3 Observer Variability

If the contrast of a stimulus against its surroundings is progressively reduced there will naturally come a time when it can no longer be seen. However, this 'threshold' point will vary from observation to observation. If many observations are made, and if the number of times that the threshold is above given values is plotted as a percentage of the total number of observations, a cumulative probability curve will result (see for instance Blackwell[1]). Such a curve is conventionally known as a 'frequency of seeing' curve. One may equally expect a form of frequency of seeing curve if presentation time is varied for a fixed stimulus, if size or scene luminance is progressively varied for fixed contrast and presentation time, or if a stimulus is caused to move at various rates during presentation. However, the most common form of frequency of seeing curve to be found in literature is, without a doubt, that as a function of stimulus contrast. This is reasonable since contrast is, by definition, a measure of differential energy, and hence should be related to concepts of signal to noise ratio.

In studying threshold performance, then, it is possible to study the probability of acquisition as a function of one or more basic properties of the viewed scene, or to determine the trend of the 50% probability of acquisition as a function of scene parameters. The majority of threshold studies to be discussed in this book will be concerned with the trends in 50% probability of acquisition. However, before proceeding to such studies it is necessary to survey the factors which contribute to threshold variability and their extent. For convenience these may be divided into 'within observer' variability, 'between observer' variability and influence of environment.

3.1 WITHIN OBSERVER VARIABILITY

3.1.1 The frequency of seeing curve

One of the largest sets of experimental data from which frequency of seeing curves have been extracted is that reported by Blackwell,[1] who was involved in a major detection experiment using disc stimuli in the early 1940's. This experiment employed 20 female observers over a period of between six months and 2½ years, and involved some two million observations covering stimulus diameters from 0.15 mrad to 100 mrad and scene luminance levels from moderate daylight (350 cd/m^2) down to starlight (3 x 10^{-6} cd/m^2). At each presentation the observers were forced to make a decision about the stimulus. Such experimentation is known as 'forced choice' experimentation. The results reported – based on statistical analysis of some 450 000 observations – claimed

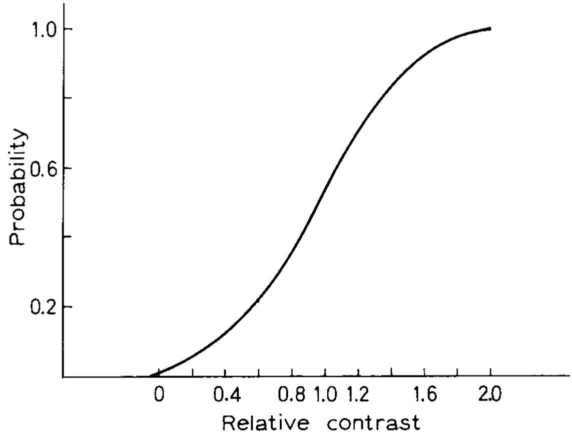

Fig. 3.1. Mean experimental within-observer frequency of seeing curve (Reproduced from Blackwell[1] by courtesy of the Journal of the Optical Society of America).

that the frequency of seeing curves, if plotted on a base of relative contrast, were virtually independent of presentation conditions over the whole gamut of sizes and luminances tested. Further it was claimed that they could be adequately described by a cumulative normal distribution function. The basic form of average observer curve was as shown in Fig. 3.1, where it will be seen that the difference in contrast required to change from 10% probability to 90% probability is of the order of 4:1. The results of many additional studies by Blackwell and coworkers have been collected together in two further papers by Blackwell.[2,3] It is shown that the form of frequency of seeing curve for detection of simple stimuli is remarkably consistent for forced choice viewing over a very wide range of conditions.

For several years we have questioned whether the 'relative contrast' base assumed by Blackwell for fitting most of his data is correct, since it seems inconceivable that there is a finite probability of detection with contrast tending to zero as implied by Fig. 3.1. It should be noted that the sets of stimuli from which Blackwell's frequency of seeing curves were obtained usually had a range of contrasts of 4:1 only – that is, they only, on average, provided data between approximately the 10% and 90% points. With such limitations on range of contrasts it would be difficult to prove that a cumulative normal distribution function with a base of relative contrast was correct with any degree of certainty. It appears from the literature that the only other form of cumulative probability function studied for adequacy of fit was a cumulative normal function with logarithmic contrast as the base. In most cases this was found to yield a worse fit than the function based on contrast ratios.

Several other workers have studied forced choice frequency of seeing and come up with similar findings to those of Blackwell in terms of both shape, spread and constancy irrespective of conditions (e.g. Crozier[4] and Taylor[5]). Blackwell[3] compares a large number of sets of data (mainly obtained by his own co-workers) and finds that the only factor which appears to alter the frequency of seeing curves significantly and predictably is the presentation time. Here he finds that, as presentation time is reduced, there is a tendency for the frequency of seeing curves to steepen, the maximum increase in slope being of the order of 30% with the shortest presentation times.

The lack of confirmation of the absolute form of frequency of seeing curves in the literature must be put down to the fact that the regions which define the detailed shape – from 0 to 10% and from 90 to 100% – are regions where the accumulation of sufficient data to establish a probability score is a huge exercise in itself. For instance, at the 5% level 20 observations are required at a given stimulus presentation condition in order to get one positive response on average. In order to have any degree of confidence about the absolute probability, several hundred observations must be made by a single observer at the one stimulus condition. Not even an experiment the size of the Tiffany one[1] can look at such detail. The alternative, that of examining the required detail at one or two points in the multidimensional threshold space, must leave many questions unanswered about the universality of any findings.

In the light of the above it must be taken as fairly conclusively verified that the frequency of seeing curves for large samples of data under forced choice conditions can be adequately described by a curve of the form shown in Fig. 3.1

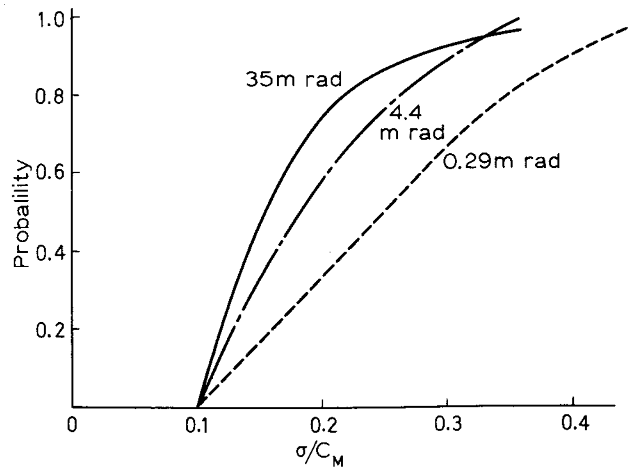

Fig. 3.2. Probability of occurance of individual session frequency of seeing curves having standard deviations less than σ/C_M for various disc stimuli – 1/3 second presentation time, mean of results for 4 observers. (Data from Taylor[5]).

for controlled laboratory experiments involving simple stimuli, although this may not be the *best* descriptor.

If now we look at the form of frequency of seeing curve for individual short experimental periods, instead of Blackwell's overall average, a rather different picture emerges. Silverthorn[6] has chosen to carry out a detailed study of original experimental data obtained by Taylor[5] in terms of the probability of occurance of given standard deviations of frequency of seeing within experimental sessions. The results are summarised in Fig. 3.2. It will be seen that the variation from experimental session to experimental session is very large. However, what is considered most striking, and will be discussed again later, is the constant *positive* deviation independent of size at zero probability – in other words, the implication that the session variability of threshold cannot be less than approximately 0.1 C_M where C_M is the session mean threshold contrast.

3.1.2 Temporal variability of probability

The alternative way to study variability of observer threshold performance is to study the probability of acquisition of a constant form of stimulus presentation within the threshold region as a function of time. Several such studies have been carried out[7–10]. From them it would appear that there are several predominant

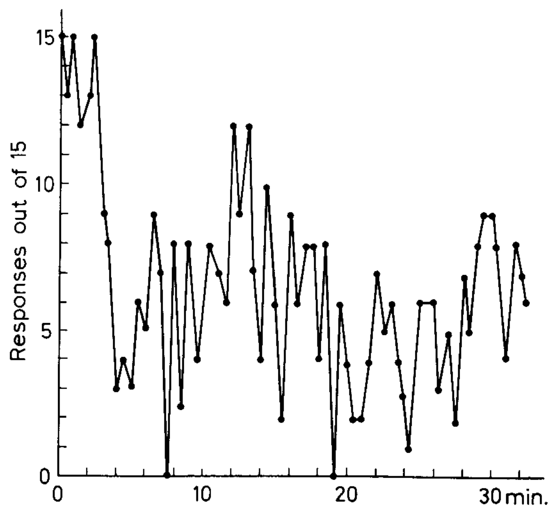

Fig. 3.3. Time course of perception probability for repeated presentations of flash stimuli every 2 s for a period of 30 min. The testing was carried out at 0.175 rad retinal eccentricity, each point representing the number of flashes perceived from a batch of 15. (Reproduced from Ronchi and Brancato[7] by courtesy of S. Karger AG. Basel).

periodic trends in threshold level varying from a few seconds to several hours. For instance, Ronchi and Brancato[7] refer to a periodicity of between 6 and 10 s and a further strong periodicity of around 2–4 min (see Fig. 3.3), whilst Ronchi and Novakova[8] found marked minima in probability at well defined times of the day – particularly mid morning and late afternoon (Fig. 3.4). It is tempting to consider that one may separate out the Blackwell frequency of seeing curve into components on the basis of these periodicities and the probability of various standard deviations discussed in Section 3.1.1. One might then possibly apportion a standard deviation of about 0.1 C_M to the short term variations of a few seconds period, whilst the diurnal variations might be expected to account

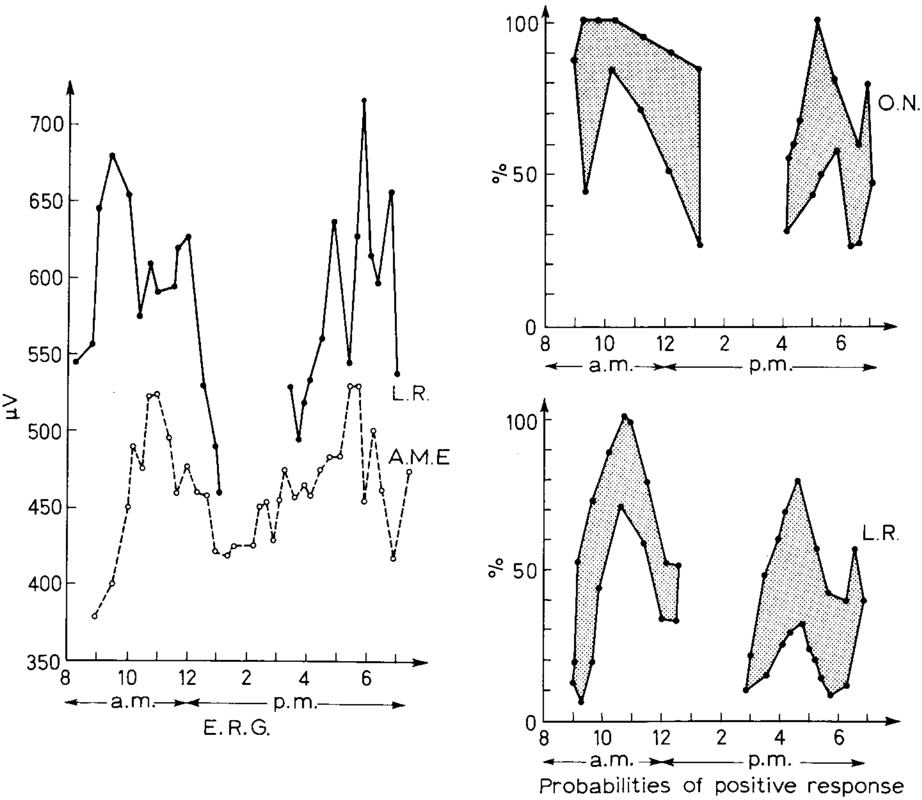

Fig. 3.4. Time course, during the day, of both ERG scotopic response (b-wave amplitude) for observers L.R. and A.M.E. and perception probability for observers L.R. and O.N.. The stimulus was a small, brief test flash at a given point on the dark adapted retina. The dashed areas show intra-session variability. Note the peak of responsiveness mid-morning and mid-afternoon for all observers and sessions. (Reproduced from Ronchi and Novakova[8] by courtesy of the Italian National Institute of Optics, Florence).

for much of the remainder. In addition some part of the total variation might be expected to be on a longer timescale again, according to threshold variations obtained in repeated experiments on visual acuity by Spicer[11] and also according to Sweeney *et al.*[5] although Blackwell[2] refutes such a suggestion.

A possible explanation of part of the short term variation of threshold may be found in considering the actual processes of vision. When an object is being viewed, the vision processes are such that the retinal image is repositioned periodically. The repositioning – known as a saccade – takes place on average about 3 times a second, although it may be as frequent as 10 times a second or as little as possibly once a second on occasion (see for instance Ford *et al*[12]). The shift of image position in a saccade is typically 1.5 mrad. After each saccade a 'fixation' follows during which time the retinal image (of a stationary object) is relatively stable (that is apart from a residual tremor of about ±0.15 mrad and a slow drift – intersaccadic drift – of the order of 6–9 mrad/s). See Lavin,[13] Ditchburn and Foley–Fisher[14] for a comprehensive description of these involuntary eye movements.

Now, as discussed in Chapter 2, the retina contains large numbers of individual receptors – rods and cones – which transmit information about local detail in the retinal image to the brain via the neural networks. As with any detector, each receptor and its associated neural networks must have associated with them some basic sensitivity to light energy. This means that the complete data received by the brain from a stimulus covering several receptors must have some variability about it, dependent on the discrete sensitivities of the set of receptors on which the image falls. Since this group will change from glimpse to glimpse, the effective stimulus, if around threshold, will sometimes appear stronger than others, according to exactly where on the retina it falls. In addition it is unlikely that the decision processes are binary in form – there is most probably some region of indeterminance for a given received stimulus, where the decision as to whether it is present will vary from time to time.

Both the above factors make it imperative that the visual process is probabilistic in nature. Thus there will be a range of contrasts for a given viewing situation where, given a large number of observations, there will be less than unity but greater than zero chance of seeing the stimulus. Thus, at least part of the variance associated with the short time frequency of seeing curve can be directly attributed to signal/noise relationships in the received visual stimulus.

3.2 BETWEEN OBSERVER VARIABILITY

If all observers could be considered identical then, for a given task, a single observer frequency of seeing curve could be expected to predict performance of a group of observers. Unfortunately it is not admissible to consider observers as identical. The 50% probability response may vary from one observer to another due to a number of factors. The primary and most obvious one is visual acuity (see Chapter 5.2), which for uncorrected vision can vary from 6/4 to 6/9 without the observer necessarily being considered to have defective eyesight. With corrected vision it is to be expected that the tolerance is somewhat closer, although tests on many observers at BAC(GW)* suggests that a range from 6/4 to 6/7.5 might still be expected. In addition to this fairly readily determined variability in observer eyesight when looking at high contrast letters there appears to be a considerable interaction between observer ability and task. For instance Spicer and Ensall[15] have found strong interactions between observer abilities when looking at high contrast and low contrast letters. Equally a very considerable lack of agreement in the rank order of performance has been shown for 8 observers at BAC(GW) on a variety of acquisition tasks.[16]

It would seem from the foregoing that one must expect very significant

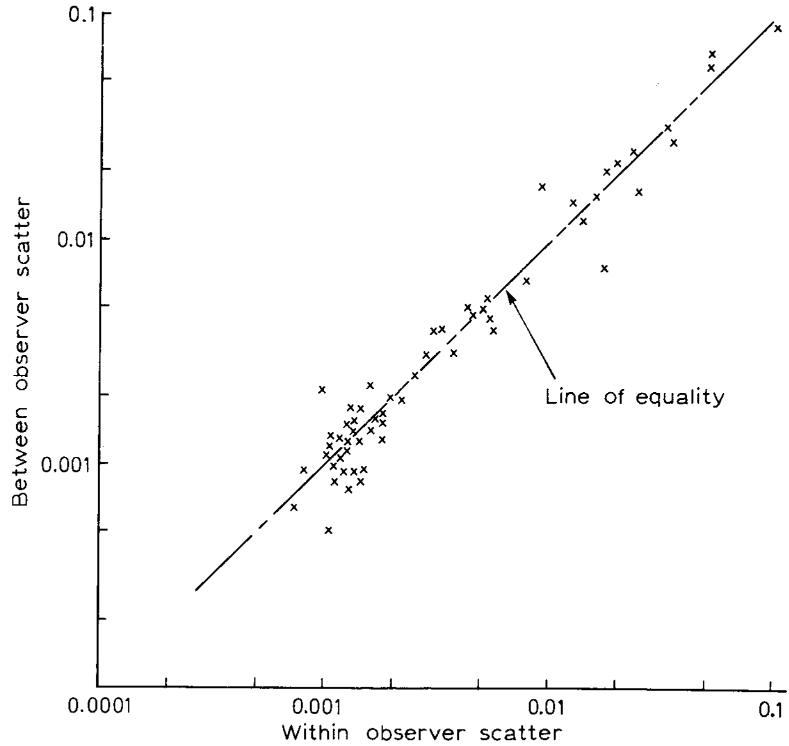

Fig. 3.5. Correlation between within-observer and between-observer standard deviations for foveal detection of various sizes and aspect ratios of rectangular stimuli at various rates of motion. Each point represents one size, aspect ratio and rate of motion (data from Hole[17]).

*British Aircraft Corporation (Guided Weapons Division).

differences in performance between observers for a variety of reasons. Unlike the within observer variability, the extent of this between observer variance is, as far as the author is aware, not well documented. However, it is implied by some authors that the spread is probably of the same order as that shown in Fig. 3.1 for populations of observers with good eyesight. Some limited experimental support for this view is to be found in a recent experiment by Hole[17]. The results of this experiment, basically studying the contrast threshold trends for moving targets as a function of motion, size and shape (see Section 4.10), were analysed to yield standard deviations of frequency of seeing both within and between subjects for each size and shape tested. The individual values of the ratios of within and between observer standard deviation are plotted in Fig. 3.5, where it can be seen that there is a very high correlation.

3.3 THE INFLUENCE OF ENVIRONMENT

In Section 3.1.1, mention was made of the Blackwell threshold being obtained by a *forced choice* presentation method. If we now think for a moment, it will be realised that, in many realistic situations, one is not forced to make a decision. We may thus rightly pose the question 'Is the frequency of seeing curve under *free choice* conditions (when the observer is free to withold a decision) the same as that under 'forced choice' conditions?'

Now it would seem reasonable to assume that, if the decision about a stimulus is 'forced', it will be made at a low confidence level. This is the Blackwell (Tiffany) situation and, indeed, is confirmed by the debriefing of Blackwell's observers, who were said to have no confidence at all in the existence of the stimulus until its contrast was at a level where they were making 90% correct

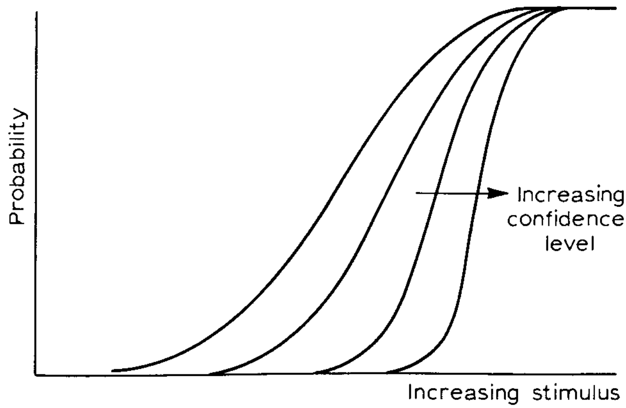

Fig. 3.6. Hypothetical changes of slope of frequency of seeing curves as a function of confidence level.

responses.[1] In the extreme 'free' choice situation, on the other hand, one might expect decisions only to be made when there was nearly 100% confidence. Under such circumstances decisions that a stimulus was present might be expected to be subject to a much closer tolerance in contrast. This might be expected to lead to a set of frequency of seeing curves of the form shown in Fig. 3.6, the value of contrast for 50% probability and the slope of the curve both increasing with increasing freedom of choice. In practice, Blackwell[2] has found larger but *more indefinite* thresholds for free choice than for forced choice situations. However, the greater indeterminacy does not appear to follow a stable and simple cumulative probability form. This same increased randomness in probability functions for free choice viewing has been found by other workers and is not currently understood to the author's knowledge.

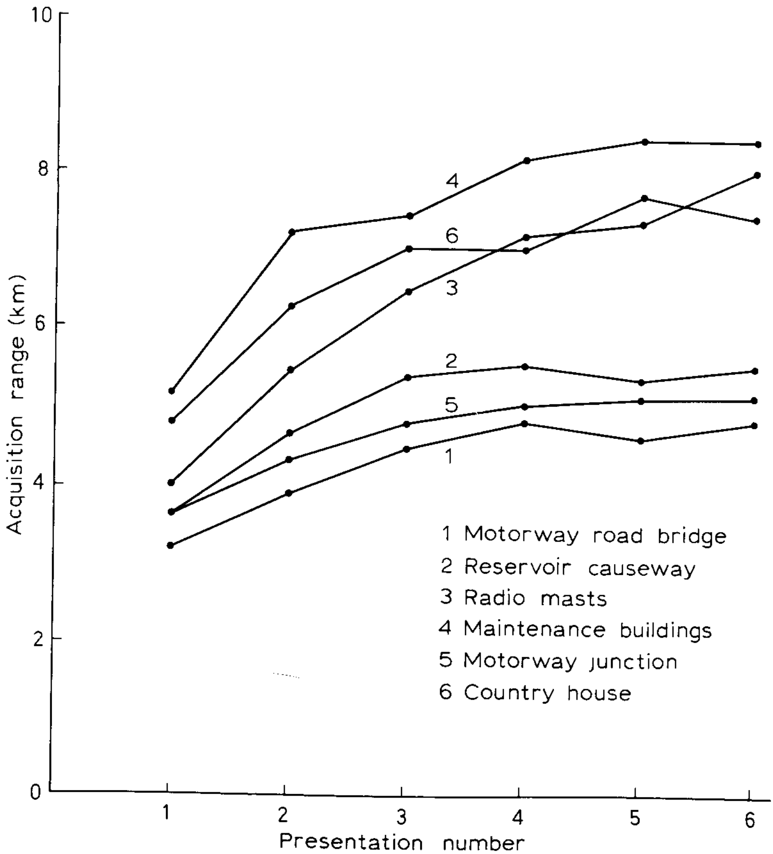

Fig. 3.7. Typical threshold trends due to learning. (after Milnes–Walker[18]).

Other factors which are known to influence the threshold level are the state of learning, motivation and briefing of the task. These three factors may be considered to be loosely related, and to be all a form of state of learning. Studies on the effects of state of learning on laboratory thresholds have been carried out be several workers including Blackwell,[2] Milnes-Walker[18] and Bloomfield.[19] In general it has been found that thresholds improve towards an optimum plateau according to a negative exponential law with increasing number of sets of observations. A typical set of data is shown in Fig. 3.7. Similar trends were found in simulated and real field trials by the present author and colleagues.[20] However, Blackwell found certain interactions between learning and motivation. Other workers, such as Gilinsky[21] and Campbell,[22] have shown an implied form of learning by preadaptation to specific patterns to produce similar enhancements, whilst preadaptation to antagonistic patterns resulted in a depression of thresholds – akin to forgetfulness.

3.4 ATTEMPTED MODELLING OF FREQUENCY OF SEEING

A number of attempts have been made to provide forms of predictive modelling of frequency of seeing curves. Such modelling must, of necessity, attempt to take some account of the reasons for uncertainties of response, and of the basic effects of such factors as the confidence level at which the decision is made. Two of the more major attempts at such modelling will be discussed.

3.4.1 The effect of quantum fluctuations

A basically simple way to consider frequency of seeing is in terms of the number of quanta which need to be absorbed by a retinal receptor in order that a stimulus shall be detected. It will be seen later (Chapters 6, 7, 12 and 13) that this is a great oversimplification of the mechanisms of vision for extended objects, but nevertheless it can serve as a very useful introduction to modelling of vision and is believed by the author to be most probably close to the truth as an explanation of the *input* of information to the neural networks from the retinal image.[32] Pirenne[23] provides a very useful discussion of the concept, this being that a sensation of seeing a flash at absolute threshold will result from the rhodopsin or other receptor photopigments having absorbed a certain critical number of quanta N_p in a given trial. But such a value of N_p must be a variable due to the quantum nature of light, the quantum fluctuations normally being assumed to be Poissonian.[25] Pirenne shows that the forms of probability curves for absorption of N_p or more than N_p quanta in one trial, when the mean quanta absorbed per trial are U_p, are as shown in Fig. 3.8. The present author believes that such a set of functions should also be applicable to differential thresholds if the value N_p is applied to local differences in quanta absorbed. Note the striking similarity between the curves of Fig. 3.8 and those

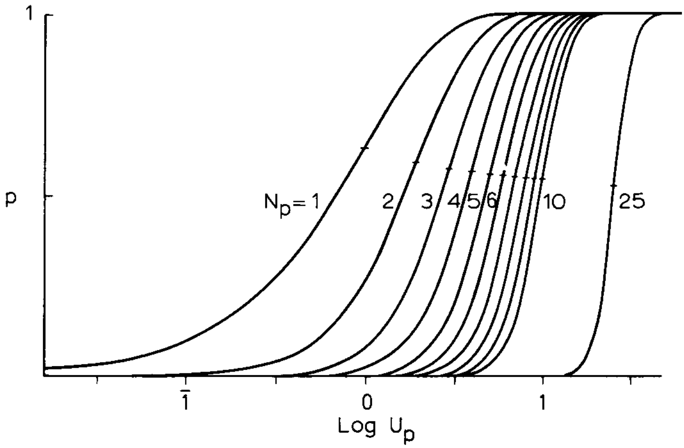

Fig. 3.8. Poissonian cumulative probability functions for various numbers of quanta absorbed when the mean number absorbed is N_p.

suggested by Fig. 3.6 as a function of confidence level. Pirenne shows, as confirmation of the *shape* of his predicted frequency of seeing curves, the results of an experiment carried out by Hecht, Schlaer and Pirenne,[25] showing that good fits to this experiment are obtained by assuming N_p lies between 5 and 7, the exact number varying with observer. It has been shown recently[26] that a Poisson distribution curve with $N_p = 6$ is almost identical in shape, above the 5% point, to a cumulative normal distribution function with $\sigma \approx 0.43\ C_M$ (the average value found to fit a wide range of experimental results by Blackwell[3]). The range of N_p from 5 to 7 as found by Pirenne is thus well matched to the range of σ found by Blackwell. The Poisson function has the merit, however, that it goes to zero for a zero stimulus, thus overcoming a basic objection to the cumulative normal function.

3.4.2 Decision theory

Whilst Pirenne's modelling possibly appears to account for the fluctuations of performance due to fluctuations of *input*, it seems unreasonable to suppose that there are *no* fluctuations and uncertainties within the visual system itself, most particularly at the decision level of the brain. An approach which appears to provide at least some ability to take account of these genuinely 'within observer' variations is decision theory as discussed, for instance, by Tanner and Swets[27] and Swets, Tanner and Birdsall.[28]

Conventionally it is assumed that the frequency of seeing curve is a 'betting' curve, there being normally a finite chance of a positive response when no

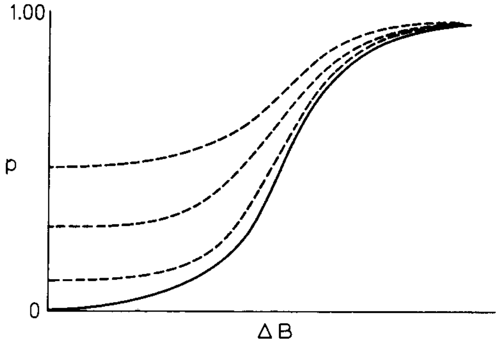

Fig. 3.9. Conventional frequency of seeing curves with various guess rates.

differential stimulus is present (false positive response). The lower the level of confidence at which a decision is made, the larger will be the expected chance of false positives, resulting in a set of curves like those shown in Fig. 3.9. Normally such frequency of seeing curves as Blackwell's are corrected for false positives by applying the formula

$$p = \frac{p' - Q_{fp}}{1 - Q_{fp}} \tag{3.1}$$

where p' is the observed probability of positive responses, p is the corrected probability of positive responses, and Q_{fp} is the false positive response when $\Delta B = 0$.

The justification for such corrections is an assumption that a false positive is a guess which is independent of level of background signal intensity and hence of sensory activity.

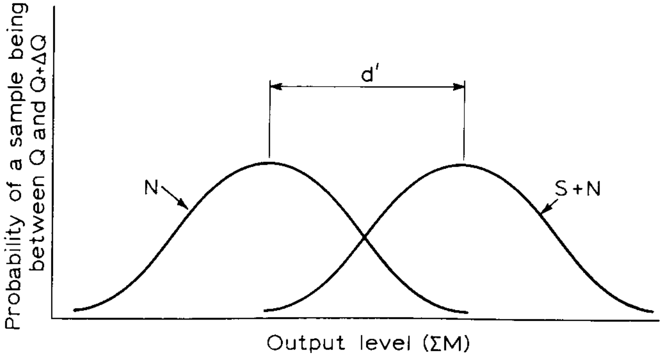

Fig. 3.10. Hypothetical distribution of noise (N) and signal plus noise (S + N). (Reprinted by permission from Tanner and Swets[27]. Copyright (1954) by the American Psychological Association).

Tanner and Swets chose, instead, to assume that false alarm rate and correct detection rate vary together, the level of neural activity being assumed to be a monotonically increasing function of light intensity. Their general concept is then that the sampled noise may have an envelope N as shown in Fig. 3.10, where N includes both internal and external noise. The sampled signal must then have an envelope $(S+N)$ which is of the same form as N, but displaced by a distance d'. The observer makes an observation ΣM, such that the greater the value of ΣM the more likely the observation is to be a signal. Based on experience and the level of ΣM, the observer must make a decision as to the presence or otherwise of a signal. It should be clear that, if a criterion point is chosen such that all observations less than the criterion level are registered as noise and all observations greater than the criterion level are registered as signal, there will be a finite probability of noise being registered as signal, this

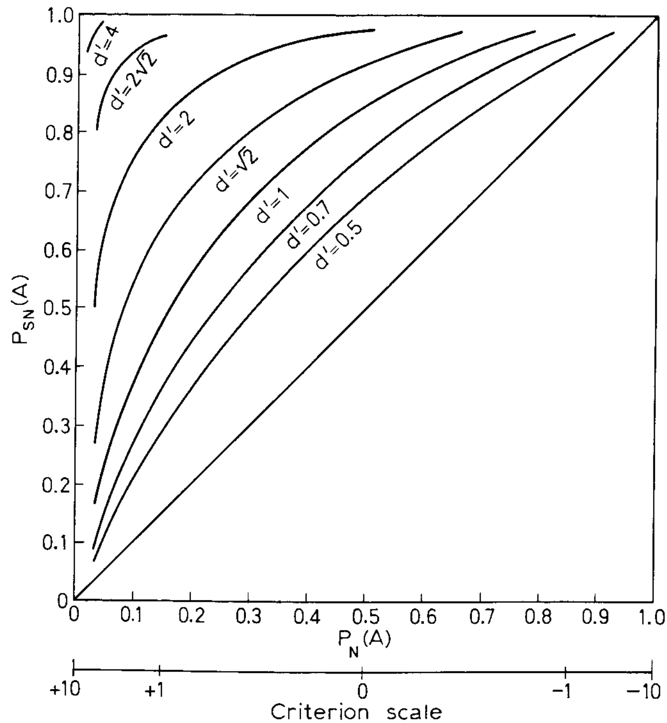

Fig. 3.11. The relationship between probability of positive response to signal plus noise ($p_{SN}(A)$) and probability of positive response to noise alone ($p_N(A)$) for various normalised values of d'. The criterion scale shows the corresponding criteria expressed in terms of R.M.S. noise σ_N from noise mean M_N. (Reprinted by permission from Tanner and Swets[27]. Copyright (1954) by the American Psychological Association).

probability depending on the position of the criterion point. Equally, if the $(S+N)$ envelope is displaced by d', there will be a finite and greater probability of $(S+N)$ being registered as a signal. Tanner and Swets developed diagrams illustrating the joint probabilities of noise being observed as signal ($p_N(A)$) and signal being observed as signal ($p_{SN}(A)$) as a function of criterion level and d'. Such a diagram, assuming the noise distribution to be gaussian (which is a close approximation to Poissonian as already discussed), and with d' being normalised to units of RMS noise, is shown at Fig. 3.11. It will be seen that, as d' tends to zero, the signal and noise probabilities tend to equality. Conversely, as d' becomes greater than 2, the signal detection probability rapidly approaches unity for low noise detection probabilities. It is claimed that such curves can be used to determine maximal behaviour in a given experiment requiring a simple yes/no decision as a point on a particular d' curve having a slope $\beta_{d'}$, given where

$$\beta_{d'} = \frac{1-p(SN)}{p(SN)} \cdot \frac{(V_{N\cdot CA} + K_{N\cdot A})}{(V_{SN\cdot A} + K_{SN\cdot CA})} \tag{3.2}$$

In the above, $p(SN)$ is the *a Priori* probability that a signal exists, $V_{N\cdot CA}$ is the value of a correct rejection, $K_{N\cdot A}$ is the cost of a false alarm, $V_{SN\cdot A}$ is the value of a correct detection and $K_{SN\cdot CA}$ is the cost of a miss.

Thus, within this theory should exist the basis for determining the forms of frequency of seeing curves *and* the shift of 50% threshold as a function of task motivation and similar psychological factors.

The frequency of seeing curves predicted by this form of modelling are very different from the conventional ones, a set of curves for different criterion levels being as shown in Fig. 3.12. Here it will be seen that, as criterion level reduces

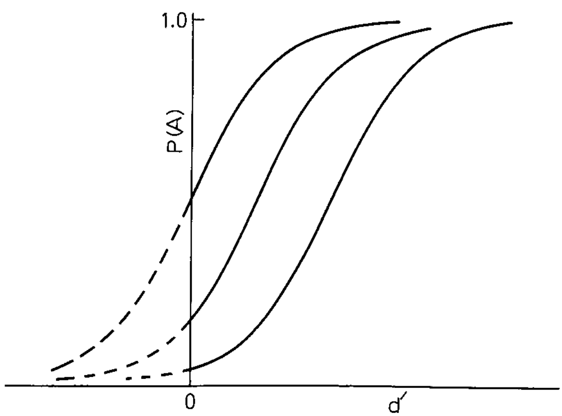

Fig. 3.12. Probabilities of positive response p(A) as a function of d′ for various criterion levels. (Reprinted by permission from Tanner and Swets[27]. Copyright (1954) by the American Psychological Association).

(i.e. a lower confidence, higher chance situation) the probability curve shifts bodily to the left, the dotted portions indicating the incomplete nature of the curve. If frequency of seeing behaviour is really as predicted here then correction of chance false positives according to Equation 3.1 is very definitely wrong!

The reader wishing to pursue this aspect of the subject in more depth should read Tanner and Swets,[27] Swets *et al*,[28] Wald[29] and Peterson *et al.*[30]

3.5 DISCUSSION

It will be seen from the foregoing that the form of frequency of seeing curve for a given data set will be very dependent on a host of factors. In the remainder of this book the majority of acquisition data will be discussed in terms of a 50% probability of seeing. Because of the very considerable dependence of frequency of seeing on so many factors it is inevitable that any set of absolute thresholds will only be relevant to the particular circumstances under which they were obtained and the particular time. Changes of observers, experience, briefing, time of day, season, will all be expected to have a significant influence on experimental results. Thus one should never place too much importance on differences between two sets of threshold data gathered at different times or in different ways, but only on the trends within a balanced set of data. It is essential that the reader remembers this as he proceeds to study the rest of the book.

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