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THE EFFECT OF BACKGROUND LUMINANCE ON BRIGHTNESS DISCRIMINATION

by

O. Thomas Law, Jr.

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THE EFFECT OF BACKGROUND LUMINANCE ON BRIGHTNESS DISCRIMINATION

by O. Thomas Law

This study is concerned with the influence of background luminance, B, on the threshold of visual brightness discrimination, $\overline{\Delta B}$. Three general problems were investigated: (1) Does $\overline{\Delta B}/B$ reach a lower asymptote for large B, or is there a reversal in the trend of values of $\overline{\Delta B}/B$ at large B; (2) Does $\overline{\Delta B}$ reach a limiting value for small B, or is there a reversal in the trend of values of $\overline{\Delta B}$ for small B; (3) Is the variability of $\overline{\Delta B}$ proportional to the value of $\overline{\Delta B}$ for all values of B?

Threshold determinations were made by the method of constant stimulus by each of 4 observers. Threshold data under each experimental condition have been analyzed by fitting the integrals of normal frequency distributions to them in a manner satisfying the maximum likelihood criterion. Monocular vision and a 1 mm. artificial pupil were employed. Refractive errors were reduced to negligible magnitude. Experimental conditions included the following: white light; target sizes of 1 and 45 minutes of arc; target duration of 1/100th second; values of B from "zero" to 1,000 foot-Lamberts. More than 38,000 observations were made in all.

Data for the four observers were in close quantitative agreement throughout. The method of data analysis was shown to be empirically justified for all the experimental data. It was found that: (1) Values of $\overline{\Delta B}/B$ decreased regularly to an asymptotic

value as B was increased; (2) Values of $\overline{\Delta B}$ decreased regularly to a limiting value as B was decreased; and (3) The variability of $\overline{\Delta B}$ was generally proportional to the value of $\overline{\Delta B}$ for all values of B investigated.

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Mr. James G. Ohmart was indispensable in the maintenance and operation of the complex apparatus. The mathematical analysis of the data was carried out under the direction of Dr. Wilfred M. Kincaid. Dr. John H. Taylor contributed his technical skill to the optics and photometry of the experiments. The figures and miscellaneous drafting, as well as untold help throughout this work, are the efforts of Patricia J. Law.

To all who shared in the work here presented, I wish to express my deepest appreciation.

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I. INTRODUCTION*

The history of investigations of visual brightness discrimination is one of the most interesting in experimental psychology. Being the most accessible and most versatile of the sensory systems, the visual modality was early selected as a fecund area of sensory research. Considerable attention was given to visual brightness discrimination, perhaps because this discrimination appeared to be the least confounded case of visual sensation. Perhaps because of the relative ease of manipulation of variables associated with brightness discrimination, this problem has been one of the most completely explored of all problems of experimental psychology.

What is perhaps the simplest example of brightness discrimination may be described in the following way. A large area, referred to as the adaptation or prevailing luminance, or simply as the background, is uniformly illuminated to a predetermined level over its entire surface. The luminance of the surface may be symbolized by the letter B. An additional quantity of light, ΔB is added to some portion of the large area for some brief duration. The precise amount of this quantity is varied until a response is evoked from the observer indicating that he has detected a lack of uniformity in the luminance of the background for the brief duration of the increment. The value of ΔB which evokes the signalling response 50% of the time is referred to as the brightness difference threshold, $\overline{\Delta B}$. The relations between the brightness difference threshold and various aspects of the stimulus situation

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* Much of the discussion in this section is derived from Boring (1).

have been extensively studied.

A. THE DUPLICITY THEORY

Investigations of the physiology of the retina were conducted concomitantly with the development of knowledge of visual discriminations. Evidence from both sources suggested the existence of two structurally and functionally distinct visual systems. The notion that there were two such systems has become known as the "duplicity theory", since von Kries suggested the name in 1894. Evidence for the existence of two structurally distinct systems came from the work of Schultze, who in 1866 established the histological reality of two populations of discrete receptor cells in the retina. Subsequent work by Boll in 1876 on visual purple, and by Koenig in 1889 on visual yellow was confirmatory. Evidence that there are two functionally distinct systems has accumulated since von Kries. The work of Hecht (25) is particularly notable in this connection.

Among other sensory discriminations, brightness discrimination may be shown to vary between the two functional systems identified with the structures, rods and cones. Figure 1 exhibits data taken from Steinhardt (36) showing the characteristic duplex curve for brightness discrimination data. The two limbs of the curve are attributed to the two classes of receptor elements in the retina. The left-hand limb is identified with the function of the rods, the right-hand limb is associated with the cones.

B. THE RELATION BETWEEN $\Delta B/B$ AND B

The earliest known study of visual brightness discrimination was made by Bouguer, who in 1760 studied the relation between the threshold

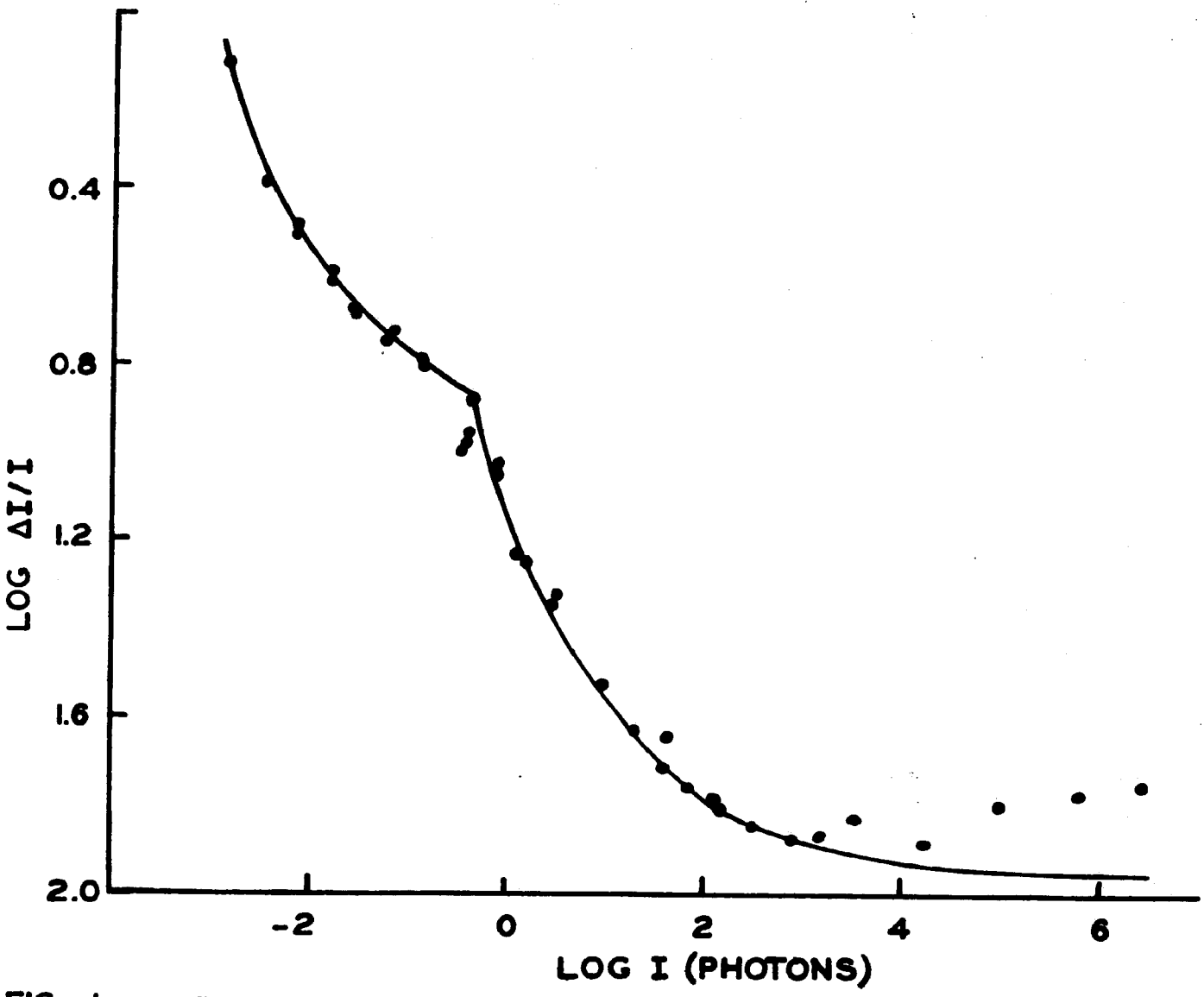


FIG. 1 Contrast threshold curve involving retinal periphery and fovea. 24° target. (from Steinhardt.)

increment of luminance, $\overline{\Delta B}$, and the prevailing luminance, B. Bouguer reported that the ratio of $\overline{\Delta B}$ and B was constant for the several values of B investigated. In 1834 Weber reported this same constant proportionality in the case of kinesthetic discrimination of differences in lifted weights. Weber's conclusion assumed importance through its generalization by Fechner, who assumed the constant proportionality between $\overline{\Delta B}$ and B to be a general law. In making this generalization, Fechner ignored the earlier contradictory evidence of Masson, whose work was reported in 1845. Masson showed that $\overline{\Delta B}/B$ was a function of B.

Fechner's assumption of generality for constant proportionality between $\overline{\Delta B}$ and B was soon shown conclusively to be unjustified. Many separate studies showed that $\overline{\Delta B}/B$ could be described as constant only over a limited range of luminance. Typical of this research is the work of Koenig and Brodhun (32,33) whose results are reproduced in figure 2. We note the marked absence of constancy for the ratio $\overline{\Delta B}/B$ as a function of B.

The data of Koenig and Brodhun contributed to the disposition of one controversy, but have figured prominently in another. This controversy concerns what has become known as the "upturn". The question is whether or not the value of $\overline{\Delta B}/B$ continues to decrease as B increases, when B is large. A second increase in $\overline{\Delta B}/B$ for large B, would represent an "upturn" in the curve relating $\overline{\Delta B}/B$ to B.

We note that the Koenig and Brodhun data exhibit an upturn at high values of B; we note also that Steinhardt's data presented in Figure 1 exhibit an upturn.

The question of the upturn has assumed special interest on theoretical grounds. Hecht (24) has proposed a theory of visual brightness

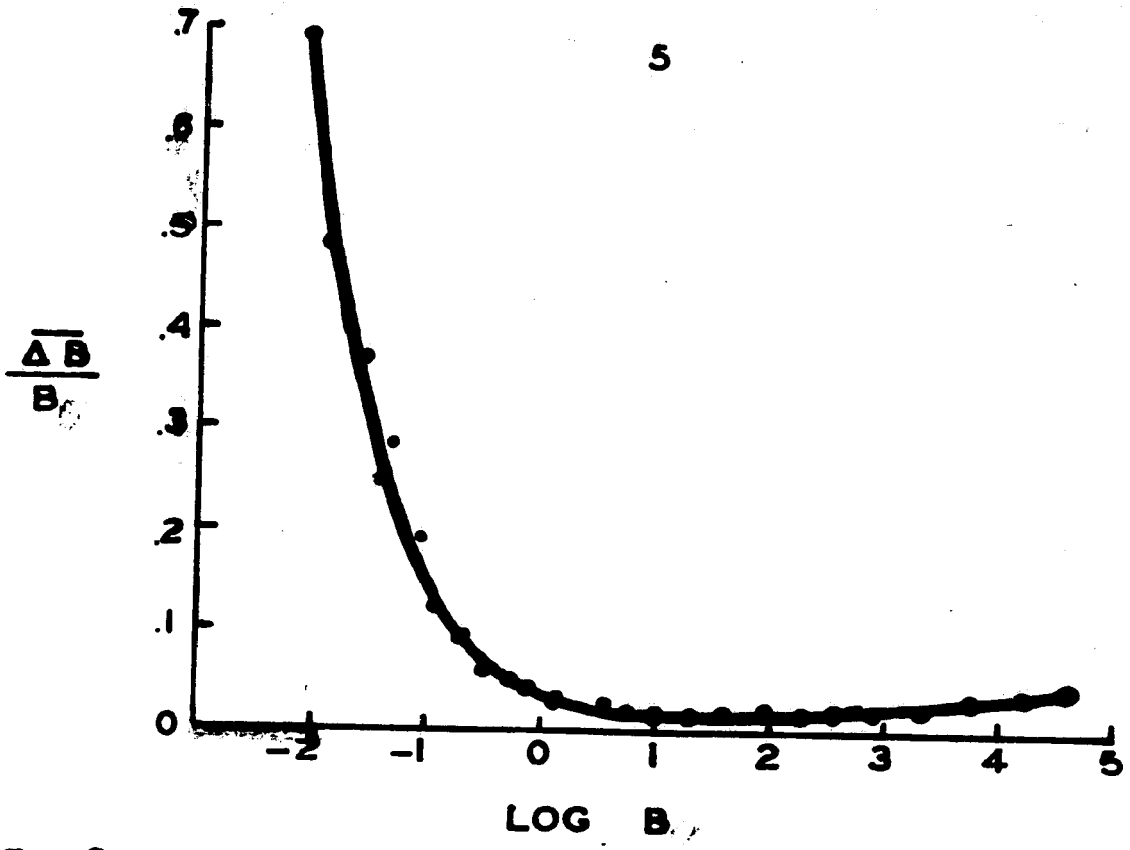


FIG. 2 Differential brightness sensitivity. (from Koenig and Brodhun)

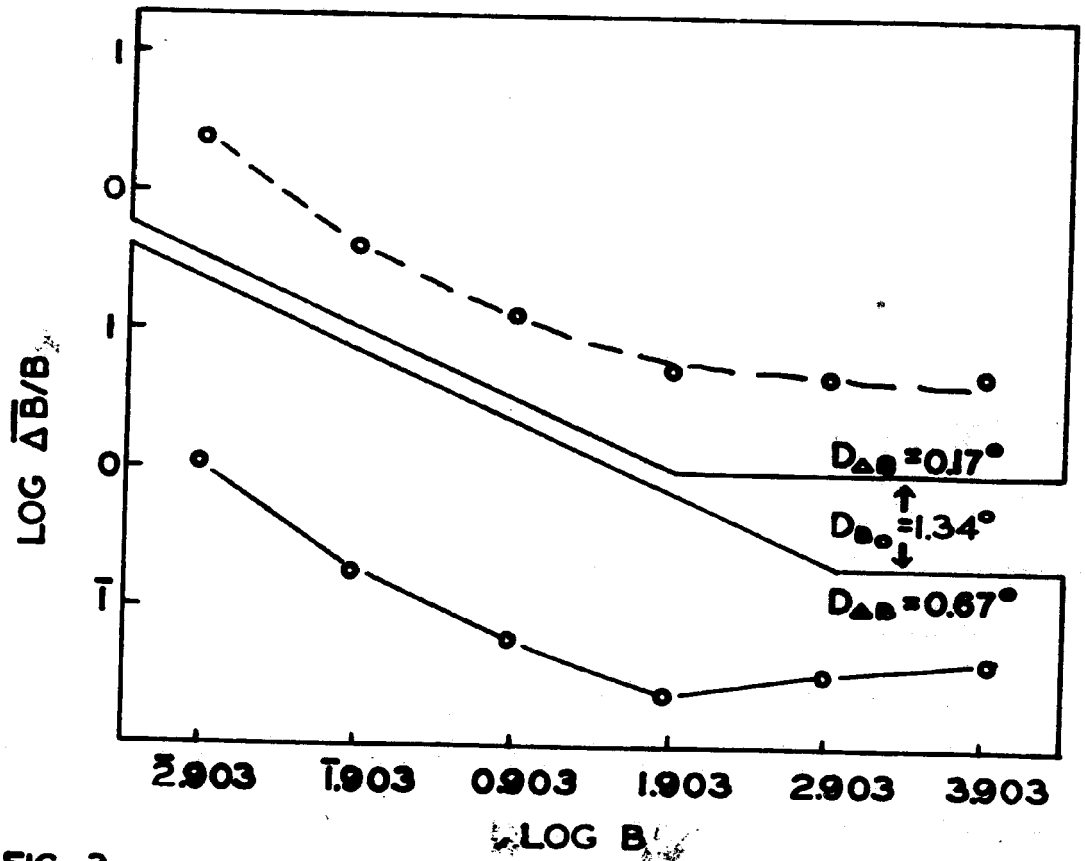


FIG. 3 Contrast threshold curves for two target sizes from Ratoosh and Graham. D_B is the target diameter, D_{B_o} is the background diameter.

discrimination which predicts that $\overline{\Delta B}/B$ will continue to decline as B increases until an asymptotic value is reached. Hecht attempted to explain the existence of the upturn in the Koenig and Brodhun, and Steinhardt data on the basis that somehow "adaptation" is inadequate at high values of B.

An apparently more adequate explanation has been offered by Graham and Kemp (23). The argument begins with the relation between critical duration and B. (Critical duration is the exposure duration for a stimulus presentation below which duration and $\overline{\Delta B}$ are reciprocally related.) Graham and Kemp have shown that critical duration decreases as B increases. Now suppose that the exposure duration used in an experimental study of various values of B is larger than critical duration at some, and smaller at other, values of B. The relation between $\overline{\Delta B}$ and B will be different than it would be either if the duration were always smaller, or always larger, than critical duration. Graham and Kemp have shown analytically that use of an exposure duration which is sometimes larger, sometimes smaller, than critical duration can lead to an "upturn". Keller (31) has determined the relation between critical duration and B more precisely and has exhibited examples of curves with "upturns" produced in this way.

Figure 3 represents data taken from a recent study by Ratoosh and Graham (35) which again display the upturn. Data are presented for two sizes, the larger of which shows the upturn, while the smaller size does not. These investigators used a duration of 0.02 seconds. Extrapolating from the data of Graham and Kemp, a duration of 0.02 seconds will represent the critical duration at a luminance of approximately 1500 ml. Since the upturn in the Ratoosh and Graham data extends from about 800 to 8000

ml., it seems likely that it may be attributable to the introduction of the effects of critical duration. The principal shortcoming of this explanation is that it applies with equal force to both stimulus sizes, and yet the upturn appears only with the larger stimulus. Perhaps the difference between the two stimulus sizes can be attributed to differences in critical duration as a function of size. Available data do not permit us to evaluate this possibility.

The crucial test of the explanation of upturn on the basis of critical duration is to study the relation between $\overline{\Delta B}$ and B for very short durations, which may be expected to be smaller than the critical duration at all values of B.

In addition to the controversy concerning the form of the $\overline{\Delta B}/B$ relation for very large values of B, there is some question as to the exact form of the relation for very small values of B. There are few reported studies which have been concerned with the relation of $\overline{\Delta B}$ to B at low luminance values. Evidently, this relation will be most obvious when the threshold data are plotted in terms of $\overline{\Delta B}$ and B. The usual procedure involves plotting the values of contrast, $\overline{\Delta B}/B$, and B . Blackwell (2) has plotted his data in terms of $\overline{\Delta B}$ and B as is shown in Figure 4. We note the discontinuities in the curves,presumably corresponding to the use of rod and cone receptors. The right-hand portion of each curve corresponds to the use of cones, the left-hand portion to the use of rods.

Let us consider only the cone portion of each curve. In the case of the smaller targets, it appears that $\overline{\Delta B}$ becomes constant for small values of B. In the case of the larger targets, it seems possible that the cone curve would eventually come to $\overline{\Delta B}$ constancy if it could be

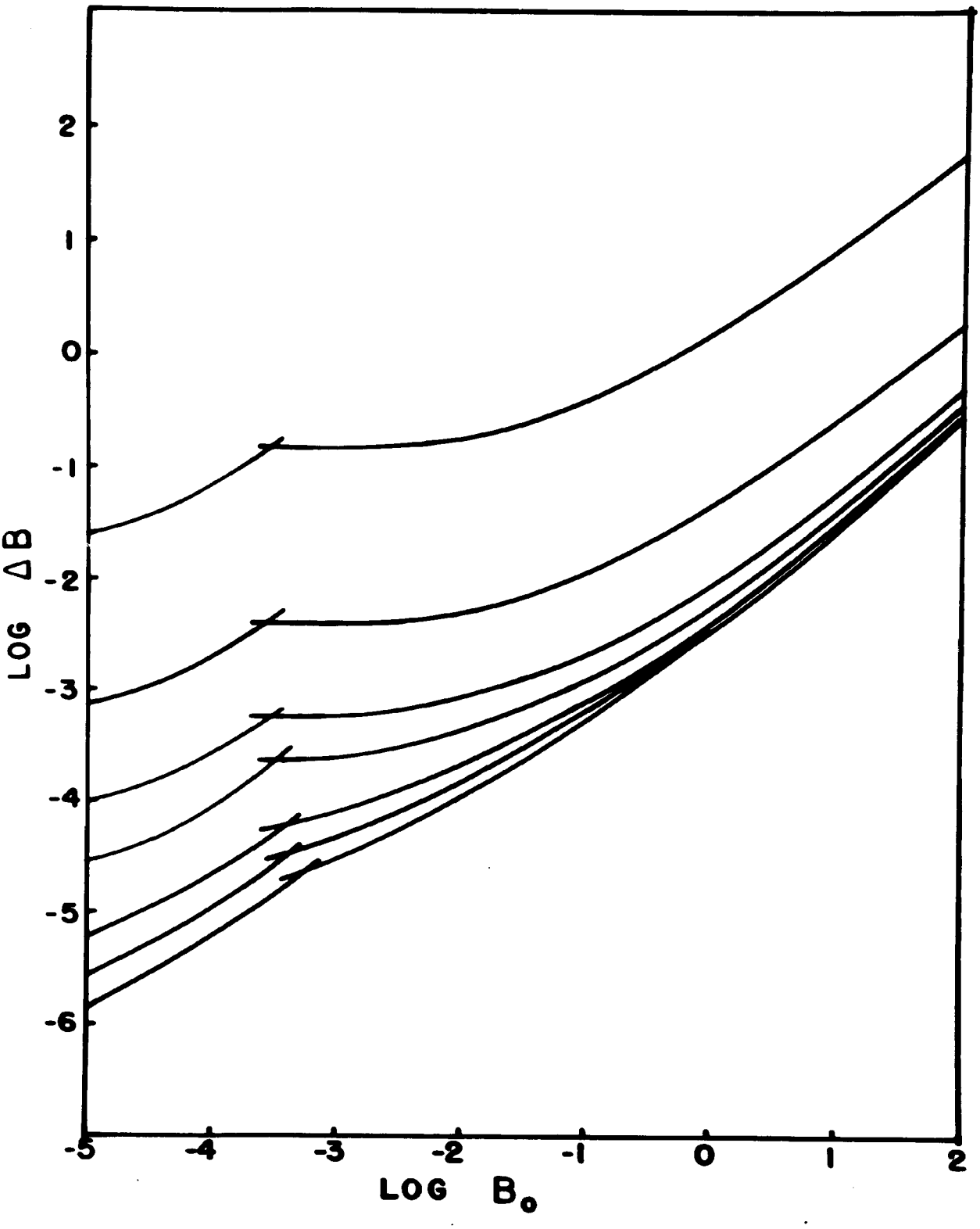


FIG. 4. Brightness Discrimination Thresholds for 7 Target Sizes. From Top to Bottom, Curves Represent 0.595, 3.60, 9.68, 18.2, 55.2, 121., 360. minutes. (Blackwell)

continued to the low luminances at which rod function appears to have been elicited. We could presumably obtain this continuation of the cone curve if we studied foveal vision, since rods are believed to be entirely missing from the foveal retina. We may well wonder to what extent $\overline{\Delta B}$ will be independent of B for low luminances. Blackwell's data encourage us in the belief in this independence, although we cannot consider this simplification to have been demonstrated conclusively from the reported data.

Indications that the value of $\overline{\Delta B}$ is <u>not</u> constant for low luminances have recently been advanced by Crozier (9). Crozier has reported that $\overline{\Delta B}$ is smaller at values of B somewhat greater than zero than it is at zero. Crozier has described this effect as "photosensitization". Such a result runs counter to the notion that $\overline{\Delta B}$ decreases gradually as B is decreased and reaches the minimum value at B equal to zero. Unfortunately, detailed data from Crozier's experiments are not available. Certain preliminary data from a pilot study by Blackwell, Pritchard, and Ohmart (6) reveal no such decline at low background brightnesses. The points are too few, however, to be decisive.

C. CROZIER'S LAW*

Thus far, we have concerned ourselves only with the relation between values of $\overline{\Delta B}$ and B. The threshold, $\overline{\Delta B}$, is not an absolute quantity. It has been known since Fechner that values of $\overline{\Delta B}$ vary from moment to moment, due presumably to momentary variations in the sensitivity of the visual system. We now turn to certain facts

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* I am much indebted to Professor H. Richard Blackwell for permission to quote from his manuscript (4) which contains an excellent and exhaustive critical review of the vast amount of work done by Crozier and his colleagues. For further detail, consult this reference.

concerning the nature of the variability of the threshold. Let us measure this variability by its standard deviation, specified as $\sigma_{\Delta B}$.

Crozier's law states that $\sigma_{\Delta B}$ and $\overline{\Delta B}$ are directly proportional. This proportionality was suggested by Weber in 1834, but little significance was attached to it. Willis and Urban (38) presented fragmentary evidence for the proportionality. It remained for Crozier and his colleagues to collect and present extensive evidence to support the generalization, thoroughly justifying the designation of the relationship as Crozier's law.

Evidence for Crozier's law comes from a number of studies of visual discriminations of a number of other animal forms. We are interested here primarily in the data obtained on human observers. We may note in passing that the proportionality has been shown to exist on fourteen animal forms in addition to the human. Let us consider the human data in somewhat greater detail.

Upton and Crozier (37) found the proportionality in auditory discrimination of differences in intensity presented to the two ears. Holway and Crozier (27,28) found the proportionality in discrimination of somesthetic pressure. Holway and Hurvich (29), and Holway, Smith, and Zigler (30) found it for the discrimination of kinesthetic differences in a weight-lifting experiment. Crozier and Holway (10) found the proportionality in the case of cutaneous pressure discrimination.

Most of the evidence for Crozier's law come from the investigations of the visual modality. The proportionality was shown to exist in brightness discrimination by Holway (26) and Crozier and Holway (11, 12, 13). It has been demonstrated most widely in studies of visual flicker discrimination as reported by Crozier and Wolf (14, 15, 16, 17, 18, 19) and by Crozier, Wolf, and Zerrahn-Wolf (20).

All these studies involved comparatively crude methods of measurement. The subjects obtained psychophysical thresholds by methods of adjustment or methods of serial exploration. As Blackwell has shown elsewhere (4), the measures of variability of the threshold computed from data obtained in either of these ways are not solely dependent upon sensory events. For this reason, it is not obvious from the studies cited above that Crozier's law represents a basic law of the sensory systems.

Thresholds obtained by methods of constant stimuli are considered by Blackwell to be independent of non-sensory variables to a much greater extent than is the case with the other methods. We may ask to what extent Crozier's law has been demonstrated among data obtained by the method of constant stimuli. Such data have been reported by Blackwell (3,4). The data represented a large sample of experimental results obtained under a variety of conditions of background luminance and target size. White light was used throughout. To a good approximation, $\sigma_{\Delta B}$ and $\overline{\Delta B}$ were proportional. Data from Mueller reported by Graham (22) also indicate the approximate proportionality of $\sigma_{\Delta B}$ and $\overline{\Delta B}$. These data were obtained with the method of constant stimuli. White light was used in this experiment also.

Unfortunately, both the Blackwell and the Mueller studies were carried out with binocular vision and natural pupils. The most fundamental relations would probably be expected to exist under the simplest experimantal conditions, represented by the use of monocular vision and artificial pupil. One set of data are available, reported recently by Crozier (8), in which monocular vision and artificial pupil were utilized. In this research, Crozier used the method of constant stimuli. The targets were chromatic point sources. The data showed a complete break-down of

the proportionality between $\sigma_{\overline{\Delta B}}$ and $\overline{\Delta B}$. We may wonder to what extent Crozier's law depends upon the use of white light, and to what extent upon the use of binocular vision and natural pupils.

We have noted three general problems with respect to brightness discrimination for which we do not have adequate answers: (1) Will values of $\overline{\Delta B}/B$ decline steadily as B increases until an asymptotic value is reached, or will an "upturn" exist, provided the target duration is shorter than the critical duration at any value of B? (2) Will values of $\overline{\Delta B}$ decline steadily as B decreases until an asymptotic value is reached, or will there be a "photosensitization" effect? (3) Will Crozier's law apply to data obtained with white light, when monocular vision and artificial pupil are utilized?

The present research is intended to investigate these general questions.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

The present study is intended to provide evidence on the fundamental nature of the relation between threshold luminance increment, $\overline{\Delta B}$, and background luminance, B, for the foveal retina. The extent of knowledge of the functioning of the visual system is sufficiently advanced so that it is possible to specify a number of experimental conditions which must be met if fundamental data are to be obtained. These conditions, may be listed briefly as follows:

1. Control of the location of the target on the approximate center of the foveal retina;
2. Control of the pupillary aperture;
3. Control of the refractive state of the eye;
4. Control of the background luminance; and
5. Control of the size, luminance, and duration of the target.

The ways in which these controls were maintained are described in detail in the following account of experimental apparatus and procedures.

A. OBSERVERS

Four observers were used throughout the experiments in order that the results would have reasonable generality. Two of the observers were adult females, one (LP) an emmetrope, and one (HF) with corrected low-order myopia and astigmatism; and two adult males, one (TL) a corrected myope of moderately high-order, the other (AK) with corrected low-order myopia.

All observers were thoroughly trained prior to recording the experimental data. Three of the observers were graduate students in experimental psychology, the fourth was a laboratory technician. Motivation seemed well sustained throughout the long and tedious series of experiments.

Because of individual differences in threshold among the observers, it was at times necessary to collect data on groups of two observers at a time; at other times, because of the nature of the orientation light system, it was necessary to collect data on observers singly. In general, all observers worked at a given luminance level before they all proceeded to work at the next luminance level. The possible influence of practice effects due to increases in the observers' familiarity with the conditions and procedures, and their facility in response, was in great part obviated by a protracted period of practice (about two weeks) in the observing situation, and further mitigated by the experimental procedure, described below. Observers were practiced in the situation until their threshold curves showed no further improvement.

B. APPARATUS

The apparatus used to produce the background and target luminances is illustrated schematically in Figure 5. The observers viewed the far wall of a large cube, which served as the background luminance, through a large opening in the near wall. The far wall was lighted by a series of incandescent lamps located on the near wall of the cube around the opening, which were shielded from the observers' eyes. The target appeared from time to time in the center of the far wall, as a luminance increment. The target was produced by a projection system located behind the far wall. The larger portion of the far wall was covered with a milk-plastic screen. The target was produced by transilluminating the screen over a restricted area. The screen was located an average of 10.8 feet from the eyes of the observers.

High background luminances were produced by four arrays of 100-watt lamps, one array on each of the sides of the opening in the near wall.

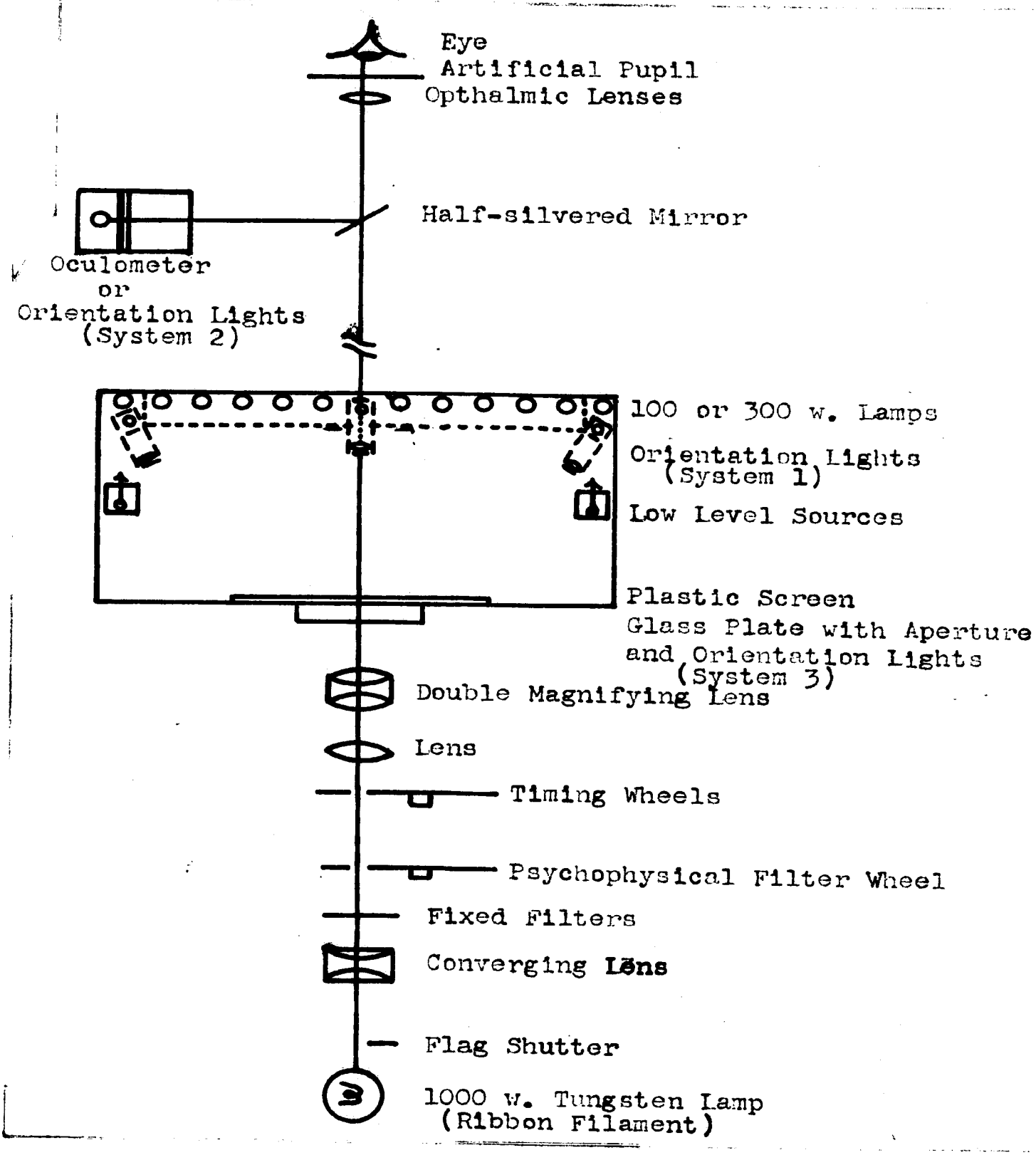


FIG. 5 Schematic diagram of optical system (not drawn to scale).

Reduction in the number of these lamps was used to produce luminances in the range from 3 to 100 ft.-L. A level of 1 ft.-L. was produced by three 40-watt incandescent lamps, one at each of the sides and top of the near wall. In each case, direct illumination of the plastic screen by the lamps was prevented by disc deflectors placed on the lamps. For all values below 1 ft.-L., the luminance of the plastic screen was provided by two small integrating light boxes containing 6-volt, 32-candle-power incandescent lamps. Each light-box had an opal glass screen. These screens were not used to illuminate the plastic screen directly, but were used to illuminate the near wall of the cube directly, and the plastic screen by reflection from the near wall. These two boxes were mounted against the sides of the cube walls at a point which prevented the observers from viewing the opal glass surfaces directly. The luminance of the plastic screen produced by the light-boxes was adjusted by use of Wratten neutral filters, placed over the opal screens of these boxes.

The target projector was based upon a special tungsten ribbon-filament lamp developed by the General Electric Company, the output of which was equivalent to a 1000-watt monoplane projection lamp. The ribbon-filament lamp was operated at 6-volts AC. Two sets of Wratten neutral filters were used to adjust target luminance: "fixed" filters reduced the target luminance to approximately the desired value. These filters were fixed during any given experimental session. Additional adjustment of the target luminance was obtained by the psychophysical filters. These filters adjusted the target luminance to the values desired within the psychophysical series. Five psychophysical filters were used, mounted on an electrically-driven filter-selector which could

position one or another of them in the projection beam. Transmission values for these filters were: 1.000, 0.752, 0.450, 0.287, and 0.172.

The presentation of the target was controlled by the operation of a flag-type shutter. Whenever a solenoid was activated the shutter was removed from the projection beam.

The optical system of the projector is indicated in Figure 5. The converging lens formed an image of the filament in the plane of a pair of timing wheels, to be described below. A lens was located anterior to the timing wheel which collimated the beam. When point targets were desired, the beam then passed through a positive lens which formed an image of the filament on a glass plate, one side of which bore a piece of thin brass shimstock with a hole drilled in it of 0.035 inch diameter. The positive lens is indicated in Figure 5 as a double magnifying lens. The side of the glass plate bearing the shimstock was opaque except for the center area circumscribed by the hole, and was in contact with the rear of the plastic screen.

When a large target was used, a negative lens was used in place of the double magnifying lens, to provide a uniform large area of illumination of the rear of the plastic screen. In this case, the glass plate bore a piece of shimstock with a 1.56 inch diameter hole.

The side of the plastic screen facing the observers was covered with an extremely thin layer of white sphere paint, designed to eliminate the specularity of the plastic screen without introducing spectral selectivity. The color temperatures of the target and of the background luminance were set for 2850° K.

The timing of the target presentation was arranged and controlled by a timer comprising two discs mounted on a single shaft, one rotating

at seven times the speed of the other, and designed to juxtapose two adjustable slots in the perimeters of the discs and the projection beam. The timer wheels intercepted the projector beam in the plane of a filament image. Variation in the chord length of the slots can be utilised to produce continuous variation in the duration of the pulse of light from about 1/30 to 1/1000 second. The time required for the target to come to full luminance was 1/10,000 second. (A ribbon-filament was used in order to minimize the onset time.)

In the present experiment, an exposure duration of 1/100 second was used throughout. This duration was selected to be shorter than the critical duration at all values of B.

The optical system used provided overall increase in luminance of the large target as it is presented, rather than a "shadow" type of onset. The point target was produced by a "shadow" type of onset, but in this case this procedure is entirely acceptable since the eye cannot resolve spatial aspects of a point target.

Experiments were conducted with each of two target sizes, representing 1 and 45 minutes of arc. These two sizes represent the extremes of a point source and an extended source which covers nearly the entire rod-free area of the central fovea. There is no evidence to suggest that Crozier's law will apply more with large than with small targets, nor is there any evidence that "photosensitization" will be more evident with small or large targets. The Ratoosh and Graham data suggest that the upturn is more likely to occur for large than small targets.

C. EXPERIMENTAL PROCEDURES

1. Psychophysical Method

Because of its superior validity and reliability, the temporal

forced-choice variant of the method of constant stimuli as described in detail by Blackwell (5) was used in this study. Essentially, the temporal forced-choice method presents the observer with four successive, aurally delineated, 2-second time intervals. In one of these only, as determined randomly by the presentation sequence, there appears a target of randomly selected luminance. After a cycle of four temporal intervals is completed, the observer is allowed eight seconds to press one of four buttons located on his arm rest indicating in which of the four intervals he believes the stimulus to have appeared. These responses are then automatically tallied in a distant room on electrical counters and punched on cards for permanent reference. Although ten targets of the same luminance succeed each other, each block of ten is randomly arranged with respect to all other blocks of ten in terms of luminance. Five such blocks, ranging in difficulty from a target visible nearly 100% of the time to a value virtually never visible are presented in one experimental session.

After the presentation of fifty targets observers were permitted a five minute break while the equipment was re-set. A fifteen minute break for refreshment customarily followed the third block of stimuli.

Fortunately, automatic presentation and recording equipment designed for use with this method, described by Blackwell, Pritchard, and Ohmart (7) was made available to the writer. The amassing of the great amounts of data necessary to this study would otherwise have been impossible.

The basic experimental data were percentages of correct choice for each of five target luminances. Analysis of the data begins by eliminating the effect of chance successes by the relation:

$$p' = \frac{p - .25}{.75}$$

where p' = corrected proportion, and

p = raw proportion.

The corrected proportions were analyzed by a variant of the probit analysis developed by Professor Blackwell and Dr. W. M. Kincaid of the Vision Research Laboratory of the University of Michigan, based on the probit method of Finney (21). Basically, the probit method fits a theoretical curve to the data to satisfy the maximum likelihood criterion. In this case, the theoretical curve was the normal ogive. Analysis of the data in this manner yields the value of the threshold, the standard error of the threshold, the slope of the ogive, the standard error of the slope, and an estimate of the goodness of fit determined by the Chi-square test.

2. Photometric Procedures

The basis of all photometry was the Macbeth Illuminometer, calibrated against standard lamps and standard reflectance surfaces certified by the Electrical Testing Laboratories, New York. The calibration of the Macbeth and filterswas checked several times during the experiments.

High luminances of the screen were measured directly with the Macbeth, fitted with a lens which imaged the screen in the photometric cube of the Macbeth. Low luminances, produced by the light boxes described above, were photometered indirectly. The ratio between the luminances of the opal screens of these light boxes and the resulting screen luminance was measured at maximum output of the light-boxes. When the output of

the light boxes was reduced by filters to produce low luminances of the screen, the luminances of the opal screens of the light boxes were measured and the ratio used to compute the screen luminance. This procedure is entirely adequate since the optics of the light sources was not altered by the use of the filters to reduce luminance.

The luminance of the large target was measured directly with the Macbeth, with all fixed and psychophysical filters removed from the projector. The luminances of the targets actually used in the experiments were computed from the luminance without filters and the transmissions of the filters. The transmissions of the filters were determined by standard photometric procedures, on an optical bench photometer.

The luminance of the small target was more difficult to photometer. The basic measurement involved what may be called a "candlepower box". A closed metal box was made with an opal disc at one end and a small aperture at the other. The aperture was fitted snugly against the screen so that the transilluminated target lay entirely within it. The target thus became a source for illumination of the opal disc at the other end of the box. Baffles were placed within the box to eliminate interreflections. The luminance of the opal disc was measured routinely with the Macbeth. From the transmission of the opal disc and the inverse square law, the intensity of the transilluminated target could be determined. From known size of the transilluminated target, the brightness of the target could be computed.

The measurement with the candlepower box is somewhat tedious. Accordingly, occasional measurements were made in this way and more frequent measurements were made with a photoelectric telephotometer,

calibrated in terms of the candlepower box measurements. The telephotometer consisted of a telescope which imaged the small target on the cathode of a 931 photomultiplier tube. The relative luminance of the target was determined by the emf required to compensate the photoelectric current produced by the target.

3. Order of Experiments

All experimental measurements with the 1 minute target were first made and then the measurements were made with the 45 minute target. Studies with the 1 minute target are designated Experiment I whereas those with the 45 minute target are designated Experiment II.

Experiments were begun for Experiment I with a background luminance of 10 ft.-L. which was then reduced in one log unit steps in successive sessions to a terminal background value of "zero."* Keeping all other conditions constant, background luminance was then increased from 3.3×10^{-6} ft.-L. in one log unit steps to 33 ft.-L. and finally to 1000 ft.-L. and back to 100 ft.-L. No differential effects of practice or boredom were observed.

Experiment II began at a background luminance of zero and increased in one log unit steps to 1×10^{-4} ft.-L. Experiments were then conducted at 10 ft.-L. and the background luminance was decreased in one log unit steps to 1×10^{-3} ft.-L., followed by experiments at 100 ft.-L. and 1000 ft.-L. The order of presentation of experiments appears in the tabulated results.

4. Other Experimental Procedures

To insure stimulation of the same region of the foveal retina under all conditions, observers' heads were fixed in position by means of

* i.e., a background value considerably less than 10^{-6} but photometrically indeterminate. Presence or absence of background luminance was undetectable with the dark-adapted eye.

hardened wax dental impressions in which the observers' teeth were clamped during all stimulus presentations. These dental impressions in turn were bolted to supports fastened to the arm rests of the observation chairs.

Constant fixation and accommodation of the eye at the point of eventual appearance of the stimulus was obviously desirable; however, no single method of producing this result could be discovered which would serve satisfactorily throughout the extensive range of background luminance. Consequently, three different systems producing identical effects were employed. In each case, the system produced four spots of light, each of approximately one minute of arc diameter, surrounding the stimulus spot and equidistant from it to a constant distance of eighteen minutes of arc. These four spots were arranged in the form of the terminal points of the arms of a cross, with the point of stimulus appearance located at the intersection of an imaginary line through each of the vertical and horizontal pairs. The orientation spots were maintained at a luminance value approximating ten times the average threshold of the group for the prevailing luminance, a level pre-determined to be comfortable and visible over long periods.

The system used for producing orientation lights for background values ranging from 1 ft.-L. to 1×10^{-3} ft.-L. consisted of four projectors using the images of the filaments of 6-volt, 32-candlepower tungsten lamps mounted on each of the four sides of the back of the cube.

The system used for background values less than 1×10^{-3} ft.-L. is illustrated in Figure 6, and consisted of another 32 candlepower, 6-volt lamp housed in a light-tight metal case with four small holes

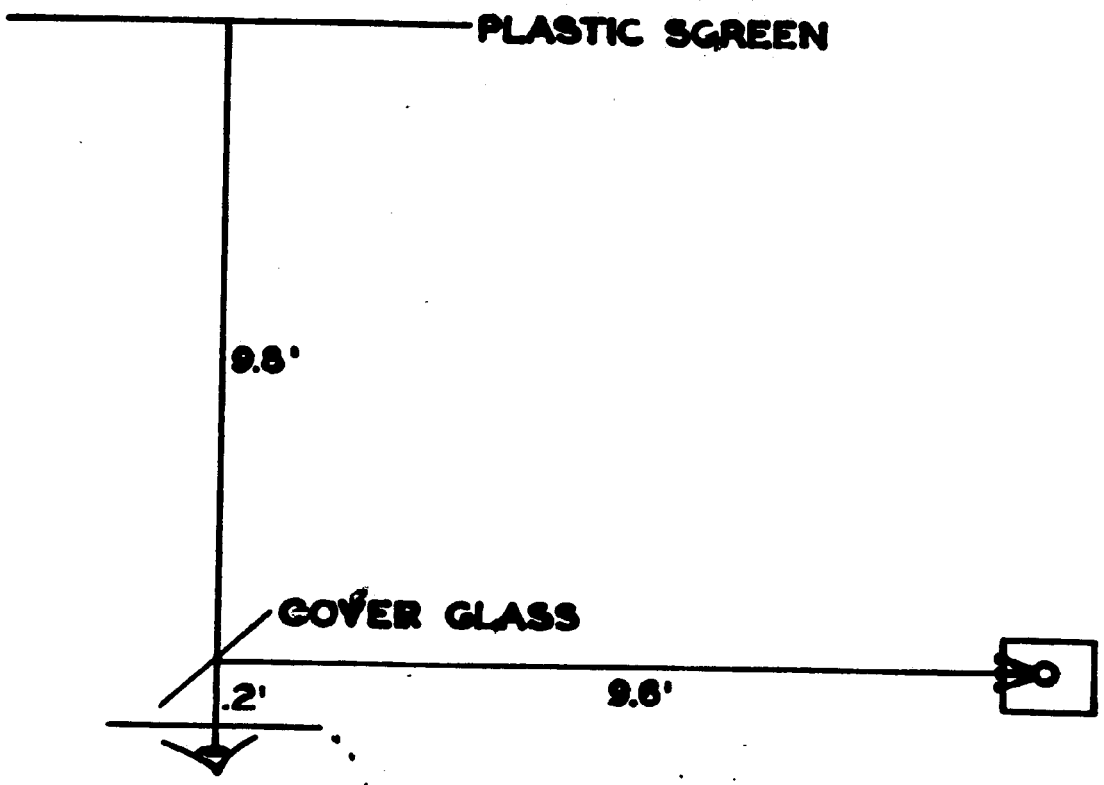


FIG. 6 Orientation light system for low background luminance.

providing the orientation spots for Experiment I. Because of the necessarily greater separation of the orientation lights, these were replaced by four 2.2 volt lamps (G. E. No. 222) with small spherical lenses for Experiment II. This arrangement was placed at right angles to the observers' line of sight and at an optical distance equal to that of the distance from observer to plastic screen; a cover glass at forty-five degrees before the observers' eye provided reflection of the four spots. (The values of $\overline{\Delta B}$ and of B were of course corrected for the transmission of this cover glass.)

The third system of producing orientation lights suitable for backgrounds of 10, 100, and 1000 ft.-L. consisted of four pieces of shimstock with holes made with a number 64 drill which were fixed to the side of the glass plate bearing the target aperture. A light box containing one 2.2 volt lamp was mounted behind each of these, so the orientation spot now appeared on the face of the screen by transillumination from behind. The luminance of these spots was controlled by means of a variable density 16 mm. photographic film, placed between each light source and the screen. Different positions of the film strip produced different luminances of the individual orientation spots.

Throughout the experiments, monocular vision was employed, using the right eye of each observer.

In order to eliminate variations in retinal illumination with changes in the diameter of the natural pupil attendant on luminance changes of the background and to prevent the necessity of determining for these experimental conditions the extent of the Stiles-Crawford effect*, an artificial pupil was fixed 0.2 to 0.3 inches before the

* Light entering the eye near the edge of the pupil, i.e., non-normal to the retina, has less effect than light entering on the optic axis.

eye of each observer, and on line with the optic axis.

Initially a 2 mm. artificial pupil was selected for these experiments, but it was noticed that when viewing a surface of uniform luminance through this aperture, the surface appeared to have several distinct areas differing in apparent brightness. Figure 7 illustrates the appearance of the surface of uniform luminance, when a 1 mm. pupil was employed. The appearance of the field differed when the 2 mm. pupil was utilized in that the central dark area was smaller.

This effect of an artificial pupil has apparently never been reported and considerable exploratory experimentation was required to determine the basis for the observed effect. Professor Blackwell demonstrated that the effect could be duplicated in an entirely physical way, demonstrating the absence of the phenomenon with an aperture placed at the first principal point of a simple opthalmic lens (paralleling the case of the natural pupil of the eye), and the presence of the phenomenon with a second aperture about four to six inches before this (paralleling the case with the artificial pupil). The effect is apparently due to the presence of spherical aberration. The annulus of light surrounding the darker inner circle represents an excessive accumulation of light due to the fact that these rays are more nearly in focus than are the rays arriving at other points on the retina.

In the course of the investigation of the bright annulus phenomenon, it was discovered that no artificial pupil failed to produce the non-uniform field. As a result, an artificial pupil was selected to increase the extent of the dark inner circle as much as possible so that the apparent brightness of the central field would be as uniform as possible. A 1 mm. aperture was found to give the pattern of apparent

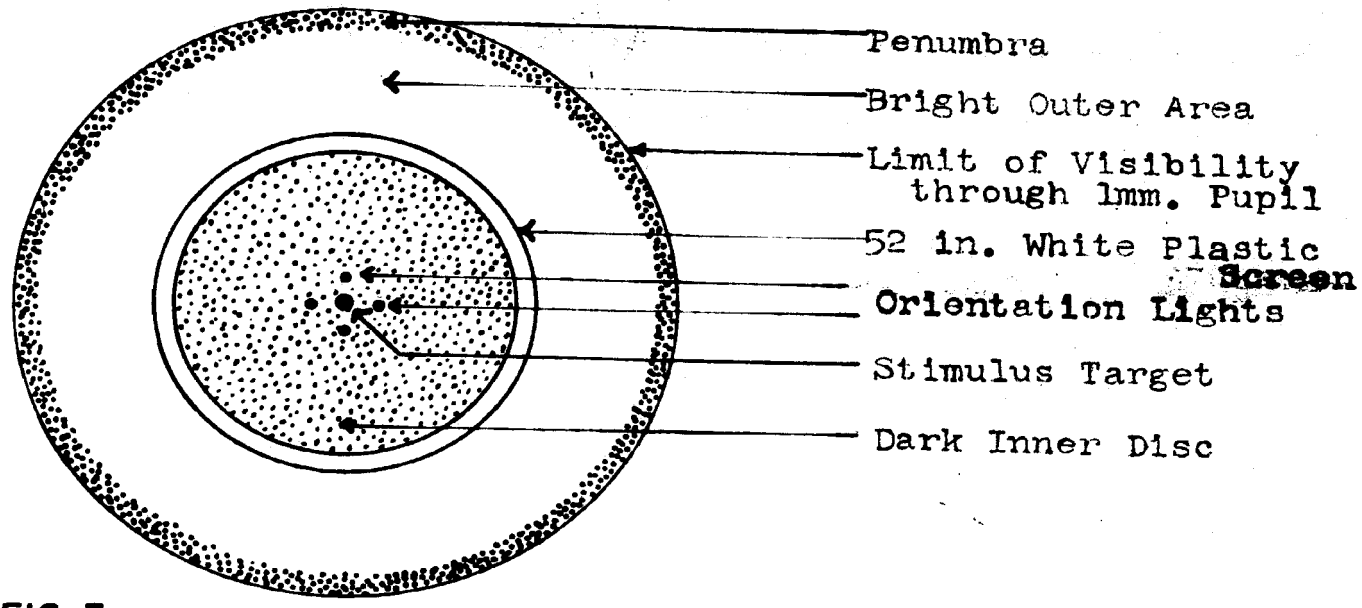


FIG. 7 View of stimulus presentation area as seen through 1 millimeter artificial pupil.

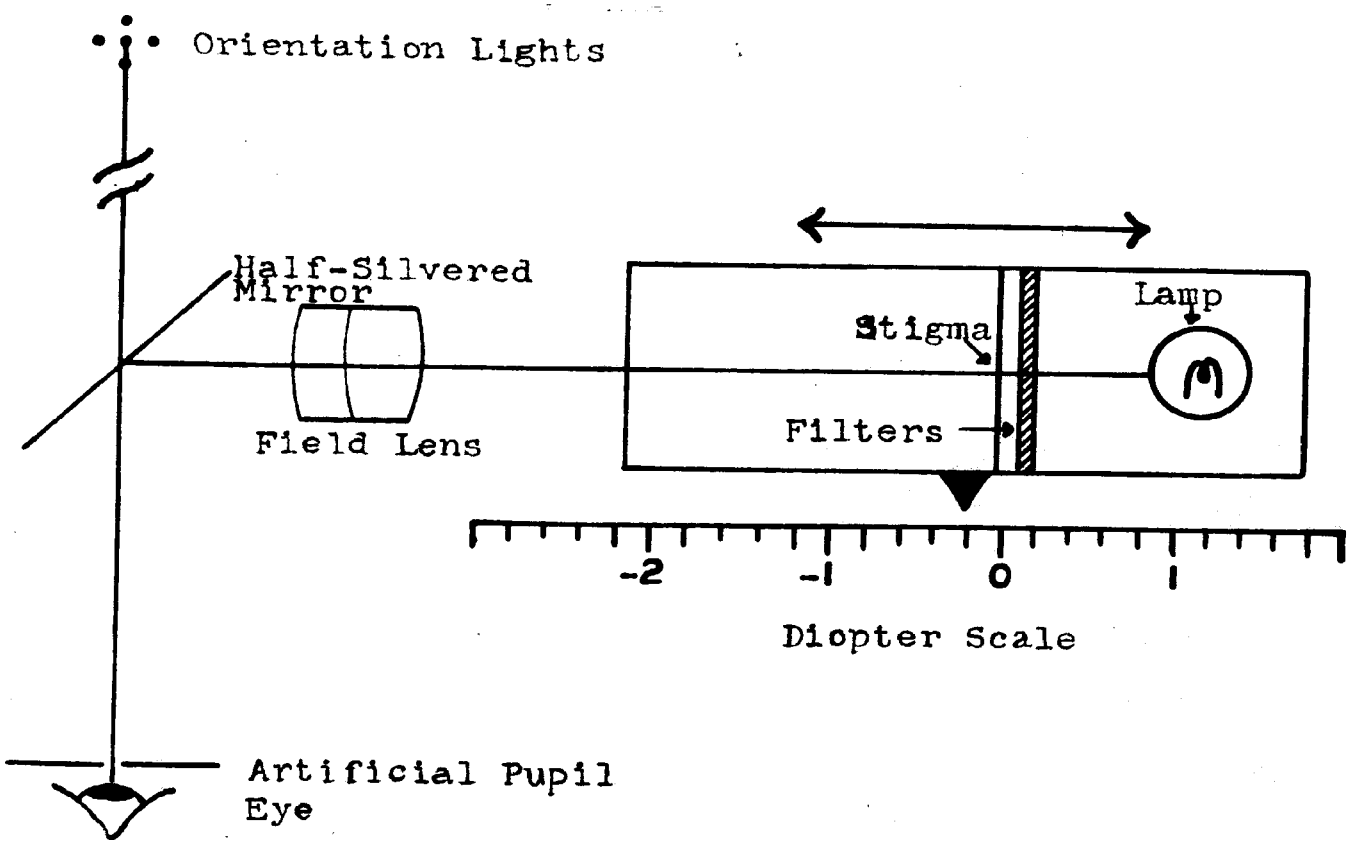


FIG. 8 Schematic optical diagram of the oculometer as used to measure refractive error (not drawn to scale).

brightness shown in Figure 7, which was considered to be satisfactory. Accordingly a 1 mm. artificial pupil was placed about 0.2 to 0.3 inches from the eye.

The refractive condition of the eye of each observer was determined under the conditions of the experiment by a method outlined by Ogle (34). Figure 8 exhibits a schematic drawing of the oculometer used for these measurements. Measurements are made with this apparatus under conditions identical with those of the experiment proper, with the exceptions that a stigma, or point of light appears in the apparent location usually occupied by the target. The stigma is seen by reflection from the half-silvered mirror in the oculometer. The principal oculometric measurements were made with a 2 mm. artificial pupil to increase the precision of measurement. With the 1 mm. pupil, the depth of focus of the eye is considerable. There is no a priori reason to expect there to be a difference between refractive error with 1 and 2 mm. pupils. However, a crude check was made by obtaining oculometric readings first with the 1 and then with the 2 mm. pupil. No systematic differences were found .

Oculometric readings were taken at each of two background luminances: 10 ft-L. and zero. There is no a priori reason to expect differences in refractive condition as a function of background luminance, and none were found to exist.

The basic oculometric procedure may be described as follows: the observer fixates the orientation spots situated 10.8 feet from the eye and observes changes in appearance of the bright stigma centered among them. The assembly which houses the tungsten lamp, stigma, and reduction filters is movable along the optic axis parallel to a scale. The distance from

the eye to the field lens is made equal to the focal length of the latter, making possible a linear scale calibrated in diopters whose modulus is determined bythe dioptric strength of the field lens. The zero point of the scale corresponds to the point at which the stigma-to-lens distance is equal to the focal length of the field lens and the image is at infinity. Using the method of limits, the observer adjusts the position of the lamp housing until the stigma appears to have minimum size. A mean of many such settings translated into diopters by the affixed scale, reveals the refractive state of the eye. Accommodation on the stigma would give a spurious result. This possibility is precluded by causing the lamp to flash intermittently, the "off" period being sustained considerably longer than the "on".

The discrepancy between the mean of these oculometric settings and the theoretical "normal" refractive state of the eye (-0.33 diopters) at this distance represents the refractive "error" of each observer. From refractive errors, it is possible to compute refractive corrections. Oculometric measurements were repeated after corrections were made. This procedure was continued until the refractive state of the eye as measured by this method closely approximated -0.33 diopters.

Results of the oculometric measurements are presented in Table 1. We note that one observer obtained negligible refractive errors without correction whereas three obtained negligible refractive errors with corrections. The three observers used the indicated corrections during the experiments.

Although the method described can be used to give a measure of the astigmatic error, it was not considered sufficiently sensitive for specification and correction of the cylindrical error noted in one observer.

TABLE I

OCULOMETRIC DATA

Mean Settings of Oculometer (Diopters)

Observer	Uncorrected	Corrected	Strength of Opthalmic lens (D)
AK	-0.66	-0.33	-0.375s*
TL	-4.46	-0.37	-4.00 s
HF	-0.76	-0.31	-0.375s; -0.75c**
LP	-0.34	---	

*s represents a spherical lens, c a cylindrical.

** axis 165°.

Accordingly, the method of Tait, using the Stenopaic slit was employed in this instance. This method involves determining the refractive error in each of several meridians by a subjective technique. The observer reports on the least positive correction which gives clear imagery in each meridian and the astigmatic error is computed from the difference between the most different meridians.

III. RESULTS

Threshold values resulting from the probit analysis of the experimental proportions are available for each observer for each of the two targets. The data for the 1 minute target are presented in Tables 2, 3, 4, and 5; data for the 45 minute target are presented in Tables 6, 7, 8, and 9. In each case, the symbols have the following meanings. Values of $\overline{\Delta B}$ represent target luminances for which p' = .50. Values of $\sigma_{\overline{\Delta B}}$ represent the standard errors of the corresponding values of $\overline{\Delta B}$. Values of σ represent the standard deviations of the normal frequency distributions from which the ogives were computed by integration. Values of $\sigma\sigma$ represent standard errors of the values of σ. Values of χ^2 have the usual statistical meaning, as do values of d.f.. Values of $P(\chi^2)$ represent the probabilities that values of χ^2 as large as those obtained, or larger, could have occurred by chance. Values of $\sigma/\overline{\Delta B}$ are obtained by dividing the indicated quantities directly. Values of $\sigma_{\sigma/\overline{\Delta B}}$ represent standard errors of these quotients. The data represent in all more than 38,000 observations. The threshold values are presented in Figures 9-16, as functions of log B. There is a separate graph for each observer's experiments with each target size. Values of the ratio, $\sigma/\overline{\Delta B}$, are presented in Figures 17 and 18, as a function of log B. A separate graph is presented for each target size. It is to be noted that the points in Figures 17 and 18 are not connected by continuous curves. Since the plotted data exhibit considerable variation but do not appear to represent

a systematic function, it was not considered desirable to connect them in any pre-conceived manner.

We may inquire to what extent the probit analysis in terms of normal ogives was justified by the data. Data for each individual were tested for goodness of fit of the data to each normal ogive, using the χ^2 test of conformity. These values of χ^2 appear summed at the bottom of the individual data tables. The probabilities of values of χ^2 this large or larger for each of the eight sets of data are as follows: .19, .59, .47, .023, .075, .19, .87, .074. Considering the severity of this test, we may consider the agreement of experimental data to theoretical ogives to be excellent. The probit analysis may be considered to be entirely justified.

TABLE 2

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER AK, EXPERIMENT I, 1 MINUTE TARGET

Order	B (ft.-L.)	$\Delta\bar{B}$	$\sigma_{\Delta\bar{B}}$	σ	$\sigma\sigma$	χ^2	d.f.	$P(\chi^2)$	$\sigma/\Delta\bar{B}$	$\sigma\sigma/\Delta\bar{B}$
1	10.5	292.	10.8	57.0	11.1	2.30	3	.51	.511	.0409
2	1.67	159.	12.1	68.9	10.9	1.35	3	.73	.432	.0818
3	.0932	91.4	6.06	41.7	6.53	3.31	3	.35	.459	.0871
4	1.07×10^{-2}	73.5	5.21	32.3	5.20	.318	3	.96	.440	.0875
5	1.37×10^{-3}	87.4	6.42	47.2	9.79	6.33	3	.097	.540	.103
6	1.20×10^{-4}	97.7	6.35	47.5	7.76	2.36	3	.49	.486	.0933
7	$.915 \times 10^{-5}$	98.3	4.97	30.1	5.19	4.88	3	.19	.307	.0603
8	$.814 \times 10^{-6}$	90.2	5.38	39.0	6.46	4.23	3	.24	.433	.0827
9	0.0	102.	6.23	45.6	9.09	.583	3	.90	.448	.0992
10	3.61×10^{-6}	84.4	5.45	38.3	6.05	1.91	3	.59	.454	.0863
11	3.09×10^{-5}	95.5	5.36	36.6	6.05	5.31	3	.16	.383	.0731
12	3.00×10^{-4}	84.2	5.80	42.8	6.74	4.66	3	.20	.508	.0972
13	2.58×10^{-3}	104.	4.39	26.5	4.98	1.66	3	.64	.255	.0522
14	1.65×10^{-2}	87.9	7.20	48.4	9.33	9.26	3	.027	.550	.127
15	.295	90.2	5.10	29.5	5.12	1.55	3	.68	.327	.0663
16	3.17	160.	7.62	57.5	12.0	2.80	3	.42	.361	.0706
17	30.2	432.	16.8	97.3	20.8	4.55	3	.20	.225	.0505
18	301.	2050.	77.3	434.	84.5	2.60	3	.46	.212	.0442
19	1210.	4660.	259.	1800.	304.	4.89	3	.19	.387	.0744
20	101.	801.	46.8	338.	57.3	5.16	3	.16	.423	.0817
					Total	70.0	60			

$P(\chi^2) = .19$

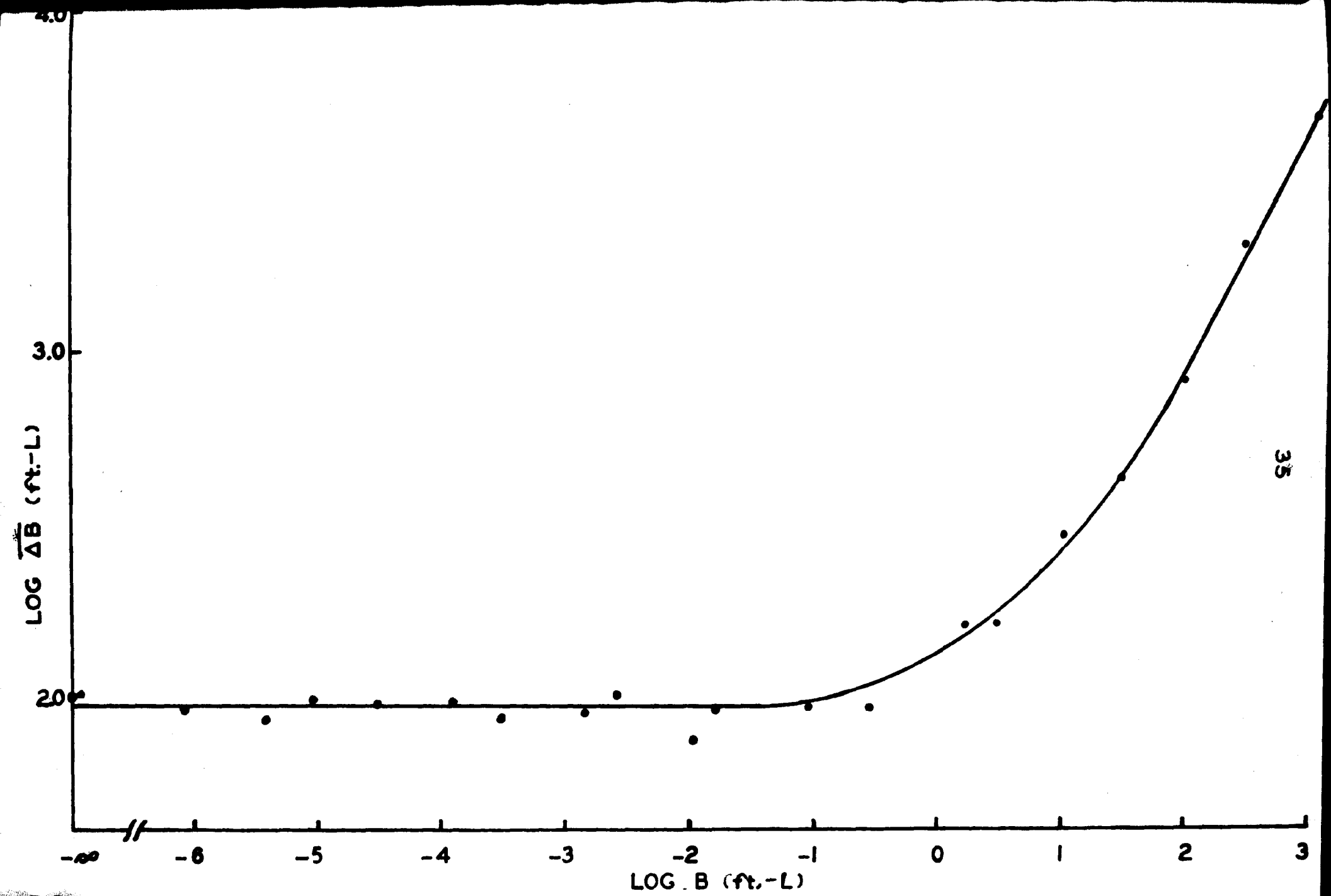


FIG. 9 Threshold curve for observer AK: 1' target

TABLE 3

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER HF, EXPERIMENT I, 1 MINUTE TARGET

Order	B (ft.-L.)	$\overline{\Delta B}$	$\sigma_{\overline{\Delta B}}$	σ	$\sigma\sigma$	χ^2	d.f.	$P(\chi^2)$	$\sigma/\overline{\Delta B}$	$\sigma\sigma/\overline{\Delta B}$
1	10.8	393.	20.0	137.	16.3	4.19	3	.24	.349	.0695
2	.908	143.	9.71	66.7	10.3	3.63	3	.31	.468	.0892
3	.0972	119.	7.08	46.7	7.53	1.64	3	.66	.393	.0748
4	.0112	127.	9.20	46.7	14.5	1.99	3	.59	.367	.101
5	.00127	137.	5.89	33.6	7.11	2.24	3	.51	.246	.0546
6	1.44×10^{-4}	114.	6.41	45.9	7.90	.511	3	.91	.401	.0780
7	$.921 \times 10^{-5}$	115.	5.72	38.2	6.86	1.55	3	.68	.332	.0660
8	$.977 \times 10^{-6}$	140.	9.70	60.6	9.69	1.27	3	.73	.434	.0858
9	0.0	99.6	5.18	32.0	5.50	3.50	3	.33	.321	.0632
10	2.63×10^{-6}	138.	10.3	65.3	10.4	19.0	3	.0003	.474	.0950
11	3.09×10^{-5}	119.	6.80	47.3	7.82	.271	3	.960	.399	.0762
12	3.00×10^{-4}	105.	5.74	41.2	7.30	1.51	3	.68	.391	.0791
13	2.82×10^{-3}	116	5.99	41.0	7.30	.627	3	.90	.352	.0697
14	1.65×10^{-2}	99.6	7.38	46.8	7.41	.831	3	.85	.470	.0935
15	.295	96.5	7.07	40.3	68.9	5.13	3	.17	.418	.0874
16	3.17	205.	13.8	106.	17.5	2.87	3	.42	.519	.100
17	30.2	503.	26.0	190.	30.1	1.02	3	.80	.345	.0674
18	301.	2000.	106.	4780.	96.9	.0622	3	.99	.239	.0563
19	1210.	5890.	323.	1930.	332.	5.09	3	.17	.327	.0655
20	101.	803.	36.1	171.	33.1	.711	3	.87	.213	.0455
					Total	57.6	60			

$P(\chi^2) = .59$

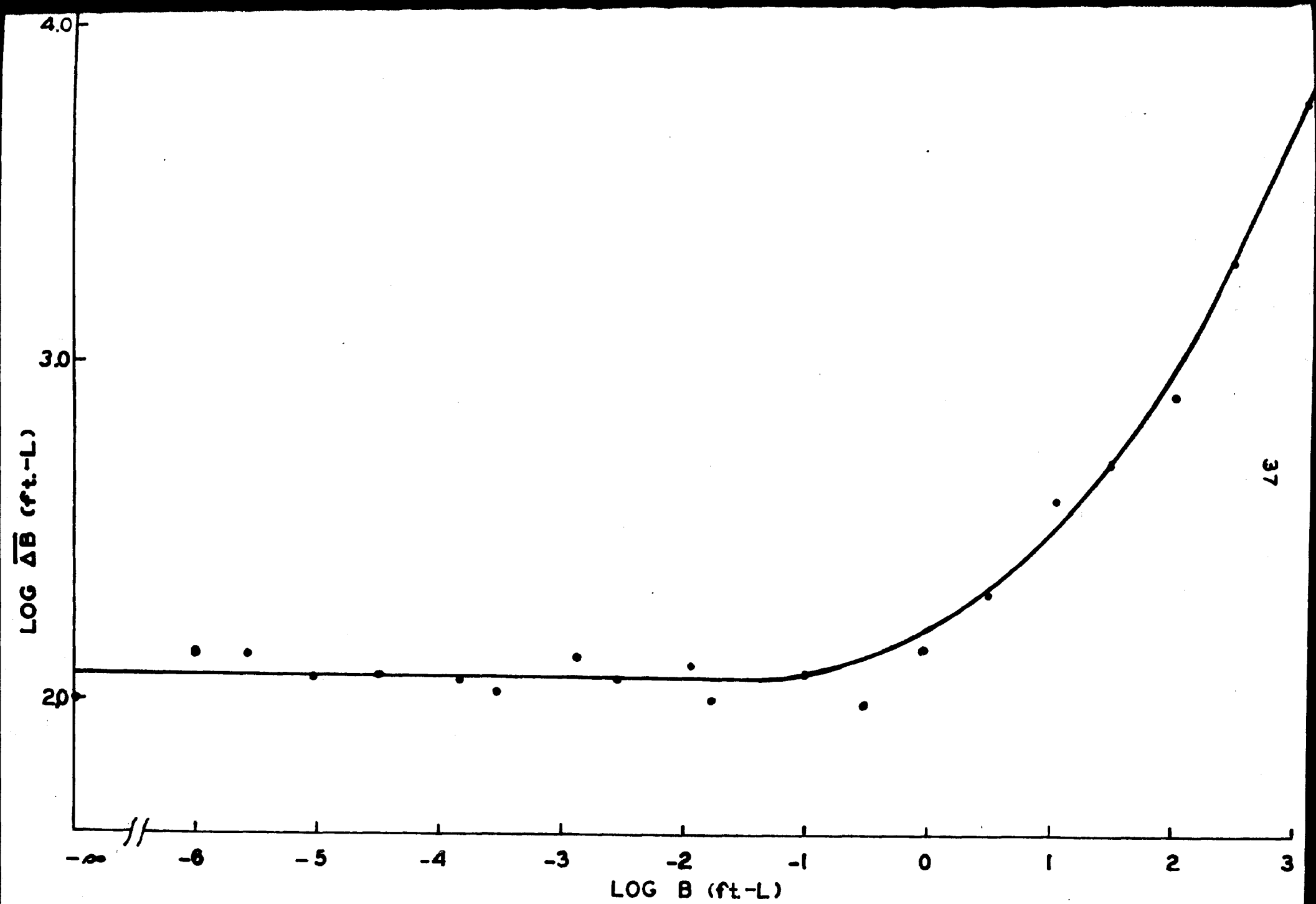


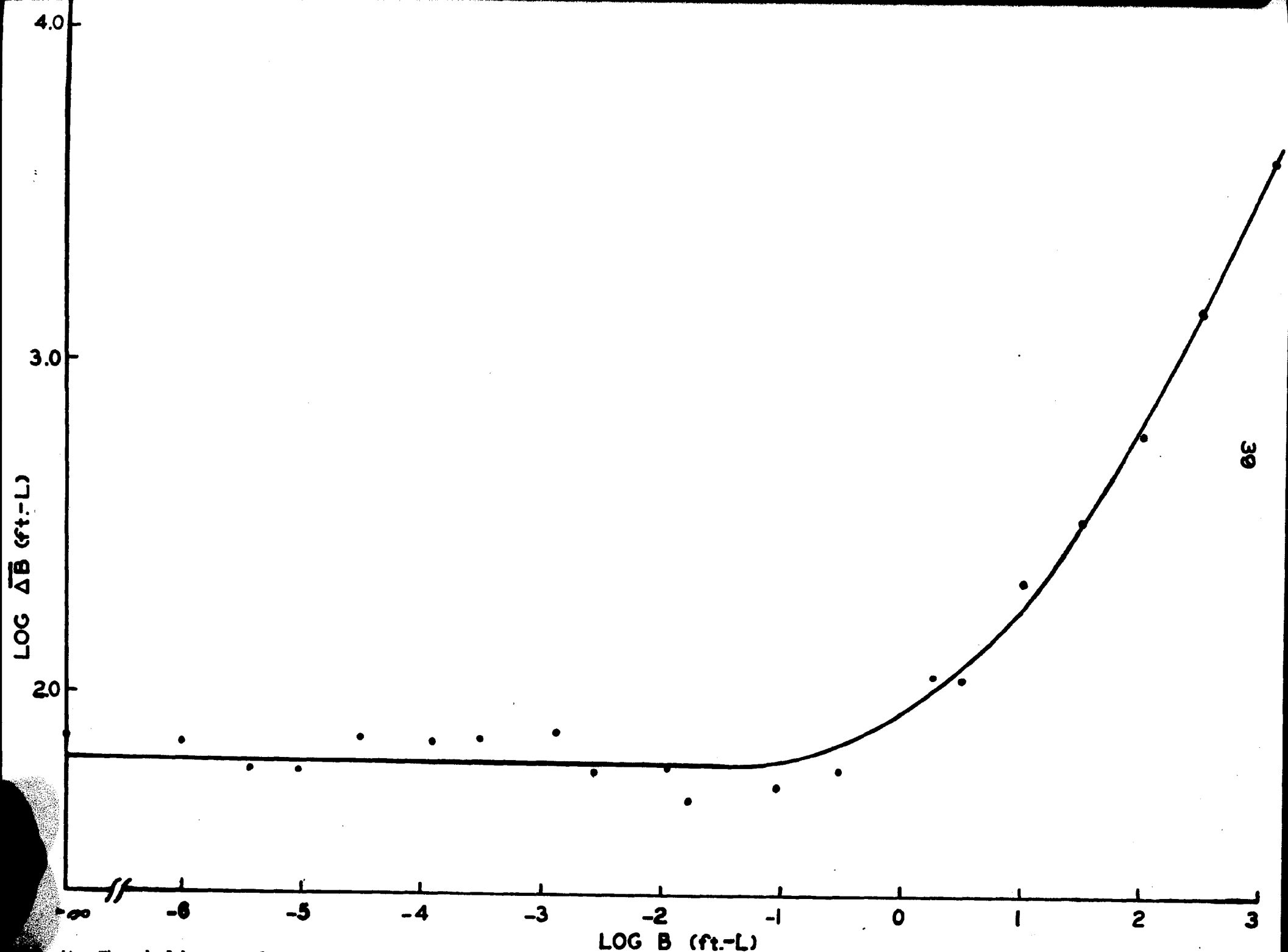
FIG. 1C Threshold curve for observer HF: 1' target

TABLE 4

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER LP, EXPERIMENT I,1 MINUTE TARGET

Order	B (ft.-L.)	$\overline{\Delta B}$	$\sigma_{\overline{\Delta B}}$	σ	$\sigma\sigma$	χ^2	d.f.	$P(\chi^2)$	$\sigma/\overline{\Delta B}$	$\sigma\sigma/\overline{\Delta B}$
1	10.5	222.	10.9	75.6	15.2	3.61	3	.31	.340	.0725
2	1.67	115.	9.70	42.3	7.14	8.67	3	.03	.367	.0706
3	.0932	54.4	4.31	31.6	4.90	1.27	3	.73	.582	.115
4	1.12×10^{-2}	62.2	.456	28.7	4.48	6.08	3	.11	.462	.0875
5	1.37×10^{-3}	75.8	4.11	29.2	5.15	3.89	3	.26	.386	.0759
6	1.20×10^{-4}	73.2	4.49	34.9	6.37	2.80	3	.42	.476	.0954
7	$.921 \times 10^{-5}$	59.6	5.14	32.8	5.23	1.61	3	.66	.925	.115
8	$.969 \times 10^{-6}$	71.6	4.13	27.6	4.50	2.21	3	.53	.386	.0738
9	0.0	73.6	4.47	32.2	5.24	.804	3	.85	.437	.0833
10	3.61×10^{-6}	60.2	4.48	30.6	4.87	1.31	3	.71	.508	.104
11	3.09×10^{-5}	75.4	3.93	24.5	4.19	1.43	3	.71	.324	.0636
12	3.07×10^{-4}	75.1	4.13	25.6	4.30	1.92	3	.59	.341	.0668
13	2.82×10^{-3}	59.9	4.45	31.3	4.79	.709	3	.87	.523	.101
14	1.65×10^{-2}	49.0	4.84	27.8	5.55	8.69	3	.04	.567	.148
15	.295	60.5	5.29	32.5	5.33	1.02	3	.80	.538	.115
16	3.17	111.	6.30	33.9	6.08	3.18	3	.36	.304	.0634
17	30.2	340.	18.5	131.	23.0	1.30	3	.73	.386	.0754
18	301.	1470.	214.	380.	65.7	6.40	3	.11	.259	.0506
19	1200.	3990.	217.	1310.	223.	3.46	3	.33	.328	.0652
20	101.	622.	31.6	150.	30.0	1.52	3	.68	.241	.0548
					Total	61.9	60			

$P(\chi^2) = .47$

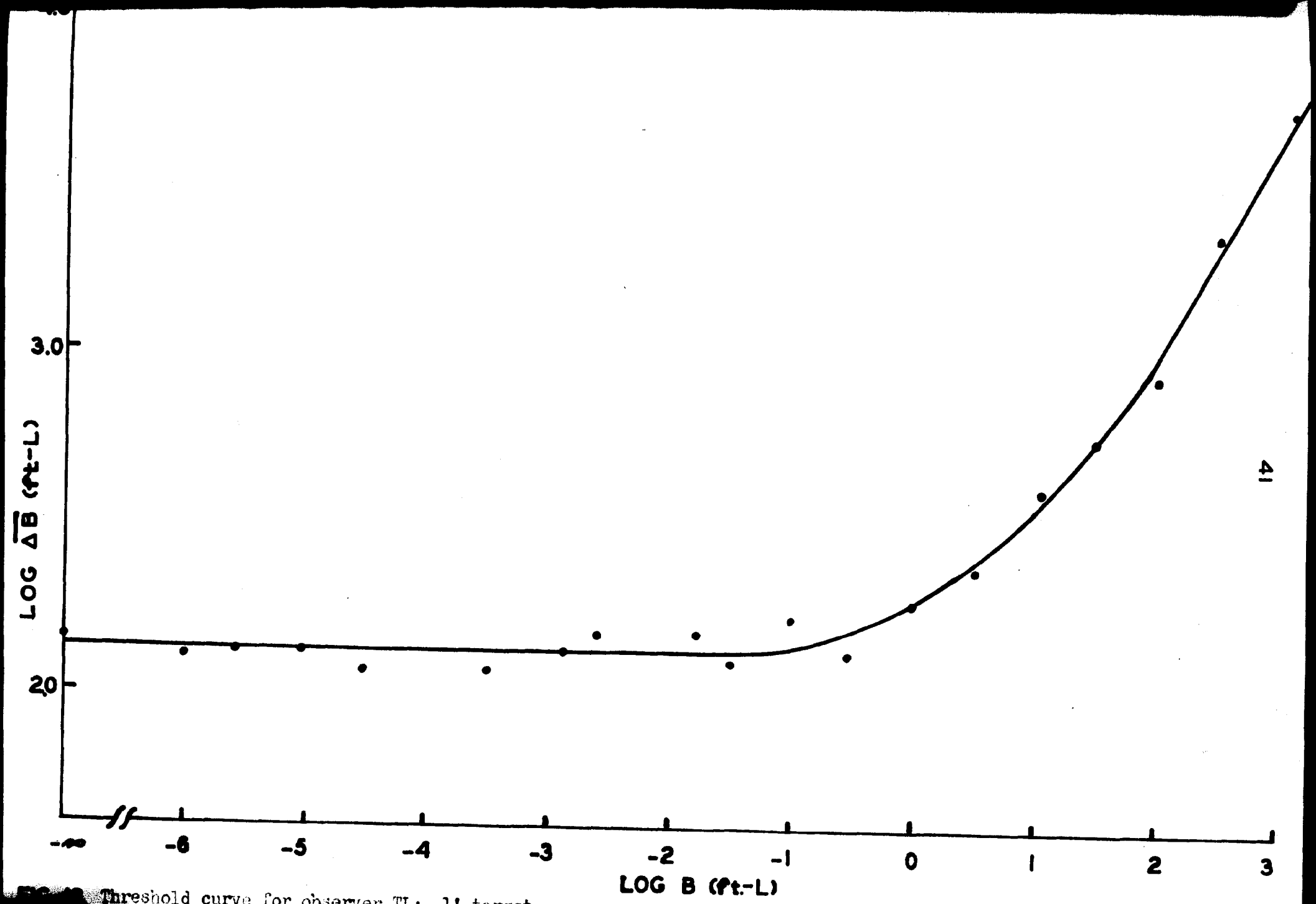


. 11 Threshold curve for observer LP: 1' target

TABLE 5

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER TL, EXPERIMENT I, 1 MINUTE TARGET

Order	B (ft.-L.)	ΔB	$\sigma_{\Delta B}$	σ	$\sigma\sigma$	χ^2	d.f.	$P(\chi^2)$	$\sigma/\Delta B$	$\sigma\sigma/\Delta B$
1	10.5	406.	22.1	125.	36.2	1.09	3	.78	.307	.0839
2	.908	182.	11.3	85.5	14.4	2.78	3	.42	.469	.0906
3	.0972	171.	11.3	79.3	12.6	4.45	3	.22	.464	.0892
4	1.12×10^{-2}	127.	7.27	53.9	9.24	2.99	3	.39	.440	.0855
5	1.27×10^{-3}	136.	8.34	56.7	9.06	4.70	3	.20	.418	.0811
6	$.921 \times 10^{-5}$	131.	8.19	54.9	8.70	6.35	3	.094	.420	.0800
7	$.977 \times 10^{-6}$	125.	7.99	52.3	8.31	2.67	3	.46	.418	.0800
8	0.0	141.	9.33	73.1	15.4	.865	3	.83	.520	.111
9	2.62×10^{-6}	130.	5.92	38.0	6.77	7.89	3	.050	.291	.0588
10	2.86×10^{-5}	113.	7.13	53.6	8.84	2.53	3	.49	.475	.0911
11	3.00×10^{-4}	115.	18.7	62.5	9.60	2.41	3	.49	.543	.106
12	2.57×10^{-3}	152.	10.2	77.0	13.1	1.75	3	.64	.508	.101
13	1.65×10^{-2}	153.	8.93	68.4	11.5	5.36	3	.14	.446	.0835
14	.295	132.	9.26	64.1	14.0	5.15	3	.16	.487	.0941
15	3.17	236.	12.4	84.9	14.7	1.79	3	.61	.359	.0701
16	30.2	556.	27.2	183.	33.3	6.28	3	.10	.330	.0659
17	301.	2320.	516.	1270.	2040.	5.06	3	.17	.549	.108
18	1210.	5400.	3730.	2510.	390.	6.07	3	.11	.465	.0893
19	101.	847.	62.2	403.	63.1	10.4	3	.019	.476	.0960
					Total	80.4	57			
						$P(\chi^2) = .023$				



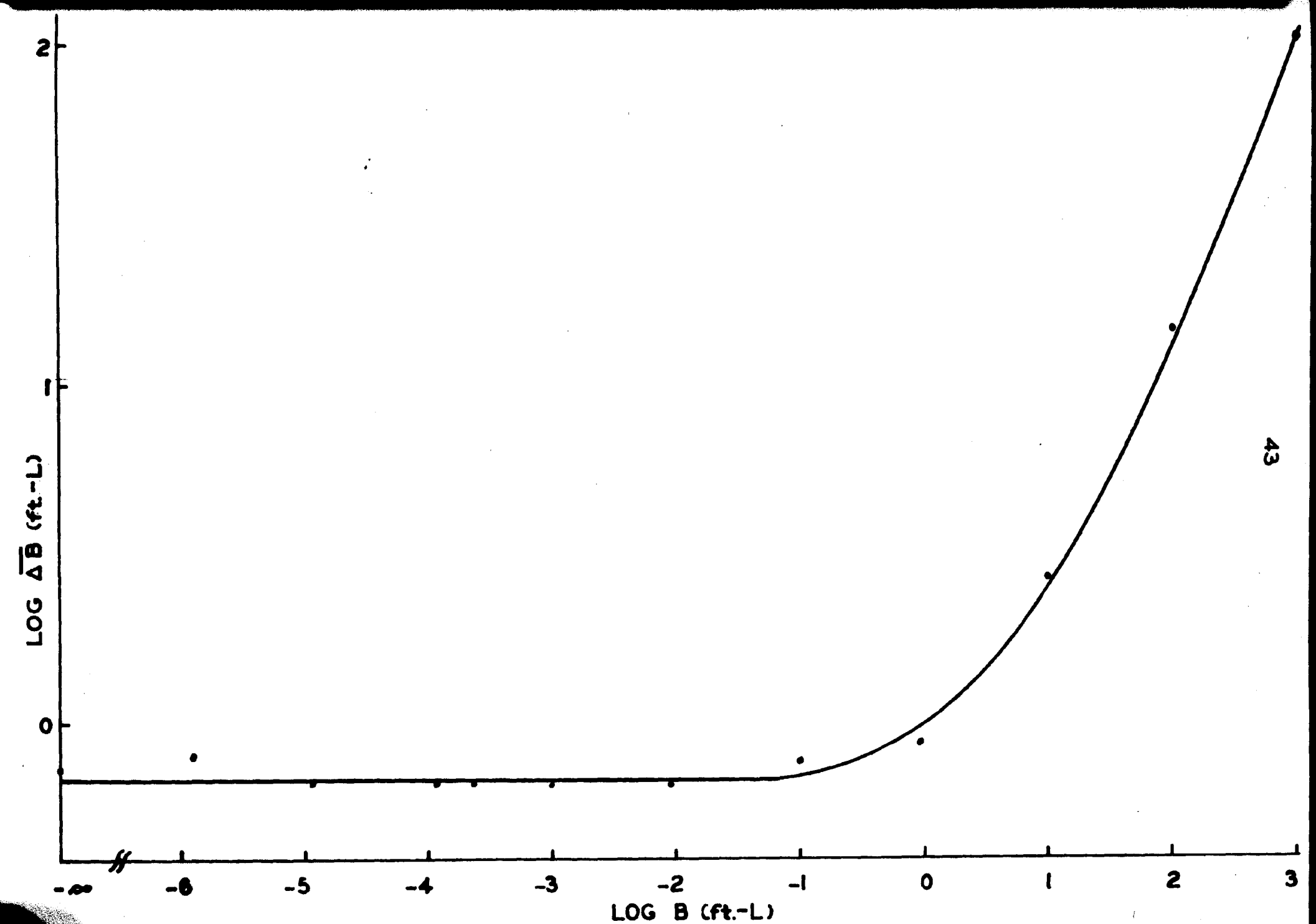
Threshold curve for observer TL: 1' target

TABLE 6

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER AK, EXPERIMENT II, 45 MINUTE TARGET

Order	B (ft.-L.)	$\overline{\Delta B}$	$\sigma_{\overline{\Delta B}}$	σ	σ_σ	χ^2	d.f.	$P(\chi^2)$	$\sigma/\overline{\Delta B}$	$\sigma_{\sigma/\overline{\Delta B}}$
1	0.0	.737	.0511	.322	.0513	1.31	3	.73	.437	.0858
2	1.22×10^{-6}	.814	.0387	.256	.0466	4.20	3	.24	.315	.0630
3	1.14×10^{-5}	.675	.0465	.263	.0432	14.9	3	.0018	.390	.0772
4	1.11×10^{-4}	.669	.0513	.419	.0719	7.79	3	.050	.626	.128
5	2.32×10^{-4}	.682	.0342	.241	.0440	3.15	3	.36	.353	.0700
6	10.0	2.66	.151	1.03	.170	3.50	3	.33	.389	.0743
7	.961	.886	.0583	.451	.0757	.463	3	.92	.509	.0992
8	$.985 \times 10^{-1}$	.789	.0398	.250	.0432	1.27	3	.73	.317	.0626
9	$.942 \times 10^{-2}$	.528	.0291	.184	.0307	5.51	3	.14	.349	.0677
10	$.981 \times 10^{-3}$	.524	.0452	.323	.0496	1.92	3	.59	.616	.126
11	104.	12.4	.456	2.53	.487	1.06	3	.78	.204	.00420
12	1210.	120.	5.72	35.0	9.09	4.17	3	.24	.283	.0739
					Total	49.2	36			

$P(\chi^2) = .075$



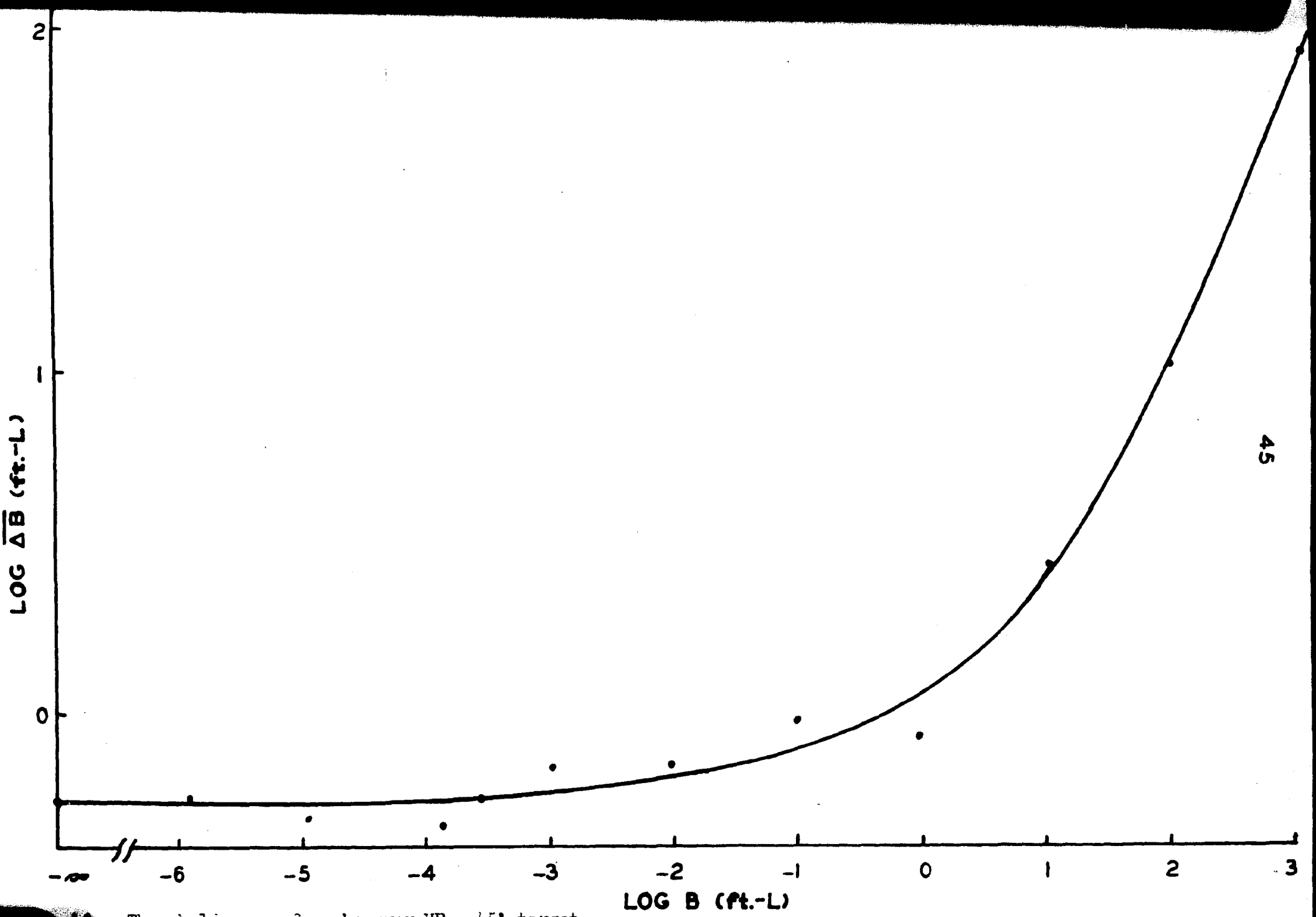
13 Threshold curve for observer AK: 45' target

TABLE 7

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER HF, EXPERIMENT II, 45 MINUTE TARGET

Order	B (ft.-L.)	$\overline{\Delta B}$	$\sigma_{\overline{\Delta B}}$	σ	σ_σ	χ^2	d.f.	$P(\chi^2)$	$\sigma/\overline{\Delta B}$	$\sigma_{\sigma/\overline{\Delta B}}$
1	0.0	.551	.0349	.228	.0354	5.21	3	.16	.396	.0773
2	1.22×10^{-6}	.564	.0394	.280	.0433	.495	3	.92	.497	.0950
3	1.11×10^{-5}	.490	.0279	.195	.0323	3.77	3	.28	.398	.0762
4	1.35×10^{-4}	.464	.0340	.275	.0472	5.24	3	.16	.593	.120
5	2.78×10^{-4}	.570	.0328	.247	.0143	.822	3	.85	.434	.0866
6	10.0	2.64	.138	.860	.147	1.42	3	.71	.326	.0638
7	.961	.842	.0587	.456	.0750	.999	3	.80	.541	.106
8	$.985 \times 10^{-1}$	.956	.0541	.392	.0796	8.15	3	.042	.410	.0864
9	$.942 \times 10^{-2}$	.696	.0455	.330	.0521	2.66	3	.46	.437	.0899
10	1.04×10^{-3}	.696	.0439	.304	.0481	3.17	3	.36	.437	.103
11	104.	10.2	.597	4.34	.729	9.27	3	.027	.428	.0822
12	1210.	82.8	5.47	42.7	7.23	2.55	3	.46	.516	.101
					Total	43.7	36			

$P(\chi^2) = .19$



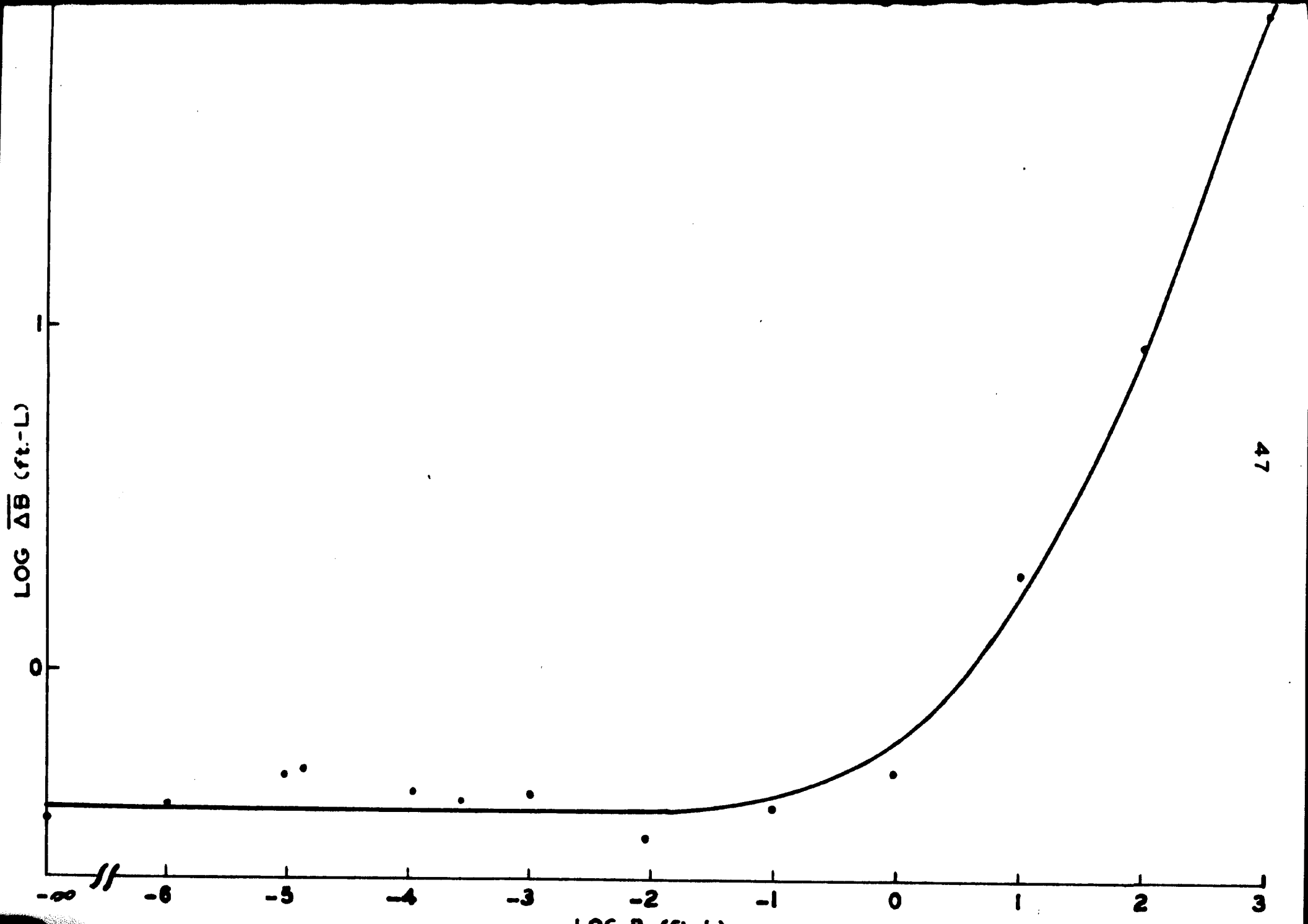
14 Threshold curve for observer HF: 45' target

TABLE 8

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER LP, EXPERIMENT II, 45 MINUTE TARGET

Order	B (ft.-L.)	$\Delta\bar{B}$	$\sigma_{\Delta\bar{B}}$	σ	σ_σ	χ^2	d.f.	$P(\chi^2)$	$\sigma/\Delta\bar{B}$	$\sigma_{\sigma/\Delta\bar{B}}$
1	0.0	.369	.0275	.186	.0294	.397	3	.94	.494	.100
2	1.02×10^{-6}	.405	.0325	.240	.0370	14.6	3	.0030	.593	.118
3	$.95 \times 10^{-5}$	.506	.0304	.217	.0353	1.80	3	.61	.428	.0814
4	1.12×10^{-4}	.451	.0303	.221	.0348	1.47	3	.68	.491	.0934
5	2.78×10^{-4}	.424	.0330	.252	.0397	1.19	3	.75	.594	.118
6	10.1	1.91	.103	.719	.126	3.00	3	.39	.376	.0736
7	.961	.520	.0430	.259	.0429	.676	3	.87	.498	.106
8	$.985 \times 10^{-1}$	.406	.0281	.130	.0299	.327	3	.96	.320	.0421
9	$.942 \times 10^{-2}$	.331	.0331	.220	.0347	3.18	3	.36	.665	.148
10	$.981 \times 10^{-3}$	.443	.0356	.214	.0353	1.23	3	.75	.483	.101
11	104.	9.09	.427	2.16	.437	3.37	3	.33	.238	.0195
12	1210.	84.8	4.90	34.5	5.94	6.25	3	.10	.407	.0804
13	1.36×10^{-5}	.525	.0303	.226	.0394	2.66	3	.46	.430	.0835
					Total	27.0	39			

$P(\chi^2) = .87$



Threshold curve for observer LP: 45' target

TABLE 9

SUMMARY OF PROBIT ANALYSIS OF THRESHOLD PSYCHOPHYSICAL DATA.
OBSERVER TL, EXPERIMENT II, 45 MINUTE TARGET

Order	B (ft.-L.)	$\Delta\bar{B}$	$\sigma_{\Delta\bar{B}}$	σ	σ_σ	χ^2	d.f.	$P(\chi^2)$	$\sigma/\Delta\bar{B}$	$\sigma_\sigma/\Delta\bar{B}$
1	0.0	.588	.055	.418	.0683	1.02	3	.80	.491	.0911
2	1.11×10^{-6}	.632	.0509	.313	.0550	1.87	3	.59	.302	.0599
3	1.21×10^{-5}	.682	.0522	.376	.0652	6.04	3	.11	.380	.0731
4	1.13×10^{-4}	.646	.0642	.488	.0845	9.57	3	.022	.464	.0907
5	2.32×10^{-4}	.532	.0579	.413	.0644	5.65	3	.13	.481	.0931
6	10.1	.933	.232	1.35	.380	.135	3	.99	.505	.122
7	.961	.851	.0734	.484	.133	8.60	3	.035	.390	.102
8	$.985 \times 10^{-1}$	.821	.0573	.403	.0919	4.45	3	.22	.391	.0881
9	$.942 \times 10^{-2}$	.933	.0486	.349	.0687	1.45	3	.68	.375	.0780
10	$.981 \times 10^{-3}$	.903	.0473	.341	.0677	5.54	3	.13	.377	.0791
11	104.	10.7	.543	3.61	.621	3.44	3	.33	.377	.0659
12	1210.	83.4	4.79	33.7	5.59	1.60	3	.66	.405	.0773
					Total	49.4	36			

$P(\chi^2) = .074$

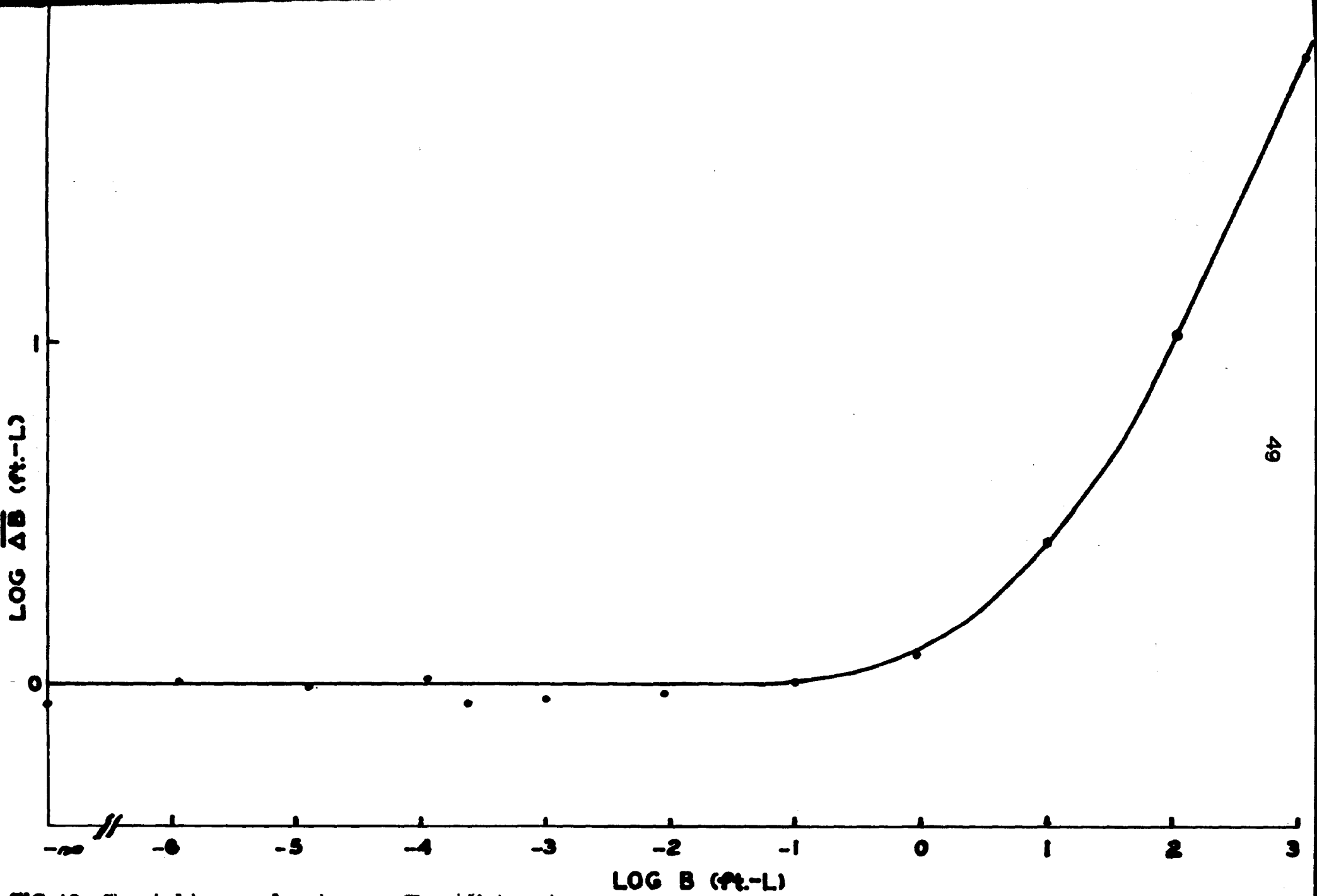


FIG. 16 Threshold curve for observer TL: 45' target

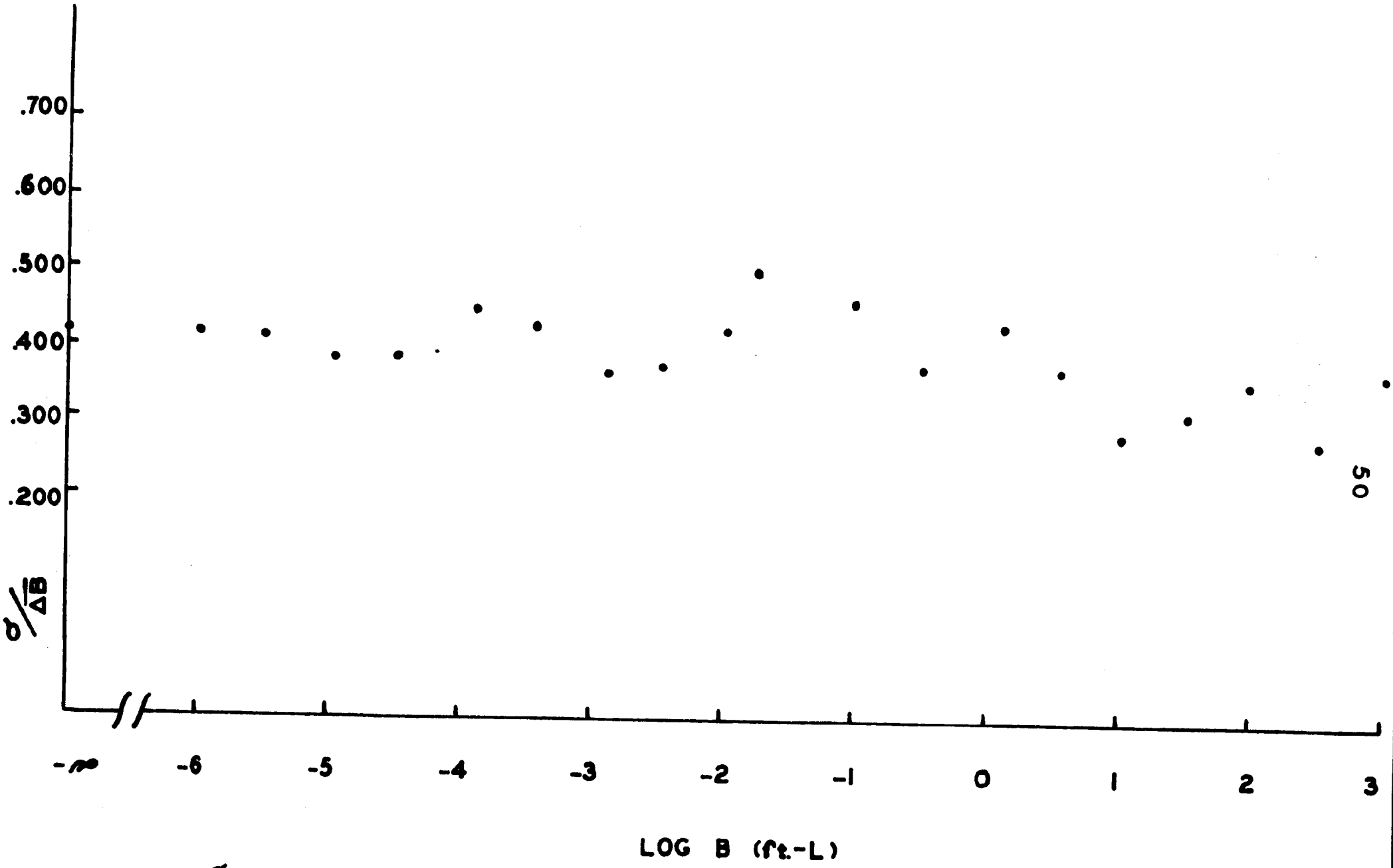


FIG. 17 Averaged $\sigma/\sqrt{\Delta B}$ data for four observers: 1' target

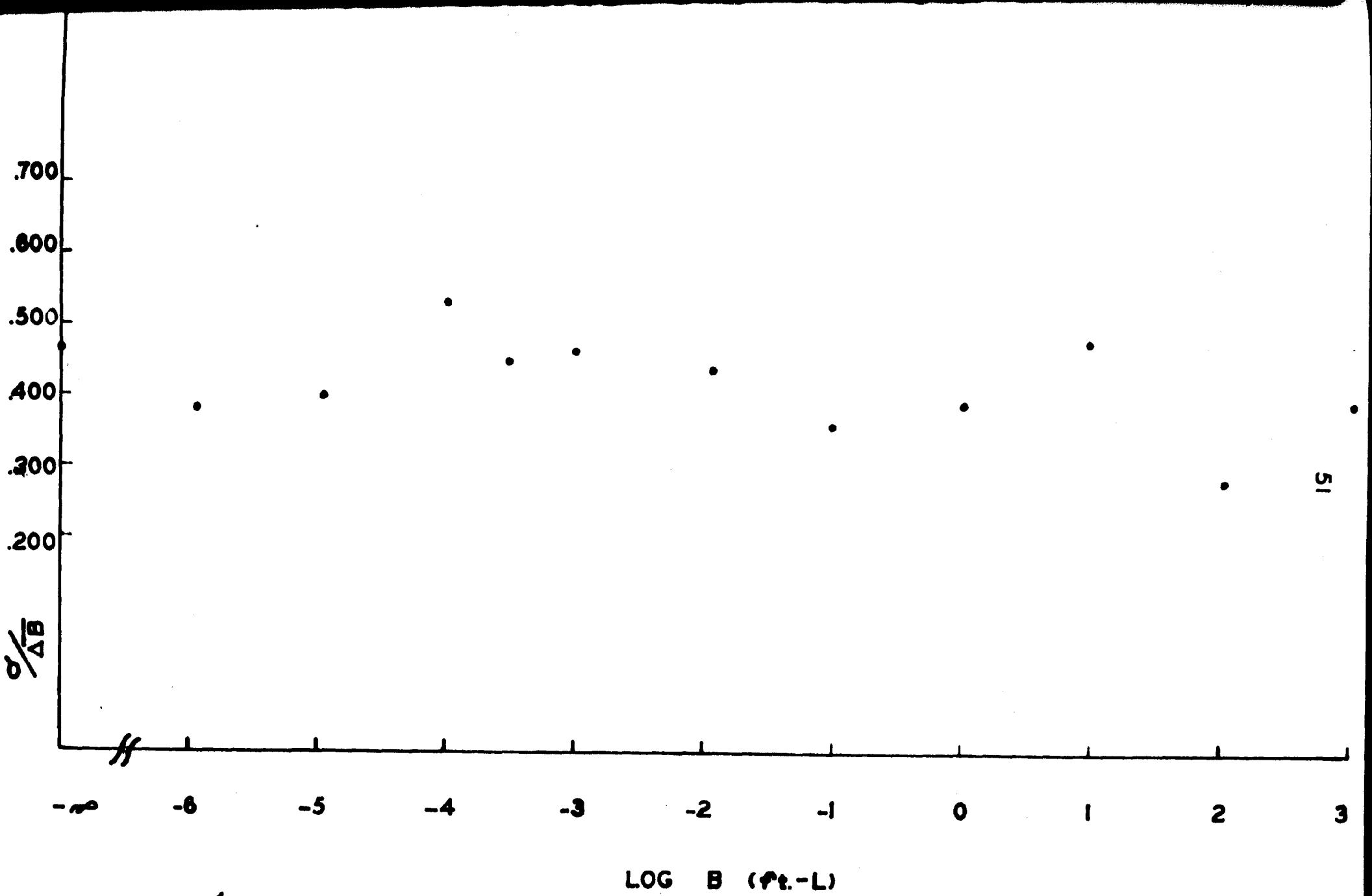


FIG. 18 Averaged $\sigma/\sqrt{\Delta B}$ data for four observers: 45' target

TABLE 10

X^2 TABLE FOR $\sigma_{\sigma/\Delta B}$

Observer	Experiment	X^2	d.f.	$P(X^2)$*
AK	I	52.4	19	.000131
AK	II	65.2	11	.000002
HF	I	27.6	19	.0834
HF	II	7.30	11	.799
LP	I	50.2	19	.000131
LP	II	50.9	12	.000001
TL	I	48.6	18	.000075
TL	II	6.64	11	.799

*$P(X^2)$ = the probability of a value this large or larger occurring by chance alone.

IV. DISCUSSION

It is apparent from examination of figures 9-12 that the data for the four observers obtained with the 1 minute target are very similar, both with respect to the general form of the relation between $\overline{\Delta B}$ and B, and with respect to the absolute values of $\overline{\Delta B}$ obtained. The data obtained by the four observers with the 45 minute target, and presented in Figures 13-16, are also very similar. The general form of the relation between $\overline{\Delta B}$ and B is quite similar for the two target sizes. The absolute magnitudes of the values of $\overline{\Delta B}$ are much smaller for the 45 minute target, as we expected.

We may evaluate the existence of the upturn and of photosensitization from these data. An upturn at large values of B would appear on these figures as a slope greater than 45°. There is absolutely no suggestion of such a slope. Photosensitization would appear on these figures as a reduction in $\overline{\Delta B}$ at some B greater than zero. There is no suggestion of such an effect.

These data suggest that the upturn is a spurious result which may be encountered if the experimental conditions involve introduction of an uncontrolled variable, such as the use of an exposure duration which is smaller than the critical duration at some values of B, and larger at other values of B.

The data also reveal that photosensitization does not always exist. We may wonder to what extent the effect reported by Crozier depends upon the exact experimental conditions. Unfortunately, the account of these data is so brief that it is

impossible to be certain just what experimental conditions Crozier used.

Since the experimental data approach asymptotes of constant $\overline{\Delta B}$ for low luminance, and constant $\overline{\Delta B}/B$ at high luminance, they are in general agreement with the Hecht theory of brightness discrimination. This fact, however, lends no more than coincidental credence to a photochemical theory of visual discrimination, since the form of equations described by Hecht can be readily duplicated by proceeding from other than his postulates, as has been done on a purely statistical basis by Crozier. It would seem that the contradictory results which have occasionally appeared in previous studies may indeed be due to contamination of the data by intrusion of the critical duration phenomenon at higher brightnesses, producing a spuriously high threshold.

Data from the experiment pertaining to the hypothesis of the constancy of $\sigma/\overline{\Delta B}$ are presented graphically in Figures 17 and 18; the individual data tables contain the values of $\sigma/\overline{\Delta B}$ plotted. For both targets and for all background luminances, $\sigma/\overline{\Delta B}$ is approximately constant. The hypothesis of the constancy of $\sigma/\overline{\Delta B}$ was subjected to statistical test by means of a X^2 test based on measures weighted for reliability. The results of this test are presented in Table 10. The probability of X^2 values in the table represent the expectation that a value of X^2 this large or larger will occur by chance alone. It may be seen that, with two or possibly three exceptions, the data may not be represented as arising

from a single universe. On a purely statistical basis, then, we must reject the hypothesis that $\sigma/\overline{\Delta B} = K$.

It must be added that the test applied in this case is not entirely fair to the hypothesis; it represents an extremely conservative estimate of the probability, since the deviations of $\sigma/\overline{\Delta B}$ from their central value may presumably vary due to day-to-day variability of threshold data. In this case, it is a choice between rejecting an hypothesis uncertainly determined to be false, and failing to reject a false one. Since the test applied in this instance seems the best available, and since it fails to confirm the hypothesis in question, we are forced to reject the relationship referred to as Crozier's law.

The fact remains that values of $\sigma/\overline{\Delta B}$ are remarkably constant as $\overline{\Delta B}$ varies over a considerable range. In fact, values of the ratio appear to be equivalent for the two target sizes. This fact alone is of considerable interest to research workers in sensory psychology. Certain theoretical principles which rely upon this result are currently in preparation by Blackwell and Kincaid.

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