VISUAL DETECTION OF NOISY PATTERNS

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Abstract

Experiments are reported in which the quantum noise limitation of visual thresholds is explored further by the addition of noise to test patterns presented to the observers. The results show the characteristics predicted by a statistical theory of vision developed to account for the influence of the added noise, which was reported earlier.

In particular, these measurements make it possible to calculate independent values for quantum efficiency and for Rose's factor of certainty.

List of Symbols

A	the area of summation of the eye
a_o	the effective area of the stimulus (see Beurle et al$^{(2)}$)
α_p	the area of the pupil of the eye
β	a factor dependent on the mechanism of noise integration within a summation area
C	threshold contrast (^1/I)
I	the luminance of a display
k	the factor of certainty
N	the number of scintillations per unit area per second
n	the number of events in a sample
$\bar{n}$	the mean number of events in a sample
P	the number of quanta per photopic lumen
Q_{min}	the energy of a scintillation at the minimum
S	$- S_O \alpha_P P$
S_o	the quantum efficiency
T	the integration time of the eye
V	the distance of an observer from a display

1. Introduction

In a previous paper(1) a statistical theory of visual thresholds was reported which accounts for the influence both of quantum noise and of visual noise added to the test patterns. This theory finds particular application in the prediction of thresholds of vision through image intensifying systems which superimpose system noise on the observed scenes. In a subsequent paper(2) an additional factor was introduced to allow for alternative mechanisms of noise integration within the summation areas.

Here we report the results of continued experimental work designed to validate and to extend these theories of vision with noisy displays. In particular, an unequivocal experimental demonstration of the predicted double-threshold response is reported. An experimental measurement of the background luminance, for which the stimulus-threshold contrast has a minimum value, allows the calculation of two important parameters of vision. These factors are:-

(i) The quantum efficiency (S_o) of the eye, defined as the ratio of the number of quanta effectively absorbed at the retina to the number of quanta entering the eye. Thus, S_O is a purely physical factor representative of sensitivity.

(ii) The factor of certainty (k). A detection threshold in the theory is considered to be the result of a decision with a predetermined probability of freedom from error, k is a measure of this probability; it is a subjective factor which can be varied by changing the instructions given to observers.

In normal visual threshold determinations, these factors are not readily separable; it is the addition of the extra quantum-like noise to the test patterns that permits their separation. In our experiments, these factors were determined for a range of observers.

2. The experimental system

The added visual noise used in the experiment was quantum noise of the type obtained in the output from an image intensifier. The noise arises in intensifying systems as a result of the detection of individual photons at the input photocathode. The form of the added noise is similar to that of retinal quantum noise, except that the 'quantum' presented to the retina by the intensifier is much larger. To avoid confusion, the added noise will be referred to as 'scintillation noise[1].

The experimental realisation of such a noisy display consisted of cinematographically projected loops of film of electronically produced random dot patterns. The presence of a stimulus was signalled by an increase in the mean scintillation density over the area of the stimulus. The individual scintillations were small (~ 3 min. of arc in diameter), circular, of uniform energy, and of very high contrast relative to the background.

Psycho-physical measurements of detection thresholds were made on the display using a modified method of limits. The subjects controlled the luminance of the display. The contrast was maintained constant for an individual threshold measurement.

3. The predicted effect on thresholds of the added noise

In a paper by Beurle et al$^{(2)}$ a general expression is derived for the threshold contrast of a stimulus in a noisy display. A summary of the derivation of the theory is given below; for the detail the original paper should be consulted.

(i) The suggestion that statistical fluctuations in the arrival of photons may present a fundamental limit to the performance of the eye at low light levels was first fully developed by Rose. (3,4) The basis of Rose's theory is an ideal detector continually sampling a statistically stationary random display of equal energy events resulting in a mean count of rf events. An incremental increase An in the number of events in a sample will be required for the presence of the increment to be detected against the presence of the statistical fluctuations around the mean . The magnitude of the increment required for a predetermined certainty of detection is given by

$$\Delta n = k\sqrt{\bar{n}} \qquad [1]$$

A Poisson distribution for the detected photons is assumed in representing the magnitude of the noise present in a sample by /N. k is a constant named by Rose "the limiting signal to noise ratio of the device" but is referred to in this paper as the factor of certainty. The notions of signal detection theory are considered in depth in papers by Tanner and Swets'^) and Green.^

Rose's equation can thus be used to relate the threshold contrast $\Delta n/\bar{n}$ to the mean $\bar{n}$ viz.

$$\Delta n/\bar{n} = k\sqrt{1/\bar{n}} \qquad [2]$$

Taking into account the quantum efficiency of detection at the retina the symbol $\bar{n}$ can be expressed as a function of the background illumination, we have then the equation

$$\Delta I/I_B = k\sqrt{1/I_B} \qquad [3]$$

This equation represents the effect on detection of quantum noise in the background arising in the process of detection of light at the retina.

(ii) In the theory discussed by Beurle et al(2) a primary detection unit is postulated which samples within an area of radial symmetry the dimensions of which are a function of the mean background luminance and are stimulus invariant. Integration of the light falling within two summation areas strategically placed with respect to the retinal image of the stimulus enables the signal and background contributions to be determined. The difference between these outputs is taken as an indicator of the presence of a signal. A spatial weighting function for the summation unit has been determined that gives a reasonable fit to experimental data on the detection thresholds of a range of disc sizes and contrasts.

(iii) Rose's equation is combined with the empirical spatial weighting function and data from the literature on summation time and pupil area as a function of background luminance. These together enable threshold predictions to be made of the detection thresholds of relatively complex patterns on uniform backgrounds at low light levels. In the higher scotopic and in the mesopic range of luminances for patterns with extended borders, a linear or edge detector replaces the primary or area detector.

(iv) The theory is extended to deal with scintillation noise in visual displays by determining the additional statistical fluctuation in the light detected at the retina. The total noise in the output of a summation unit is calculated as the sum of the quantum noise generated at the retina and the scintillation noise derived from the display. The general expression for the threshold contrast of a stimulus in a noisy display is shown$^{(2)}$ to be:

$$C = \frac{k}{a_o}\left(\frac{\pi}{N}\right)^{\frac{1}{2}}\sqrt{\frac{A\beta}{SQT} + \frac{A}{10T\pi v^2}} \qquad [4]$$

The terms within the square root sign can be identified with the two sources of noise. The first term is representative of retinal quantum noise, and decreases with increasing display luminance. The second term is representative of the scintillation noise, and increases with increasing display luminance. The threshold contrast has a minimum when the terms within the root sign have a minimum. At this minimum, when the stimulus is large compared with the summation area, it is further$^{(2)}$ ' shown that:

$$\frac{S_o}{\beta} = \frac{10\pi v^2}{Q_{min}\,\alpha_p P} \qquad [5]$$

The theory thus predicts that, for a given stimulus, a graph of threshold contrast against display luminance will the "U"-shaped. In a display without added noise, within the luminance range of our experiments, the threshold contrast is known to decrease monotonically with increasing background luminance. (Kdnig and Brodhum^'?).

4. Experimental results

All of the subjects investigated to date have shown the "U"-shaped threshold contrast curves predicted by the theory. In addition to a general investigation for a range of stimuli, a large number of measurements were made using four subjects, the same stimulus and identical noise films. The mean curves calculated from these results are plotted in Fig.I. The expected error in a threshold plotted on the mean curve for any subject was less than 0*05 log. units; this figure includes the effect of within-session and day-to-day variations. Examination of the four curves reveals a range between subjects of 0.8 log. units in the value of the background luminance at the contrast minima. C.A., R.H. and A.G. show a change from peripheral to foveal vision at the high-contrast, high-luminance end of the visibility curve. With subject P.K., it was found that peripheral vision gave increased visibility within the luminance range of the system.

Substitution of the observed values for Qmin into equation [5] enabled the quantum efficiencies of the observers to be calculated. The calculated values of S , and the values of the various parameters of the display and the visual system, appropriate to the contrast threshold at the lowest background level investigated, were inserted into equation [4], and k was evaluated for each observer. The values of α_p(8) and T(9,10) were obtained from the literature. The results are tabulated below.

Subject	k	S_o	Background luminance at the minimum
C.A.	0·52	3·1%	-3·86 log. mL
P.K.	1·58	2·5%	-3·68 log. mL
R.H.	1·07	0·5(3)%	-3·12 log. mL
A.G.	1·76	0·5(4)%	-3·04 log. mL

Subject	Range of visibility at a contrast of 0·5
C.A.	∿2·9 log. units
P.K.	∿1·6 log. units
R.H.	∿2·2 log. units
A.G.	∿1·1 log. units

(These results are calculated attributing to β a value of 0.1, see Beurle et al(2)).

Observer C.A. was able to see the stimulus over the greatest luminance range; examination of the table of results shows that he has a relatively high quantum efficiency and a low factor of certainty. P.K. has a similar quantum efficiency to C.A., but his higher factor of certainty resulted in his reduced range of backgrounds for which the stimulus was visible. Observer R.H. had a low quantum efficiency relative to P.K., but his lower factor of certainty allowed him to detect the stimulus over a larger range. Subject C.A., having both a low S_o and a high k, was able to detect the stimulus over the smallest range of background luminances.

The calculated quantum efficiencies fall within the range of 0.5% - 52 calculated by Rose (3) on the assumption that k = 5. These efficiencies are less than the 62 derived by Barlow,(11) but considering the large number of parameters involved in the determination, the agreement is reasonable.

5. Conclusions

The experiments reported here were performed at low background luminances with an upper limit of about-2 log. ml.. Experiments now in progress are not subject to this limit, and thresholds can be determined by varying the contrast instead of the overall luminances of the display. Several phenomena are being investigated, including the peripheral/foveal changeover. It is thought that this work will lead to an extension of the empirical model of the visual detection process for patterns immersed in noise.

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7. References

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Fig.1. Graphs of threshold contrast against background luminance - Stimulus 110 min. of arc diameter disc.