Predicting Human Performance:

1. Estimating The Probability of Visual Detection

Warren H. Teichner
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Technical Report 1

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PREDICTING HUMAN PERFORMANCE: I. ESTIMATING THE PROBABILITY OF VISUAL DETECTION

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TECHNICAL REPORT NUMBER 1

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SUMMARY

As a first step toward the development of a system for predicting human performance, the literature on the absolute threshold for seeing and on the contrast threshold was examined and within each data were collated across studies. In each case, Crozier's Law for the relation between the standard deviation and the threshold of a psychophysical function was found to hold, and an appropriate constant was developed. It is possible and practical, therefore, to estimate the probability of detection for both given only a threshold value as information.

The availability of extensive parametric studies of contrast allow for the prediction of that threshold with fair confidence. Such studies are not available for the absolute threshold.

The literature was used, therefore, to develop a basis for predicting the luminance threshold as a function of target size and duration. The result is useful at least as a first approximation and, along with the above, may serve (1) as a direct aid in solving applied problems requiring a prediction of the probability of visual detection or the design of a visual signal, and (2) as an aid to the development of methods for predicting more complex kinds of performance.

In addition, the analysis made supports the general conclusion about the absolute threshold that for small visual areas and up to a critical duration, there is a reciprocity between duration and luminance and that the critical duration decreases with increasing area. The analysis did not support a similar reciprocity between luminance and area, a finding in disagreement with the generally-held understanding. The latter result has implications for visual theory and for the design of quantum-type experiments which are noted briefly. It is pointed out that the data can be explained by assuming

that the threshold depends on excitation of some minimum number of receptors if statistical variation of sensitivity is assumed.

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INTRODUCTION

This report is the first in a series intended to develop methods or models which maximize the use of the scientific literature as a basis for predicting human performance. By attempting this we hope not only to verify already established relationships and possibly to extract new ones, but also we hope to do this so as to predict absolute measures of performance. That is to say, by collating and comparing studies within a class of performance we are placing a great deal of faith in the absolute values of dependent measures as reported by investigators.

The general approach has been described by Teichner and Olson (1969). They classified human performance as falling into a few simple classes defined primarily by the various dependent measures which are commonly used. In these terms the probability of detection, p(D), the reaction time, number correct, etc., are each part of the definition of a unique class of performance. The assumption was made that certain classes of performance depend upon other, more simple or temporally primary ones. It was hypothesized, for example, that the speed of response to a signal depends upon the probability of detecting the signal; the greater the detection probability, the faster the speed of response. For such hypotheses, a function was assumed and a tentative method developed for actually predicting the dependent measure. For the most part, however, the functions which were assumed were developed with little empirical justification. At that time, the intent was to consider what kinds of assumptions might be important rather than to test or develop them. This report presents a similar development, but on an empirical basis. That is, we were concerned here with sensory performance defined in terms of the p(D) of a flash of light. The basis for developing predictions of p(D) was the empirical and theoretical literature. Where the literature is lacking as a basis for developing appropriate functions, our intent was to propose assumed functions. Doing this has the advantage of suggesting organization for an area of inquiry, of identifying critical gaps in knowledge, and to a greater extent than is now possible of providing data and predictive methods of value to engineering psychology.

Whether or not a target is detected depends on its visibility, i.e., on the degree to which target energy parameters exceed the energy requirements of the human eye. For the most part, research on visibility has been concerned with the threshold energy level, i.e., that level which is visible 50% of the time. Later interests in non-sensory performance will require that it be possible to state p(D) for any stimulus condition. Moreover, that knowledge is required as a data base for a variety of applied problems. It was the major purpose of this study, therefore, to attempt to establish a means for estimating p(D) for a flash of light and, since, generally only the threshold value is reported in the literature, to do this knowing just that datum.

The visibility of a target depends upon its contrast, luminance, size, duration of exposure, wavelength, shape, and the sensitivity of the retina. The latter depends upon conditions of exposure prior to appearance of the target and position on the retina. It was not our aim to develop an exhaustive model for estimating p(D) given all of those factors, but rather to make progress toward such an accomplishment by developing a more limited predictive system. Part I of this report is restricted to the detection of a target light having zero background luminance; the relevant literature concerns the absolute threshold for seeing. Part II concerns the contrast threshold. Both are restricted primarily to exposure duration, size of target, and for contrast, to background luminance as independent variables. Other variables have been considered only to the extent that they involve critical interactions or that the literature has demanded an analysis in terms of them in order to extract the effects of the primary variables. For example, originally, we had intended to restrict our inquiry to binocular detection of white light for the dark-adapted eyes. As will be seen, although the last restriction was maintained, the literature describing the absolute threshold for foveal and white light conditions is so small that we had to consider peripheral detection and monochromatic signals in order to have enough data with which to establish trends.

Originally Teichner and Olson (1969) had proposed that probability functions be developed for the effects of target size and duration. Those probabilities were then to be employed in a simple model describing the probability of detection of the target based on detecting at least one of its characteristics.

The model proposed rested very importantly on the assumption of mutually exclusive, independent events. In terms of vision this implies that the detectability of a target based upon any one target characteristic does not depend on the value of any other characteristic. This assumption was not considered to be highly valid, but it was hoped that a useful first approximation could be extracted from the literature which might serve as an early working model. While we still think that such a probability approach could be valuable, we have not used it here due to a lack of data with which to test it. Instead we have attempted to develop a means for estimating a single probability function in the conventional manner.

I. DETECTION OF LUMINANCE

The Absolute Threshold: Status of the Literature

The older literature concerned with the absolute threshold is the source for most of today's generalizations about the effects on human detection of such variables as retinal position, exposure time, target size, etc. Of the many studies of the threshold available, this review was limited primarily to those which have reported p(D) data or which have provided a measure of variability of individual measures around the threshold (i.e., the mean) which either was or could be transformed to a standard deviation. A total of seven such studies were found of which one was concerned with day-to-day variations rather than variations associated with different values of independent factors. That study (Jackson, 1965) is summarized in Figures 1 and 2 which show respectively the variations of the threshold and of the standard deviation (σ_L) over 50 days of successive measurement on each of six female subjects. Each daily value was based on 50 threshold determinations. The figures are meant only to illustrate the rather wide variation in daily individual values and to serve as a caution against the uncritical acceptance of average data when making predictions about the individual. On the other hand, as will be revealed by the consistencies below, average data are fairly reliable even when based on as few as two subjects if the subjects are very highly practiced, as was the case for all of the data to be presented.

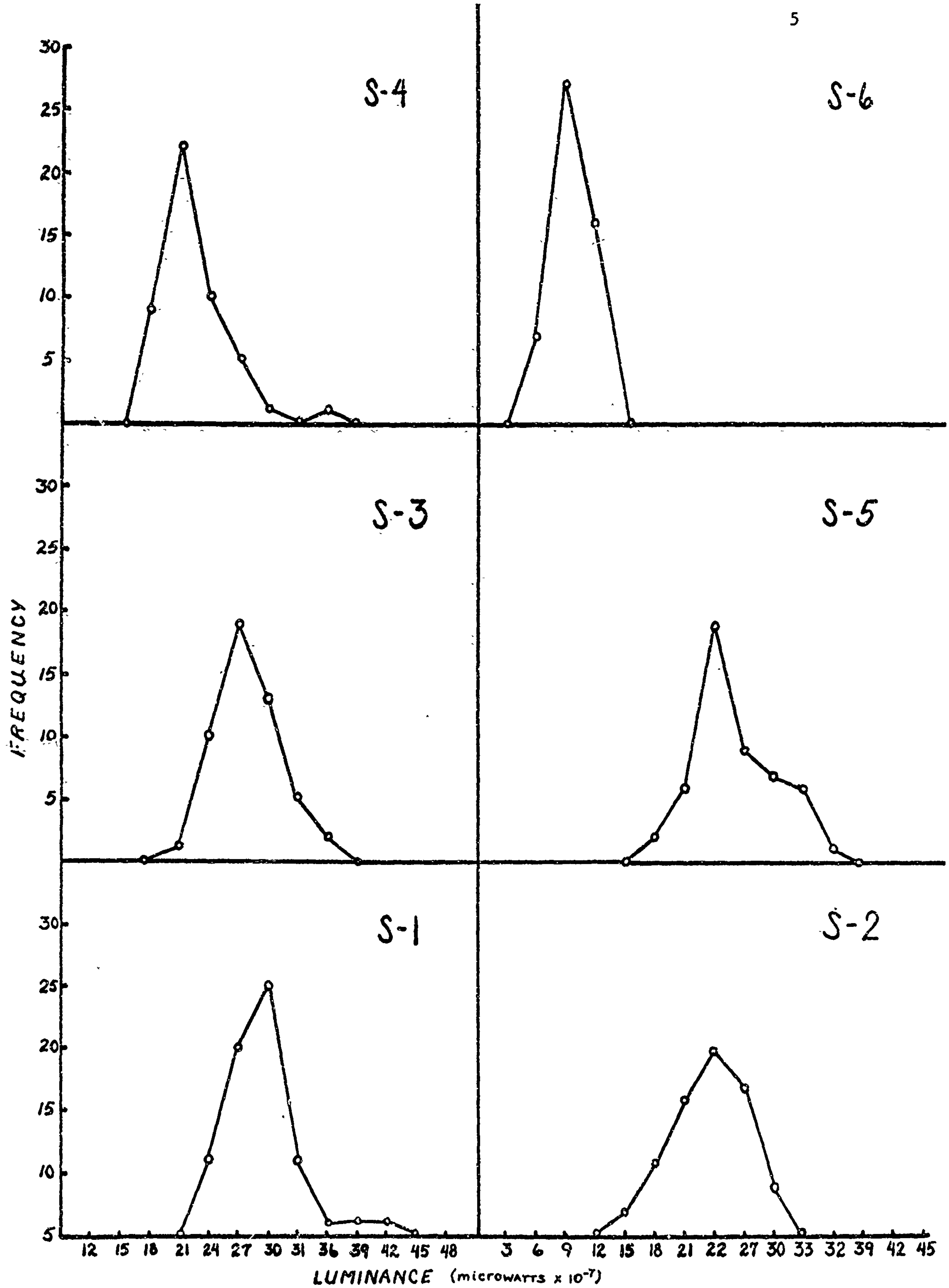

Figure 1. Variations of individual thresholds over 50 successive days. Data from Jackson (1965).

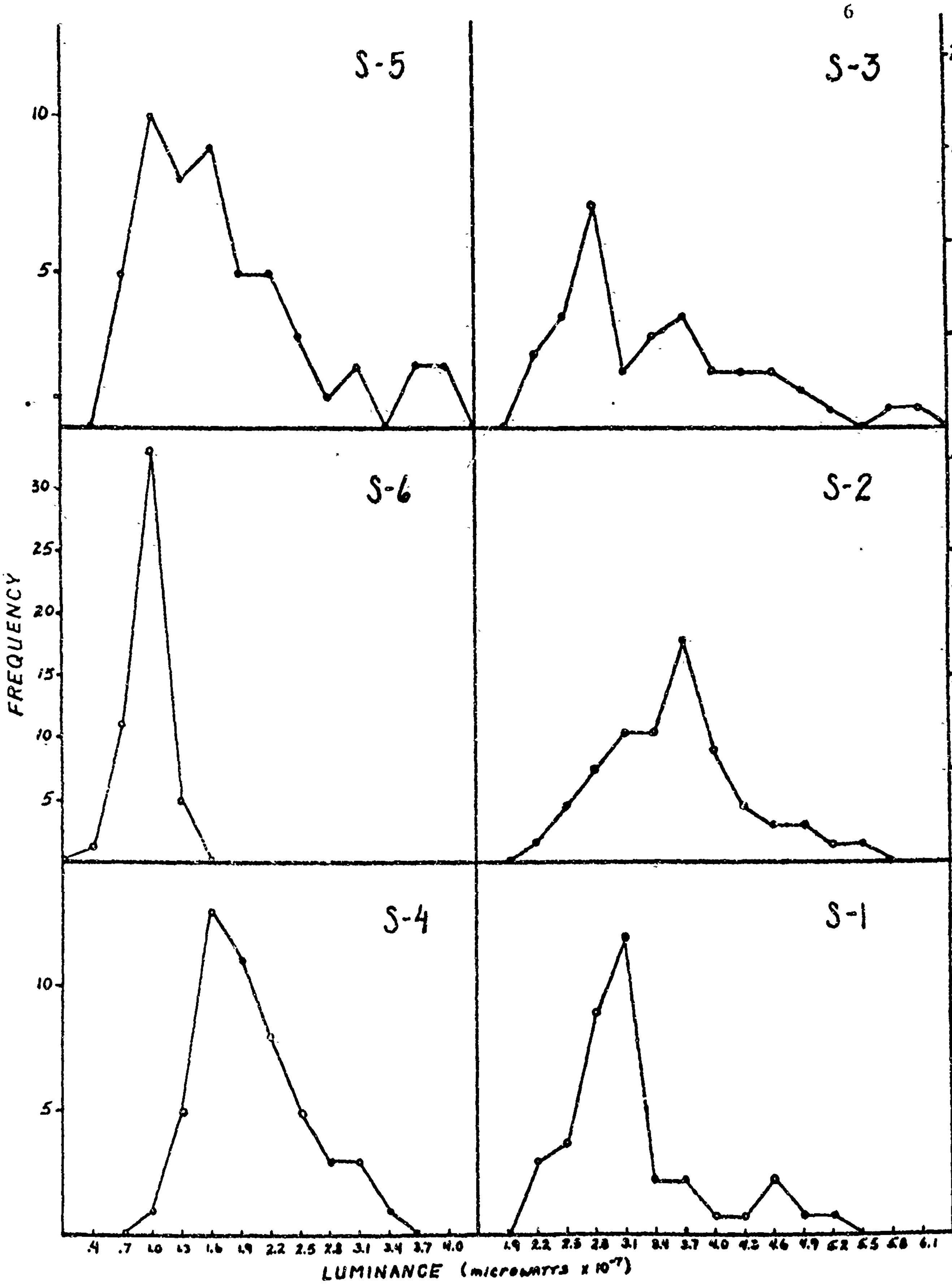

Figure 2. Variations of individual standard deviations over 50 successive days. Data from Jackson (1965).

In the real world as well as for other than psychophysical questions of human response to a signal light, signals are not always presented for peripheral stimulation. In fact, the large majority of experimental work in regard to other kinds of performance has involved foveal viewing. For this reason, as noted above, our original intention was to restrict this analysis to data obtained from studies of central vision. As it has turned out, most of the psychophysical studies have used peripheral stimulation. Thus, we have had to face the question of how to generalize such data to the fovea. In addition, as was also noted earlier, our search was concerned primarily with studies providing measures of variability. It was only after completing that search and realizing that further data were needed to answer critical questions, that we allowed ourselves to make use of selected other papers. Even so, we cannot report that this is a rich literature source nor do we believe that we have overlooked studies relevant to our particular questions which also provide information in addition to that to be presented. Finally, by way of general criticism, although the data are surprisingly consistent from study to study, they are invariably based on very few subjects, usually the authors themselves, often just two. No studies are available which might be thought of as parameter-estimating.

Other problems confronted us in our attempt to develop empirical relationships using the available data. For one thing, in spite of the fact that the field of research has been quite rigorous in its demands for physical control and description, we have been required to reject some studies for lack of reporting such critical information as the exposure time of the stimulus. Other studies have been reported in arbitrary units or relative measures without a reference which would permit conversions to absolute units. The experimental designs of some studies have been too badly confounded for use and, finally, the measures reported are in a variety of photometric and radiometric units, thereby requiring conversion to a common scale for comparison.* In addition, the measures were based upon a variety of psychophysical methods. We have chosen to ignore the differences in psychophysical method and wherever possible to accept data since we have had so little from which to select.

We have also had to make a variety of methodological decisions. In particular we have decided that the best way to express p(D) is in terms of the cumulative percentile curve. Other options available are the normalized ogive and the Poisson curve. This decision was based in part on the fact that most of the data available are amenable to description in these terms and on Blackwell's (1953) extensive study of psychophysical methodology from which he found that a simple cumulative curve was most frequently a good fit to the data and that where the others were also good fits, the simple probability curve was at least as good.

Laws of the Absolute Threshold

A number of excellent reviews of the topic are available, e.g., Graham, 1965; Hecht, 1934; LeGrande, 1957; Pirenne, 1962. Of particular interest to this discussion is that studies of the effects of exposure time (t) have

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*All of the studies used were converted to luminance in millilamberts (mL), visual angle in degrees of arc, and exposure time in seconds. All data to be reported are presented in these units except the data of Figures 1 and 2.

found that with small retinal areas, the amount of energy required at threshold is a constant up to some critical duration, t_c. That is,

$$L_{50}t = C \qquad t \leq t_c \qquad (1)$$

where L_{50} is the threshold, i.e., that luminance detectable 50% of the time.

This is the Bunsen-Roscoe law of photochemistry. As applied to vision, it is often called Bloch's Law. For values of $t>t_c$, $L_{50}t$ increases to some value after which t has no further effect and L_{50} is constant.

Similar relationships have been reported for the effect of target size expressed as retinal area (A). These relationships have been expressed in terms of the product of L_{50} and some index of A such as the visual angle subtended by a target radius or the solid angle subtended. The exact nature of the relationship has been concluded to depend upon retinal position and, for short exposure times, to hold up to some critical area, A_c. Expressing this relationship in terms of L_{50} and the solid angle,

$$L_{50} = C/\omega^K \qquad (2)$$

For visual angles less than 30 minutes of arc K varies between 0.9 at 7° and K = 1.00 at 30° (Weinstein and Arnulf, 1946). For visual targets between 1.0 and 5.0 degrees of arc, K varies from between K = 0.6 at 15° to K = 0.7 at 25° (Wald, 1938). At the fovea for visual angles less than 1.0 degree of arc, K = .33 according to Piéron and for targets greater than 10 degrees of arc, L_{50} is constant anywhere on the retina (Defay and Schwegler, 1930; LeGrand, 1957).

Although these and other time and area relationships have been proposed, and have tended to be in agreement with analogous data obtained from neurophysiological preparations, each relationship has been descriptive of the range to which it was first applied. The area function, as such, is not presently established although there is no question that the luminance threshold decreases within limits as retinal area increases. To resolve both the area and duration questions, extensive factorial experimental designs are needed to provide estimates of the A×t interaction. Only one factorial study (Graham and Margaria, 1935) appears to be available and, therefore, we have made much use of its data in our analysis. In any case, to a considerable degree, our efforts in this study have been a re-evaluation of the exposure time and area laws.

The Probability of Detection, p(D)

Assuming an underlying normal distribution, the familiar cumulative probability curve (ogive) has a mean at p(D) = .50 and σ which is equal to one-half of the range between p(D) = .84 and p(D) = .16. When put into the form of z-scores, z = 0 at the mean and z = 1.00 at one σ above the mean. Thus, a knowledge of the mean and standard deviation is all that is needed to generate the expected ogive. Unfortunately, although the threshold or mean value is always reported, other values of the ogive, including the standard deviation, are rarely reported. Of the six studies found which did either provide σ_L or provided a basis for deriving or estimating it under a variety of experimental conditions, only one (Brown, 1947) reported that σ_L was constant (except for non-systematic fluctuations)* with variations in the threshold. The remaining five studies were plotted as in

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*A Rho correlation for Brown's 12 $\overline{X}_L - \sigma_L$ pairs was found to be -.407, (cont'd next page)

Figure 3 and a line drawn by eye to represent them. As may be seen the line is linear, increasing, and provides a reasonable fit across the five experiments. It may also be seen that the experiments vary widely in experimental conditions and that while Brown's data, which were not used to develop the line, are somewhat deviant from expectation, they do fall within the general features of the trend.

The equation for the line shown in Figure 3 is of great interest because it provides substantiation of Crozier's Law for the relationship between the mean and σ. The same slope constant has also been reported by several individual authors in the past, as reviewed by LeGrande (1957). Figure 3, then, shows that Crozier's Law holds not only for within-experiment data, but also for between-experiment data for the absolute threshold. Thus, for situations for which only the mean or threshold value is available, a probability curve can be constructed by using a value of one-half of the threshold as σ_L. In view of the demonstrated consistency of this result, it would seem to have validity for general use.

Applying Crozier's Law to the absolute threshold for the estimation of p(D) for luminances above or below threshold requires only a knowledge of threshold luminance for the conditions of interest. Assuming the dark-adapted eye, we shall attempt to develop a procedure for estimating the

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(cont'd from previous page) $p > .05$. In addition, six of the σ_L's were larger than the mean, the largest of those differences being by a factor of 10^5. In all other studies obtained, without exception σ_L was always smaller than the mean. In spite of this, the 12 means were exactly in line with the general form of related studies (cf Figure 4).

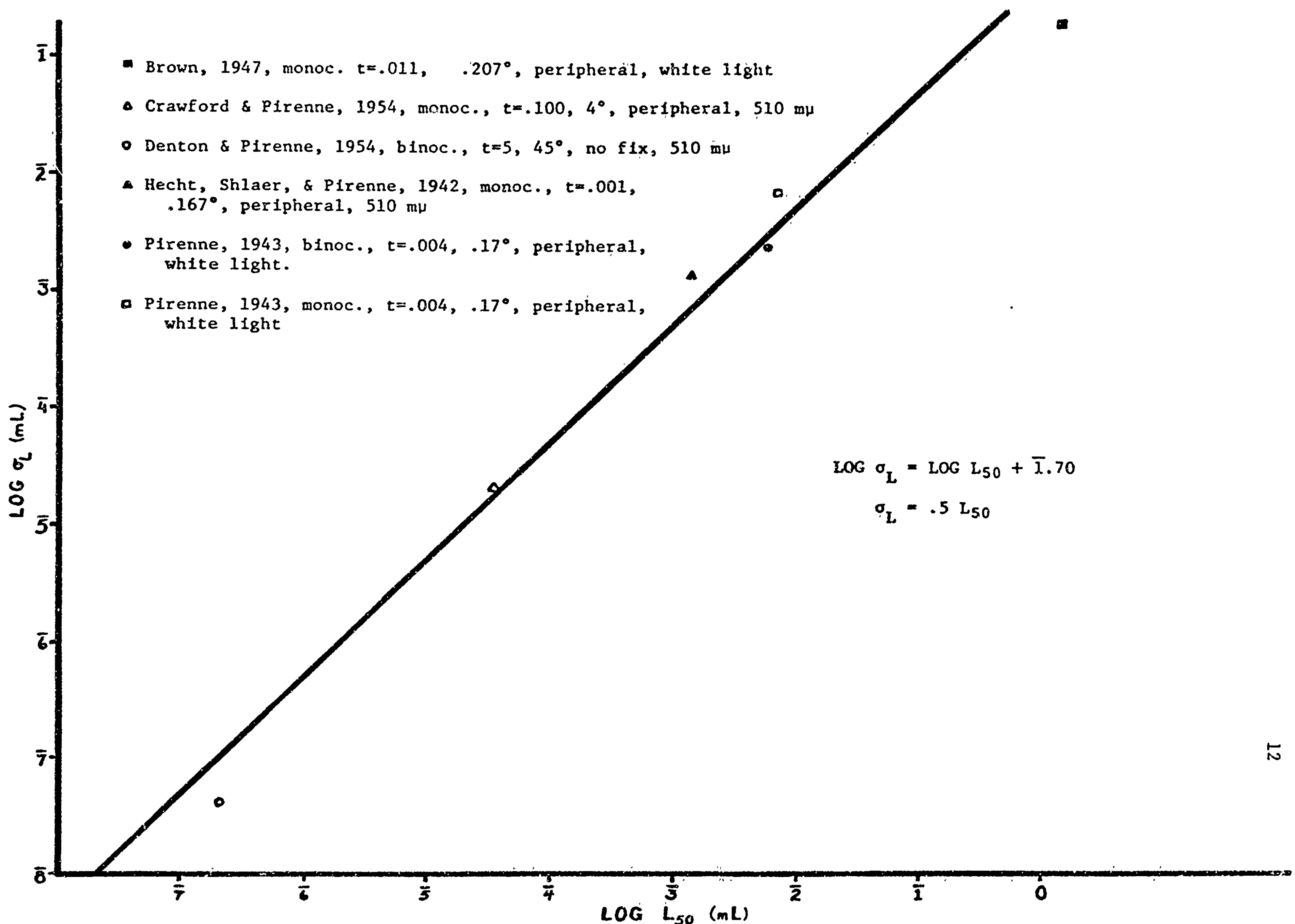

Figure 3. Relation between σ_L and L_{50}.

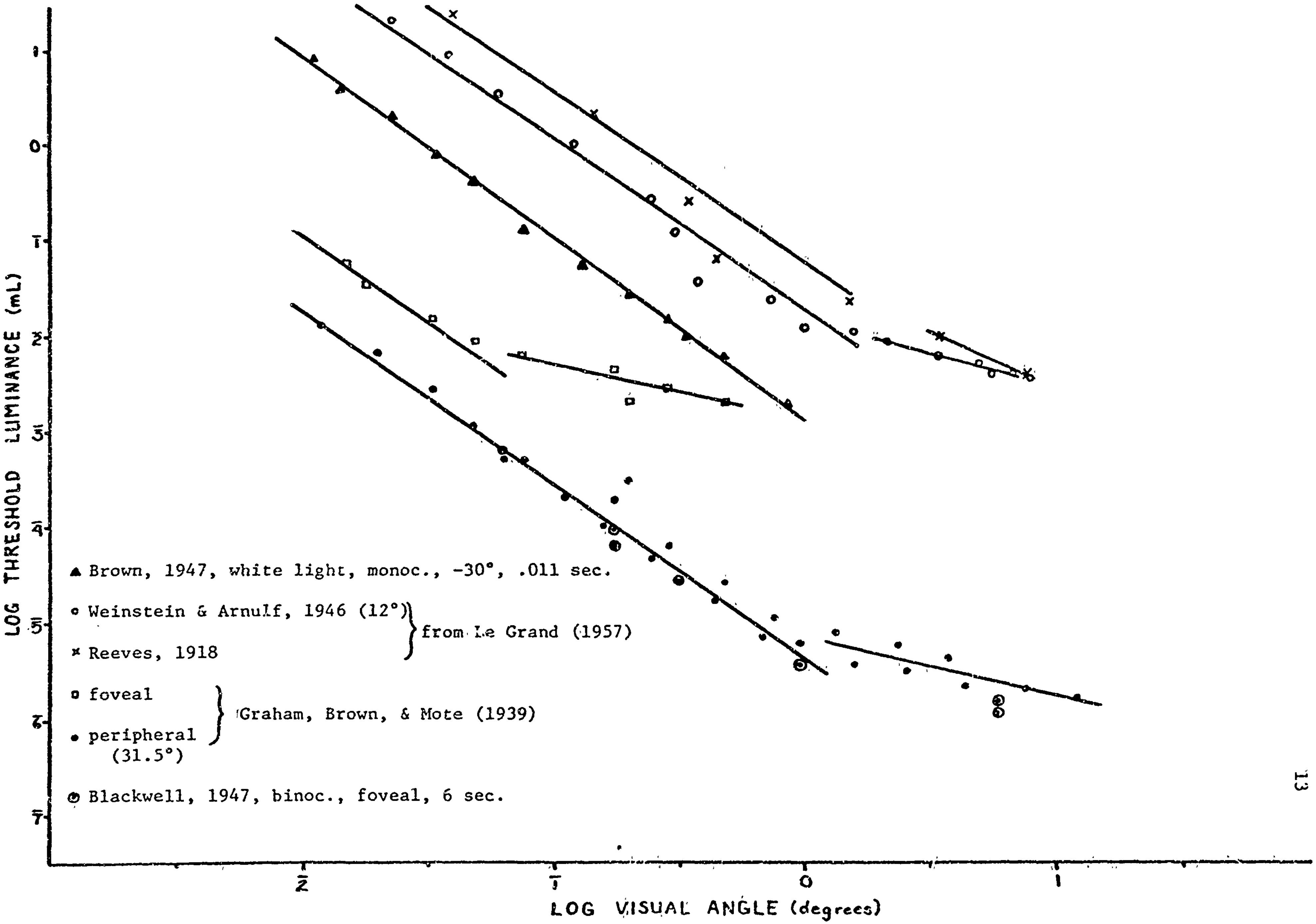

Figure 4. The L_{50} as a function of area for a variety of experimental conditions.

threshold for combinations of size and exposure time for the peripheral and central retina. It should be emphasized that the result will necessarily be tentative and require experimental test and further development or alteration. Nevertheless, in the absence of any other basis for making a prediction of the luminance threshold, even a rough guide may have considerable value.

Area, Retinal Position, and the L_{50}

Plotted in Figure 4 are six sets of data based on five experimental investigations of the effect of retinal area (target size at the eye) on the luminance threshold. The lines, drawn by eye, are attempts to follow the linearly decreasing trends of each data set as far as possible. An exception is provided by the data of Blackwell (1947) for which no line was drawn.

The studies presented in Figure 4 represent a variety of experimental conditions. In spite of this they provide a set of essentially parallel lines from their smallest areas to the end of the linear trends. Of these various studies, exposure time information is available only for the data of Brown (1939) and of Blackwell (1947). The stimulus duration used by Graham, Brown, and Mote (1939) is indeterminate due to the nature of the experimental procedure and those of Weinstein and Arnulf (1946) and of Reeves (1918) are not known to us. It is possible that if the exposure times were known, the large discrepancies between the absolute values of data collected at the same retinal position might be explainable. Regardless, all of these studies are consistent in demonstrating a linear area-luminance relationship up to some critical size. All of the peripheral data and the binocular, foveal data of Blackwell agree in suggesting that the critical area is approximately 1.0°. The foveal data of Graham, Brown, and Mote suggest a critical area of a little larger than .07°. After the critical area, however, the data still suggest a linear relationship, but with a different slope up to perhaps 10° of arc for peripheral conditions and 0.5° for foveal, monocular viewing. These suggestions are not in complete accord with the general conclusions summarized earlier, nor in fact with the conclusions of the authors from the same data.

One result provided in Figure 4 is a comparison of foveal and peripheral (31.5°) sensitivity at nine points under the same experimental conditions. Figure 5 presents a plot of the differences between these points. The smooth line, drawn by eye, is not meant to have any theoretical significance, but only to provide an aid in estimating the difference for areas which might be interpolated between those which were studied. The dashed line extrapolates that curve to 1.0°. At that point the difference is 0.60 log units. Inspection of the standard relative luminosity curve suggests that the largest difference between *maximum* foveal sensitivity and *maximum* peripheral sensitivity for the one area used is about 0.35 log units. The curve drawn and extrapolated, therefore, does provide a rough guide to the differences and we shall use it for correcting peripherally-obtained luminance thresholds for white light to foveal ones recognizing that the error could be even larger. For monochromatic light, the standard relative luminosity coefficients may be used directly, or more recent scotopic and photopic relative luminosity functions may be used. Bartlett (1965) provides an excellent summary of the available data. Of more direct value would be systematic data for increasing distances from the fovea for constant values of size, exposure time, and wavelength. But although in a sense relative sensitivities

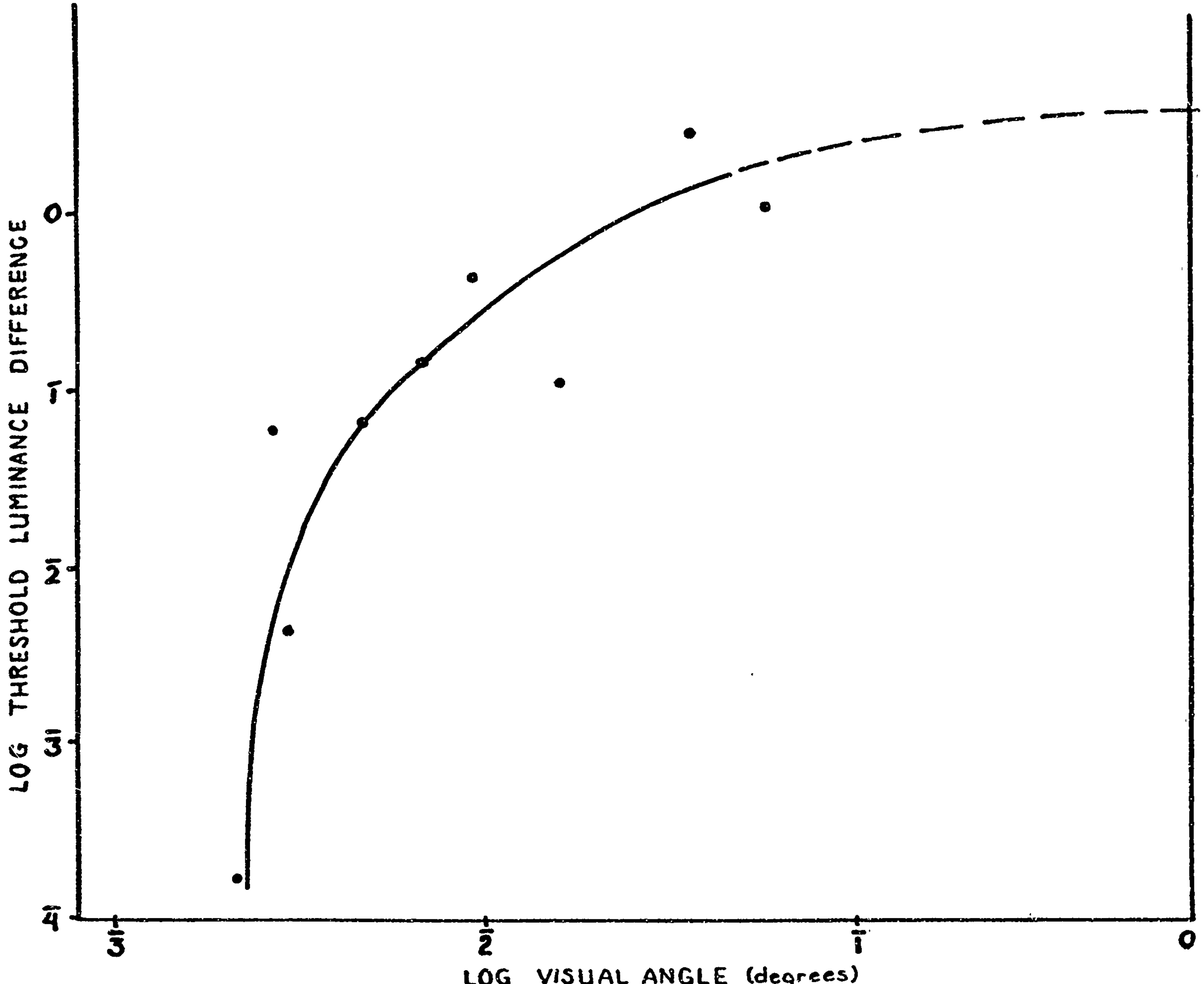

Figure 5. Difference between foveal and peripheral (31.5°) threshold for white light. Based on Graham, Brown, and Mote, 1939.

may be inferred from rod-cone distributions or from the relative luminosity function, no quantitative data appear to be available which describe the luminance threshold at more than a few positions and those data are confounded by such other variables as wavelength, exposure time, etc.; none deal with white light.

Temporal Relationship and the Combined Effect of Area and Time

Figure 6 presents the relationship between the threshold energy per unit area and the duration of exposure of the stimulus. The uppermost line describes the data of Karn (1936); the remaining data are those of Graham and Margaria (1935). The latter study appears to be the only systematic study available which provides a factorial arrangement of conditions and thereby allows for inspection of the A×t interaction. There is suggested a constant energy requirement up to a critical value, at least for stimuli of up to 3.0° of arc. After t_c for all areas, the energy requirement increases. Figure 6 also shows that t_c, indicated by the break in the horizontal lines, decreases as A increases. The diagonal line in the figure will be explained below.

Figure 7 presents the peripheral luminance threshold as a function of exposure time. For the moment consider only the lines with data points, i.e., the lines for 2', 16', 1.0°, and 3.0°. The points were calculated from Table 1 of Graham and Margaria (1935) and, therefore, are related to the previous figure. It may be seen that the luminance threshold decreases linearly as a function of duration up to a value of t_c which decreases with increasing area. The lines were drawn through the points by inspection. The curved lines were drawn independently and are not extensions of the

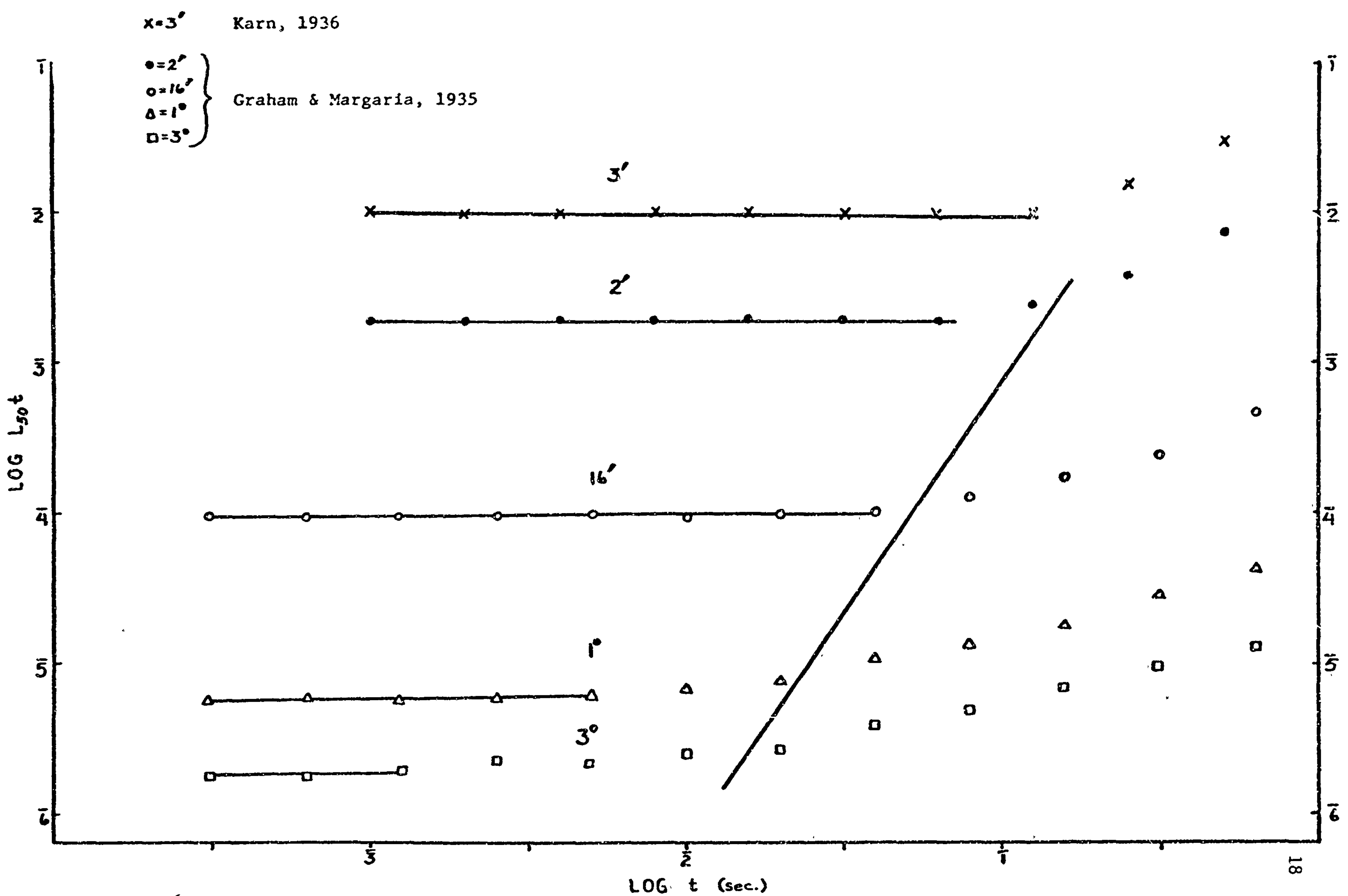

Figure 6. Threshold energy per unit area in relation to exposure time.

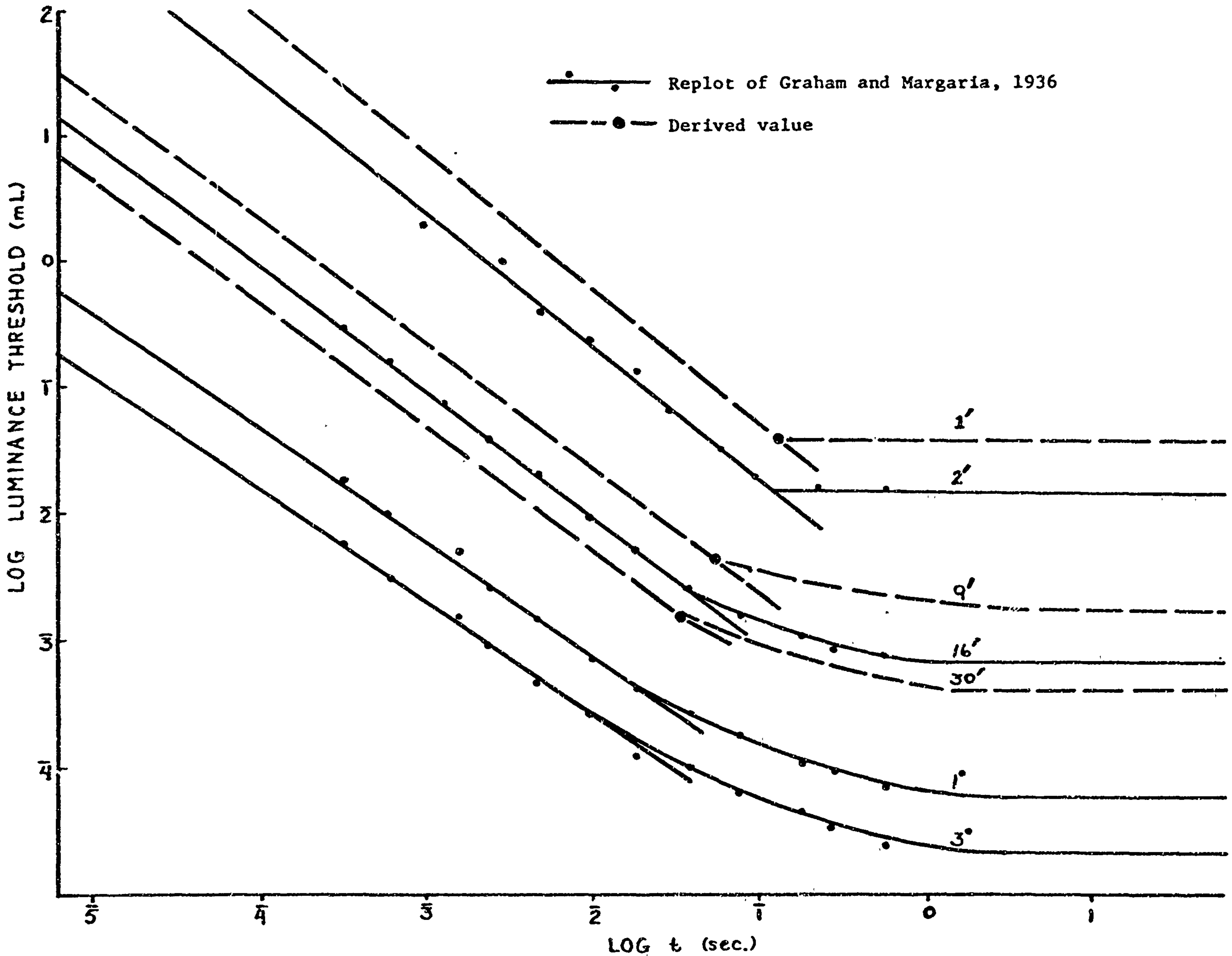

Figure 7. L_{50} as a function of exposure time and target size.

straight lines. On the contrary, we have assumed that a different function is involved and that a good estimate of t_c may be obtained as the point at which the straight line and curved line intersect. The solid, diagonal line of Figure 6 is drawn through the four intersections.

The general indication of the figure is that for values of $t > t_c$, L_{50} decreases to a constant level. The data suggest that this may happen almost immediately with very small areas and that the exposure time at which L_{50} becomes constant decreases systematically with increased area.

The intersections with which we defined t_c in Figure 7 are plotted as points in Figure 8 along with their associated luminance thresholds. The abscissa is the visual angle. A straight line appears to represent the findings for both t_c and L_{50}. The latter decreases more rapidly. Assuming that the lines shown in this figure are reasonable descriptions, and in view of the fact that the data shown in Figure 7 provide a family of parallel lines, t_c and an associated L_{50} can be obtained from the lines of Figure 8 for any area over the range of values covered. The t_c can then be entered into Figure 7 and a line constructed to the ordinate parallel to the original data. A second, curved line can also be drawn consistent with the trends of the curved lines already present. This has been done for 1', 9', and 30'. For these values the derived t_c is shown as a single point; the lines drawn from it are dashed.

To the extent that the original data of Graham and Margaria (1935) are representative, Figure 7, taken as a whole, provides a basis for estimating the luminance threshold for any combination of exposure time and area at least up to 3° and down to almost .0001 sec. With the values obtained for L_{50} and with the aid of Crozier's Law, p(D) can be estimated for any of

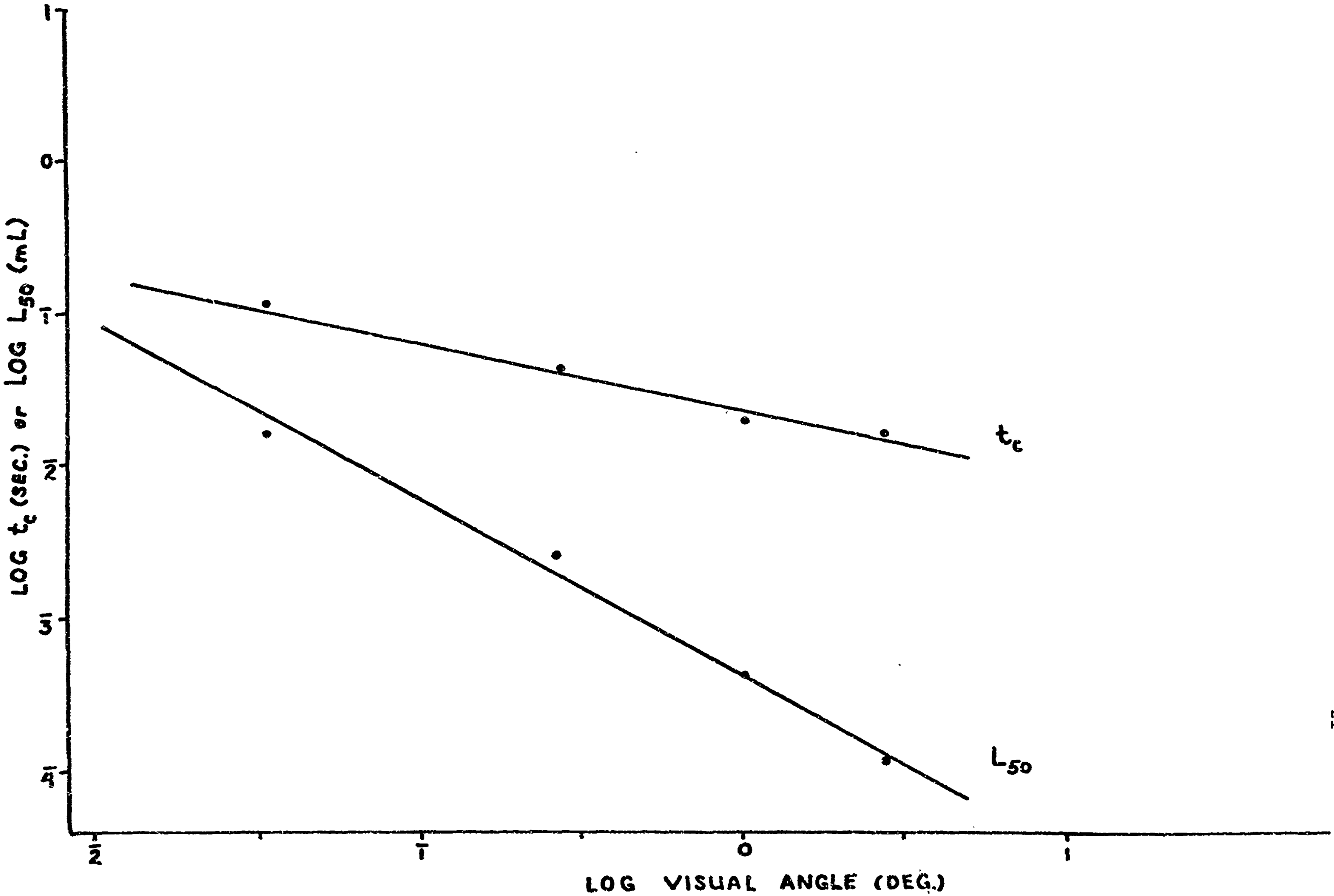

Figure 8. Critical exposure duration (t_c) and associated L_{50} as a function of target size.

these combinations of conditions. If the viewing condition is foveal rather than peripheral, L_{50} can be increased by the value indicated in Figure 5 for the size of target involved. The value of σ_L in that case should be one-half of the increased value. A straight line through the two points, L_{50} and $(L_{50} + \sigma_L)$ when plotted on arithmetic probability paper will then provide the desired probability function. That line, in turn, may be used to determine the estimated p(D) of any luminance for the combination of conditions or, conversely, of selecting a luminance for that set of conditions in accordance with a desired p(D). The function may also be used to establish trade-offs within the ranges of constant energy per unit area for a given area of stimulation.

Area and the Energy Requirement

As noted earlier, a variety of laws have been proposed which are intended to describe the summation of energy and area. As shown in Figure 6, the data of Graham and Margaria (1935) and of Karn (1936) indicate that up to at least 1.0° of visual angle the threshold energy per unit area decreases as the area increases. Perfect summation of area would be indicated by a reciprocity between L_{50} and A or between $(L_{50}t)$ and A. Thus, summation for the data of Figure 6 would be indicated by the finding that the total energy $(L_{50}tA)$ is constant with increases in area. Similarly, for a single value of exposure time, the product, $L_{50}A$, or $L_{50} \times f(A)$ should be constant for increases in A. It has been generally concluded that such summation occurs within limits.

This expectation has been one of the assumptions incorporated into experimental approaches designed to determine the minimum amount of energy required for seeing (for example, cf Pirenne, 1962). It has also been one of the arguments used to provide a similarity between the functions of the single cell and the human visual response (e.g., Graham and Margaria, 1935).

Figure 9 was developed from the data shown in Figure 4. It provides plots of $L_{50}A$ for constant exposure durations as a function of area. There is no evidence in this figure of summation; $L_{50}A$ decreases systematically as area increases over the entire range for all studies. Figure 10 shows what happens to the total energy requirement as a function of area. These data were obtained by calculation using those two studies of Figure 4 which provided exposure time information (upper line) and by plotting t_c as obtained from Figure 7 (lower line). Figure 11 uses the data of Graham and Margaria (1935) to plot total energy as a function of duration and area.*

Both Figures 10 and 11 are very clear in showing that the total energy requirement is not constant for small areas. In fact, it *decreases* with increases in area. Hallet, Marriott, and Rodger (1962) reported a smaller total threshold energy for a field of 5.64° diameter than for a field of 10' of arc in diameter with a .0026-second flash. The present analysis provides very strong support for this finding.

From the above analysis, we must conclude that as area increases *both* the threshold energy per unit area decreases and the threshold total energy decreases. Therefore, the assumption of reciprocity with area is not supported for the human psychophysical response. The implications of this

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*Graham and Margaria provide a similar figure which, unfortunately, is in error, and which led them to conclude erroneously.

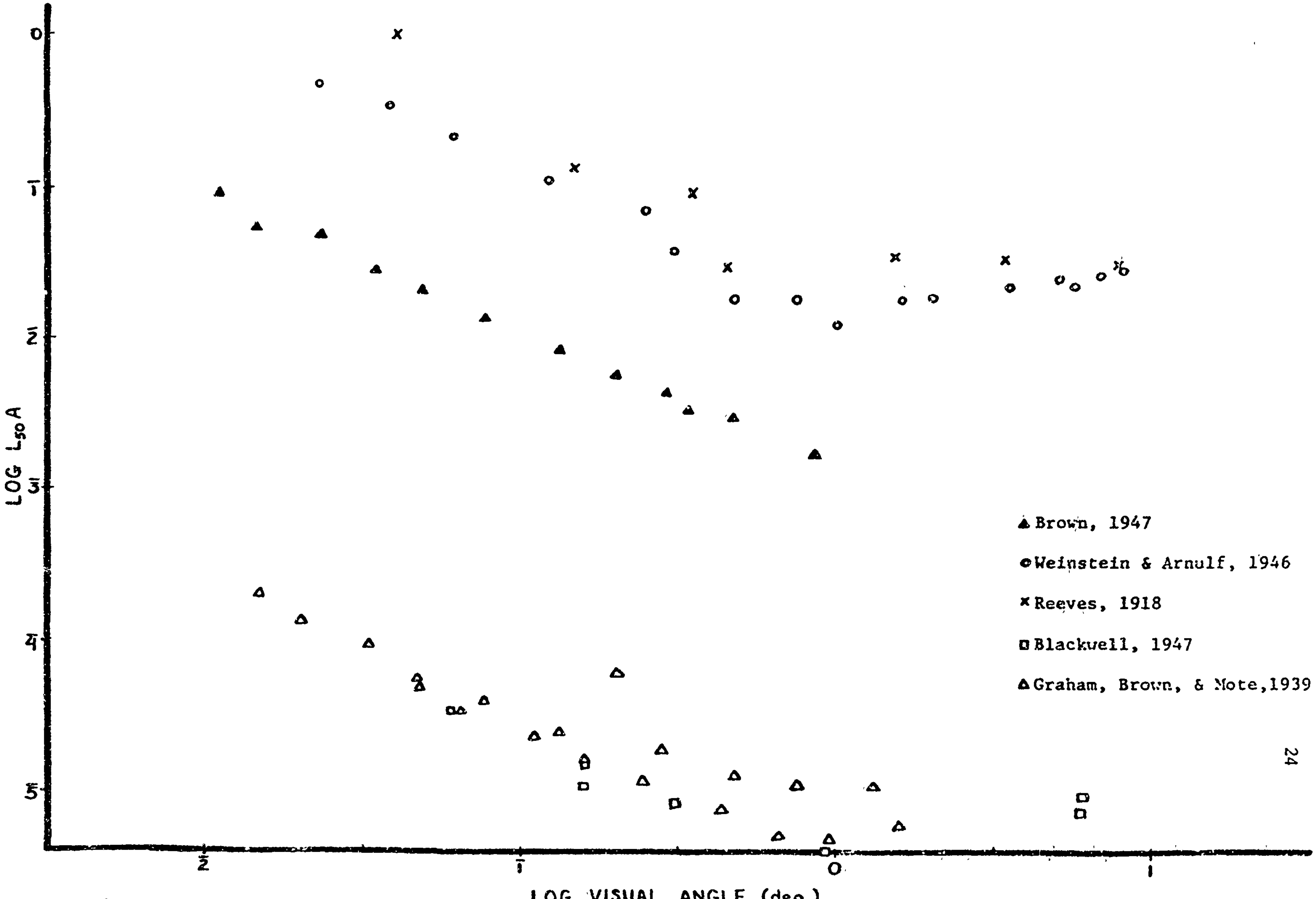

Figure 9. L_{50} as a function of A for the studies reported in Figure 4.

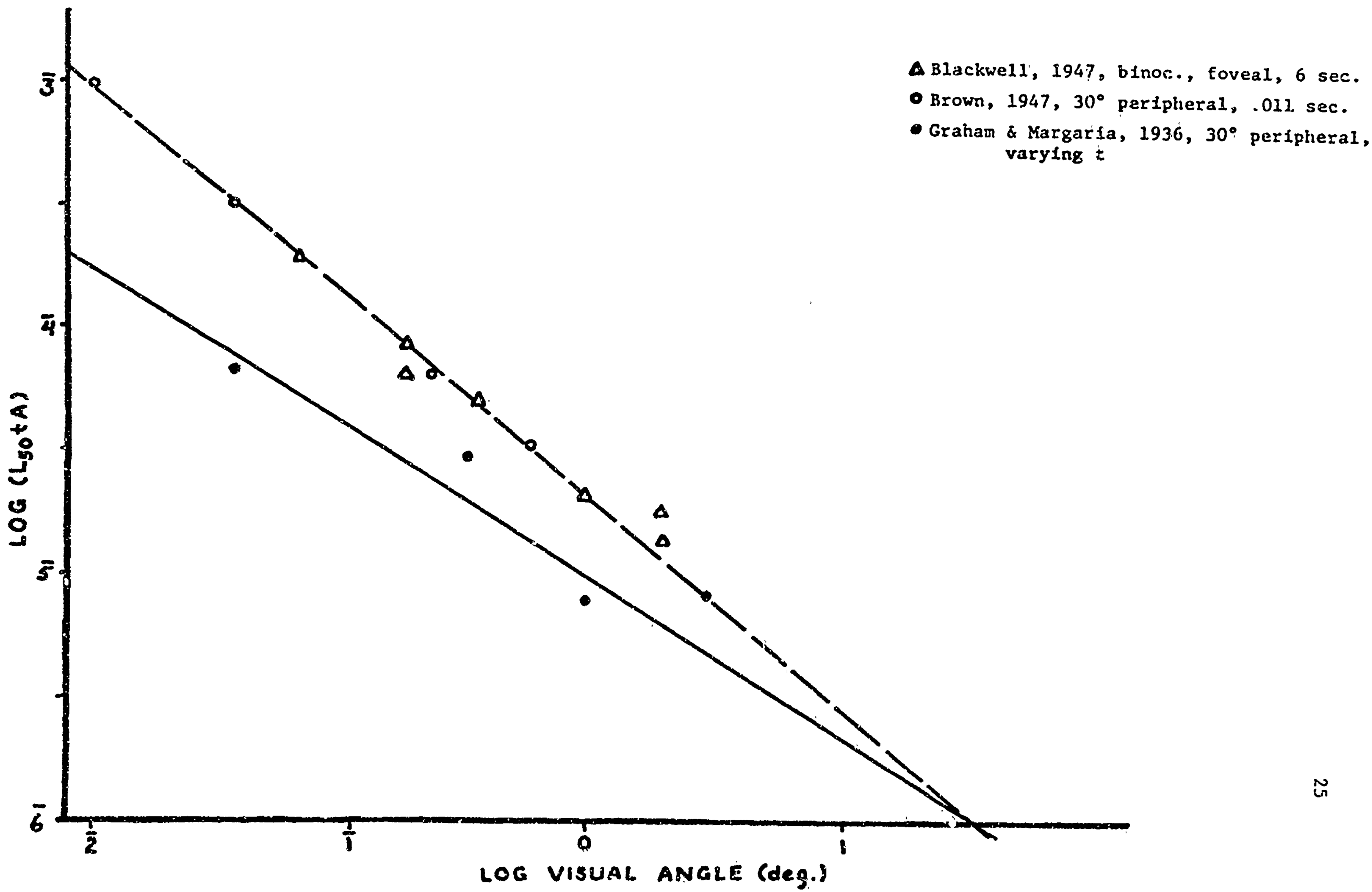

Figure 10. Threshold total energy as a function of area.

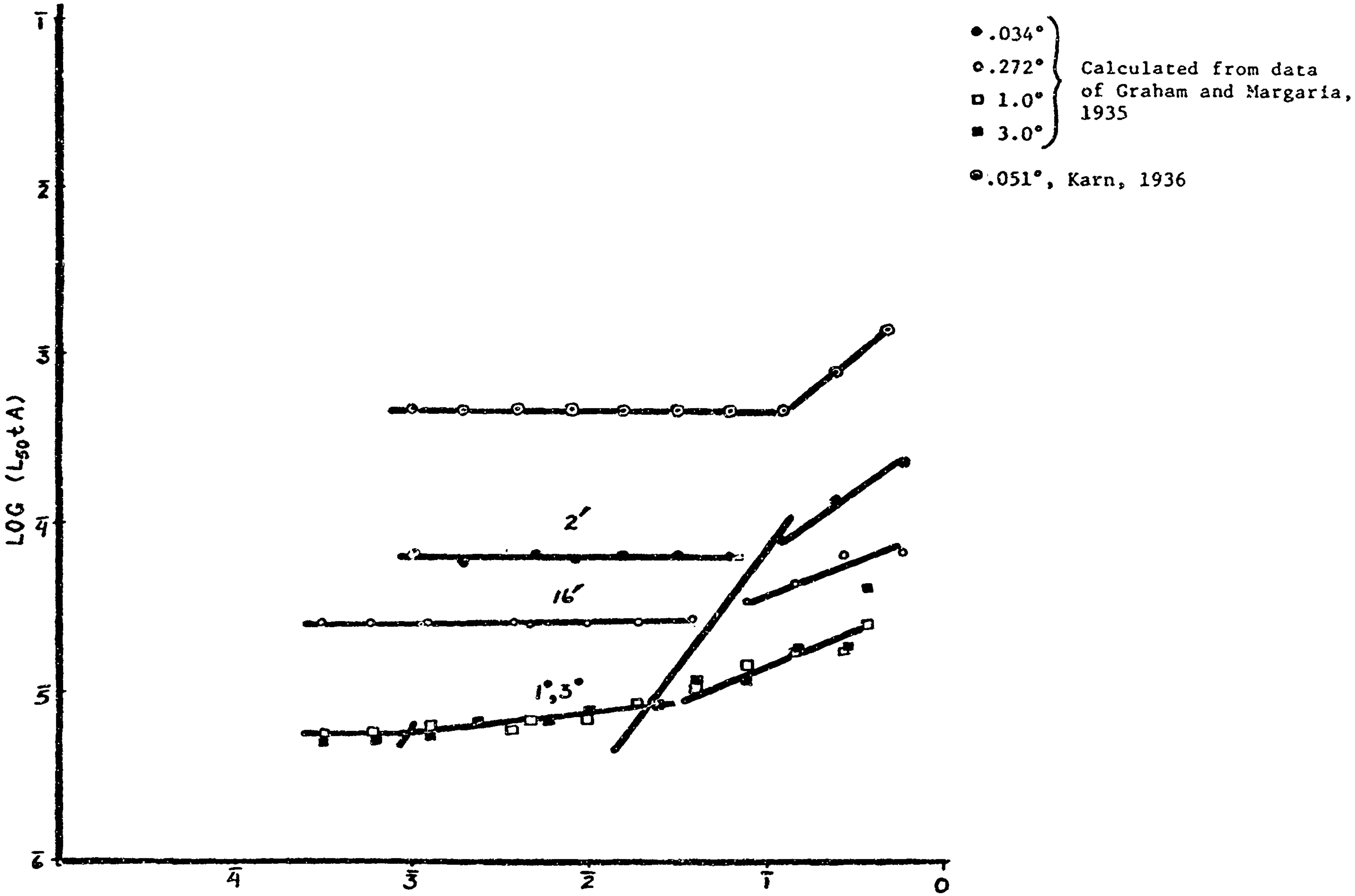

Figure 11. Threshold total energy as a function of duration with area as a parameter.

conclusion for threshold determinations of vision, especially as they are used to evaluate quantum energy relationships must be carefully evaluated. It would seem that some form of facilitation occurs with increasing area. This might be accounted for by assuming: (1) A statistical variation of receptor sensitivity over the retina, or (2) A statistical variation of receptor sensitivity from moment-to-moment, (3) Both kinds of variation, and (4) That the threshold for seeing depends primarily on the excitation of some minimum number of receptors. The fourth assumption plus any selection of the others would account for the data. We are not prepared at this time to discuss the implications of these assumptions to quantum theory or to attempts to relate the neurophysiological data to the human psychophysical response. It is clear, though, that if a model which uses assumptions of this sort is required, some revision of the present quantum model is required.

II. DETECTION OF A LUMINANCE DIFFERENCE

We were concerned above with the probability of detection of a light in a lightless background. We shall now be concerned with the detection of a difference in luminance between a uniform field of light (L) and a test area. The domain of research involves the luminance difference threshold (ΔL_{50}) and the Weber ratio ($\Delta L_{50}/L$). The latter is also called the contrast sensitivity and it is this term that we shall use. As before, most of the research has been concerned with the effects of stimulus parameters and retinal factors on the threshold. We shall designate the threshold contrast as C_{50}, thereby providing a terminology for other probability values such as C_{80}, etc.

Unlike studies of the L_{50} which have been primarily peripheral, studies of the C_{50} have been mainly foveal. This is in accord with the differential sensitivity of the fovea and of the peripheral retina under conditions of light and dark. Our particular interests in foveal vision are, therefore, more easy to satisfy with the contrast literature. In fact, as will be seen, there are available extensive data on binocular contrast sensitivity and these data are especially relevant to questions of complex task performance since such performance generally involves binocular viewing.

As before, we are concerned with two primary problems: (1) the estimation of any p(D) given only C_{50} as information, and (2) the estimation of C_{50} as a function of target size (retinal area of luminance change), exposure duration of the target (i.e., the change), and not in common with the L_{50}, with the luminance of the adapting or background field (L). Otherwise the approach is the same. We are assuming that the subject is adapted to the pre-target luminance, and that the underlying distribution of psychophysical responses is normal. If so, and if Crozier's Law holds with respect to the C_{50} and σ_c, a linear (or ogival) probability function can be established based upon any threshold and application made of the law to obtain the σ_c.

An extensive search of the literature was performed to find those studies of contrast sensitivity which reported values of p(D) or a measure of variability which could be transformed to a standard deviation. Of 14 such studies found, only 10 could be accepted as providing reliable information. In general, rejection was based upon the finding that the standard deviation was larger than the mean (i.e., threshold). Such a state of affairs must be viewed as having provided unreliable data even though the trend of the mean values was reasonable.

Table 1 lists the 10 studies which were accepted for further consideration. The studies may be seen to vary widely in terms of the slope constant obtained. Only five of the studies reported the number of observations made per subject per single threshold. It may also be seen that the number of subjects used is characteristically very small (usually the authors). Every effort was made to find a parametric basis for the variation in the slope constant, e.g., monocular vs. binocular, foveal vs. peripheral, white light vs. monochromatic light, area, duration, etc. No systematic arrangement appeared. We decided, therefore, to estimate the slope constant using only those studies having the larger subject samples. Arbitrarily, we selected those studies having five or more subjects for this purpose. Table 1 is arranged with those studies as the first four listings. The median of the six values presented for those four studies is 0.46. In view of the fact that Blackwell's (1947) study provides the largest number of measures and that Cobb and Moss, also having a large number of measures provided essentially the same value as that of Blackwell two out of three times, and considering that 0.50 held for the L_{50}, the expression

$$\sigma_c = .47C_{50} \qquad (3)$$

seems appropriate for general use. It may be said then that Crozier's Law holds for both the L_{50} and the C_{50} using the constants provided. It should be noted too that Blackwell (1962) has developed applications of his data (along with other of his data) to lighting design using this slope constant. The present analysis verifies that procedure.

Estimating the Contrast Threshold

The contrast threshold has been studied with a variety of test methods. All of them involve a comparison of a standa luminance with a test

Table 1. Mean slope constants (K) for $\sigma_c = KC_{50}$, the number of observations per single threshold (n), and number of subjects (N) on which σ_c and C_{50} are based.*

Author	N	n	K
Blackwell, 1947	9	320	.47
Cobb & Moss, 1928**	9	220	.48, .47, .30
Lamar, Hecht, Shlaer, & Hendley, 1947	5	not reported	.44
Vallerie & Link, 1968	6	not reported	.34
Blackwell, 1953	4	200-320	.14
Crozier & Holway, 1939	1-3	120-180	.11
Heinz & Lippay, 1928	2	not reported	.36
Herrick, 1970	2	260	.14
Holway & Hurvich, 1938	2	not reported	.08
Muller, 1951	2	approx. 160	.34

*All values of K were calculated from data provided by the authors except that for Blackwell (1947) which was reported in that paper. All values are means of the various individual estimates over all conditions except for Cobb and Moss.

**Cobb and Moss published "relative probable error" values. We assumed that these were probable errors and transformed them to standard deviations. The three values of K represent background luminances of 100 mL, 20 mL, and 1.0 mL.

luminance. Of the two really extensive studies, Blackwell (1947) used white light in a circular field as a background and a smaller circular area centered within it as a test patch. A comparison of test patch brighter than the field with the test patch less bright than the field, but at the same ratio of difference showed that when the difference between the two is small compared to the larger field, sensitivity is the same. For larger differences, the case of the dimmer test patch was about 15% more sensitive. It should be noted that at values of contrast greater than the C_{50}, the difference is larger. As a guess, we recommend that the correction be applied whenever a contrast of C_{75} or greater is to be employed for conditions which approximate those used by Blackwell or, following LeGrande (1957), whenever the diameter of the test patch is 1.0 degree of arc or less. Figure 12 provides Blackwell's data for a 6-sec. exposure for the case of the brighter test field.

Cobb and Moss (1928) used two parallel dark bars on a light background as a test condition. This procedure also represents the case of the brighter test patch and the same recommendations apply. Figure 13 shows their results for an exposure time of 0.17 sec. and varying size. Figure 14 shows the effect of different exposure times. Although both investigations provide functions of area, they do not provide them at comparable exposure times. They should be used as separate data sources, therefore.

The data of Figures 12-14 may be found in a variety of standard sources. They are unquestionably the most reliable data available for what they cover. Since our primary interest is in binocular viewing, monocular data will not be presented. Such data may also be found in most standard

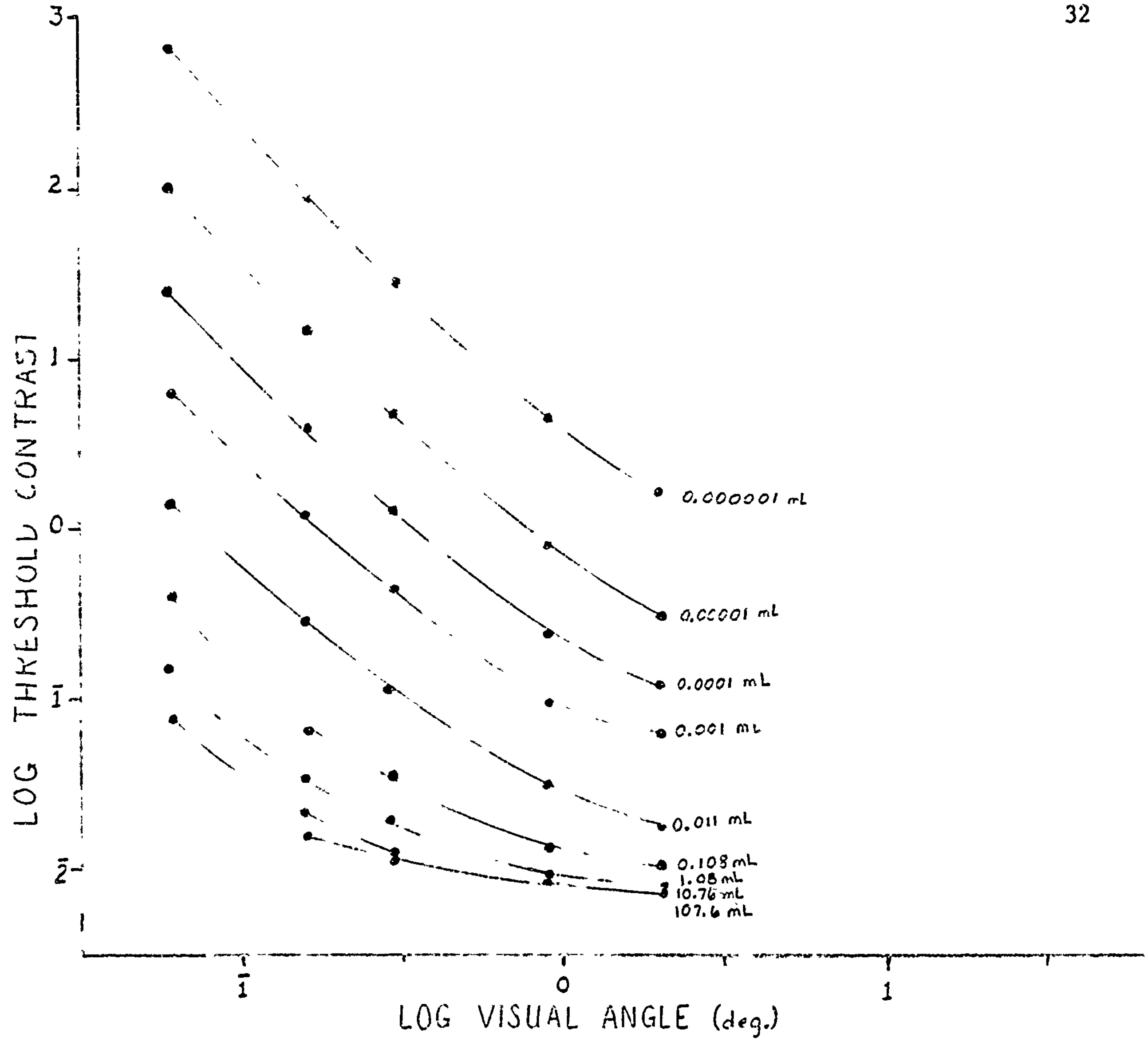

Figure 12. Binocular contrast threshold as a function of size and background luminance. Exposure duration = 6 sec. Data from Blackwell, 1947.

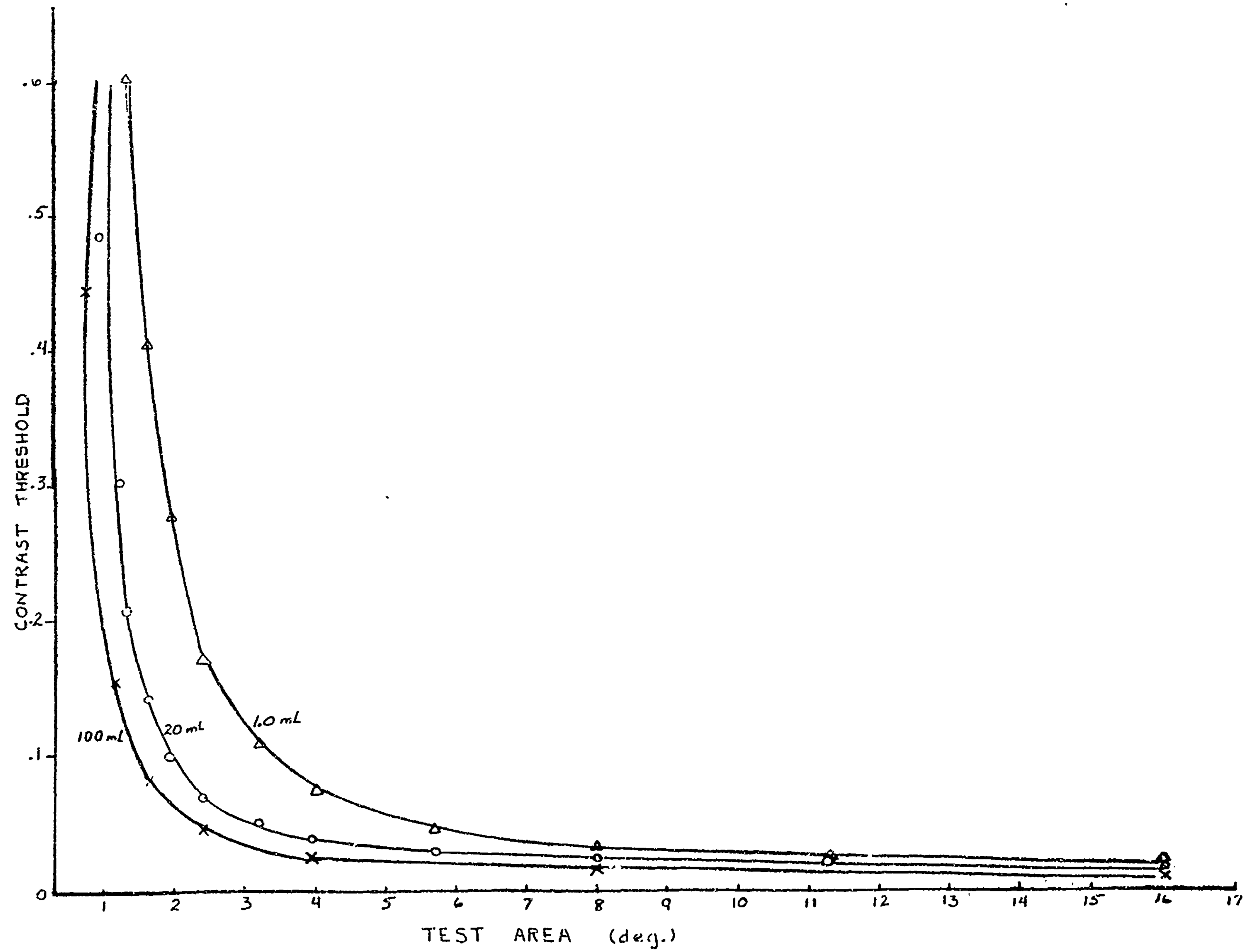

Figure 13. Contrast threshold as a function of test area with background luminance as parameter, for a constant flash duration of 0.17 sec. Data from Cobb and Moss, 1928.

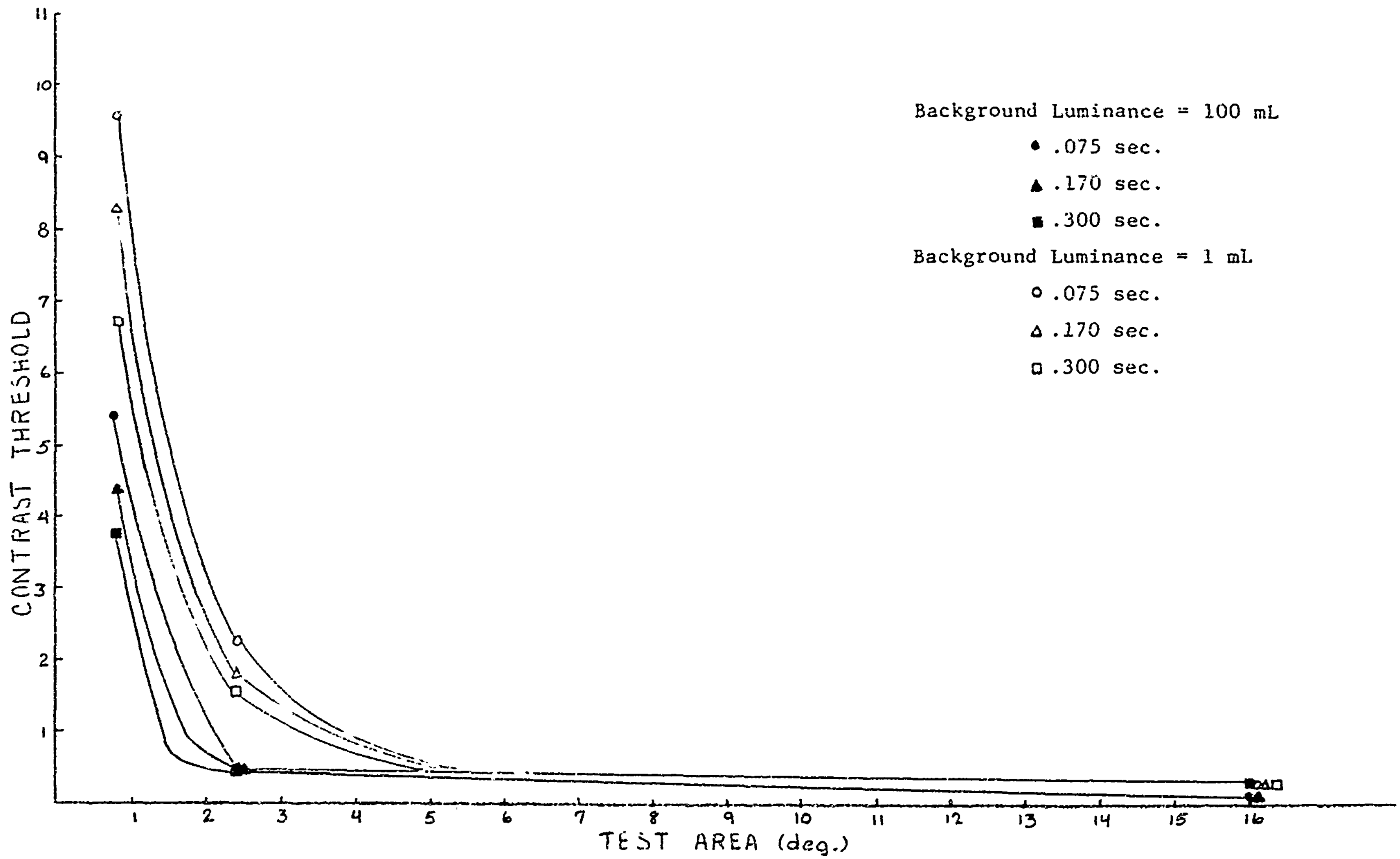

Figure 14. Contrast threshold as a function of test area with signal duration as a parameter. Data of Cobb and Moss, 1928.

sources, e.g., the reviews listed earlier. In addition all of the studies listed in Table 1 are detailed in our data base.

Retinal Position

The only systematic study of the contrast threshold at different retinal positions for binocular viewing appears to be that of Vallerie and Link (1968). The C_{50} for their three retinal positions calculated from their data is shown in Figure 15. It is clear that up to the limit studied, the relationship is linear. Figure 16 presents a plot of the increase in the C_{50} at different angles of eccentricity relative to the fovea. The increase is also linear and rapid.

Calculation of p(D)

Figures 12-14 should cover the range of viewing conditions of interest to human task performance. These conditions are for binocular viewing with straight-ahead fixation. For questions involving the detection of a luminance difference when the stimulus is at an angle with respect to the line of sight, Figure 16 may be used to correct the C_{50} obtained from Figures 12-14. Equation 3 should not be applied until all corrections have been made.

Evaluation

Our particular interest was in finding as reliable a way as possible to estimate p(D) for binocular viewing. The method depended upon the available literature and the results, therefore, cannot be more reliable than the data in that literature. It is clear that information about the

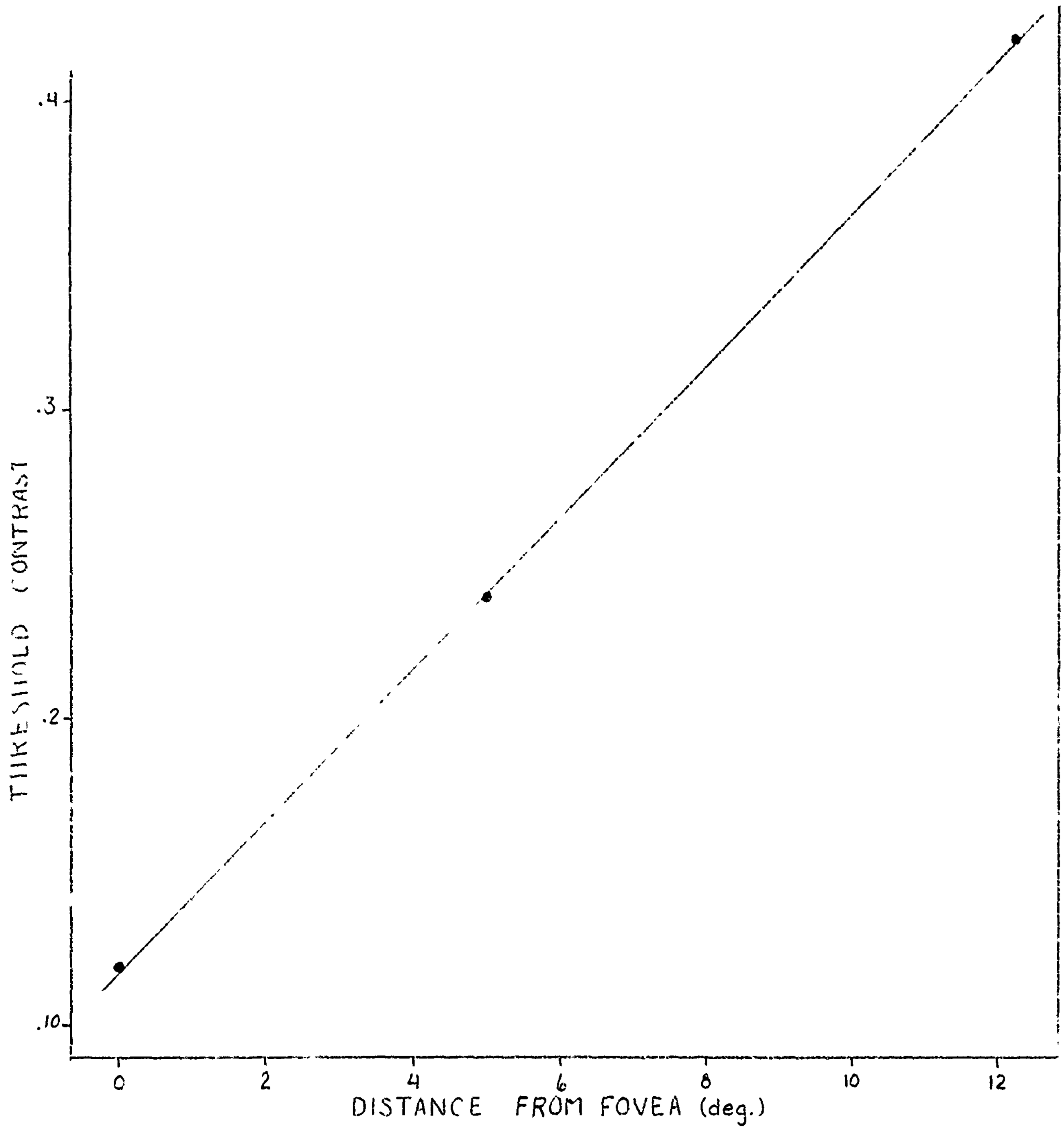

Figure 15. C_{50} as a function of retinal position. Average background [illegible] test flash of 0.55° diameter. Based on V[illegible]llerie & Link (196[illegible]).

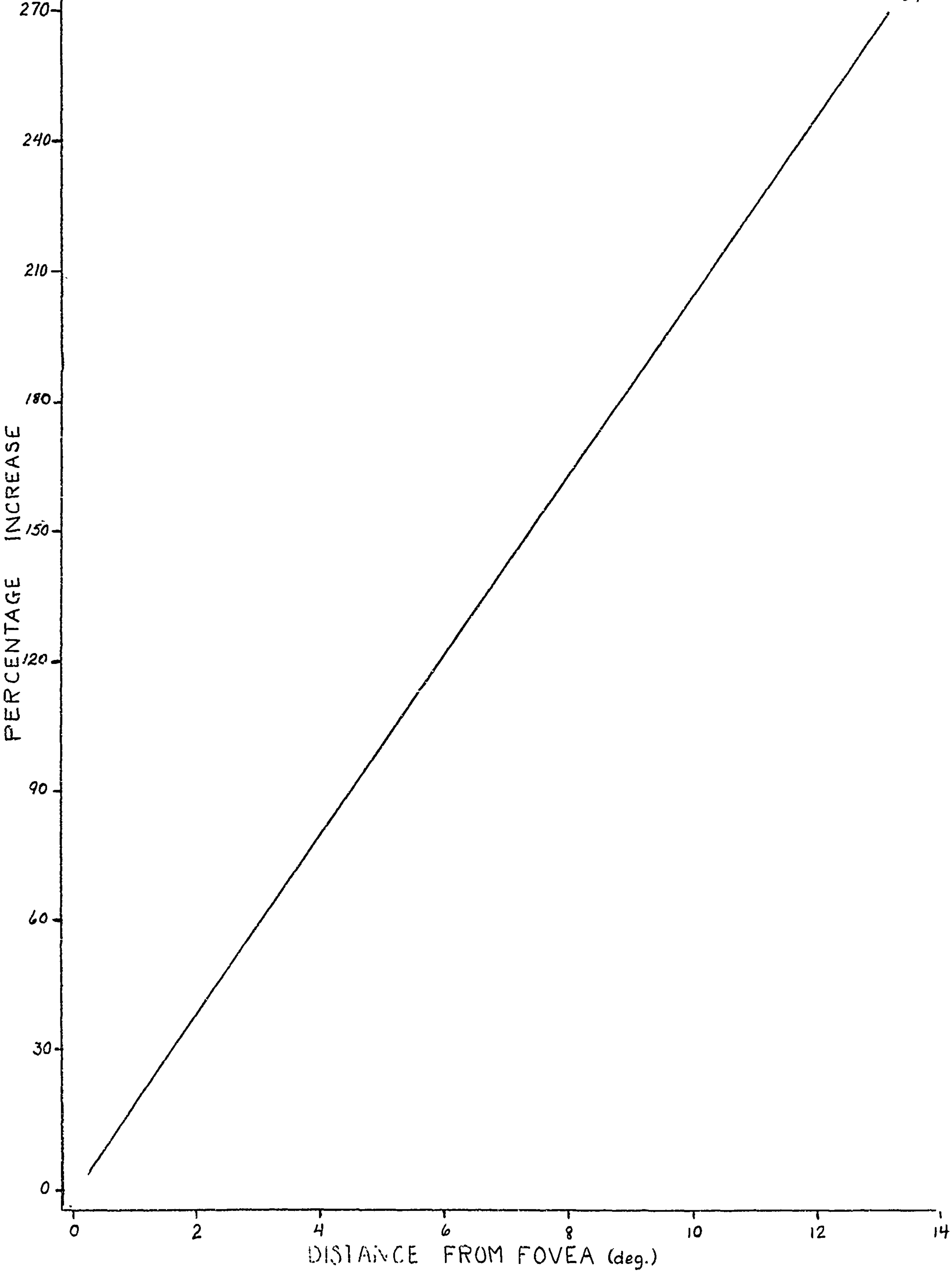

Figure 16. Percentage increase in C_{50} as a function of retinal position. Based on the data of Valerie & Link (1966).

parameters of contrast sensitivity are much more acceptable than they are for the absolute threshold. On the other hand, as we have tried to demonstrate, studies based upon the absolute threshold tend to have a fair enough degree of similarity in their absolute values to provide at least first estimates. Parametric studies similar to those for contrast are badly needed, however, if what has been done here is to be improved.

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13. ABSTRACT

Relevant studies from the literature on human visual detection were transformed into common units, collated and used to develop Crozier's law for the relationship between the threshold and the standard deviation. As a result, it now seems practical to estimate the probability of detection of any luminance or contrast given only a threshold value. The literature was also used to establish a basis for estimating the binocular contrast threshold and the absolute threshold. In regard to the latter, a detailed re-examination of the published data revealed that there is no reciprocity between luminance and retinal area as is general supposed. Bloch's law for the summation of luminance and duration was found to hold up to a limit.

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