ERRATA

Technical Report No. 18

Page vi, ABSTRACT, last sentence, should read: ...for the conventional assumption of <u>independence</u> between false-alarm rate and detection probability.

Page 10, Fig. 5, left hand curve should be labeled "<u>N</u>"; right hand curve should be labeled "<u>S + N</u>".

Page 29, Appendix C: Change Explanation of Symbols in Tables 2, 3, and 4 to read $K_{SN \cdot CA}$ = cost of a <u>miss</u>, and $K_{N \cdot A}$ = cost of a <u>false-alarm</u>.

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A NEW THEORY OF VISUAL DETECTION

Technical Report No. 18
Electronic Defense Group
Department of Electrical Engineering

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Project M970

TASK ORDER NO. EDG-3
CONTRACT NO.DA-36-039 sc-15358
SIGNAL CORPS, DEPARTMENT OF THE ARMY
DEPARTMENT OF ARMY PROJECT NO. 3-99-04-042
SIGNAL CORPS PROJECT NO. 29-194B-0

September, 1953

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ACKNOWLEDGEMENT

The thinking underlying the theory presented in this report has its origins in a series of seminars conducted by Dr. H. R. Blackwell and in the "Theory of Signal Detectability" by Mr. W. W. Peterson and Mr. T. G. Birdsall. The assistance of Dr. Blackwell, Mr. Peterson, and Mr. Birdsall throughout the development of the theory is greatly appreciated. Dr. Blackwell also contributed the use of his laboratory for the experiments reported here, and together with Dr. W. M. Kincaid of his staff, provided valuable assistance in designing the experiments.

To many of the other members of the Electronics Defense Group we are greatly indebted. Dr. A. B. Macnee, Dr. H. W. Welch, and Mr. Harold Harger have assisted in reading the report, and have made many useful suggestions.

The authors also wish to acknowledge their indebtedness to Patricia Belmore and Richard Ranney for their assistance in the preparation of the text.

ABSTRACT

A theory of visual detection is presented, considering the visual system as a communication channel with internal noise. The critical assumptions of this theory are compared to the assumptions of conventional theory. Predictions are made concerning the form of psychophysical data from yes-no and forced-choice experiments. Experiments are reported showing the consistency of these predictions, and furnishing the basis for the rejection of the conventional assumption of dependence between false-alarm rate and detection probability.

A NEW THEORY OF VISUAL DETECTION

1. INTRODUCTION

The human observer does not observe the environment directly. He observes a representation of the environment presented as the output of a communication channel; i.e., one or more of his sensory systems. Enough of the properties of these channels are known to make possible, with the aid of some simple assumptions, the construction of a mathematical model describing the information which can be transmitted by such a channel. If the general form and content of the information handled by this channel is analyzed, then one is able to deduce the kind of decisions which can be based on information of this nature. The ability of observers to make decisions of the type specified by the theory dealt with in this report can then be tested empirically.

In this study a single communication channel, the visual system, is under consideration, and the discussion is restricted to a simple information problem, that of the detection of the presence or absence of a signal. This is a problem to which psychologists have directed a great deal of attention.

Conventionally, visual detection has been treated as a function of physical variables. Standard data analysis and current theory appear to be based on the assumption that any physiological activity of the visual system is a linear function of light intensity (Ref. 1). An empirical function is sought for the relationship between probability of detection and light intensity. This function is then assumed to be the same as the function expressing the relationship between probability of detection and nervous system activity.

A second assumption underlying standard psychophysical thinking is that the experience of seeing occurs when some predetermined quantity of neural activity occurs. The observer will not often risk a response of accepting a signal when it is not present. This is, perhaps, due largely to his acquaintance with the social stigma against hallucinations. He is, in effect, a Neyman-Pearso observer who must accept an established false-alarm allowance. This orientation of the observer cannot be changed to meet specific conditions. If a quantity of neural activity which can occur on a chance basis alone (with a small, fixed probability) occurs, then seeing is presumed to result. If this quantity of neural activity does not occur, then there is no experience. This criterion quantity is regarded as invariant for an individual observer, or at least subject only to a slight temporal variability (Ref. 1).

Based on these conventional assumptions, three types of "yes" response can occur in a yes-no psychophysical experiment. The first of these is the "yes" response based on neural activity which is related to the physical existenc of a signal.[1] The second is based on random neural activity of the visual systen which exceeds the criterion quantity on a chance basis alone (no signal exists), this occuring with a probability which is so low that it is negligible. The third is an out-and-out guess (induced by habituation, expectations, or response habits) assumed to be independent of any neural activity in the visual system. (Psychophysical experiments are carried out under carefully controlled conditions

[1] The word signal will be used here to represent a physical event, as the word stimulus has too many psychological and physiological connotations.

so that a fourth logical possibility, "yes" responses resulting from noise on the screen, can be ignored). If a measurable value of "yes" responses occurs when no physical signal exists, then this value is assumed to represent almost entirely responses of the third type, and is an indication of the total number of guesses occurring throughout the experiment. If a signal of given intensity yields a percentage of "yes" responses, this percentage is made up of a percentage of responses when the observer actually saw the signal plus a percentage of guesses. As statistical independence is assumed to exist between the two types of response, the percentage of "yes" responses when no signal exists can be used as a correction factor. The correction is made by applying the formula

$$p = \frac{p' - c}{1 - c} \qquad (1)$$

where p = corrected percentage

p' = observed percentage

c = percentage of yes response when no signal existed (false alarms)

The argument is shown graphically in Figure 1. The probability of a positive response is plotted as a function of signal intensity. The solid curve represents the "true" seeing curve which results when the observer does not guess. The probability of seeing when no signal is presented is a very small value. The dotted lines represented the influence of guesses on this curve.

The percentage of guessing is given by the equation

$$c = \frac{P_o - P_t}{1 - P_t} \qquad (2)$$

where c = percentage of guesses

P_o = intercept of dotted curve at intensity = 0

P_t = intercept of solid curve at intensity = 0

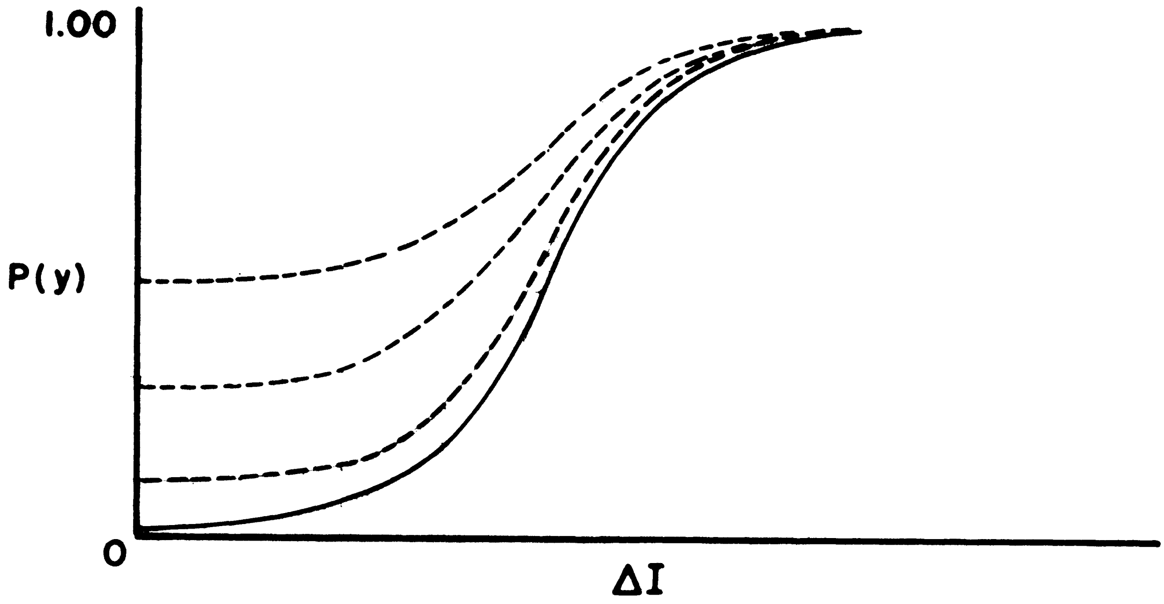


FIG I
CONVENTIONAL "SEEING FREQUENCY CURVE"

The solid line is the "true" curve. The dotted lines represent the influence of guessing. Supposedly the application of Equation (1) to a dotted curve yields the solid curve.

P_t is usually assumed to be negligible, and thus P_o is used as the estimate of c. The procedure actually is one of normalizing the obtained data. If the guessing hypothesis and the invariant-criterion hypothesis hold, all observed curves should correct to the same curve.

Another way of showing this graphically is to hold intensity of the signal constant, letting percentage of guesses vary. Now each curve represents the relationship between the number of incorrect guesses and the number of detections plus correct guesses for a given value of signal intensity (Figure 2). The "true" seeing curve of Figure 1 can be constructed by plotting the values of the intercept on the vertical axis against the intensity value for each curve. The dotted curves are obtained by plotting the intercepts of any other vertical projection against the intensity values of the curves. Thus, the intercepts of

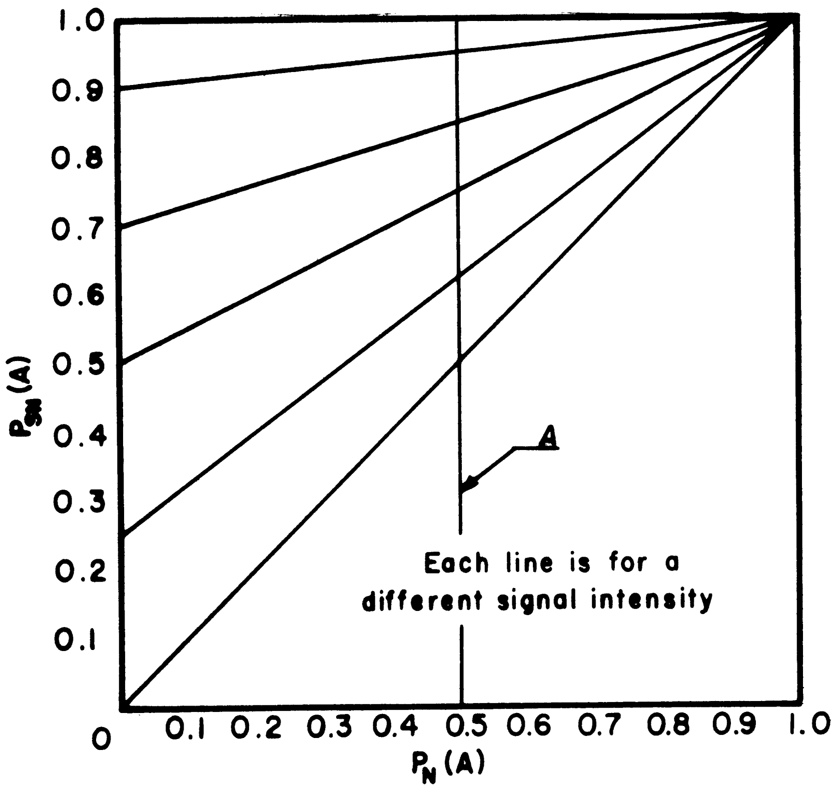


FIG 2

$P_{SN}(A)$ as a function of $P_N(A)$ based on the guessing hypothesis. $P_N(A)$ = percentage of guesses.

$$P_{SN}(A) = P_{SN_0}(A) + P_N(A)\left[1 - P_{SN_0}(A)\right]$$

the line A and the lines of Figure 2 when plotted against intensity yield the dotted curve for 50 per cent guesses of Figure 1.

In the forced-choice experiments two types of correct responses are assumed to occur: (1) the neural criterion is satisfied or (2) the observer guesses. The same correction is applied, with $c = \frac{1}{n}$, where n is the number of choices. The fact that both "forced-choice" and "yes-no" experiments yield empirical fits to the cumulative normal probability function (when the corrected probability of detection is compared to signal intensity) is used as an argument in support of the classical assumptions stated above.

The theory presented in this report differs from classical theory in two respects:

1. Statistical dependence is assumed between false-alarm rate and neural activity. The criterion quantity of neural activity is variable over time within an individual, tending to maximize in a specific situation.

2. No assumption is made concerning the nature of the relationship between neural activity and signal intensity. This relationship can be experimentally determined.

The theory constructs a model of the visual system as a communication channel based on accepted physiological knowledge. The output of this channel is analyzed for the information contained, and the types of decisions which can be based on this information in both forced-choice and yes-no experiments are specified mathematically. Experiments are reported testing the validity of the classical assumptions and of the assumptions upon which this theory is based.

2. PHYSIOLOGICAL BASES

The visual system consists of an optical system, receptor cells and three stages of neurons before the information is delivered to the visual cortex. While it is impossible to say at which neural level a decision is actually made, all available evidence suggests that, in the human being at least, a decision is impossible at any level prior to the visual cortex. A block diagram of the system is shown in Figure 3.

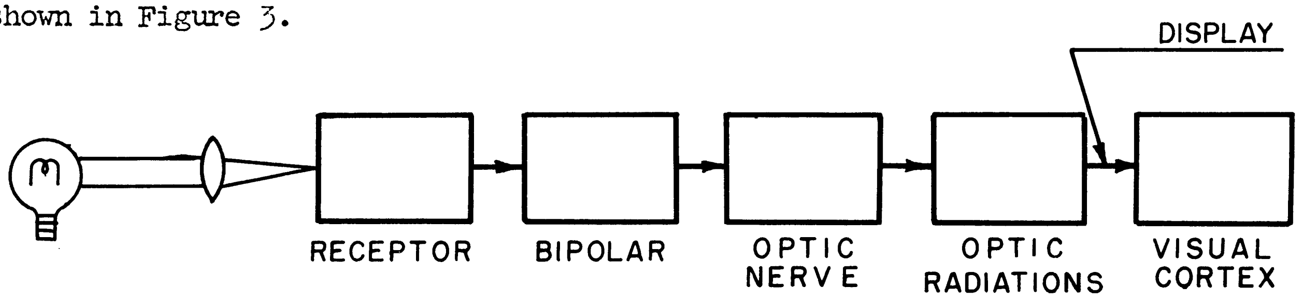


FIG 3
BLOCK DIAGRAM OF THE VISUAL CHANNEL

The light in the environment is focussed by the optical system (lens of the eye) on the photo sensitive layer of the retina. This layer acts as either an antenna or a photocell and, in conjunction with the bipolar cells, transforms light energy into neural energy. This neural energy is in the form of impulses, and is of the same form in the bipolars, optic nerve, and optic radiations. The optic radiations present to the visual cortex impulses which represent light energies. Little is known about the functions of the intermediate stages other than to transmit information. Amplification and detection are two obvious guesses.

The elements which transmit the information are the neurons. A neuron reacts in a way which is roughly analagous to a relaxation oscillator, the bias of which is determined by a photocell (Figure 4).

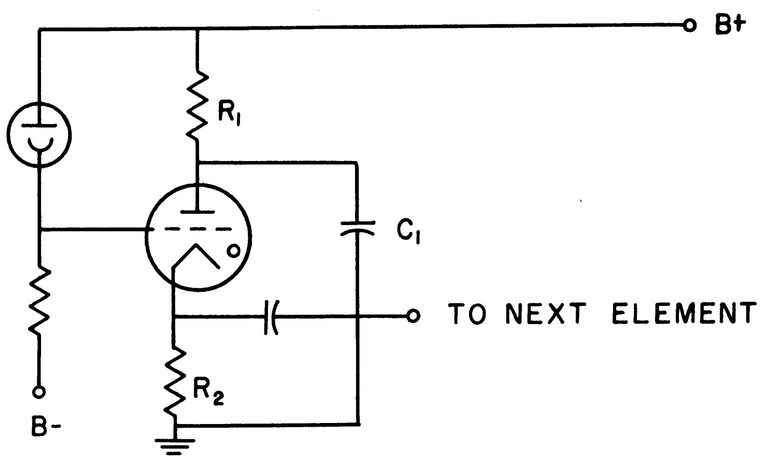


FIG 4

AN ELECTRONIC CIRCUIT WHICH BEHAVES AS A RECEPTOR AND NERVE CELL

T_2 is a gas triode biased so that it will oscillate when T_1, the photo sensitive tube, is dark. R_2 is small compared to R_1 so that the impulse delivered to the next neuron is of the spike form known to be the case with neurons. If a light is focused on T_1, the bias on T_2 becomes more positive and the frequency of impulses delivered to the next neuron increases. Thus, the frequency of impulses is a function of light intensity.

The receptor cells are small, of the order of .5-3 microns. Whenever there is a visual signal of any size, a number of these receptor cells are involved. Thus, for any light signal, groups of these neural elements deliver impulses to the next stage, at frequencies which are determined by the amount of light energy focused on the receptor cells. Two assumptions are necessary for the purpose of the analysis here:

1. The frequency of impulses from any neuron for a given light intensity is not completely regular. If an impulse occurs at time $t = 0$, there exists a probability distribution over time for the occurance of the next impulse such that at t_i the probability that the next impulse will have occured is .5. The level of light energy determines the value of t_i.

2. If the receptor cells for a group of neurons all receive the same light energy, the t_i's for the group are randomly distributed.

The assumption that there is internal noise in the system, and that this noise has random properties is based on assumptions 1 and 2 (above), together with the knowledge that oscillations occur even in darkness. The dependence of t_i on the light intensity indicates that the visual detection problem is the problem of detecting signals in noise. For mathematical convenience it is further assumed that the problem is one of detecting Gaussian signals in Gaussian noise (the Gaussian properties of the distribution can be derived from assumptions 1 and 2 as long as large numbers of neurons are involved). The Gaussian assumption pertains to the output of the optic radiations or some further set of neurons within the visual cortex which yeild the neural display upon which the decision is actually based.

3. A NEW THEORY OF VISUAL DETECTION

The assumptions of Part 2 reduce the problem of visual detection to that of the detection of Gaussian signals in Gaussian noise; this is the problem of accepting or rejecting statistical hypotheses. Two particular type of decisions are considered here. These involve the decisions demanded of the observer in visual threshold experiments employing the forced-choice and the yes-no techniques of data collection. The specific situation considered is that of the occurrence of a light signal in a uniformly illuminated background. The exact location of the signal is known to the observers, and the signal is known to occur, if it does, in a wall defined interval in time. Each judgment is presumably based on some measure of neural activity during the specified time interval, perhaps an integration of the number of impulses arriving at the cortex. As the impulses arrive at rates exhibiting randomness, there exists a sampling distribution of the measures resulting when no signal is presented, and there also exist sampling distributions of measures for each signal intensity level. Figure 5 shows hypothetical sampling distributions of noise (when no signal has been presented), and signal plus noise (when a signal has been presented). The means of these distributions are proportional to the t_i of Part 2. d' is the distance between the means of the distributions expressed in terms of the standard deviation of N (σ_n) the noise distribution. $\Sigma(m)$ is the summed value of the nerve impulses for samples of duration of the expected signal, and p is probability density.

In the forced-choice experiment the observer is told that there will be a signal occurring in one of four intervals (either in time or space). In the

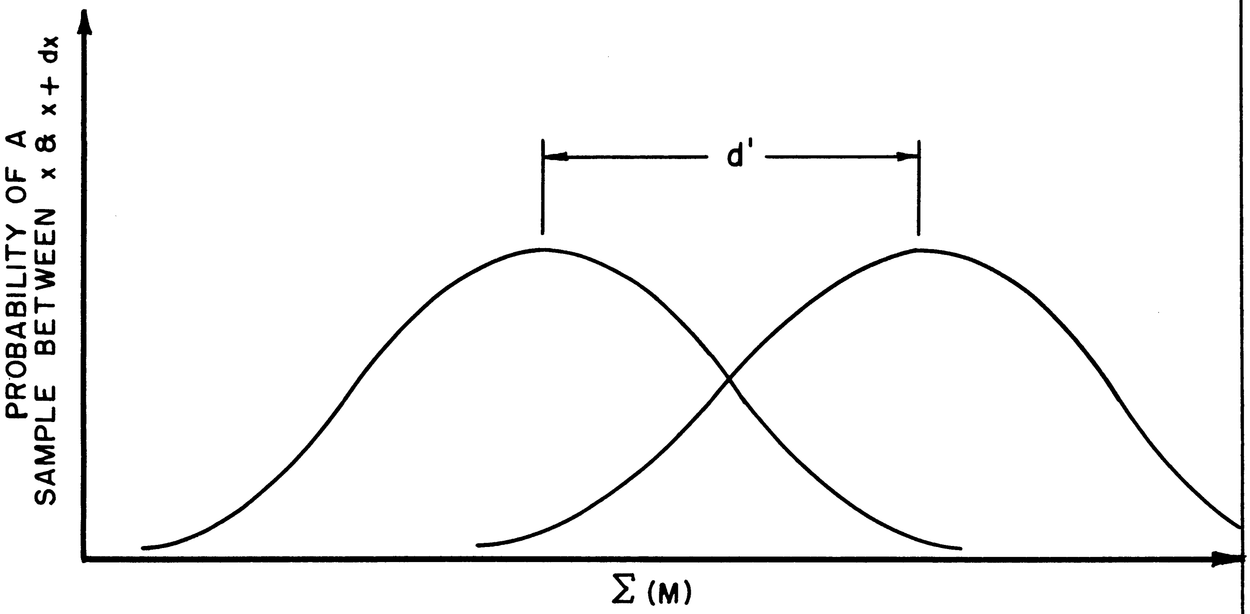


FIG 5

$\Sigma(M)$ is a measure of neural activity taken during the time interval upon which the decision is based. N = distribution of samples when no signal exists. S + N = distribution of samples when signal exists. d' is the distance between the means of N and S + N in terms of σ_n.

temporal case the location of the signal in the background is known, and in the spatial case the time is known. In three of the intervals samples of N are examined, in the fourth interval a sample of S + N is examined. The probability that the observer will choose the interval in which the signal actually occured is the probability that the sample from S + N is more representative of S + N than any of the three samples from N. This can be stated as the probability that a drawing from S + N is greater than the greatest of three drawings from N. By assuming equal variance for S and S + N it is possible to determine this probability for a given value of d' (expressed in terms of σ_n). P(c), the probability of correctly determining the interval in which the signal occurs, is shown as a function of d' in Figure 6. It should be noted that the predicted value of P(c) does not vary with d' in the same way the P(c) varies with light intensity increments reported by sensory psychologists.

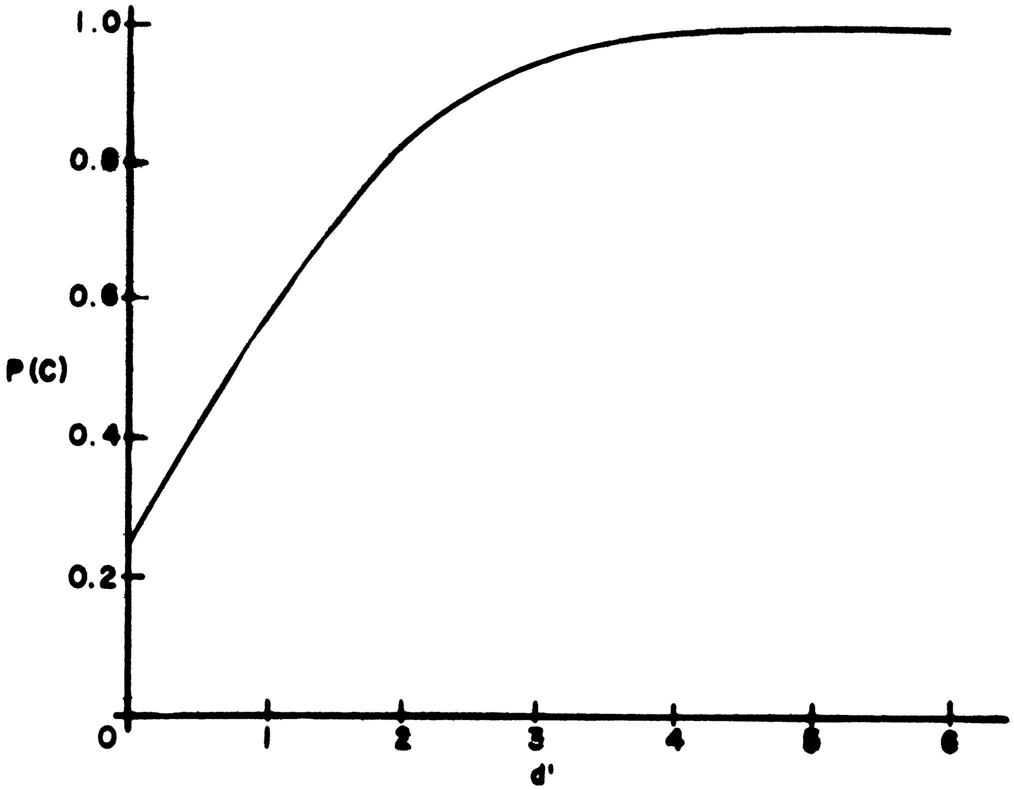


FIG 6

P(C) AS A FUNCTION OF d' — A THEORETICAL CURVE

Probability of a correct response,

$$P(C) = \int_{-\infty}^{+\infty} F(x)^3 g(x)\,dx \qquad \text{where}$$

F(x) is the area under N of Fig 5, and g(x) is the ordinate of S + N

In the yes-no experiments it is necessary to consider the detection problem in terms of a criterion of acceptance. That a fixed, well-defined criterion can serve as a basis for psychological judgment is not claimed to be the case. It is more likely that a probability distribution exists such that a sensory effect of a given degree will be accepted as representing a signal with a probability P(A). This distribution can reflect the lack of absolute stability as well as lack of definition of a criterion. A shift in criterion is then a shift in this probability distribution. The uncertainty introduced by a lack of definition and a lack of stability of a criterion is the same as the uncertainty resulting from noise when the criterion is fixed. Thus, while the theory and analysis of data presented in this report treats the criterion as fixed and stable for periods of time, this is merely a matter of mathematical convenience. As a direct measurement of the noise in the human neural system is not possible, the instability and lack of definition of the "seeing" criterion in these experiments is included in the inferred measurement of the noise, and data can now be treated as if there is a well defined criterion.

Peterson and Birdsall (Ref. 3) in their theory of signal detectibility have furnished a mathematical treatment of the yes-no experiment. It should be pointed out, however, that their treatment starts with the knowledge of the characteristics of the noise and of the signal, and observer results are calculated. In the case of the psychophysical experiment in which the noise and signal parameters of interest are assumed to be physiological, it is necessary to start with results from which these parameters can be inferred. As a check on the inference, two sets of predictions have been developed. The inference is made from one, and then checked by trying to predict the second on the basis of the inference.

Figure 5 shows hypothetical distributions of signal plus noise and noise alone. A well defined criterion is a point on the abscissa such that any sample to the right of that point is accepted as indicating the existence of a signal. For a given criterion there are two probabilities which will be considered:

$$P_N(A) = \int_{x=c}^{\infty} f(x)\, dx \qquad (3)$$

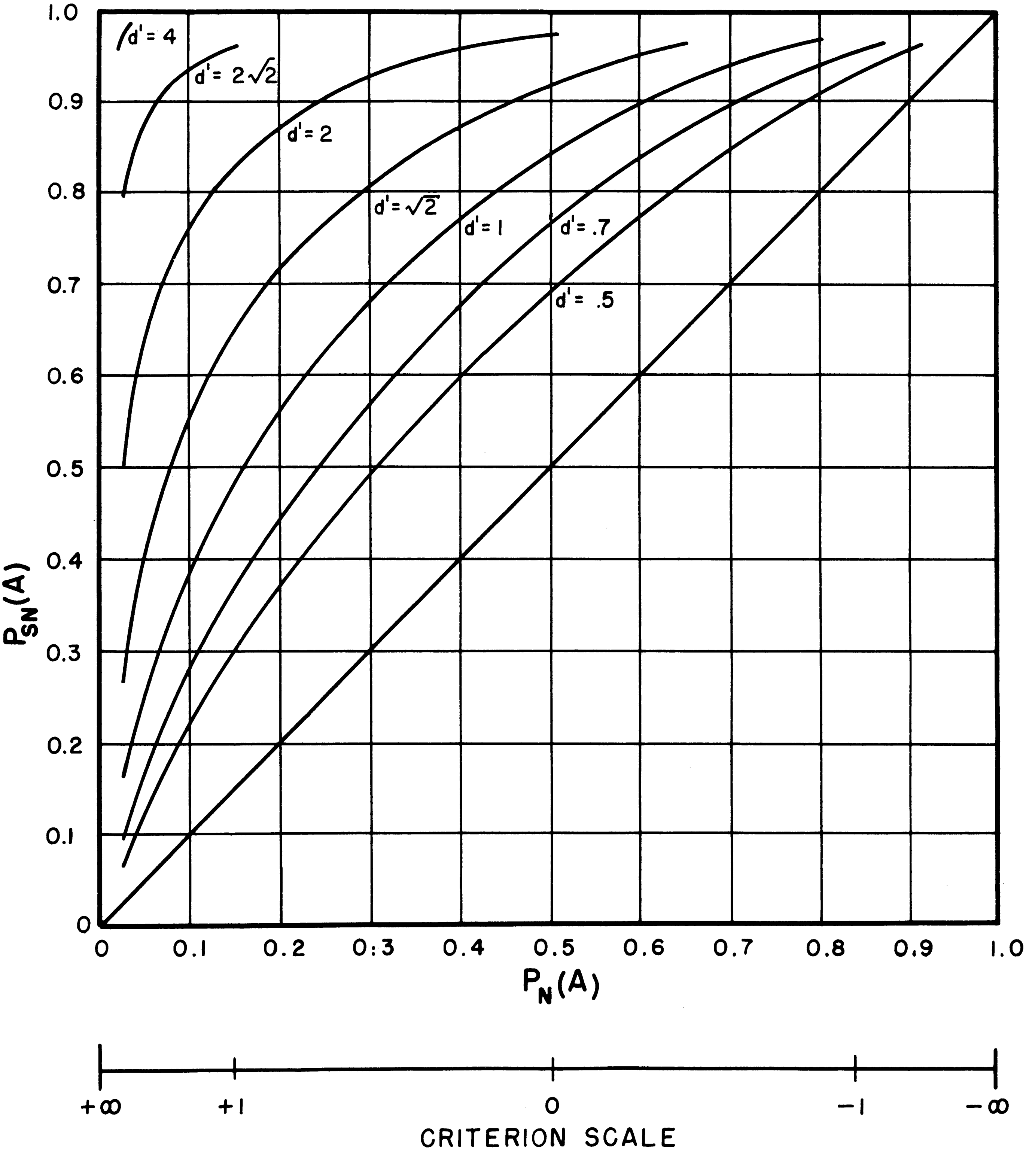
$$P_{SN}(A) = \int_{x=c}^{\infty} g(x)\, dx \qquad (4)$$

where $P_N(A)$ is the probability of accepting a sample from the noise alone as indicating the existence of a signal, c is the criterion value of x, and f(x) is the N function. $P_{SN}(A)$ is the probability of accepting a sample from S + N as a signal, and g(x) is the S + N function. For a signal distribution of a given d', $P_N(A)$ and $P_{SN}(A)$ are functions of c. Figure 7 shows a family of curves, each for a value of d' showing the correlated values of $P_N(A)$ and $P_{SN}(A)$ as c varies.

Another way of showing this relationship is to plot the probability of a "yes" response as a function of d'. For a single curve a criterion value must be assumed. Thus, each curve in Figure 8 represents the probability of acceptance as a function of d' for a given criterion. The dotted portions of the curves represent mathematical calculations for distributions with negative (d')'s, and are included to show the fallacy of any attempt to normalize the solid parts of the curve only. If these curves are all of the same form and are monotone increasing, then a linear transformation moving the curves horizontally is necessary to make all of the curves superimpose on a single curve. This is a difference between this theory and the conventional theory in which the correction moved the points on the curve vertically (Fig. 1).

4. EXPERIMENTAL CONSIDERATIONS

Peterson and Birdsall (Ref. 2) have shown that, for a given signal or set of signals, an optimum criterion of acceptance can be determined if the "a priori" probability of the existence of the signal, and the weightings of the two correct judgments and the two incorrect judgments are known. A single number β, a function of these variables, is used in this determination. It should follow then, that if an observer attempts to maximize, the experiment in which these variables are changed will serve to test the validity of the central hypothesis of this study; i.e., that the mechanism of "seeing" is the mechanism



SIGNAL DETECTOR CURVES

$P_N(A)$ VS $P_{SN}(A)$. THE CRITERION SCALE SHOWS THE CORRESPONDING CRITERIA EXPRESSED IN TERMS OF σ_N FROM M_N

FIG 7

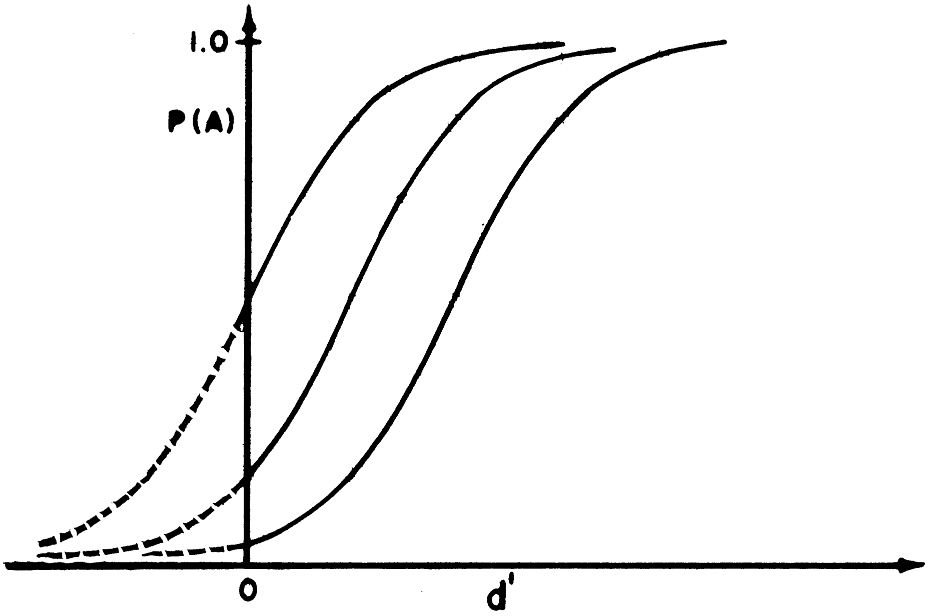


FIG 8
P(A) AS A FUNCTION OF d'

Each curve is for a given criterion. Note that if negative values of d' are considered the curve is normalized. The chance correction normalizes the portion of the curve $d' \geq 0$

of testing statistical hypotheses. The relationship between $P_N(A)$ and $P_{SN}(A)$ as indicated by observed percentages of correct acceptances and false alarms will show whether the false alarms represent errors as a result of sensory noise, or merely guesses. If a series of yes-no experiments are performed in such a way that the values of $P_N(A)$ vary from experiment to experiment, the values of $P_{SN}(A)$ for a particular signal should vary with $P_N(A)$ according to the relationship indicated by the particular d' curve for that signal in Figure 7.

As this is a procedure which demands the comparison of data collected on different experimental days, the danger of day-to-day variability must be considered. The "yes-no" technique has long been recognized as a test lacking reliability. However, conventional psychophysical theories tend to consider "seeing" as an all-or-none event (as indicated by the use of chance-correction) with a built-in, unchangeable criterion. Usually, training procedures tend to discourage false alarms, a procedure which is justified only if the assumption of the fixed criterion is valid. If the criterion is not fixed, the percentage of "yes" responses when no signal is presented can be used as an estimate of $P_N(A)$. The value of $P_N(A)$ permits the location of the criterion. Discouragement of false alarms results in a criterion which yields a value of $P_N(A)$ that is difficult to measure experimentally and, consequently, permits large criterion changes which are not detectable through changes in $P_N(A)$. The apparent lack of reliability of yes-no data might be a reflection of criterion changes that are not detected by the experimenter.

A second argument suggesting the feasibility of making day to day comparisons is that the theory depends only on signal-to-noise ratios rather than on absolute values. It seems reasonable, since both distributions depend on light intensity in the environment, that changes in one will be accompanied by changes in the other, and the signal-to-noise ratios will tend to exhibit reliability.

The theory presented here embodies two sets of predictions based on the same neural and statistical assumptions. If the same observers are used in both forced-choice and yes-no experiments, the data will furnish a basis for testing the theory. There are three ways in which the data can be handled, all equivalent. The theory can be assumed for the forced-choice experiment. Observed percentages of correct choices can be used as estimates of P(c). P(c) can then be used for determining the value of d' for each signal intensity. This is done merely by reading the value of d' corresponding to P(c) on the curve of Figure 6. For each signal intensity, d' has a specific value. Using these values, yes-no data can be predicted for any criterion as indicated by

$P_N(A)$, and these predictions can then be compared to the yes-no results.

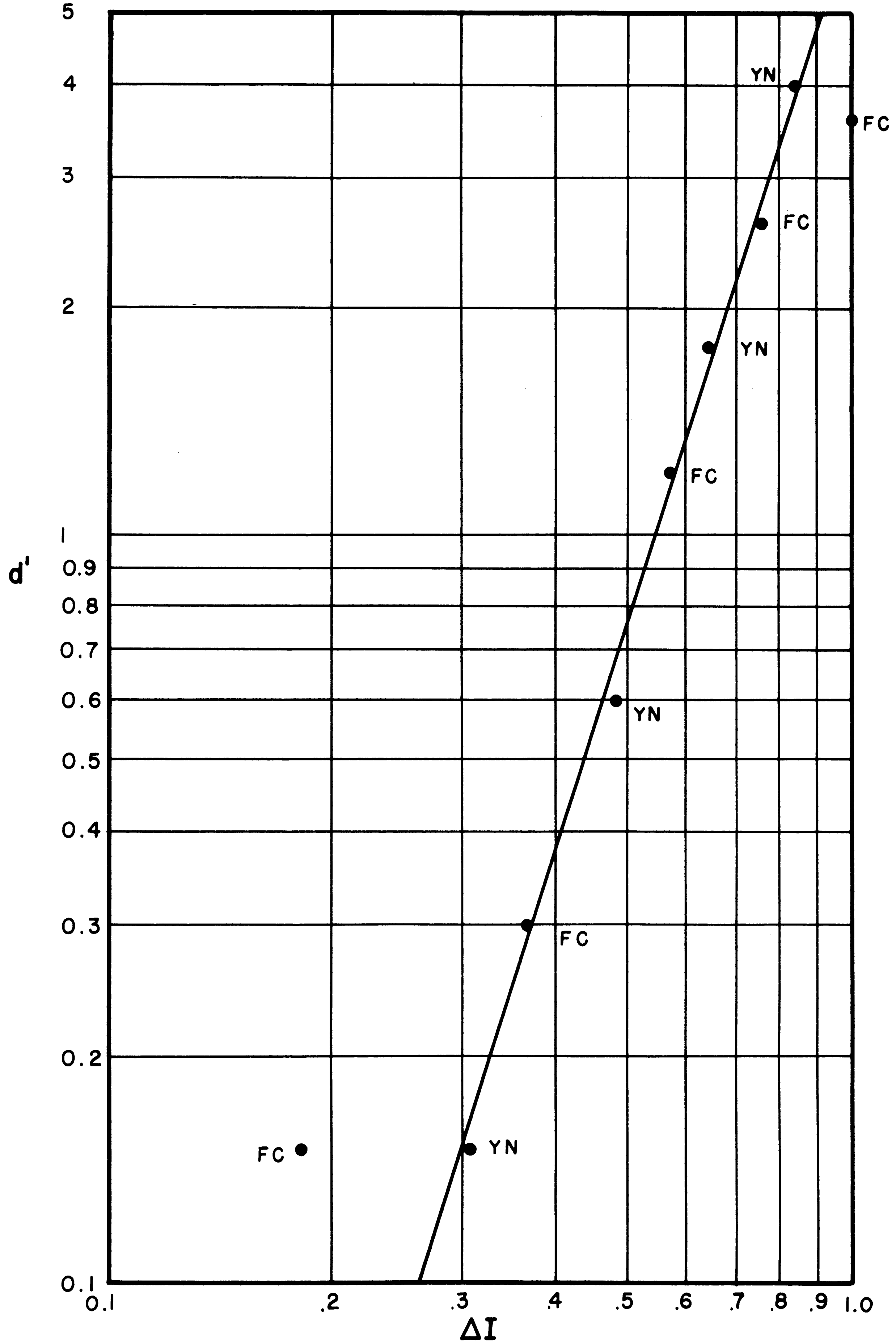
A second method is to assume the theory for the yes-no experiments and estimate the values of d' from these experiments. Now the observed percentages of correct forced-choices can be compared with the P(c) for the d' value specified by the curve of Figure 6.

The third method is to estimate d' from both sets of experiments and compare the estimates. In the experiments reported in this report all three methods were employed.

5. EXPERIMENTAL PROCEDURE AND RESULTS

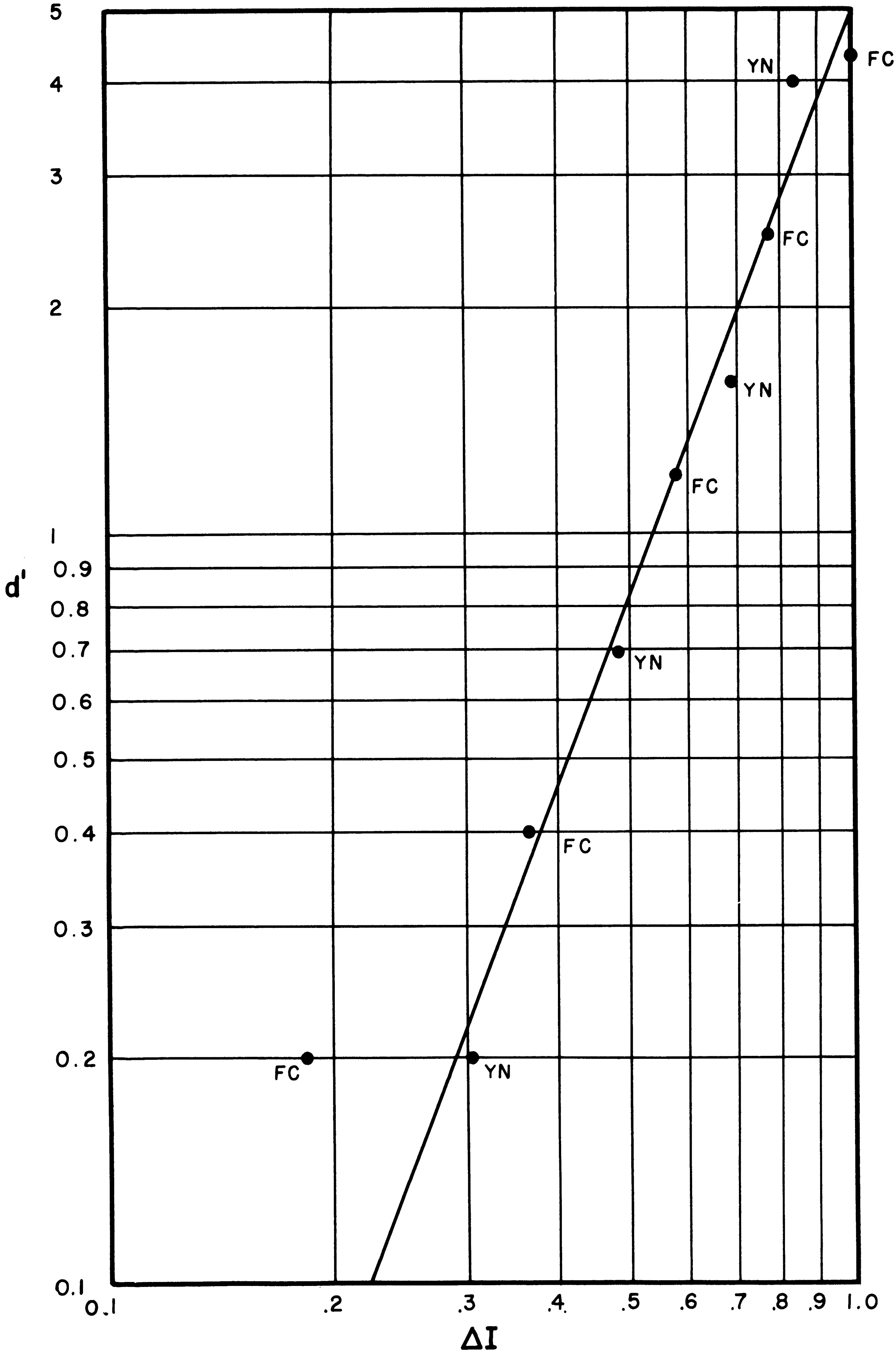
Three observers served in a series of forced-choice experiments followed by a series of yes-no experiments. All of the experiments involved the presentation of a 30 minute circular signal of 1/100 second duration flashed on a uniform background (10 ft. lamberts).[1] There were five intensity values of the signal (ΔI) in each experiment, all greater than 0 in the forced-choice experiments, four greater than 0 and one equal to 0 in the yes-no experiments. Two "a priori" values of presentation were used in the yes-no experiments; P(S) = .80, and P(S) = .40. The observers were informed in the instructions of the "a priori" value before each experimental session. A pay off matrix was presented before each experimental session, setting the values of correct detections and correct rejections, and fines for incorrect detections and rejections. The observers were paid cash in accordance with these matrices for each session. These matrices along with the results are presented in Appendix C. It was possible for the observers to earn as much as $2.00 in addition to their hourly rate of pay in a single experimental session. At no time was it possible to adopt a strategy which amounted to a criterion of $-\infty$ or $+\infty$ and improve the observer's actual performance.

[1] For a description of the apparatus, see Ref. 2.



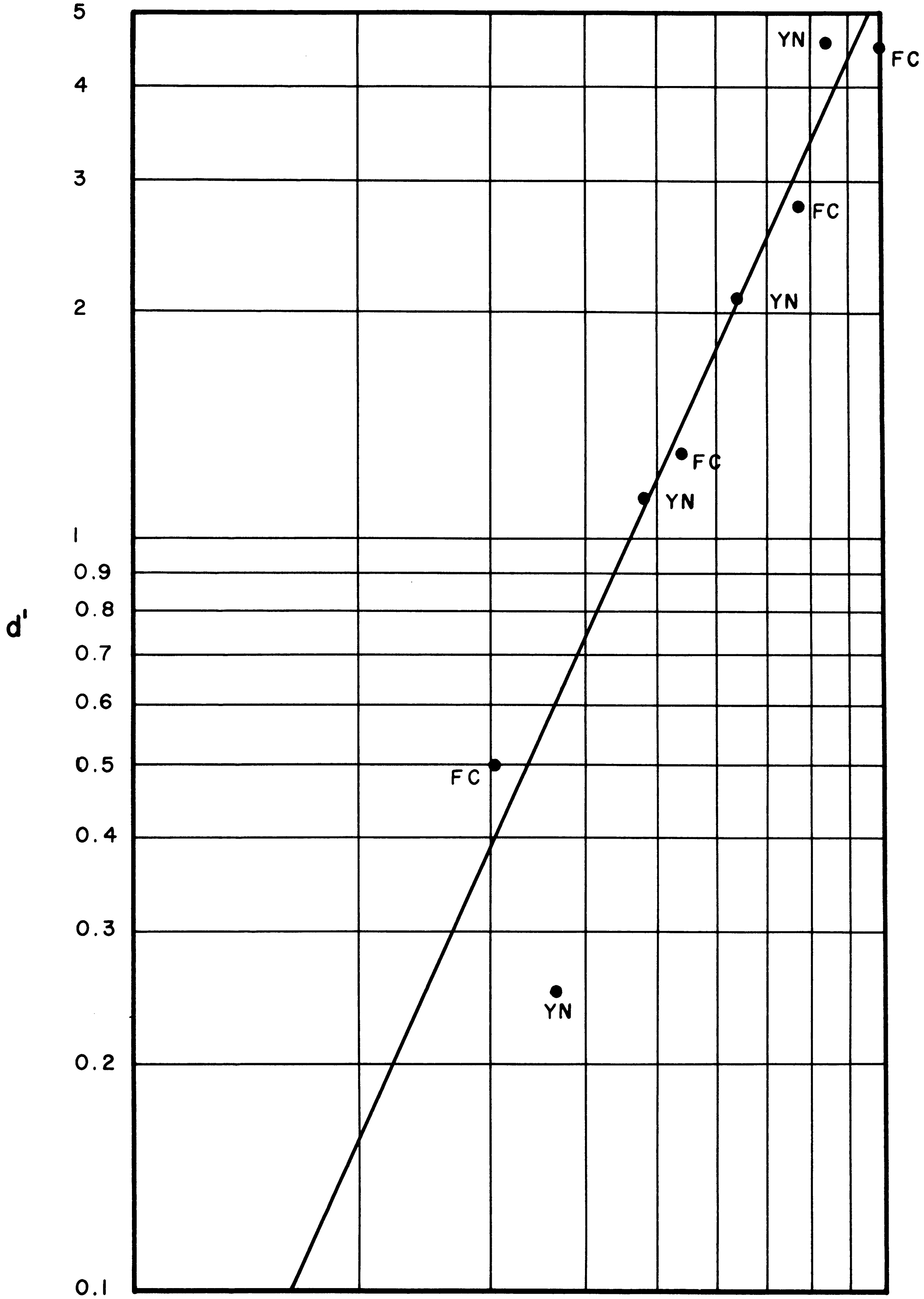
OBSERVER I

FIG 9A



OBSERVER 2

FIG 9B



OBSERVER 3

FIG 9C

Each yes-no experiment yields an estimate of $P_N(A)$ and $P_{SN}(A)$ for each signal intensity for that experiment. For each observer, and for each signal value, a scatter diagram of the $P_N(A)$ vs $P_{SN}(A)$ was constructed and compared to the curves of Figure 7. As the fits seemed satisfactory on visual inspection, these points were then plotted on double probability paper, and the best fitting straight line was determined; where $P_{SN}(A) = .5$, $P_N(A) = d'$. Figure 9 shows d' as a function of ΔI for each observer. The points are estimates of d' as a function of ΔI from yes-no (YN) and forced-choice (FC) experiments. Each YN estimate is based on 520 observations, each forced-choice on 100 observations.

The plot of d' against ΔI approximates a straight line on log-log paper, suggesting that d' is a power function of ΔI. The meaning of this relationship must be carefully considered. ΔI is a light increment above an adaptation level I. Consequently, d' is a change in activity from a noise level adapted to the level I, and it is d' which is the power function of ΔI (change in intensity) which exists for a period of time too short to permit adaptation to the new level. Nothing is indicated here about the adaptation level of neural activity as a function of light intensity. It certainly does not follow from the evidence presented here that the adapted level of neural activity is a power function of light intensity.

As slightly different values of ΔI were used in the forced-choice experiments, values of d' for each ΔI used in the forced-choice were determined, based on the relationship derived from the yes-no experiments. The percentages of correct responses were then used as estimates of P(c). P(c) was then plotted as a function of d' (Figure 10), and these points were compared to the theoretical curve shown in Figure 6. Visual inspection indicates satisfactory agreement. That the psychophysical threshold problem is the problem of detecting signals in noise is an hypothesis which is supported by the experimental data reported here.

The curves are the theoretical curves of Figure 6. The points are the forced-choice percentages plotted against values of d' as determined from the yes-no experiments for each observer.

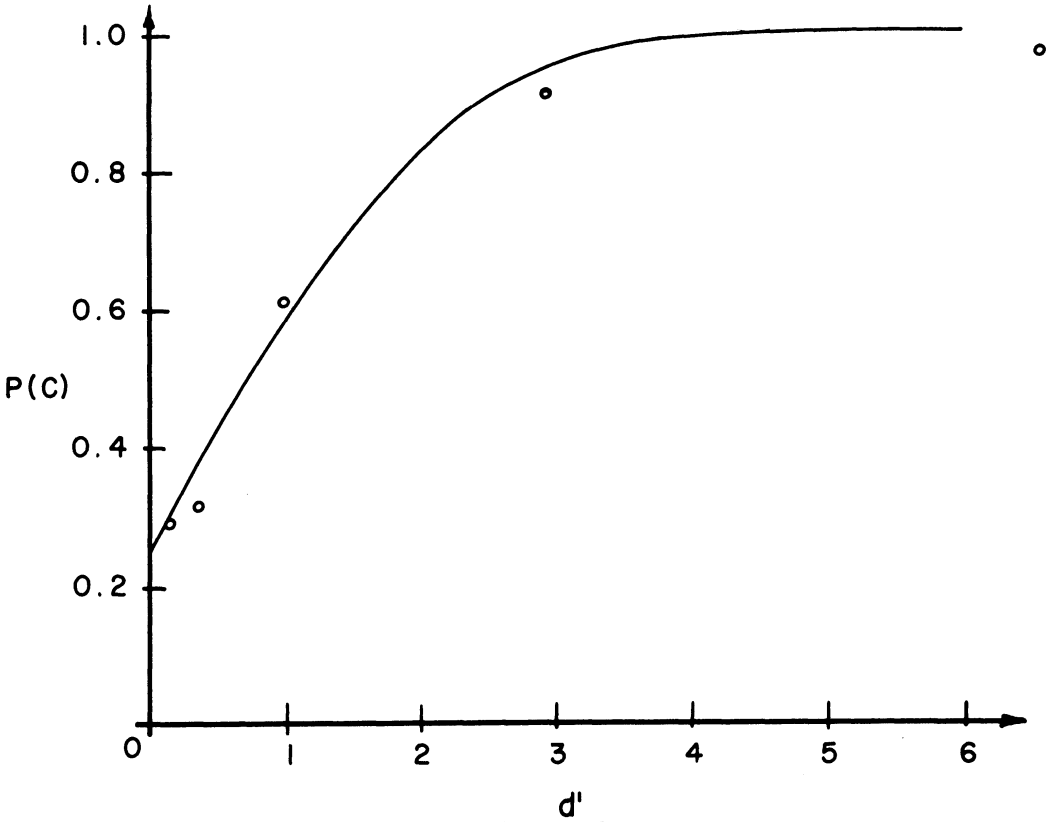


FIG 10A
OBSERVER 1

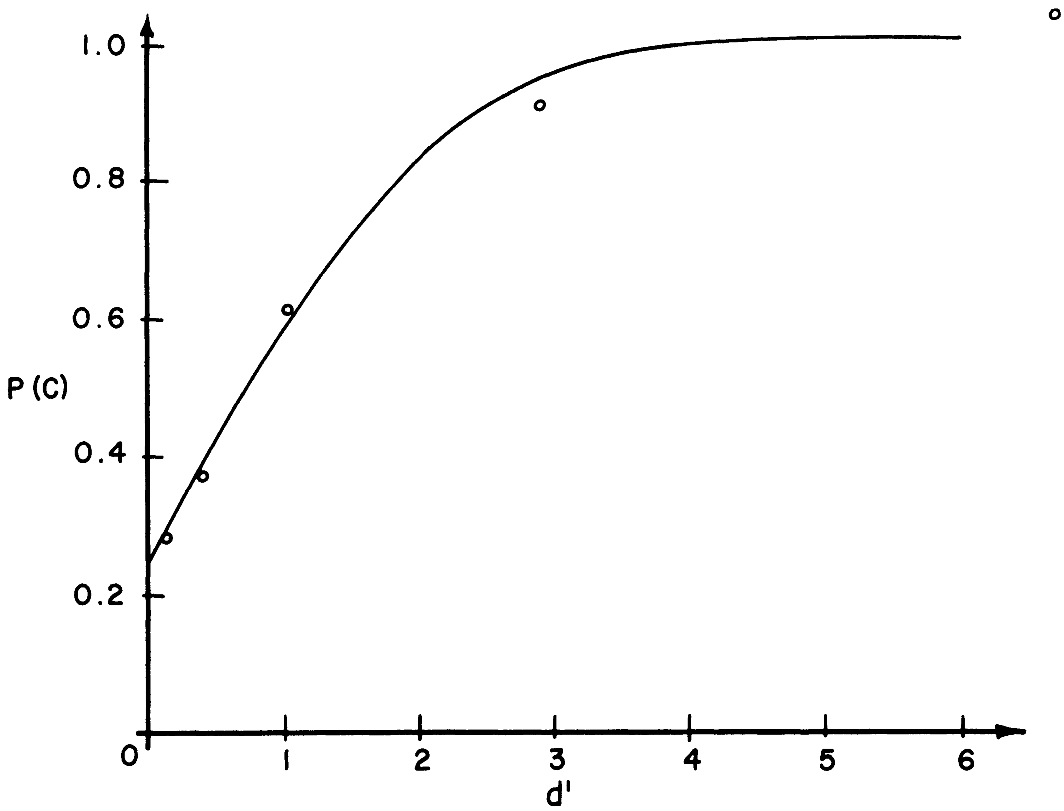


FIG 10B
OBSERVER 2

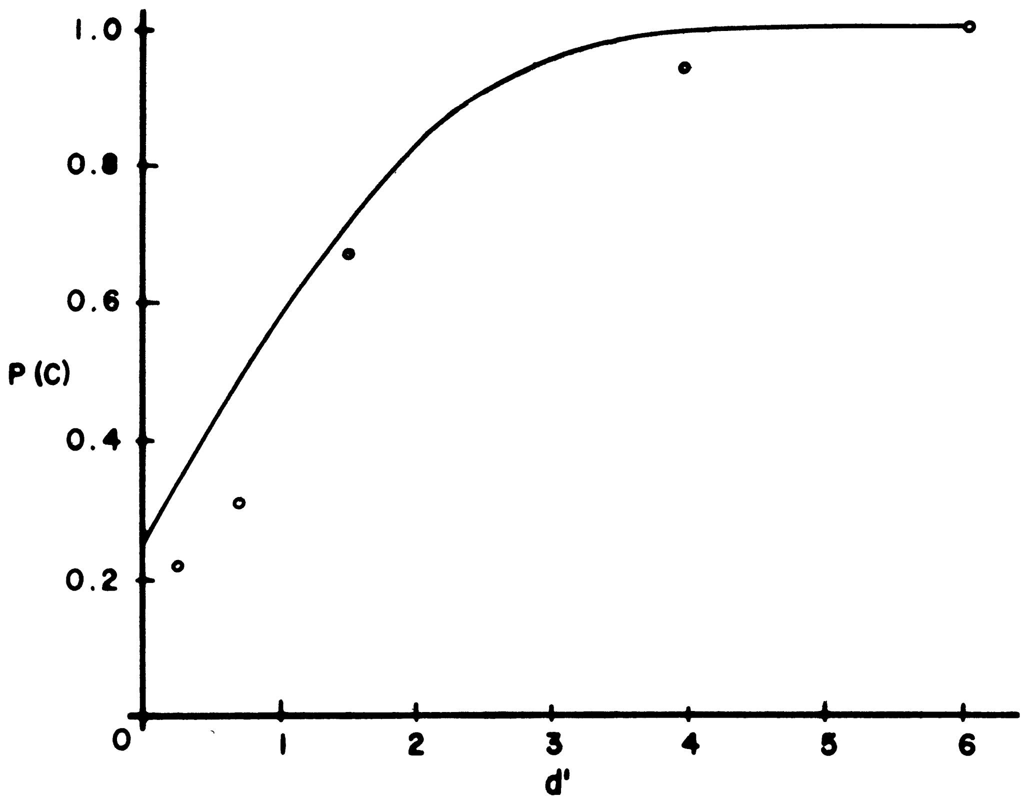


FIG 10C
OBSERVER 3

As this theory and the predictions derived from it appear inconsistent with results from a large number of reported psychophysical experiments, the inconsistency deserves consideration. For this reason, several predictions were made concerning the expected form of the data if the percentage of false alarms merely represent guesses. These predictions consider the guessing hypothesis as a null hypothesis. Statistical tests indicate that there is adequate ground for rejecting the guessing hypotheses (see Appendix A).

The second point is the fact that a large number of authors have reported that the percentage of correct detections either in forced-choice or yes-no experiments is a normal function of ΔI (Ref. 1). The theoretical curves predicted by this theory were expanded by the d' to ΔI function, the chance correction then applied, and the resulting curve was then plotted on probability paper. It is very doubtful that the difference between this curve and a normal curve could be distinguished experimentally. The coincidence is not so obvious in the yes-no experiments, but neither have the reported fits to normals been so good as those in the forced-choice experiments. For details, see Appendix B.

6. DISCUSSION

That the phenomenal experience of seeing depends on variables which are not purely sensory is certainly suggested by the data in this experiment. In order to gain additional evidence on this point, two experiments were conducted in which three categories of response (yes, no, and doubtful) were permitted. The observers were instructed to detect as well as they could, but to be sure of being correct if they chose either a yes or no response. Two sessions were run, one with an "a priori" probability of signal existence of .8, the other with a probability of .4. Even in these experiments a false-alarm probability appeared to exist, being higher when the "a priori" probability was .8, as one would expect.

The observers in these experiments were all college students who had an acquaintance with the probability theory and its relation to the problem under consideration. The observers were interviewed and reported that their yes responses were actually based on phenomenal "seeing"; this suggests that they had experienced something akin to hallucinations. That they responded yes when no signal was presented, even through they had been exposed to an extended observing experience, suggests that an individual learns to "see" through experience. The observer builds up a set of expectancies (a-priori probabilities) and value scales (pay-off matrices in which the penalty for false-alarm is socially severe), places "bets", right or wrong, until finally, phenomenal "seeing" evolves. If one is permitted enough experience to alter the sets of expectancies and values, then one begins to "see" on a different basis.

In these experiments the observers were placed in a situation in which is was profitable to them to use information it would ordinarily be profitable to ignore. As the experiment progressed, the actual criterion of seeing changed until it became possible for them to see things they had been unable to see. This change in seeing ability was accompanied by a change in false-alarm rate.

7. SUMMARY

A new theory of visual detection is presented. The theory is based on the theory of signal detection of Peterson and Birdsall (Ref. 3), who consider the problem as that of evaluating statistical hypotheses. Predictions based on this theory are compared with predictions based on conventional psychophysical theory. The following conclusions based on experimental data are reached:

1). The guessing hypothesis of conventional theory, at least as a complete explanation, is rejected on the basis of statistical tests.

2). The mathematical model of signal detection is applicable to the problem of visual detection.

3). The amount of change in neural activity from an adaption level is a power function of the change in light intensity rather than the linear function conventionally assumed.

4). The observer uses a criterion approximating an optimum in observing the neural display.

5). The experimental data supports the logical connection between the forced-choice and yes-no techniques developed by the theory.

APPENDIX A

There are two ways of considering the guessing hypothesis, in which statistical independence is assumed to exist between $P_N(A)$ and $P_{SN}(A)$, except for a spurious dependence resulting from the guesses included in $P_{SN}(A)$. If the conventional analysis of the data is performed, employing the chance correction, there should be no correlation between $P_N(A)$ and the calculated threshold (Appendix C). (The threshold is the classical index of performance; it is defined as the ratio of the value of ΔI detected 50 per cent of time to the background intensity.) The rank-order correlations for $P_N(A)$ vs corrected thresholds for all of the yes-no experiments for the three observers were .30(P = .284), .71(P = .002), and .67(P = .004) in the direction predicted by the theory of dependence. For the three subjects combined, P = .000002. The product-moment correlations were .37(P = .156), .59(P = .016), and .51(P = .034). For the three subjects combined, P = .00008. Because non-linearity was introduced by including those experiments in which no value scale was presented, product-moment correlation based only on days 5-16 were computed. These are .37(P = .245), .60(P = .039), and .81(P = .001). For the three subjects combined, P = .00001.

A second method is to assume the theory of independence and fit the scatter-diagram $P_N(A)$ vs $P_{SN}(A)$ by straight lines. According to the independence theory, these straight lines should intercept the point (1.00, 1.00). Sampling error would be expected to send some of the lines to each side of this point. All twelve lines intersect the line $P_{SN}(A) = 1.00$ at values of $P_N(A)$ between 0 and 1.00 in an order which would be predicted if these lines were arcs of the curves for $P_N(A)$ vs $P_{SN}(A)$ as defined by the theory of signal detectability.

APPENDIX B

The experimental evidence previously reported in the literature (that P(c) corrected for chance in the forced-choice experiment is a cumulative normal function of ΔI) is so strong that this result must be explained in terms of the theory presented here, if this report is to be considered. Consequently, an examination of P(c) (corrected for chance as a function of ΔI) is considered, assuming the theory.

Take the force-choice theoretical curve and the d' vs ΔI function of one of the observers. Now for this observer determine a theoretical value of P(c) for several values of ΔI. Correct these values for chance by Equation 1. Plot the result on probability paper (Figure 11). Note that the approximation to a straight line is sufficiently close that it is unlikely that experimental results would show deviation from a straight line if this curve is indeed the true curve.

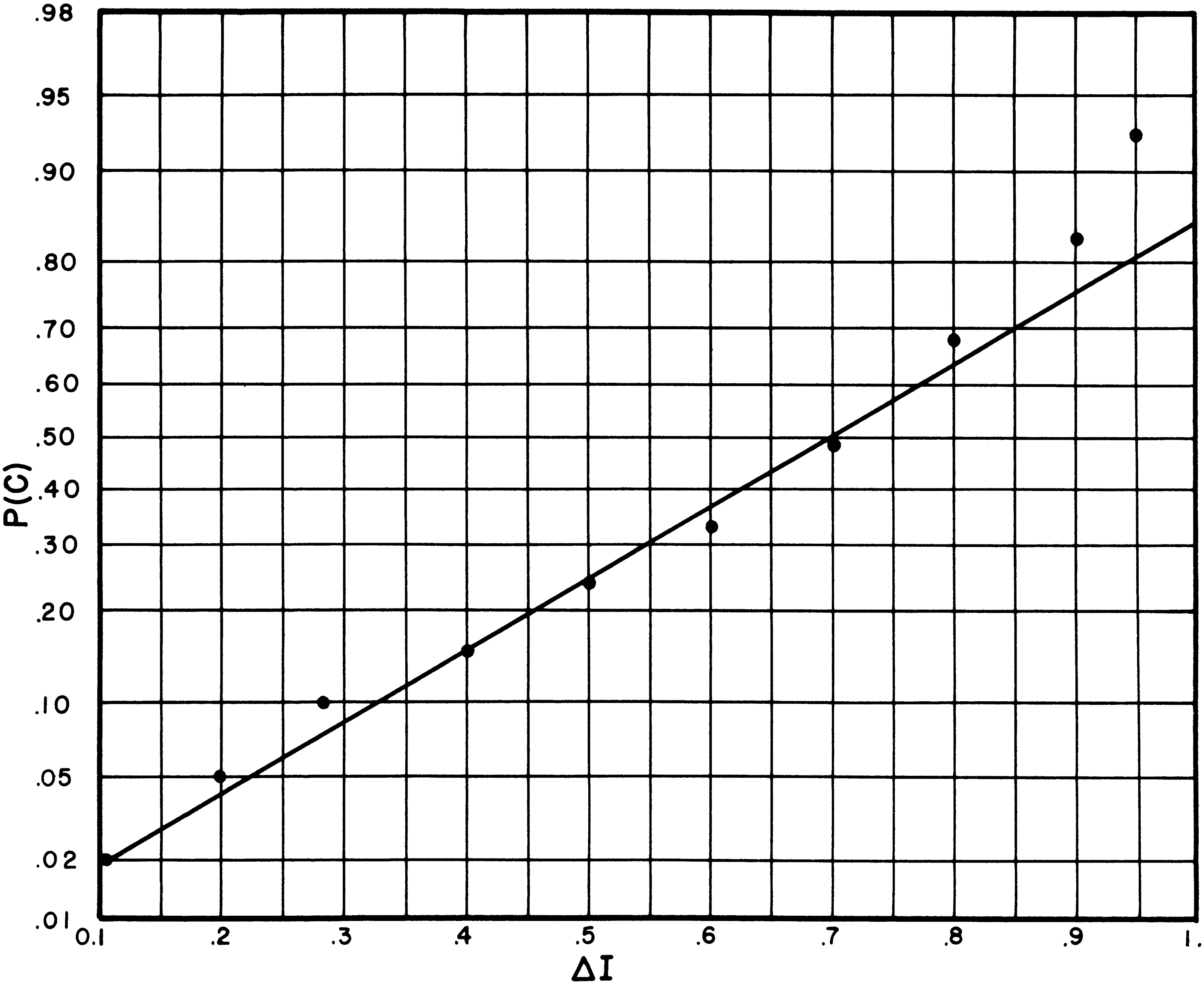


FIG II

APPENDIX C

Observer	Filter Transmission				
	.182	.365	.575	.765	1.00
1	30	33	63	91	97
2	36	39	54	91	98
3	23	31	68	93	99

TABLE I
FORCED CHOICE DATA

Each number is the total number of correct response for each signal intensity. Maximum possible per filter 100.

EXPLANATION OF SYMBOLS IN TABLES 2, 3, & 4

The analysis in this report is based on days 5-16 during which there was a value scale.

$P(SN)$ = probability of a signal

$V_{SN \cdot A}$ = value of correct detections

$K_{SN \cdot CA}$ = cost of a false alarm

$K_{N \cdot A}$ = cost of a miss

$V_{N \cdot CA}$ = value of correct rejection

$P_N(A)$ = probability of a false alarm as estimated by the percentages during the experiment

$P_{S_I N}(A)$ = probability of a correct detection for signal intensity I, etc.

Day	P(SN)	$V_{SN \cdot A}$	$K_{SN \cdot CA}$	$K_{N \cdot A}$	$V_{N \cdot CA}$	$P_N(A)$	$P_{S_1N}(A)$	$P_{S_2N}(A)$	$P_{S_3N}(A)$	P_{S_4N}(A
1	0.8	--	--	--	--	0.50	0.62	0.76	0.90	0.94
2	.8	--	--	--	--	.44	.46	.74	.84	.94
3	.4	--	--	--	--	.135	.40	.64	.76	1.00
4	.4	--	--	--	--	.215	.32	.48	.80	.96
5	.8	+1	-1	-2	+2	.44	.50	.54	.86	.98
6	.8	+1	-1	-2	+2	.12	.26	.32	.68	.98
7	.8	+1	-1	-2	+2	.36	.42	.58	.72	.96
8	.8	+1	-1	-2	+2	.38	.44	.50	.74	.84
9	.8	+1	-1	-2	+2	.30	.416	.533	.816	1.00
10	.8	+1	-1	-2	+2	.20	.366	.533	.750	.966
11	.8	+1	-1	-3	+3	.166	.266	.466	.733	.983
12	.8	+1	-1	-4	+4	.066	.083	.166	.533	.886
13	.4	+1	-1	-2	+2	.05	.066	.300	.633	.966
14	.4	+1	-1	-1	+1	.039	.166	.433	.800	.966
15	.4	+2	-2	-1	+1	.428	.466	.633	.900	1.00
16	.4	+3	-3	-1	+1	.533	.600	.800	.800	1.00

TABLE 2
YES-NO DATA FOR OBSERVER I

Day	P(SN)	$V_{SN \cdot A}$	$K_{SN \cdot CA}$	$K_{N \cdot A}$	$V_{N \cdot CA}$	$P_N(A)$	$P_{S_1N}(A)$	$P_{S_2N}(A)$	$P_{S_3N}(A)$	$P_{S_4N}(A)$
1	.8	--	--	--	--	.38	.56	.76	.86	.98
2	.8	--	--	--	--	.46	.72	.64	.88	.98
3	.4	--	--	--	--	.125	.24	.56	.64	1.00
4	.4	--	--	--	--	.11	.12	.60	.72	.96
5	.8	+1	-1	-2	+2	.36	.54	.60	.92	.96
6	.8	+1	-1	-2	+2	.18	.20	.40	.76	1.00
7	.8	+1	-1	-2	+2	.36	.42	.58	.72	..96
8	.8	+1	-1	-2	+2	.42	.50	.66	.68	.90
9	.8	+1	-1	-2	+2	.233	.233	.466	.716	.950
10	.8	+1	-1	-2	+2	.366	.433	.633	.850	.950
11	.8	+1	-1	-3	+3	.416	.466	.650	.933	1.00
12	.8	+1	-1	-4	+4	.250	.200	.416	.766	.966
13	.4	+1	-1	-2	+2	.044	---	---	.333	.800
14	.4	+1	-1	-1	+1	.030	.066	.266	.600	.966
15	.4	+2	-2	-1	+1	.260	.200	.566	.800	.966
16	.4	+3	-3	-1	+1	.350	.400	.500	.866	.966

TABLE 3

YES-NO DATA FOR OBSERVER 2

Day	P(SN)	$V_{SN \cdot A}$	$K_{SN \cdot CA}$	$K_{N \cdot A}$	$V_{N \cdot CA}$	$P_N(A)$	$P_{S_1 N}(A)$	$P_{S_2 N}(A)$	$P_{S_3 N}(A)$	$P_{S_4 N}(A)$
1	.8	--	--	--	--	.42	.54	.66	.86	1.00
2	.8	--	--	--	--	.40	.30	.62	.90	1.00
3	.4	--	--	--	--	.06	.08	.28	.60	.96
4	.4	--	--	--	--	.02	.24	.32	.48	.96
5	.8	+1	-1	-2	+2	.20	.44	.64	.84	.96
6	.8	+1	-1	-2	+2	.18	.34	.38	.84	.96
7	.8	+1	-1	-2	+2	.08	.22	.48	.74	.98
8	.8	+1	-1	-2	+2	.18	.32	.46	.74	.94
9	.8	+1	-1	-2	+2	.166	.150	.466	.850	1.00
10	.8	+1	-1	-2	+2	.150	.350	.550	.900	.966
11	.8	+1	-1	-3	+3	.066	.100	.350	.750	.966
12	.8	+1	-1	-4	+4	---	.066	.216	.616	.950
13	.4	+1	-1	-2	+2	---	.133	.166	.433	.933
14	.4	+1	-1	-1	+1	---	---	.200	.366	.800
15	.4	+2	-2	-1	+1	.24	.466	.766	.900	.966
16	.4	+3	-3	-1	+1	.288	.366	.766	.833	.966

TABLE 4

YES-NO DATA FOR OBSERVER 3

REFERENCES

1. Blackwell, H. R., "Threshold Psychophysical Measurements, I. An Analysis and Evaluation." (in preparation)

2. Blackwell, H. R., Pritchard. B. S., Ohmart, T. G., "Automatic Apparatus for Stimulus Presentation and Recording in Visual Threshold Experiments." J. Opt. Soc. Amer. (in press)

3. Peterson, W. W., and Birdsall, T. G., "The Theory of Signal Detectability. Part I, The General Theory." Technical Report No. 13, Electronic Defense Group, University of Michigan.

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