows. It is assumed that the sampling errors in P are small enough for the relation with F to be treated as linear over their range. If P was obtained from a large number of trials this would be acceptable, but it is a poor approximation, where n is of the order of 50. The results are, however, of interest in showing the conditions where the sampling error is low and for comparison with other methods.

Since M_1 and M_2 in equation (1) are not subject to sampling error,

$$S_{(F)} = S_{(Y_1-Y_2)} \frac{\mathrm{d}F}{\mathrm{d}(Y_1-Y_2)} = S_{(Y_1-Y_2)} \frac{(Y_1-Y_2)}{2(M_1^{\frac{1}{2}}-M_2^{\frac{1}{2}})^2}.$$

$S_{(Y_1-Y_2)}$ is obtained from $V_{(Y_1)}$ and $V_{(Y_2)}$ and these are related to the 'weighting coefficients' w (see Finney, 1947) which are conveniently tabulated.

$$V_{(Y)} \doteqdot V_{(P)}\left(\frac{\mathrm{d}Y}{\mathrm{d}P}\right)^2 = \frac{P(1-P)}{n}\left(\frac{\mathrm{d}Y}{\mathrm{d}P}\right)^2 = \frac{1}{nw},$$

$$S_{(Y_1-Y_2)} = \sqrt{(V_{(Y_1)}+V_{(Y_2)})} = \sqrt{\left(\frac{1}{n_1w_1}+\frac{1}{n_2w_2}\right)},$$

therefore

$$S_{(F)} \doteqdot \frac{Y_1-Y_2}{2(M_1^{\frac{1}{2}}-M_2^{\frac{1}{2}})^2}\sqrt{\left(\frac{1}{n_1w_1}+\frac{1}{n_2w_2}\right)},$$

$$= \frac{2F}{Y_1-Y_2}\sqrt{\left(\frac{1}{n_1w_1}+\frac{1}{n_2w_2}\right)}.$$

In practice it is usually more convenient to use $\log F$, for which the sampling error is

$$S_{(\log_{10}F)} \doteqdot \frac{2\log_{10}\mathrm{e}}{Y_1-Y_2}\sqrt{\left(\frac{1}{n_1w_1}+\frac{1}{n_2w_2}\right)}.$$

The weighing function w depends upon Y, and it becomes very small for values of Y far from 5 (values of P close to 0 or 1). The result is that the standard error of the estimate then becomes very large. On the other hand if both values of Y are close to 5 (P close to 0·5), the error also becomes large because Y_1-Y_2 is the denominator in the expressions above. In Fig. 2 (lower curve) $S_{(\log F)}$ is plotted against P for the case where

$$P_1 = 1-P_2, \quad \text{and} \quad n_1 = n_2 = 50;$$

i.e. there are 50 brighter and 50 dimmer flashes, and the same proportion of each is correctly classified. It will be seen that the lowest errors are obtained when the proportion of each classified correctly is about 95%, and the error is then 0·11 log. units ($\pm$28%). It increases rapidly for more extreme values of P_1 and P_2, slowly for values closer to 50%. Although these errors may seem uncomfortably large, they are small in relation to the range of variation of F, and they could, of course, be reduced by increasing the number of observations.

Comparison with other methods

If more than two intensities of stimulus are used, and the subject is still instructed to classify them into two categories according to intensity, then one would expect all values of Y and $M^{\frac{1}{2}}$ to lie near a straight line. A probit regression line can then be calculated as described by Finney (1947), and from its slope F can be derived as above. This method is laborious in calculation but accurate: for instance, if 50 flashes are delivered at 6 intensities yielding probabilities of seeing of about 0·5, 7, 30, 70, 93 and 99·5 %, then the sampling error in log F is 0·084 log. units. This is better than the two-point method with a total 100 flashes ($\pm$ 0·11 log. units),

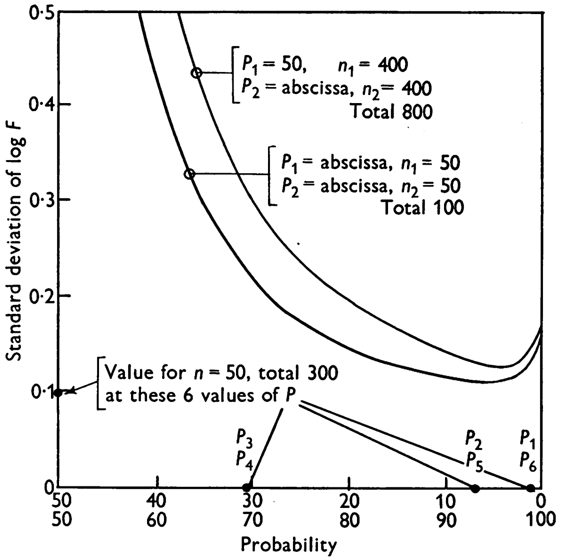

Fig. 2. Accuracy of the estimate of F by various methods. Ordinates, standard deviation of log$F$: abscissae, probabilities of exceeding the criterion for the intensities used in the determination. Top curve; log$F$ calculated from a fixed threshold (50 %) intensity and another variable intensity, using 400 trials at each, total 800. Lower curve; from two points equally spaced above and below 50 % intensity, using 50 trials at each, total 100. Arrow on ordinate scale; from slope of probit regression line based on 50 trials at each of 6 intensities, total 300, the intensities used corresponding to the probabilities shown on abscissa scale. For equal accuracy the second method (using 5 and 95 % intensities) requires rather fewer test flashes than the full frequency-of-seeing curve, and many fewer than the first method.

but worse than the two-point method would be with a total of 300 flashes ($\pm$ 0·064 log. units). The two-point method has the advantage of concentrating observations at the values of Y which yield maximum information on the slope of the regression line, and further advantages in the simplicity of the experimental procedure and the calculation.

Another interesting comparison can be made with the method of estimating quantum efficiency from threshold (50 % seen) and the false-positive rate. The top curve of Fig. 2 shows the sampling error expected for various false-positive rates when the estimate is based upon a total of

800 stimuli, 400 of threshold intensity, and 400 of zero intensity to measure false positives. The curve shows that this is less efficient than either of the other methods, even with the large number of responses (800) employed in the present example.

Error of approximations

The main approximation is the substitution of the normal distribution of the square roots for the Poisson distribution that the numbers of quanta absorbed in successive trials must actually obey. This is not accurate when c is small, and when P is near 0 or 1. The order of error introduced is best shown by examples. Take first a case where c is about as small as is encountered in practice with good observers, and where the values of P are not too extreme. From Poisson tables (e.g. Molina, 1942), one finds that for $c = 5$, changing the average number of quanta absorbed from 2 to 9 changes P from 0·053 to 0·945. If the average numbers of quanta sent into the eye from the dimmer and brighter flashes had been 20 and 90 quanta, and if the subject had classified them as brighter in the proportions above, then the quantum efficiency should be 0·10. The calculation from equation (1) gives instead 0·103, which is a trivial error.

If one takes situations more unfavourable to the approximation, bigger errors occur. For instance, with $c = 2$, and values of P near 0·05 and 0·95, the calculated value exceeds the true value by about 12%; if P_2 is very low the error can be worse still, and the calculated figure would be double the true figure for $P_2 = 0{\cdot}001$, $c = 2$. But it is easy to avoid these extreme conditions, and elsewhere the approximation is good.

The approximations involved in calculating the sampling error of F are more serious, and the results given should be taken only as a rough guide. From the fact that the experimental reproducibility tends to be better than the sampling error would admit (see Table 1, Barlow, 1962) it is probable that the calculation overestimates the error when the number of trials is small.

DISCUSSION

Relation to other efficiency measures

Since the notion of quantum efficiency is somewhat unfamilar, it may help to compare it with the mechanical efficiency of, say, an electric motor. This would normally be defined as the ratio of the mechanical energy available in the output to the electrical energy supplied. If there were difficulties in quantifying the output—as there are in the case of the eye's output—then one could measure efficiency by the ratio of electric energy required by an ideal, fully efficient, electric motor to that required by the actual motor. This is equivalent to the ratio used in defining F above. It should, however, be noticed that although both mechanical and quantum efficiencies are defined as the ratio of energies, in the latter case it is not the loss of *energy* through inefficiency that interests us: it is the loss of *information* as to the exact value of the light intensity, or the loss of accuracy in its internal representation. It is, however, unnecessary to get involved in the definitions of 'information' or 'accuracy' used in communication theory or statistics, because common sense determines unambiguously that the 'efficiency' of absorption is simply the fraction of light absorbed, whatever the light is used for. In order that the efficiency of the later stages of the visual process shall be on the same scale we are forced to represent loss of information or accuracy in a way that might otherwise seem strange—i.e. as the reduction in 'sample size' that would cause the same inaccuracy.

Range of applicability of quantum efficiency

The use of this measure of visual performance is restricted in two ways. First, it can only be applied when the task is sufficiently precisely defined for it to be possible to calculate a theoretical lower limit; for instance, one cannot speak of the quantum efficiency of intensity discrimination without specifying the time allowed for the task, for there is no theoretical lower limit to the intensity required for the discrimination if the time is unlimited. Secondly, it is not directly relevant in cases where factors other than the discrimination of light intensities limit performance: for instance, in the case of the highest critical fusion frequency or minimum resolvable angle of the eye, quantum efficiency seems irrelevant, because factors other than intensity discrimination are most important in determining the position of these limits. If the performance is reduced below the optimum by reducing the light intensity, then intensity discrimination probably becomes important again, and the calculation of quantum efficiency may enable one to sort out the various factors involved. In complicated situations like this, expressing the results as quantum efficiencies may be enlightening. For instance, most measures of visual performance show a decrease on decreasing the light available, and one is thus prompted to look for the causes of reduced performance at *low* intensities. It will be shown in the following paper (Barlow, 1962) that the overall quantum efficiency for intensity discrimination decreases at *high* intensities: when quantum fluctuations are taken into account we see that it is the decline of efficiency at high intensities that requires an explanation.

Advantages as a psychophysical method

Discussion of psychophysical method tends to be more productive of argument than of knowledge, but in the wide range of tasks for which it is both applicable and relevant the measurement of quantum efficiency has the following advantages over other measures of performance: (1) It is an absolute measure in which the biological performance is compared with a theoretical physical limit and not with an arbitrary standard or biological norm. (2) It provides a common scale for comparing performance at different tasks: thus it may be possible to answer such time-worn questions as 'Is movement perception better than form perception in the peripheral field of vision?' (3) It provides a common scale for comparing psychophysical and physiological responses: for instance, the efficiency of a subject detecting a light stimulus under certain conditions can be compared with the efficiency with which the resting discharge of a retinal ganglion cell is changed by a similar stimulus under similar conditions. (4) The fact that sensory experiments involve a subjective element can cause uncertainty and disagreement in their interpretation. Brindley (1960), for instance, defines an attitude that is more rigorous than most, but even this requires a 'psychophysical linking principle' that is questionable. In estimating efficiencies one abstracts from the subject's responses something that has an indisputable physical meaning without assuming any additional principles. Furthermore, efficiencies can be measured for tasks other than matching and threshold determinations that the rigorous school habitually uses to test its hypotheses. It can, for instance, be applied to discriminations made on the brightness of the pair of stimuli (Barlow, 1962), and it could in principle be applied to any visual discrimination, and, with only minor modifications, to tasks involving other modalities of sensation.

In spite of these advantages it would be a mistake to advocate the measurement and calculation of quantum efficiency as a substitute for the simple determination of thresholds. Instead it should be thought of as supplementing or completing such determinations, for it combines in a single figure information from the mean value of the threshold (or other discriminant level) and from its variability as indicated by the slope of the psychometric function: being an absolute figure, it then enables comparisons to be made where they would otherwise be unjustifiable.

SUMMARY

The overall quantum efficiency of vision is defined, a new method of determining it is described, and the difficulties, limitations, and advantages of this and previous methods are discussed.

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