# Contrast Thresholds of the Human Eye

H. RICHARD BLACKWELL*
*Louis Comfort Tiffany Foundation, Oyster Bay, New York*
(Received July 12, 1946)

THE L. C. Tiffany Foundation is an art school in peacetime, but its facilities were completely engaged during the war years under a contract with the Office of Scientific Research and Development. The part of the war program upon which this paper is based pertains to the determination of the contrast threshold of the normal human observer under a wide variety of experimental conditions. The typical experimental procedure consisted in projecting a spot of light on a white screen some sixty feet from a group of observers who individually reported whether the stimulus had been seen. A large number of such presentations, made with varying brightness of the stimulus, provided data from which, by statistical analysis, the contrast threshold could be determined. Experiments of this sort were repeated with stimuli of varying sizes and with values of screen brightness covering a range from full daylight to slightly less than the darkest night. In all, more than two million responses to the test stimulus were recorded, some four hundred and fifty thousand of which have been statistically analyzed and reported herein.

## I. EXPERIMENTAL PROCEDURE

### Laboratory

The laboratory in which experiments were conducted is shown in Figs. 1 and 2. The entire inner surface of the observation room was covered with flat white paint, whose reflectance was approximately 0.89. A ventilation system, details of which are shown in Fig. 2, maintained a moderate temperature and kept the air relatively free from dust particles.

Illumination of the observation room was provided chiefly by a number of special lighting units. The lighting units (troffers) were strategically situated in order to provide maximum

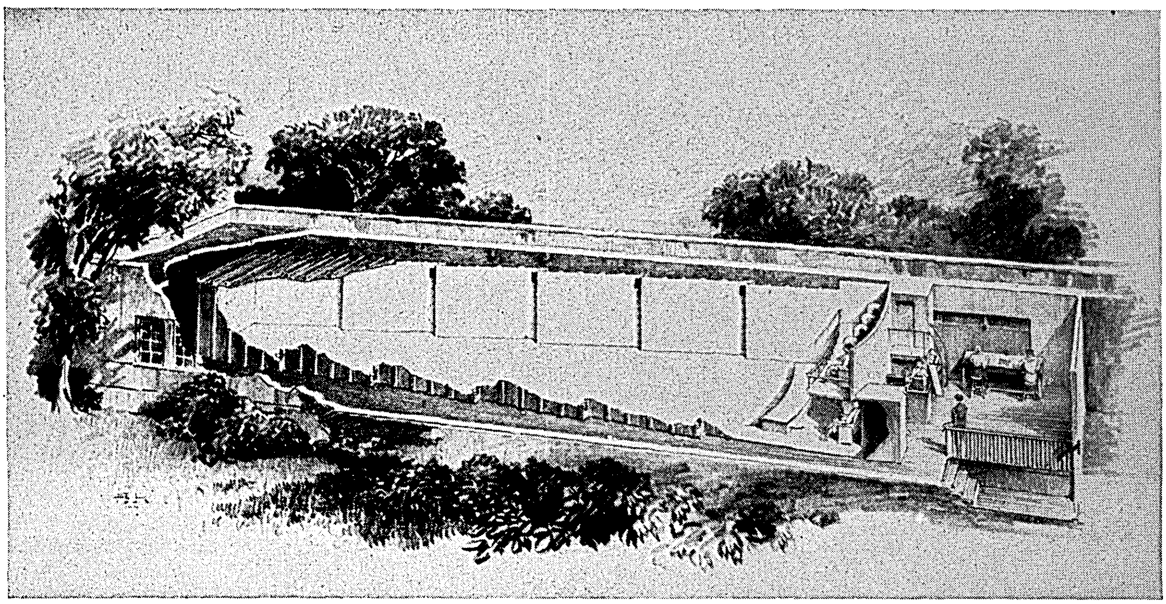

FIG. 1. Sketch of laboratory. A plywood structure was installed within an existing framework. The large plywood room served as a field of standardized brightness (the *observation room*). To the right was located the main control room. To the left was a supplementary control room.

* Now Technical Aide, Army-Navy-NRC Vision Committee, University of Michigan.

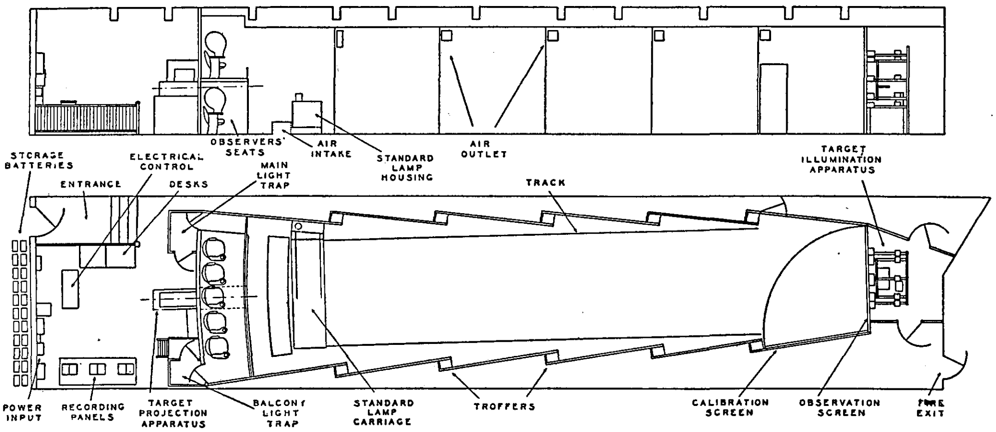


FIG. 2. Floor plan of laboratory. Dimensions of the plywood room (observation room) were: length, 63 feet; height, 10 feet, and width at the narrowest points, 10 feet.

uniformity of illumination. As can be seen in Fig. 2, five troffers were located on each of the left and right walls of the observation room. The brightness of the surfaces of the room could be varied from zero to 1000 footlamberts by adjusting the components of the troffers.

The front wall of the observation room, subtending 10° at the eyes of the observers, served as a screen upon which test stimuli were produced. The use of multiple sources of illumination and walls of high reflectance insured that the brightness of the portion of the screen upon which the stimuli were produced was uniform within the precision of visual photometry. Over the entire surface of the screen, variations in brightness did not exceed $\pm 3$ percent.

It was not possible for all surfaces of the observation room to be made equally bright. Because the troffers were directed forward, the observation screen was always somewhat brighter than other portions of the room. By careful manipulation of the output of the several troffers, surface brightnesses were made to decrease gradually from greatest brightness at the observation screen to least brightness near the rear of the room.

Figure 3 is a view of the observation screen from the rear of the room under typical illumination conditions. It is evident that no portion of the room had a greater brightness than the observation screen and that, in general, the brightness of the room decreased gradually from a maximum at the screen. The irregularities which existed were not distracting.

Preliminary experiments indicated the necessity for control not only of the brightness of the screen, but also of the pattern of brightness of the various surfaces of the observation room. It was shown that the threshold contrast of a stimulus projected onto the observation screen was a function of the pattern of brightness in the visual field surrounding the stimulus. As a consequence, the relative brightnesses of various surfaces of the observation room were rigidly controlled. The pattern of surface brightnesses illustrated by Fig. 3 was standardized. In the few instances in which deviations from this pattern were necessary, it was proved that no significant change in threshold contrast resulted.

The over-all brightness of the observation room was subject to precise control. Whenever possible, the sources of illumination were supplied by storage batteries. When the requisite power could not be produced in this way, a stabilized a.c. supply was employed.

To illuminate the observation screen to a brightness greater than 0.2 footlambert, each troffer was supplied with 120-volt, general service lamps, ranging in wattage from 20 to 300 and in number from 2 to 20. Each troffer extended the entire height of the room, but light emanated only from a flashed opal window 4 inches in width and 40 inches in height.

The output of the troffer units was varied not only by the number and wattage of lamps but also by means of a metal baffle which served to reduce the width of the diffusing window. A wooden reflector extended the full length of the

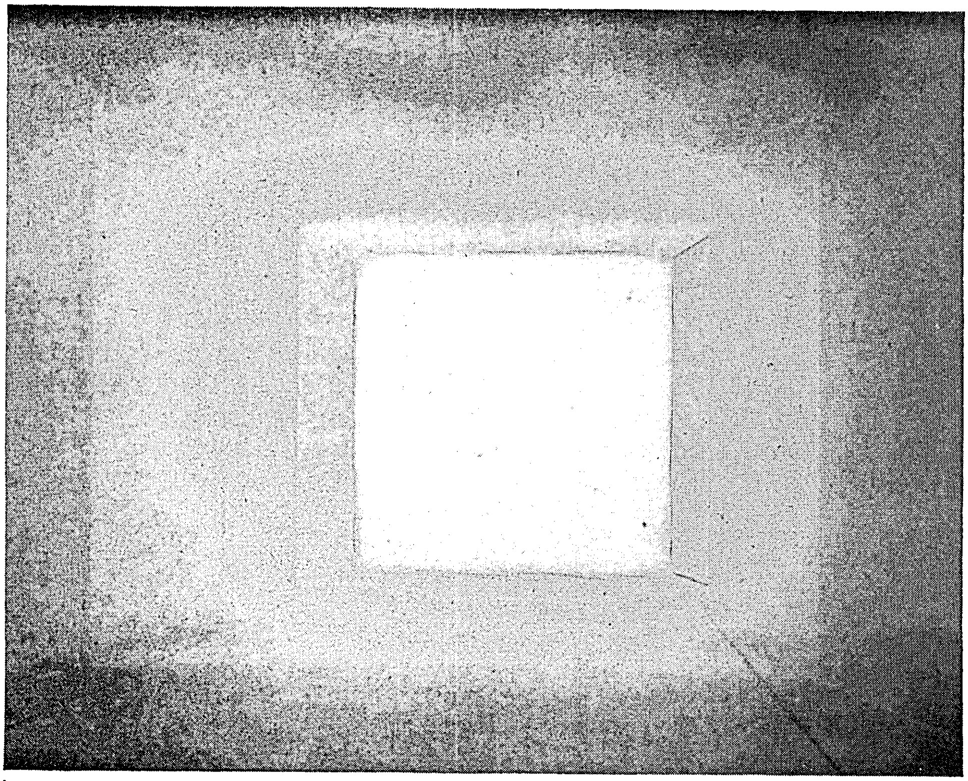

FIG. 3. Observation room with standard illumination, viewed from observers' stations.

troffer which was used to distribute output from the troffer in order to achieve maximum uniformity of illumination.

The lamps were supplied by a three-phase a.c. line, standardized by the Long Island Lighting Company. In order to insure even greater stability, the phase supplying the lamps in the two troffers nearest the observation screen on each side of the room was manually controlled by means of a variable transformer and compensator.

To illuminate the observation screen to a brightness less than 0.2 footlambert, each troffer was provided with from two to four specially designed fixtures. Each fixture was a light-tight brass tube containing an automobile head lamp and ground glass plates, which served as a secondary source. The head lamps were supplied by storage batteries. Reduction in output was obtained by varying the separation between the head lamp and the ground glass plates and by the addition of supplementary ground glass plates and opaque diaphragms. Sufficient ground glass plates were fixed in place to serve as the secondary source so that the addition of supplementary plates did not alter the optical properties of the fixtures. The flashed opal windows of the troffers were removed so that the secondary sources of the fixtures illuminated the observation room directly. Precise control over the spectral quality of the illumination was possible in this way since internal reflection within the troffers was not permitted.

Auxiliary illumination of specific portions of the observation screen was provided by projection equipment located in the control room at the rear of the observation room. Three standard Bausch and Lomb Balopticons were employed, modified somewhat for special purposes. It was sometimes necessary to illuminate extremely small areas of the observation screen. Image definition with the projection apparatus located 65 feet away was unsatisfactory. Accordingly, special techniques were devised by which the observation screen was transilluminated from the small control room shown in Fig. 2.

FIG. 4. View of observers' stations.

**Psychophysical Procedure**

Observers were seated at the rear of the observation room in upholstered chairs mounted on the floor and on a balcony (Fig. 4). The observers entered the observation room from the large control room through light traps.

A standard experimental session consisted of 320 presentations of a test stimulus. An electrical buzzer served as the signal for a stimulus presentation, remaining activated continuously during the presentation. Breaking the buzzer circuit served as a signal for the observers to indicate whether they had detected the presence of the stimulus.

The duration of the stimulus varied among experiments. In each case, a 6-second rest period followed each stimulus presentation. Additional rests were scheduled so that the observers did not become excessively fatigued.

In preparation for an experimental session, the troffers were adjusted for the desired level of illumination, and projection or transillumination equipment was prepared with a stimulus of selected size. The observers were allowed to adapt to the observation room brightness sufficiently long to insure stable visual performance. At low brightnesses, the period of adaptation was shortened by preliminary adaptation outside the laboratory with standard Polaroid dark adaptation goggles.

Five appropriate stimulus contrasts were selected on the basis of preliminary observations. Both during preliminary observations and during the regular session, each of the stimuli was presented in random sequence an equal number of times. The five stimuli were detectable by the observers with varying probability. The largest stimulus contrast was usually detected with a probability of 95 percent and the smallest stimulus contrast, with a probability of 10 percent. Three additional stimuli were selected so that an adequate function relating probability of detection and stimulus contrast was obtained. Threshold contrast was defined as the contrast which was detected with a probability of 50 percent, due allowance having been made for chance success.

The functions relating probability of detection and stimulus contrast were considered to be normal probability integrals. Graphical analysis

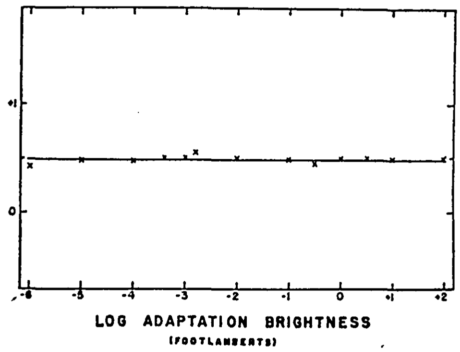


FIG. 5. The arithmetical mean of $h$ values computed from individual probability curves, plotted against adaptation brightness.

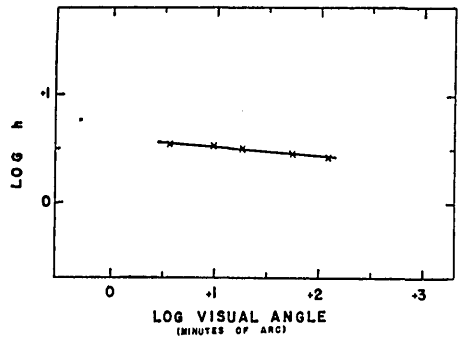


FIG. 6. The arithmetical mean of $h$ values computed from individual probability curves, plotted against stimulus area.

of large numbers of such functions revealed gratifying conformity to the predictions of the Gaussian formula.

Accordingly, solution for the contrast corresponding to 50 percent probability was accomplished by what has been called Urban's constant process.[1] This solution yields $M$, the stimulus value corresponding to a probability of 50 percent, due allowance having been made for chance success, and $h$, a constant which is an inverse measure of the steepness of the probability curve. The constant $h$ can be converted into $\sigma$, the standard deviation of the normal probability integral.

The adequacy of the Urban solution was investigated for a substantial number of probability functions in the following way: A normal probability curve was generated from values of $M$ and $\sigma$ and plotted together with the appropriate experimental points. An attempt was made to improve the fit of the normal curve to the experimental points by varying the values of $M$ and $\sigma$ from those obtained by the Urban process. In no case was an $M$ found which resulted in a better fit of the date, and in only a few cases was a slightly better value of $\sigma$ found. Since only $M$ values figure in the reported results, this analysis was considered to be an adequate demonstration of the adequacy of the Urban solution. All experimental data reported herein are based upon threshold contrasts computed in this way.

At the outset of experimentation, it was supposed that the five stimulus contrasts would have to vary not only absolutely, but also relatively, among the various experimental sessions. If the steepness of the probability curves varied significantly among the various experimental sessions, in order to include an adequate range of probability values, five stimuli of different relative contrast would have to be selected. Elaborate provisions were made for the production of stimuli with different relative and absolute contrasts.

It soon became evident that an appropriate four to one variation in stimulus contrast corresponded very nearly to a variation in probability from 10 to 95 percent for all experimental sessions. In other words, the shapes of probability curves were very nearly identical in all experimental sessions. Accordingly, five contrasts bearing the same relationship to each other were employed in all experimental sessions.

The five contrast stimuli used in every experimental session were related approximately as the numbers: 1.0, 0.75, 0.55, 0.37, and 0.24. In order to produce contrasts related in this constant fashion, four gelatine filters were obtained whose

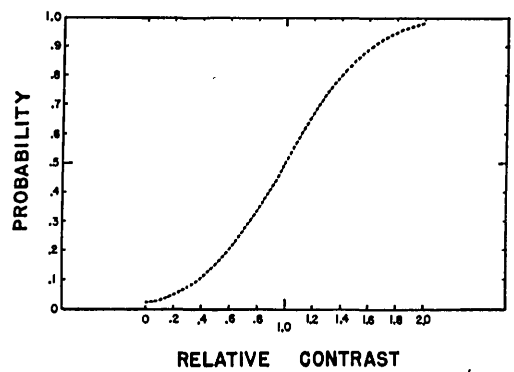


FIG. 7. Average probability curve.

[1] J. P. Guilford, *Psychometric Methods* (McGraw-Hill Book Company, Inc., New York, 1935), p. 170ff.

FIG. 8. Permanent recording of experimental data.

transmittances were identical with the last four numbers in the above series. A mechanism was constructed by which either an empty bracket or a bracket containing one of the four filters could be rotated into the projector beam.

A qualitative estimate of the extent to which the shapes of probability curves were independent of experimental variables such as adaptation brightness and stimulus area can be obtained by comparing $h$ values computed by the Urban method. Data are presented in Figs. 5 and 6, representing a total of 200,000 observations. Values of $h$ were computed by the Urban method from individual probability curves, derived from the body of data reported below in "Results, Part I."

It is apparent that substantial differences in $h$ as a function of either adaptation brightness or stimulus size do not exist.[2]

The definition of "threshold" probability as probability 50 percent greater than chance success was selected primarily because the steepness of the probability curve is greatest at this point, resulting in maximum precision in the determination of thresholds. If the "threshold" be redefined in terms of any probability other than 50 percent, the original threshold data can be converted by means of a simple constant. This procedure is valid because it has been shown that the steepness of probability curves is constant to a first approximation for all experimental conditions.

The average probability curve for all the experimental data reported in this paper was constructed in the following manner: The probability curve for each observer, for each experimental session, was solved by the Urban method for $M$ and $\sigma$. The constants $M$ and $\sigma$ for 1500 individual probability curves were averaged. From the average values of the constants, a normal probability integral was constructed from standard tables. The average probability function can be used in determining the constant which will convert the contrast thresholds presented in this paper to "thresholds" corresponding to other levels of probability.

The average probability curve for 450,000 observations is plotted in Fig. 7. The use of this curve can be illustrated by the following example: If "threshold" contrasts are desired which correspond to a probability of detection, $P=0.90$, thresholds presented in this paper should be multiplied by the constant 1.62.

Interpretation of probability data must be made with care. Trained observers can respond

[2] Although only random differences are present in Fig. 5, the data of Fig. 6 exhibit a consistent trend of smaller $h$ for larger stimuli. The differences in $h$ between the largest stimulus and each of the other stimuli were tested for significance. Value of $CR_\sigma$ and of $P$ (probability of a difference existing in the direction obtained) are presented:

| Stimulus size (ranked with respect to largest stimulus) | $CR_\sigma$ | $P$ |
|---|---|---|
| 2 | 1.83 | 0.966 |
| 3 | 4.33 | 0.999992 |
| 4 | 3.90 | 0.99995 |
| 5 | 5.13 | 0.999997 |

TABLE I. Ophthalmological records.

| Observer | Visual acuity (20 ft.) O.D. | O.S. | O.U. | Near point (mm) O.D. | O.S. | O.U. | Muscle balance 20 ft. | 33 cm |
|---|---|---|---|---|---|---|---|---|
| B.B. | 20/20− | 20/20 | 20/20+ | 100 | 110 | 110 | 0.25 Eso. | 5 Exo. |
| I.T.B. | 20/25+ | 20/25+ | 20/20− | 100 | 110 | 90 | 0.5 Eso.<br>0.25 RH. | 1.5 Exo. |
| M.J.B. (a) | 20/15− | 20/15− | 20/15− | 140 | 140 | 130 | 0.5 Eso.<br>0.25 Hyper. | Normal |
| (b)* | 20/15− | 20/15− | 20/15− | 140 | 140 | 130 | 0.5 Eso. | Normal |
| E.L.C. | 20/15− | 20/15− | 20/15 | 130 | 110 | 105 | 1.0 Exo.<br>0.5 Hyper. | Normal |
| C.C.C. (a) | 20/20− | 20/25− | 20/20+ | 120 | 108 | 95 | 0.5 Exo.<br>0.25 Hyper. | Normal |
| (b)* | 20/20+ | 20/20+ | 20/15− | 120 | 110 | 110 | 0.25 Exo.<br>1 Hyper. | Normal |
| M.C. | 20/15− | 20/15− | 20/15− | 70 | 80 | 70 | 2 Eso.<br>0.5 RH. | 1.75 Eso. |
| L.H. | 20/20+ | 20/20+ | 20/20+ | 120 | 130 | 120 | 0.75 Eso. | 0.5 Eso. |
| E.L.H. | 20/20 | 20/20 | 20/20+ | 90 | 90 | 90 | 0.5 Eso.<br>0.25 RH. | Normal |
| D.H. | 20/25+ | 20/25 | 20/20− | 110 | 110 | 100 | 0.5 Eso. | 2 Exo. |
| L.T.H. | 20/20+ | 20/15− | 20/15− | 140 | 140 | 140 | 0.5 Eso. | Normal |
| N.L.H. | 20/20 | 20/20 | 20/20 | 120 | 130 | 110 | 0.5 LH. | 0.5 Eso. |
| J.J. | 20/15− | 20/15 | 20/15 | 120 | 120 | 100 | 0.5 Exo.<br>0.5 RH. | 2 Exo. |
| E.S.K. | 20/15− | 20/15− | 20/15 | 105 | 100 | 100 | 3 Eso. | 3 Exo. |
| V.R.M. | 20/15− | 20/15− | 20/15− | 100 | 120 | 100 | 1.5 Exo. | 9 Exo. |
| M.R.R. | 20/15− | 20/15− | 20/15− | 105 | 115 | 95 | 2 Eso.<br>2 Hyper. | Normal |
| S.R. | 20/20+ | 20/15− | 20/15− | 130 | 120 | 120 | Normal | 7 Exo. |
| M.S. | 20/20+ | 20/20 | 20/15− | 100 | 110 | 90 | 0.37 RH. | 2.5 Exo. |
| J.T. | 20/20 | 20/20 | 20/20+ | 110 | 110 | 110 | 0.5 Eso. | 3 Exo. |
| G.H.W. | 20/15 | 20/15− | 20/15 | 90 | 110 | 90 | 2 Eso.<br>0.5 RH. | 2 Exo. |

*Abbreviations:* Eso. Esophoria; Exo. Exophoria; Hyper. Hyperphoria; RH. Right Heterophoria; LH. Left Heterophoria

* Repeat examinations made after three months of intensive observations.

very successfully on the basis of hunches. It was found by interrogation that the observers did not feel confident of having "seen" a stimulus unless the level of probability of detection were greater than 0.90.

## Recording of Data

The method used in recording experimental data was rapid and free from error. A large number of electrical circuits were used, each including a neon signal lamp. Master control panels were constructed, at which complete information was at all times available in the form of a constellation of excited neon lamps. Each observer recorded her responses by means of an 8-point selector switch, connected in circuit with eight neon lamps. In this way, each observer had a repertoire of eight possible responses. Projection or transillumination equipment was equipped with similar switches so that information concerning stimulus presence, stimulus location, and stimulus contrast was represented by appropriate neon signal lamps at the master control panel.

Permanent records were made for each stimulus presentation, which included characteristics of the stimulus and the response of each of the observers. This was accomplished by placing a tissue paper over the master panel and circling with pencil the locations of the excited neon lamps. A record assistant is shown in Fig. 8 recording a typical stimulus presentation. The tissue record sheets were sorted, responses were scored, and probability of detection values were obtained for each observer for each of the five stimulus contrasts. Threshold contrast was then computed for each observer by the Urban method.

### Observers

The observers were young women, aged 19–26 years, whose visual acuity in each eye and in both eyes was approximately 20/20 without refractive correction. Table I presents ophthalmological records for the young women whose observations constitute the experimental data of this paper. These and other ophthalmological examinations were made by Dr. Gertrude Rand, Columbia University, and represent a generous personal contribution to the experimental program. The observers were employed full-time for periods varying from six months to two and one-half years. Observing occupied approximately half their time, the remainder being devoted to the statistical analysis of their data. *A priori* objections to this procedure were soon overcome by the obvious stability of individual experimental results.

Observers were never considered "trained" until they had made approximately 6400 observations under varied experimental conditions. In general, the experimental data of this report were obtained with observers who had been occupied from six months to a year in preliminary experiments. Consequently, they were veterans of from 35,000–75,000 observations when the experiments reported here were begun. The exceptional experience of the young women in the task of observing resulted in unusual sensitivity and gratifying stability of response.

### Photometric Procedure

Preliminary investigations revealed that under the conditions of these experiments, the precision of ordinary photometric measurements was less than the precision of responses to visual stimulus. As a consequence elaborate photometric determinations were made throughout the experiments reported in this paper. The resulting photometric precision was always at least as good as that of responses to visual stimulus. Measurements were made of brightnesses varying from 100 to $1\times10^{-6}$ footlambert. At least two independent photometric measurements were made of each surface brightness. The two measurements ordinarily agreed within 5 percent, so that brightness values based on two measurements were accurate within less than 5 percent.

All photometric quantities were expressed in footlamberts, defined in terms of the photopic visibility function. Surface brightnesses were evaluated in terms of standard brightnesses by means of null visual photometers. The visual photometers were modifications of the Macbeth illuminometer, chosen for its stability and precision. Standard brightnesses of a special test surface were provided by means of standard lamps, varying in candlepower from 20 to 1000.

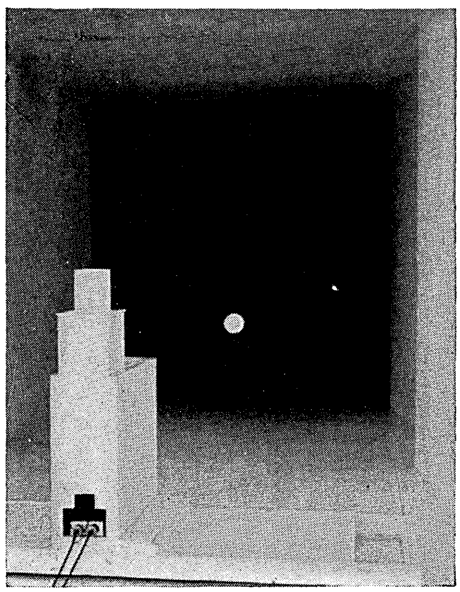

FIG. 9. Apparatus for producing standard brightnesses of a test surface.

Three sets of standard lamps were available. Their reliability was assured by cross-checks and by frequent calibrations at the Electrical Testing Laboratories, New York.

The test surface was always mounted near the observation screen. The standard lamps, in housings mounted on a carriage, could be positioned at distances from the test surface varying from 10 to 50 feet. The carriage moved on the tracks shown in Fig. 2. A black felt calibration screen was mounted before the observation screen when the test surface was illuminated by standard lamps. By preventing re-illumination of the test surface, the calibration screen made it possible for the inverse square law to be used in computing standard brightnesses. A view of the test surface, standard lamp housing, and calibration screen is shown in Fig. 9. The calibration screen was swung into place from its normal position against the right wall as indicated in Fig. 2. Standard brightnesses of the test surface could be varied from 0.006 to 10 footlamberts. When larger or smaller values were needed, gelatine filters were used in the visual photometers, the transmittance of which had been determined for the photopic eye by means of the inverse square law.

In order to fulfill the specification of the photometric unit, it was necessary either to maintain spectral equivalence between surface brightnesses and standard brightnesses, or else to make all brightness evaluations with the photopic eye. It was sometimes possible to obtain spectral equivalence with low intensities by the physical reduction of high intensity sources of known spectral quality. In these instances, evaluations were made at fairly low adaptation brightnesses. More customarily, it was impossible to maintain the spectral quality of surface brightnesses exactly because of the slight selectivity of available materials. In these instances, photometric measurements were made indirectly so that the photopic eye could always be used. Since the selectivity of materials was only slight, direct low level photometry was used occasionally as a check on the indirect photometry. Although the low level photometry exhibited less precision than the indirect photometry, no systematic discrepancy was ever discovered between the two.

The photometric policy adopted insured that surface brightnesses were evaluated correctly in footlamberts. *Apparent* brightnesses always differed somewhat from actual brightnesses because of the slight selectivity of materials, and the variations in luminosity factors of the observers. The question arose whether brightness contrasts were equivalent to *apparent* brightness contrasts. In order to compare actual and *apparent* brightness contrasts, spectrophotometric data for each surface brightness, and luminosity factors for each observer at each brightness level, would be required. Adequate spectrophotometric data were available; no information was available concerning the luminosity factors of the observers. As an approximation, interpolations from average luminosity factors offered by Jones[3] were used. Analysis indicated that significant differences between actual and *apparent* brightness contrasts did not exist.

## II. RESULTS AND DISCUSSION

### Part I

A comprehensive investigation was made to determine the mutual relationships between adaptation brightness, stimulus area, and threshold contrast. Stimuli, circular in form and brighter than the observation screen, were presented in any of eight possible positions on the screen for an exposure of six seconds. As a consequence, the observers scanned the screen at a rate comparable to that employed by lookouts in the military service in determining the position they thought the stimulus occupied.

#### *General Procedure*

Adaptation brightnesses were investigated varying from zero to 100 footlamberts. Circular stimuli varied in diameter from 121.0 to 3.60 minutes of arc. Threshold contrasts were obtained for each of a group of nine observers for each of seventy-seven experimental sessions, consisting of 320 stimulus presentations each. A total of approximately 220,000 observations was made, therefore, under experimental conditions differing only in adaptation brightness, stimulus area, and stimulus contrast.

[3] L. A. Jones, "Summary of American opinion, BS/ARP 18, British standard specification for fluorescent and phosphorescent paint," Great Britain Ministry of Home Security. RC(C) 85 (July, 1942).

Let us set the brightness of the observation screen equal to $B_0$. When a stimulus was presented, a brightness increment, $\Delta B$, was either added to or subtracted from the prevailing $B_0$. The stimulus brightness, $B_s$, equaled $B_0+\Delta B$ or $B_0-\Delta B$. Following standard practice,

$$C \text{ (contrast)} = (B_s - B_0)/B_0 \text{ for stimuli brighter than the observation screen,}$$
$$= (B_0 - B_s)/B_0 \text{ for stimuli darker than the observation screen.}$$

Values of $C$ range from 0 to $+\infty$ for stimuli brighter than the screen and from 0 to $+1$ for stimuli darker than the screen. In the experiments of this section, only stimuli brighter than the observation screen were investigated.

Near threshold, the difference between $B_s$ and $B_0$ is often less than 1 percent. In order to insure sufficient precision, $\Delta B$ was produced independently of $B_0$ by a projection system located in the control room behind the observers. The beam of the projector passed between the observers, as shown in Fig. 4, and struck the observation screen at the opposite end of the observation room.

A small red orientation point was located in the center of the observation screen. The stimulus was projected in one of eight positions on the circumference of a circle generated about the orientation point on a three degree radius. The eight positions used corresponded to the eight major points of a compass. A thin prism, rotated before a standard lantern-slide projector, provided reliable stimulus positioning. At the sound of a signal buzzer, the observers looked toward the screen and instigated a systematic search routine to attempt to locate the stimulus. The six-second exposure permitted only a rapid scanning of the stimulus orbit.

The observers were not given specific scanning instructions. They were told to fixate and to search in the manner they found most efficient. They were instructed that they might find it profitable to use parafoveal vision at low brightnesses. The scanning routine was not identical for all observers, but long experience tended to stabilize the scanning procedures so that reproducible data could be obtained.

At the conclusion of the six-second stimulus exposure, the observers selected the position which they believed the stimulus had occupied. Response consisted of rotating their recording switch until its handle assumed a position analogous to the position of the stimulus. The observers were required to respond to each presentation. They were shown their own data at the conclusion of each experimental session, and soon learned that their hunches were quite often correct. After repeated performance, their responses became semi-automatic.

Response data were recorded from the master control panels as shown in Fig. 8. Each response was scored and the probability of successful detection was computed for each observer for each of the five stimulus contrasts. Threshold contrasts were computed by the Urban method (corresponding to 50 percent probability, due allowance having been made for chance success). Under the experimental conditions, chance success could be expected in one of eight presentations.

Analysis of the response data revealed that there were no systematically favored positions. Further, if an error were made, there was equal probability that the incorrect response would fall in each of the seven positions not occupied by the stimulus. The analysis from which these conclusions were drawn was made with stimuli detected successfully only a few percent better than chance.

### *Photometric Procedure*

Values of $B_0$ and $\Delta B$ were always photometered independently in order to obtain maximum precision in the determination of contrast. When $B_0$ or $\Delta B$ was as great as 0.1 footlambert, a direct measurement was made from the rear of the observation room. A Macbeth illuminometer, fitted with a telescopic attachment, was used as a null instrument in evaluating the unknown surface brightness in terms of the standard brightness of a test surface. For brightnesses less than 0.1 footlambert, special techniques were devised so that brightnesses could legitimately be expressed in footlamberts.

Reduction in the output of the projection system used to provide $\Delta B$ was accomplished by the use of gelatine filters, chosen for their lack of selectivity. In addition, when $\Delta B$ values less than

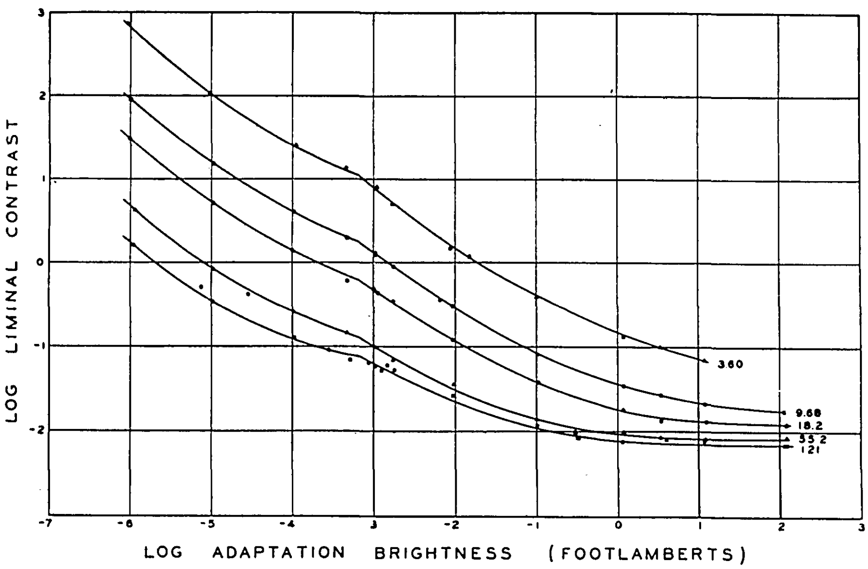


FIG. 10. The arithmetical mean of threshold contrasts, computed from individual probability curves, plotted as a function of adaptation brightness for five stimulus areas.

0.1 footlambert were required, a ground glass plate was inserted in the lantern-slide projector near the aperture. The ground glass became the secondary source of the projection system. Since the absorbing filters were inserted between the ground glass and the projection lamp, reduction in output did not alter the optical properties of the system.

Two independent measurements were made for small values of $\Delta B$:

(1) The gelatine filters were removed and the unattenuated $\Delta B$ was measured directly with the Macbeth illuminometer and telescopic attachment. The transmittance of the gelatine filters was then measured in the projection system. Ground glass plates were inserted near the projection lens, on the side away from the projection lamp. The brightness of the foremost ground glass plate was measured with a visual photometer with the gelatine filters in place and with the filters removed. The ratio of the brightnesses was taken as a measure of the visual transmittance of the filters.

(2) A photometric technique was devised in which the gelatine filters were positioned as they had been during experimentation. It was recog-

TABLE II. Arithmetical mean threshold contrast. Stimuli brighter than surround (Part I). Angular subtense of stimulus (minutes of arc).

| 121.0 | | 55.2 | | 18.2 | | 9.68 | | 3.60 | |
|---|---|---|---|---|---|---|---|---|---|
| Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ |
| 2.080 | −2.124 | 2.084 | −2.041 | 2.081 | −1.894 | 2.053 | −1.739 | 1.072 | −1.127 |
| 2.061 | −2.127 | 1.083 | −2.061 | 2.078 | −1.895 | 1.077 | −1.671 | 0.523 | −0.980 |
| 1.074 | −2.082 | 0.605 | −2.085 | 1.086 | −1.861 | 0.533 | −1.568 | 0.075 | −0.868 |
| 0.076 | −2.102 | 0.531 | −2.049 | 0.542 | −1.863 | 0.076 | −1.460 | −0.996 | −0.401 |
| −0.471 | −2.081 | 0.078 | −1.997 | 0.070 | −1.736 | −0.994 | −1.083 | −2.053 | 0.175 |
| −0.497 | −2.065 | −0.504 | −2.021 | −0.975 | −1.415 | −2.031 | −0.505 | −2.768 | 0.703 |
| −0.994 | −1.937 | −0.504 | −1.971 | −2.034 | −0.918 | −2.757 | −0.044 | −2.951 | 0.905 |
| −2.029 | −1.579 | −0.991 | −1.858 | −2.755 | −0.460 | −2.979 | 0.090 | −2.978 | 0.896 |
| −2.756 | −1.274 | −2.020 | −1.438 | −2.952 | −0.344 | −2.984 | 0.116 | −3.341 | 1.144 |
| −2.907 | −1.280 | −2.769 | −1.150 | −2.989 | −0.313 | −3.346 | 0.298 | −3.964 | 1.397 |
| −2.987 | −1.228 | −2.981 | −1.012 | −3.323 | −0.219 | −3.982 | 0.618 | −5.016 | 2.026 |
| −3.065 | −1.178 | −3.331 | −0.831 | −4.002 | 0.151 | −4.986 | 1.179 | −6.032 | 2.868 |
| −3.296 | −1.148 | −3.995 | −0.595 | −4.982 | 0.705 | −5.999 | 1.944 | | |
| −3.979 | −0.891 | −4.989 | −0.079 | −6.012 | 1.479 | | | | |
| −4.995 | −0.474 | −5.948 | 0.622 | | | | | | |
| −5.969 | 0.212 | | | | | | | | |

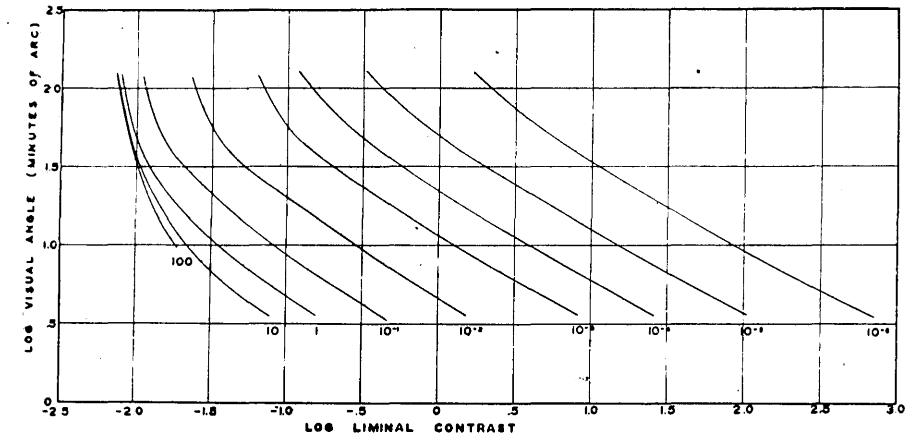


FIG. 11. Interpolations from Fig. 10. Each curve represents the relation between threshold contrast and stimulus area for a given adaptation brightness.

nized that the illumination striking the observation screen bore a constant relation to the brightness of the secondary source of the projection system. The constant factor relating $\Delta B$ to the brightness of the secondary source of the projector was established at maximum output. Subsequently, the secondary source brightness was measured and $\Delta B$ was computed.

Agreement between the two measurements of $\Delta B$ was ordinarily obtained within $\pm 3$ percent.

At low brightnesses, $B_0$ was provided by the special fixtures described under "Experimental Procedures." Since reduction did not affect the areas of the secondary sources, or in any way alter their optical properties, there was a constant relationship between the brightness of the observation screen and the brightnesses of the secondary sources of the fixtures.

At a screen brightness level of 0.1 footlambert, the constant factor relating $B_0$ to the brightnesses of the secondary sources of the fixtures was measured. For low brightnesses, $B_0$ was computed from measurements of the appropriate brightnesses.

The validity of the indirect photometric measurement was established by the following photometric technique: A disk, three feet in diameter, was mounted at the center of the observation screen. Since its surface reflectance was lower than that of the screen, the disk appeared as a large dark circular patch in the center of the observation screen. An increment of illumination could be added to the disk from the projection apparatus located in the control room behind the observers. When the appropriate increment of illumination was added, the disk became indistinguishable from the observation screen.

The group of nine observers used the disk and screen as a huge visual photometer. Increments of illumination were selected, some of which were insufficient to increase the disk brightness to that of the screen, while others made the disk brighter than the screen. The increments were presented randomly to the observers, who judged whether the disk was brighter or darker than the surrounding screen. The increment just sufficient to make the disk indistinguishable from the screen was interpolated from the psychophysical data. The spectral quality of the disk and the observation screen were carefully equated so that

TABLE III. Interpolations from Fig. 10. Log (arithmetical mean threshold contrast).

| Angular subtense of stimulus (minutes of arc) | $B_0$ 100 | 10 | 1 | $1\times10^{-1}$ | $1\times10^{-2}$ | $1\times10^{-3}$ | $1\times10^{-4}$ | $1\times10^{-5}$ | $1\times10^{-6}$ |
|---|---|---|---|---|---|---|---|---|---|
| 121.0 | −2.132 | −2.130 | −2.114 | −1.959 | −1.640 | −1.198 | −0.910 | −0.461 | 0.238 |
| 55.2 | −2.062 | −2.060 | −2.020 | −1.857 | −1.500 | −0.996 | −0.590 | −0.069 | 0.666 |
| 18.2 | −1.889 | −1.857 | −1.738 | −1.421 | −0.928 | −0.325 | 0.137 | 0.716 | 1.467 |
| 9.68 | −1.730 | −1.658 | −1.437 | −1.070 | −0.526 | 0.124 | 0.615 | 1.196 | 1.950 |
| 3.60 | — | −1.111 | −0.812 | −0.385 | 0.182 | 0.911 | 1.410 | 2.017 | 2.821 |

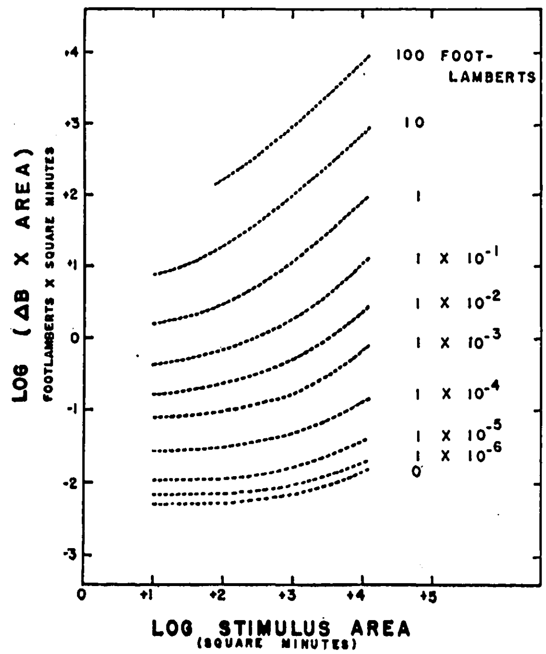


FIG. 12. Interpolations from Fig. 10. The product of $\Delta B$ and stimulus area is plotted as a function of stimulus area for various adaptation brightnesses.

evaluation errors were not introduced at low brightnesses.

The value of illumination increments from the projection system was computed in the following manner: A ground glass plate was inserted in the projection system which served as a secondary source. Reduction in the output of the optical system was accomplished by the insertion of gelatine filters between the secondary source and the projection lamp; consequently, the optical properties of the system were not altered. A constant factor related the brightness of the secondary source to the illumination striking the disk.

With $B_0$ set for 0.1 footlambert, the relation between secondary source brightness and illumination at the disk was measured. The relation between illumination required to render the disk indistinguishable from its surrounds and $B_0$ was established. Subsequently, critical values of illumination were determined from observer judgments, and $B_0$ was computed. The direct measurement of $B_0$ did not vary systematically from the value computed from the indirect photometric measurement. Random differences between the two measurements usually did not exceed ±4 percent.

The circular stimuli used in the various experimental sessions varied in size from 0.7 to 26 inches in diameter. Measurements were made to determine the exact distribution of energy in each of the stimuli. For each stimulus the diameter was considered to be that of a stimulus of equivalent flux, uniformly distributed. For large stimuli, the diameter thus computed did not differ significantly from the diameter measured with rule and calipers. For the smallest stimulus, there was a 15 percent difference between the computed diameter and the measured diameter. The diameter based upon energy considerations was considered the most adequate measure of size because in the case of a stimulus as small as 3.60 minutes of arc, the eye usually responds on the basis of total physical energy.

The experimental data are presented in Table II and are plotted in Fig. 10, fitted by empirical curves. The data represent approximately 220,000 observations obtained during a period of four months by a group of nine observers. (The open circles represent experimental data obtained under different experimental conditions. Subsequent reference will be made to these points in Part II.)

Two interesting aspects of the contrast sensitivity functions are apparent. At high brightnesses, especially for large stimuli, contrast becomes constant with respect to adaptation brightness. For a 121-minute stimulus, for example, there is no appreciable change in threshold contrast as adaptation brightness is reduced from 100 to 1 footlambert. This relation has been called the Weber-Fechner law.

Each of the curves shows a discontinuity at approximately $7\times10^{-4}$ footlambert. From interrogation, it was clear that this discontinuity

TABLE IV. Arithmetical mean threshold $\Delta B$ ($B_0=0$).

| Angular subtense of stimulus (minutes of arc) | Log $\Delta B$ |
|---|---|
| 121.0 | −5.836 |
| | −5.951 |
| 55.2 | −5.444 |
| 18.2 | −4.594 |
| 9.68 | −4.184 |
| | −4.056 |
| 3.60 | −3.268 |

TABLE V. Arithmetical mean threshold contrast. Stimuli brighter than surround (Part II). Angular subtense of stimulus (minutes of arc).

| 121.0 | | 55.2 | | 18.2 | | 9.68 | | 3.60 | |
|---|---|---|---|---|---|---|---|---|---|
| Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ |
| −2.831 | −1.208 | −4.505 | −0.372 | −2.994 | −0.308 | −2.117 | −0.434 | −1.823 | 0.078 |
| −3.551 | −1.031 | | | | | | | | |
| −5.134 | −0.297 | | | | | | | | |

corresponded to a change in the nature of scanning. Since the observers were allowed to fixate where they chose, they used foveal vision at high brightnesses and parafoveal vision at low brightnesses.

Interpolations from Fig. 10 are presented in Table III and in Fig. 11.

Figure 12 is presented in order to compare the data of Fig. 10 with data obtained at zero adaptation brightness. The basic data for zero adaptation brightness are presented in Table IV. It is apparent that the performance of the eye is very similar for adaptation brightnesses smaller than $1\times10^{-5}$ footlambert.

### *Precision*

Analysis of photometric measurements revealed that each surface brightness was accurately measured within ±4 percent. Estimates of the repeatability of the observer's response data were obtained by computing the probable errors of group probability functions constructed from all the observer data in each of the experimental sessions. The average P.E. obtained indicated that in 99 percent of repeat experiments the same response data would be obtained within ±8 percent; in 50 percent of repeat experiments, within ±2 percent.

Inspection of Fig. 10 indicates that the experimental points fall on the smoothed curve within ±5 percent on the average, with an occasional point deviating as much as 16 percent. The precision of experimental data measured in this way is in agreement, therefore, with the precision predicted from standard statistical measures. The over-all precision of the experimental procedure was approximately ±5 percent. The precision of the smoothed curve is approximately ±0.6 percent.

Examination of the data for individual observers revealed that the average deviation from a smoothed curve was ±12 percent, with an occasional deviation of 40 percent.

## Part II

An experimental program was conducted to determine whether stimuli darker than the observation screen are equivalent to stimuli brighter than the screen of equivalent contrast. For convenience, stimuli brighter than the screen will be considered *positive* and stimuli darker than the screen will be considered *negative*. (It must be emphasized that the definition of contrast results in positive values of contrast for both *negative* and *positive* stimuli.)

In almost all particulars, the experimental procedure duplicated that of Part I. Special projection apparatus was devised to permit the presentation of negative stimuli. A transparent slide containing an opaque spot was placed in an ordinary lantern-slide projector. When the entire observation screen was illuminated, a negative stimulus could be produced in any of eight locations. The negative stimulus was positioned by means of a special mechanism designed to change the position of the opaque spot in the projector beam. In order to reduce the contrast of the negative stimulus, additional illumination of the screen was provided by a second projector, adjusted to illuminate exactly the same area as the first. Additional reduction of contrast was accomplished by illuminating the screen and the remainder of the observation room with the troffer units.

It was necessary to produce five values of contrast related in a constant fashion, to be used in obtaining probability curves in each experimental session. This was accomplished by inserting one of a pair of filters of complementary transmittances in the beam of each of a pair of projectors. The initial output of the projectors was equated; as a consequence, their combined output was

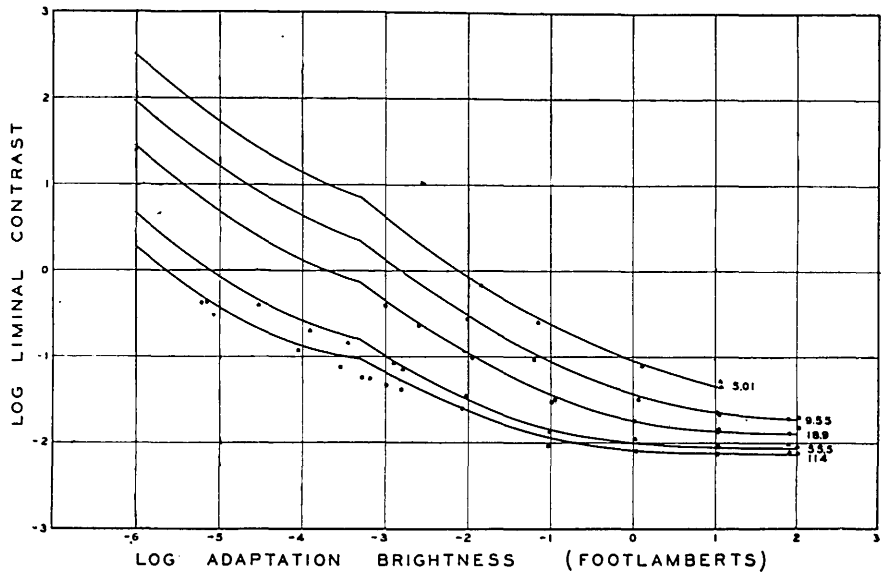


FIG. 13. The arithmetical mean of threshold contrasts computed from individual probability curves, plotted as a function of adaptation brightness for five stimulus areas. The solid curves represent interpolations from Fig. 11.

maintained constant as the relative contribution from each was varied. The transparent slide and opaque spot were included in only one of the projectors. Consequently, as the different combinations of filters were used, stimulus contrast varied in a systematic fashion. For a given experimental session, the proportions of screen brightness provided by the troffer units and the pair of projectors were adjusted so that the contrasts approximated those used in the corresponding experiment of Part I.

In order to change the position of the stimulus, it was necessary to remove the stimulus from the observation screen. Accordingly, a shutter interrupted the beams of the pair of projectors at the end of each six-second stimulus presentation. Removal of the stimulus reduced the brightness of the observation screen and affected the brightness adaptation of the observers. Accordingly, a third projector was used to compensate for the reduction in screen brightness resulting from stimulus removal. The output of the third projector equaled the combined output of the pair of projectors. A single shutter arm uncovered the

TABLE VI. Arithmetical mean threshold contrast. Stimuli darker than surround (Part II). Angular subtense of stimulus (minutes of arc).

| 114.0 | | 55.5 | | 18.9 | | 9.55 | | 5.01 | |
|---|---|---|---|---|---|---|---|---|---|
| Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ |
| 2.022 | −2.119 | 2.012 | −2.033 | 2.022 | −1.821 | 2.024 | −1.699 | 1.073 | −1.344 |
| 1.914 | −2.103 | 1.894 | −2.018 | 1.911 | −1.881 | 1.901 | −1.712 | 1.066 | −1.278 |
| 1.035 | −2.122 | 1.039 | −2.037 | 1.041 | −1.835 | 1.047 | −1.667 | 0.115 | −1.096 |
| 1.027 | −2.143 | 1.029 | −2.046 | 1.029 | −1.869 | 1.024 | −1.641 | −1.152 | −0.590 |
| 0.040 | −2.096 | 0.027 | −1.950 | 0.019 | −1.740 | 0.070 | −1.490 | −1.826 | −0.173 |
| −1.029 | −2.033 | −1.012 | −1.867 | −0.949 | −1.494 | −1.200 | −1.033 | | |
| −2.068 | −1.611 | −2.024 | −1.452 | −0.999 | −1.520 | −2.004 | −0.554 | | |
| −2.807 | −1.382 | −2.798 | −1.140 | −1.952 | −1.012 | | | | |
| −2.970 | −1.325 | −2.900 | −1.072 | −2.603 | −0.636 | | | | |
| −3.190 | −1.256 | −3.457 | −0.842 | −3.042 | −0.403 | | | | |
| −3.287 | −1.250 | −3.920 | −0.696 | | | | | | |
| −3.546 | −1.112 | −4.532 | −0.402 | | | | | | |
| −4.055 | −0.932 | | | | | | | | |
| −5.073 | −0.520 | | | | | | | | |
| −5.156 | −0.366 | | | | | | | | |
| −5.224 | −0.375 | | | | | | | | |

projection lens of the compensating projector as it covered the projection lenses of the pair of projectors. In this way, the brightness of the observation screen was unchanged during the removal and production of the stimulus.

The production of contrasts approaching the upper limit of negative stimuli (+1.0) necessitated that only the pair of projectors illuminate the observation screen. Illumination from the troffer units always served to reduce the stimulus contrast. It is apparent, therefore, that production of large stimulus contrasts was possible only by reduction in the relative amount of illumination of the screen produced by the troffers. The pattern of surface brightnesses in the observation room was somewhat different for illumination by troffers and illumination by projectors. When troffer illumination was used, the standardized distribution of brightness shown in Fig. 3 resulted. The use of projectors illuminating the observation screen alone resulted in greater brightness of the screen relative to the other brightnesses of the room. With troffer illumination, the brightness of the areas immediately adjoining the screen were 95 percent as bright as the screen. With projected illumination, the corresponding value was 44 percent.

Experiments were conducted to determine whether this variation in the pattern of brightnesses in the visual field influenced threshold contrast. The observation screen was illuminated solely by a projector. A positive stimulus increment was added by a second projector. Conditions duplicated corresponding experiments in Part I except for the difference in the pattern of brightness in the visual field. Seven experimental sessions were conducted, corresponding to the instances in which the maximum variations in the pattern of brightness were required with negative stimuli. The results are presented in Table V, and are plotted as open circles in Fig. 10. It is apparent that the maximum variation from the standardized brightness pattern encountered in the experiments of this section did not influence the threshold contrasts of positive stimuli. As a first approximation, it can be assumed that the same variation in the pattern of brightnesses did not influence the threshold contrasts of negative stimuli.

The experimental data of this section are presented in Table VI and in Fig. 13, representing a total of approximately 125,000 observations by a group of eight observers. It is apparent that in most instances there is evidence that negative stimuli are equivalent to positive stimuli of equivalent area and contrast. In the case of large stimuli and low adaptation brightnesses, however, a consistent discrepancy exists. Comparison of the threshold contrasts of the same observers in corresponding experiments of Parts I and II indicates 20 percent lower thresholds for negative stimuli.

## Part III

Preliminary experiments indicated that the six-second exposure used in the experiments of Part I and Part II did not represent sufficient time for minimal thresholds. A supplementary program was conducted to determine threshold contrasts when an indefinitely long exposure was used. In general, the experimental procedures of Parts I and II were followed very closely.

It was found that if the stimuli were presented in any of eight positions as in Parts I and II, extremely long exposures were necessary for minimal thresholds. An exposure as long as 60 seconds was not clearly sufficient for minimal thresholds under all circumstances. Accordingly, the method of experimentation was modified so that substantially shorter exposures could be used. The stimulus was always presented in the same position, in the center of the observation screen. Orientation points were provided at the four edges of the target at a distance of approximately 2 degrees from each edge. The customary five stimulus contrasts were used, interspersed with trials in which no stimulus was presented. The observers were required to respond whether they believed a stimulus had been shown. Their response consisted of rotating the handle of their recording switch to one position for "yes," another for "no." The number of positive responses obtained when no stimulus was presented was used as the "chance" score in interpreting the resulting probability curves.

In each experimental session, it was proved that doubling the exposure did not increase the frequency of correct judgments. In general, exposures of 15 seconds were adequate for minimum thresholds.

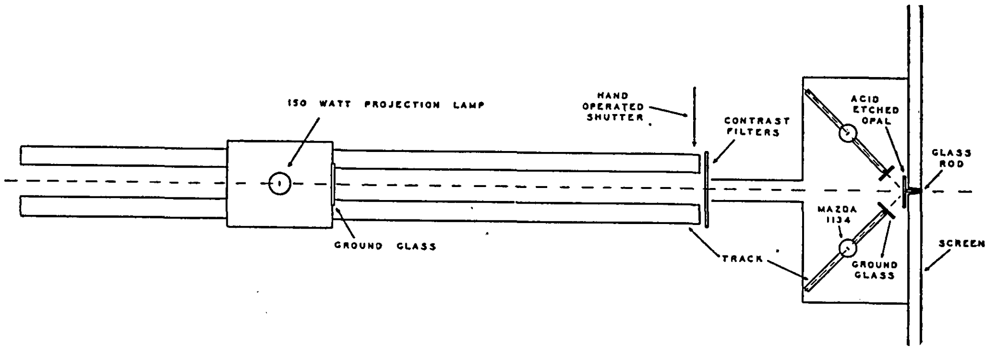


FIG. 14. Stimulus illuminating system.

Analysis of the data of Part I indicated that certain profitable changes in emphasis could be made in a supplementary program. It was apparent from the data of Fig. 10 that targets both larger and smaller than those of Part I should be investigated. The data of Fig. 12 indicated that experimentation at screen brightnesses less than $1\times 10^{-5}$ footlambert was not very necessary. In Part I, large numbers of observations were made to determine the exact nature of the discontinuities in the visual functions. Sufficient information was obtained so that less emphasis was necessary in the supplementary experimental program.

In order to produce an extremely small stimulus, it was necessary to develop a new apparatus. Since it was impossible to obtain satisfactory image definition by projection, a small stimulus was produced by transilluminating the observation screen. A section of glass rod, optically polished on each end, was inserted in the exact center of the observation screen. The front face of the rod was mounted flush with the front surface of the screen. An acid-etched opal plate was mounted 0.01 inch from the rear face of the rod. The opal plate served as the stimulus, baffled by means of the glass rod to a known diameter.

The optical system used to illuminate the opal plate is shown in Fig. 14. A balanced pair of automobile head lamps served to illuminate the opal so that its brightness equaled that of the observation screen. Additional illumination, producing a brightness increment, was provided by a lamphouse mounted on an optical bench. Preceding stimulus presentations, one of five gelatine filters was inserted (corresponding to one of five fixed stimulus contrasts) and a shutter was removed from the beam. The absolute level of the five contrasts was varied by means of the inverse square law and the addition of ground glass plates and opaque diaphragms to the face of the lamphouse.

The brightness of the opal plate through the glass rod was always measured with a Macbeth illuminometer, fitted with a lens to focus the opal plate in the cube of the photometer. It was recognized that a more adequate photometric procedure would involve the computation of stimulus brightness from a measurement of its candlepower. A test was made which indicated excellent agreement between measurements made with the alternative photometric techniques.

Investigation was made to ascertain whether a shadow around the glass rod existed, which would serve to reduce the effective candlepower of the

TABLE VII. Arithmetical mean threshold contrast. Stimuli brighter than surround (Part III). Angular subtense of stimuli (minutes of arc).

| 360.0 | | 121.0 | | 55.2 | |
|---|---|---|---|---|---|
| Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ |
| 1.857 | −2.519 | 1.850 | −2.596 | −0.053 | −2.436 |
| 1.024 | −2.455 | 1.044 | −2.510 | −0.994 | −2.174 |
| −0.051 | −2.603 | −0.052 | −2.441 | −1.859 | −1.688 |
| −1.041 | −2.296 | −1.005 | −2.209 | −2.924 | −1.149 |
| −1.883 | −2.033 | −1.878 | −1.799 | | |
| −2.948 | −1.558 | −2.939 | −1.361 | | |
| −3.997 | −1.221 | −3.969 | −1.029 | | |
| −5.052 | −0.847 | −4.974 | −0.569 | | |

| 18.2 | | 9.68 | | 3.60 | | 0.595 | |
|---|---|---|---|---|---|---|---|
| Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ | Log $B_0$ | Log $C$ |
| 1.853 | −2.462 | 1.874 | −2.063 | 1.044 | −1.559 | 1.854 | −0.323 |
| 0.070 | −2.294 | −1.023 | −1.672 | 0.039 | −1.324 | 1.034 | −0.051 |
| −0.984 | −1.971 | −1.900 | −1.075 | −1.887 | −0.384 | 0.039 | 0.264 |
| −1.871 | −1.322 | −2.953 | −0.157 | −2.965 | 0.593 | −1.019 | 0.643 |
| −2.923 | −0.655 | −3.932 | 0.425 | | | −1.894 | 1.136 |
| −4.982 | 0.584 | | | | | −2.941 | 2.104 |
| | | | | | | −3.957 | 2.756 |
| | | | | | | −4.999 | 3.397 |

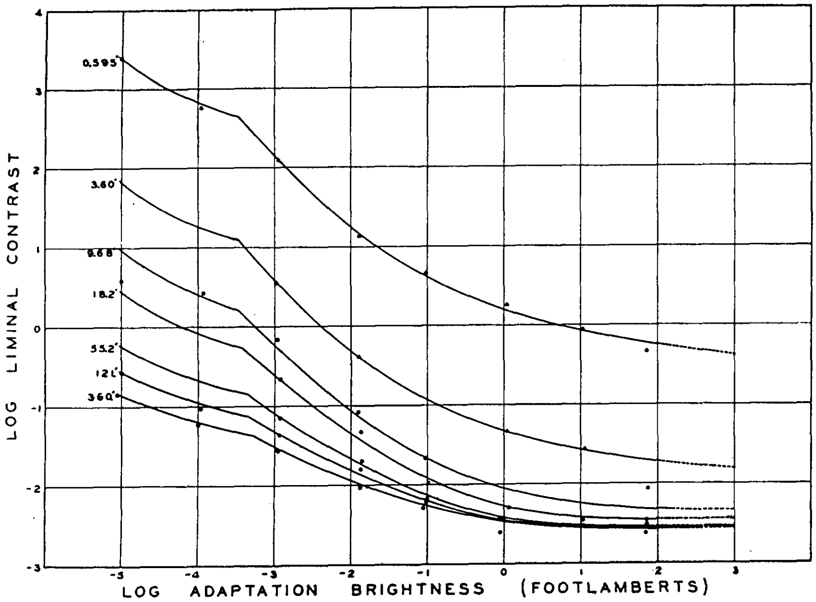


FIG. 15. The arithmetical mean of threshold contrasts computed from individual probability curves, plotted as a function of adaptation brightness for seven stimulus areas.

opal source. Measurements made with an integrating sphere and visual photometer revealed that there was no such effect.

The experimental data of this section are presented in Table VII and in Fig. 15, summarizing approximately 90,000 observations by a group of seven observers. It is evident that the precision of results is significantly less than in Part I and Part II. The lower precision is attributed to the fact that the observers were required to search for the stimulus repeatedly over a very small area. Under these conditions, the motivation and fatigue of the observers became extremely important. The curves fitted to the experimental data of Fig. 15 were empirically determined as the best-fitting curves consistent with characteristics of the contrast sensitivity functions established in Part I.

Interpolations from the smoothed curves are presented in Table VIII and in Fig. 16.

Each curve in Fig. 16 consists partially of a linear portion representing the fact that the product of area and stimulus brightness, $\Delta B$, is a constant. Stimuli whose areas place them on the linear position of these curves are effectively "point sources." The point at which each curve departs from linearity corresponds to a fundamental property of the human eye. "Critical visual angle" is defined as the angle at which the relationship: area $\times$ brightness $=$ a constant ceases to exist. "Critical visual angle" is plotted as a function of adaptation brightness in Fig. 17. The shape of this function is similar to that of the function relating threshold contrast and adaptation brightness.

Interpolations from Fig. 16 are presented in Fig. 18. The curves for most contrasts show discontinuities, indicating the change from foveal to parafoveal vision. For high contrasts, the curves are parallel, indicating that area $\times$ brightness $=$ a constant.

### ACKNOWLEDGMENTS

The dependence of the success of the experimental program upon Professor Arthur C. Hardy can scarcely be overemphasized. As Chief, Section 16.3, NDRC, he was responsible for appreciating the need for the research, for initiating both administrative and technical aspects of the program, and for maintaining close contact with experimental results and with laboratory problems encountered in obtaining them. Because he was willing to concern himself with the bothersome details of the research more completely than

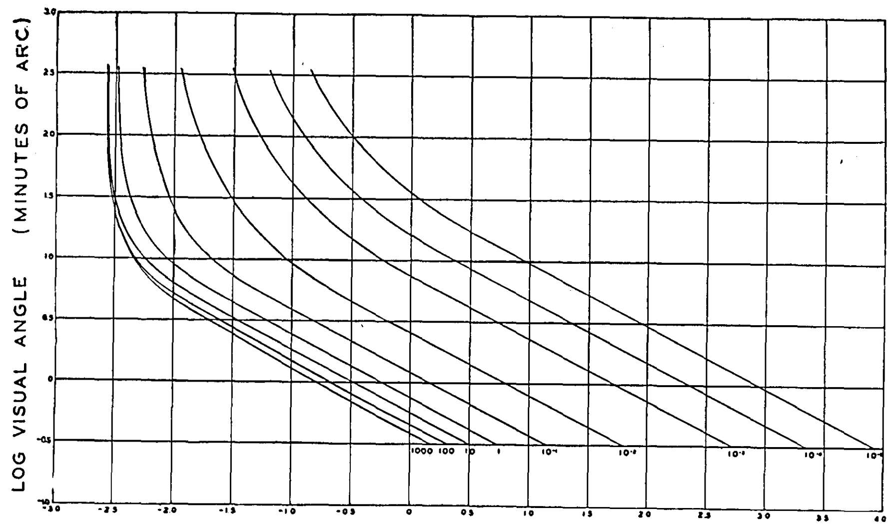


FIG. 16. Interpolations from Fig. 15. Each curve represents the relation between threshold contrast and stimulus area for a given adaptation brightness.

TABLE VIII. Log (arithmetical mean threshold contrast). Interpolations from Fig. 15.

| Angular subtense of stimuli (minutes of arc) | $B_0$ 1000 | 100 | 10 | 1 | $1\times10^{-1}$ | $1\times10^{-2}$ | $1\times10^{-3}$ | $1\times10^{-4}$ | $1\times10^{-5}$ |
|---|---|---|---|---|---|---|---|---|---|
| 360.0 | −2.566 | −2.566 | −2.558 | −2.478 | −2.272 | −1.959 | −1.519 | −1.205 | −0.866 |
| 121.0 | −2.561 | −2.561 | −2.553 | −2.464 | −2.212 | −1.818 | −1.324 | −0.967 | −0.562 |
| 55.2 | −2.547 | −2.547 | −2.538 | −2.428 | −2.131 | −1.666 | −1.096 | −0.686 | −0.239 |
| 18.2 | −2.460 | −2.460 | −2.428 | −2.276 | −1.914 | −1.341 | −0.614 | −0.094 | 0.444 |
| 9.68 | −2.339 | −2.328 | −2.241 | −2.051 | −1.672 | −1.041 | −0.208 | 0.396 | 0.978 |
| 3.60 | −1.812 | −1.721 | −1.569 | −1.322 | −0.924 | −0.300 | 0.622 | 1.253 | 1.837 |
| 0.595 | −0.383 | −0.248 | −0.060 | 0.196 | 0.607 | 1.246 | 2.179 | 2.813 | 3.397 |

could have been reasonably expected, many of the unusual features of the research technique can be attributed to him.

Dr. S. Q. Duntley, Section Technical Aide, and the members of the Section, especially Professor Edwin G. Boring, contributed invaluable professional advice to the general conduct of the research.

The professional staff employed temporarily by the Tiffany Foundation to conduct the research program varied considerably during the period of experimentation. Without exception, members of the staff devoted themselves diligently to the progress of the program. Special acknowledgment must be made to Dr. Helen M. Richardson for her earnest and often inspired work with the psychophysical aspects of the program, and to Mr. William F. Little of the Electrical Testing Laboratories, New York, with whose aid the photometric procedures were developed.

Of the many assistants, without whom the program would have been impossible, special mention should be made of Mr. B. S. Pritchard,

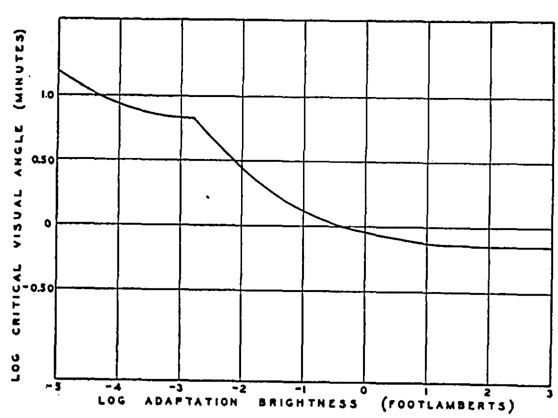


FIG. 17. "Critical visual angle" as a function of adaptation brightness. The area under the curve represents "point sources."

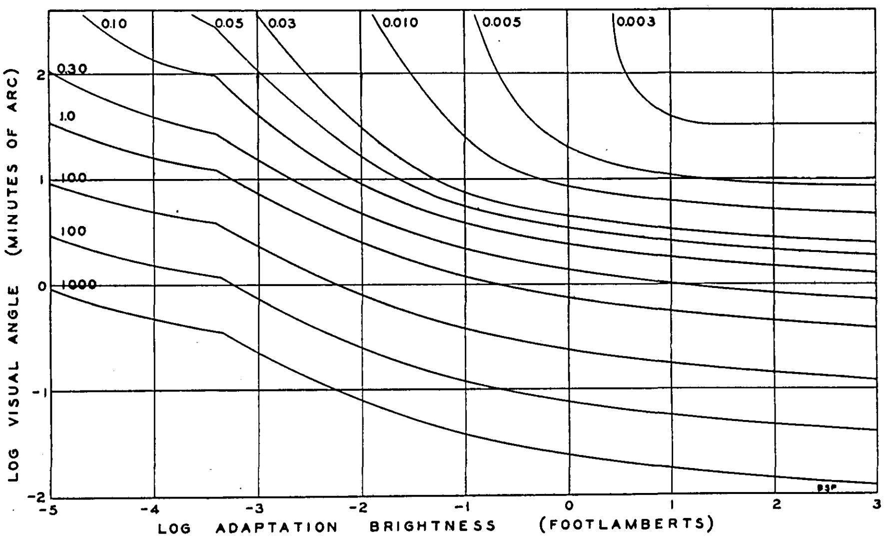


FIG. 18. Interpolations from Figs. 15 and 16. The relation between stimulus area and adaptation brightness for stimuli of various contrasts.

Mrs. S. C. Taplin, Miss M. J. Bernstein, Miss I. T. Bell, and Miss Jane Tapley.

Although not present during the conduct of the experiments reported herein, Dr. Helen Peak, Mr. Carl Foss, and Dr. Parry Moon were instrumental in designing the experimental apparatus and procedures for the earliest experiments. Some of the original apparatus and procedures were utilized in the reported experiments, whereas others were adapted.

## SUMMARY

Experimental data are presented representing approximately 450,000 responses made by trained observers under laboratory conditions. Contrast thresholds are presented for stimuli brighter and darker than their background, and for two values of stimulus exposure. In each case, wide variations were studied in the parameters: stimulus contrast, stimulus area, and adaptation brightness.