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FOVEAL CONTRAST THRESHOLDS FOR VARIOUS DURATIONS OF SINGLE PULSES

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SUMMARY

Visual detection thresholds have been determined for circular targets as a function of the level of background luminance, target size, and target exposure duration. The temporal forced-choice variant of the method of constant stimuli was used, the data being anlyzed by a variant of the probit analysis. The basic data were obtained on two highly motivated and experienced observers, and total 81,000 observations in 162 experimental sessions. Background luminance was varied from zero to 100 foot-lamberts. Target diameter was varied from 0.802 to 51.2 minutes of arc. Exposure duration was varied from 0.001 to 1 second.

The raw values of threshold contrast were first fitted by empirical curves, as reported in an earlier paper (Ref. 1). The present paper presents data obtained after a considerable computational effort to discover values which yielded smooth and continuous functional relations between all the principal variables. The smoothing process was restricted to a considerable extent by the requirement that the relations between threshold contrast and target size produce smooth "contribution functions", a theoretical constructed described elsewhere (Ref. 2). This requirement, together with the general requirement that all principal functional relations be smooth, provided effective criteria for a unique set of smooth curves. Tabular and graphical data from these smooth curves are presented for exposure durations of 1, 1/3, 1/10, 1/30, 1/100, 1/300, and 1/1000 second exposure duration. A procedure is described for converting the threshold data to other detection probabilities than 0.50.

I. INTRODUCTION

The program of vision research undertaken in these laboratories in recent years has been designed to provide a comprehensive body of data suitable for use in the solution of practical military visibility problems. It is necessary that comprehensive data exist to cover the various conditions involved in actual field situations. The luminance of the outdoor environment varies under different conditions from 10^{-5} to 10^{4} footlamberts. Targets vary in area from less than 1 to 10^{5} square minutes. The duration during which targets are visible in one part of the visual field may vary also over a considerable range. Put together, these variations in target variables represent an extremely large number of experimental conditions to be studied. There are, of course, a number of other conditions which may vary under practical conditions. Targets may vary in shape and color, and they may occur in various portions of the visual field.

In general, previous investigations have thoroughly explored the effects of background luminance, target size, and target exposure duration for these variables taken singly. For example, the effect of background luminance has been studied for a particular target size and exposure duration. These earlier investigations are most useful in providing us with a general understanding of the fundamental relations in vision, but they do not provide us with the body of comparable data representing the joint effects of all the main variables of the physical environment needed for the solution of military visibility problems.

One earlier effort to provide a comprehensive body of visual data for use in connection with military visibility problems has been reported by one of us elsewhere (Ref. 3). The Tiffany data, as they are generally known, represent studies of background luminance and target size over the considerable ranges of practical interest. There were three basic sets of data. The first set of data were collected with targets brighter than their background, with a procedure which required the observers to search for the targets during a 6 second presentation interval. The second set of data were collected under entirely comparable conditions, except that the targets were darker than their backgrounds. The third set of data involved bright targets, studied under conditions in which the observers knew precisely where the target would appear, and had as much time as was required to obtain a maximum probability of detection.

The third set of data are obviously relevant to military visibility problems in which the <u>maximum</u> possible visibility ranges are of interest. There is little doubt that the observers in this experiment exhibited as great or greater sensitivity than will be found under any practical visibility situation. The first two sets of data are relevant directly only to military problems in which the observers have about 6 seconds in which to search to about the extent required in the Tiffany experiments. These conditions are obviously not very general.

The program of vision research undertaken by these laboratories since 1946 was intended to provide a body of data which would have greater generality than the two sets of Tiffany data representing less than maximum visibility conditions. It was decided that data should be obtained with various known exposure durations of single targets. It was intended that the result to be expected during any practical situation involving visual search could be computed from operations analyses of the search pattern followed by the observer and the motion of the target with respect to the observer's line of sight.

Of course, a complete analysis of this type requires complete information on visual sensitivity for all parts of the visual field. Threshold measurements have been made in the near periphery of the visual field at various levels of background luminance, which are reported elsewhere (Ref. 4). These measurements represent only a beginning, however, since they were all made with a single value of target size and target exposure duration. Fortunately, the operations analysis can sometimes be simplified at high background luminance because the foveal retinae are so much more sensitive than the periphery. Under these circumstances, there may be essentially no probability that target detection will occur unless the target crosses the line-of-sight. In these cases, data on the sensitivity of the foveal retinae have considerable immediate value in operations analyses of practical visibility problems. Data are needed for various luminance levels for each of various target sizes. These studies were needed at various exposure durations, since the length of time a moving target will appear on the line-of-sight of an eye engaged in search and scanning can vary from perhaps 10^{-3} to 10^{2} seconds.

The present data represent an attempt to provide the first comprehensive body of data in which luminance level, target size, and target duration are studied over the wide ranges of practical interest in connection with visibility problems. The data have been collected with a procedure which provides information on various levels of detection probability. This information is of course essential for the purposes of operations analysis.

II. APPARATUS AND PROCEDURES

The basic experimental apparatus used for these studies is illustrated schematically in Figure 1. The experimental task of the observers was to detect the presence of a disc target which was produced by adding a luminance increment to a small portion of a screen of uniform luminance. The screen consituted an inner wall of a cube whose dimensions were approximately 7 feet on a side. Walls of the cube were coated with sphere paint. The observers were situated 10.25 feet from the screen. The screen of uniform luminance thus subtended approximately 40 degrees at the eyes of the observers. Other walls of the cube were also visible which were nearly as bright as the screen. These walls extended the visual field of approximate uniformity to at least 60 degrees in every direction. The observers used normal binocular vision with natural pupils. Two observers were employed throughout, who observed together.

Light sources for the illumination of the screen were incandescent lamps placed at the rear of the cube near the observers, but completely shielded from their view. The number and wattage of the lamps was varied to adjust the quantity of illumination falling upon the screen. In order to insure uniformity of luminance of the screen, direct illumination from the lamps was shielded. The apparent color temperature of the screen was 2850K.

The target was produced by transillumination of a milk-plastic screen which served as the major portion of the screen wall. Size of the target was determined by the physical size of the aperture through which the beam transilluminated the plastic screen. The aperture was pressed tightly against the rear surface of the plastic. The plastic was paper-thin. Consequently, the definition of the edge of the target was excellent. Four target sizes were employed subtending 0.802, 3.20, 12.8, and 51.2 minutes of arc at the observers' eyes.

The target was produced by a high-output projection system based upon a special ribbon-filament lamp kindly made available by the General Electric Company.

The target always appeared in a known location in the center of the screen. The observers utilized four bright points which were arranged in a diamond pattern for fixation and orientation purposes. The four points were arranged symmetrically about the target. The separations of the fixation and orientation points were determined on the basis of preliminary experiments so that the target was maximally discriminable at all times. The separations among the fixation points varied from 18 minutes in the case of the smallest target to 40 minutes in the case of the largest target. In each case, the observers fixated the center of the configuration of fixation points. Thus, all the data refer to central foveal vision. The intensity of the fixation points was adjusted to approximately ten times their luminance difference threshold. Previous experiments have indicated that fixation lights of this intensity will have minimum influence upon the discriminability of nearby targets.

The observers were not allowed to judge directly whether or not they detected the presence of the target. They were required to prove their ability to detect its presence by correctly identifying the time interval of four possible intervals in which the target occurred. The temporal intervals were each 2.5 seconds long. Following the four intervals, the observers were given 8 seconds in which to select the temporal interval they considered the target had occupied and to record their choice by depressing one of four response buttons. The observers then had 2 seconds in which to prepare themselves for the next presentation of the target.

It has been shown elsewhere (Ref. 5) that requiring observers to prove that they can discriminate is distinctly preferable to accepting their own direct evaluation of their ability to discriminate. The data obtained under the former conditions are both more reliable and more valid.

Each experimental session consisted of 250 target presentations, 50 at each of five target luminance increments intended to elicit from nearly zero to nearly 100 percent correct discrimination. Each experimental session was divided into five sub-sessions, each of which contained 10 presentations of each of the five target luminance increment values. Each sub-session lasted about 17 minutes. At the end of each sub-session, the observers were allowed a 5-10 minute rest and relaxation period. The entire experimental session lasted nearly 2 hours.

The presentation of the targets and the recording of responses was facilitated by automatic equipment described elsewhere (Ref. 6). Briefly, the schedule for presentation of targets was governed by coded holes in a paper tape. The holes excited appropriate metal roller contacts, which activated electrically controlled projection apparatus through mediation of a relay panel. The timing of all stimulus presentations depended upon a synchronous motor and a system of cam contacts situated on the drive shaft of the motor. The magnitude of the target luminance increment was varied by a filter-selector device which could intersperse one or another Wratten neutral filter in the projection beam. The interval occupied by the target could be varied by operating a shutter at one of four possible times. "Verification" equipment was provided, so that the accuracy of the electrical components in providing the desired stimulus conditions could be established.

The stimulus conditions for each presentation and the temporal interval selected by each observer were recorded automatically. The recorder was composed of 28 solenoid-driven precision punches which made coded holes in a lightweight cardboard record sheet.

The correctness of the selection made by each observer on each presentation was established by series relays and recorded by means of a bank of electric counters. One counter recorded the number of correct selections made by each observer for each target luminance increment.

In the rare event that the electrical components failed to provide the stimulus conditions required by the tape, all record of the presentation was automatically eliminated.

The basic data from each experimental session were proportions of correct answers for each observer, at each of the five target luminance increments. There is, of course, a probability of .25 that the observer will get the correct answer by chance alone. The effect of chance successes may be eliminated by the formula:

$$p' = \frac{p - .25}{.75} \qquad (1)$$

where p = raw proportion
p' = corrected proportion

Throughout the remainder of this paper, we will refer exclusively to values of p' as defined by equation (1).

The duration of the target presentation was given seven different values in different experiments: 1, 1/3, 1/10, 1/30, 1/100, 1/300, and 1/1000 seconds. Control of the target duration depended upon a large metal disc which rotated in the projection beam. The target was presented whenever the aperture in the disc was aligned with the projection beam. The size of the aperture was continuously variable. The time required for the target to increase to full intensity was approximately 0.0001 second.

The two observers whose data are reported here were graduate students at the University of Michigan, specializing in sensory psychology. One was male, the other female. The subjects were unusually interested in the experiments. Their visual acuity was known to exceed 20/20. Two other observers were used for a portion of the same experiments. These observers were undergraduates whose interest in the experiments was reasonably great but not exceptional as was the interest of the graduate students. The data from all four observers appear to be very similar. Only the data for the two graduate student observers are presented here since only these observers observed under all the experimental conditions.

Photometry of the screen luminances was performed directly with a Macbeth Illuminometer, fitted with a lens attachment to image the screen in the Macbeth cube. Photometry of the two largest targets was accomplished in a similar manner. Photometry of the two smallest targets was accomplished by what might 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 luminance of the target could be computed. Two "candlepower boxes" were used, one for each of the two smallest targets.

The target luminance increment was adjusted to the appropriate value for each experimental condition by means of Wratten gelatin filters placed in the projection beam. The transmissions of these filters were determined on an optical bench photometer. The calibration of all photometric instruments depended upon lamp and test-plate standardizations made by the Electrical Testing Laboratories of New York.

Various levels of background luminance were studied from approximately 100 foot-lamberts to 10^{-1} foot-lamberts. In addition, experiments were conducted with a totally dark background. Experiments reported elsewhere (Ref. 7) provide ample evidence to establish that the foveal threshold value of the luminance increment, ΔB, is equivalent for a totally dark background and for a background luminance of 10^{-3} foot-lamberts. Accordingly, the experiments actually conducted with a totally dark surround have been treated as though the background were in fact 10^{-3} foot-lamberts. The threshold values of ΔB are simply converted into threshold values of $\hat{C}$ by dividing them by 10^{-3}. This allows us to plot the zero background data for meaningful comparisons with other data from finite background luminance levels.

The basic data obtained by each observer in a single experimental session are proportions of correct discriminations, after correction for chance successes, and the contrast between target and background, defined as follows:

$$\text{Contrast} = \frac{\Delta B}{B} \qquad (2)$$

where ΔB = luminance increment of the target; and
B = luminance of the screen in the absence of the target.

The analysis of the data proceeds by fitting a theoretical curve to the set of experimental data obtained by each observer in each experimental session.

Figure 2 exhibits the theoretical curve which has been found adequate to represent the experimental data of all the present experiments. We note that the probability of detection increases in a sigmoid fashion as the contrast of the target increases. The theoretical curve is a normal ogive, the integral of a normal frequency distribution. Our data analysis procedure involves determining the particular ogive which best fits the five experimental points obtained by each observer in each experiment. The ogive varies in two parameters, designated M and σ. The value of M is usually called the threshold; it is the target contrast at which p' = .50. The value of σ measures the steepness of the ogive. (Sigma is actually the standard deviation of the normal distribution from which the ogive is obtained by integration.) When σ is large, the ogive is flat.

As is indicated elsewhere, (Ref. 8), the most appropriate ogive is determined for each set of experimental data by a procedure called the probit analysis. This procedure gives us values of M and σ for the ogive which best fits each set of data and also provides us with a measure of the goodness of fit of the experimental data to the theoretical curve. The analysis of the data from the present studies was carried out with a variant of the probit analysis described elsewhere in detail (Ref. 9).

III. RESULTS

A. Analyses of the Detection Probabilities

We may well begin by considering the results of the probit analyses of the individual sets of data. The curve fits of the data by normal ogives were entirely satisfactory as assessed by the chi-squared test of goodness of fit.

Values of M varied over a million to one as background luminance level, target size, and target duration were varied. Preliminary examination of the experimental data revealed the existence of a simple relation between M and σ, as M varied over this tremendous range. Values of M and σ were directly proportional; that is σ/M = constant. The existence of this simple relation between M and σ enormously simplified the problem of reporting and using the present experimental data.

The average values of σ/M for all the experimental data were .384 for one observer and .396 for the other. The theoretical curve in Figure 2 represents $\sigma/M = .390$, the average value for the two observers.

We have obtained average values of σ/M for both observers in terms of each of the three experimental variables. These are presented in Table I. Considering that values of M vary over a million to one, values of σ/M are remarkably constant. The differences as a function of target size appear haphazard. The values of σ/M appear to decrease as background luminance, B, increases although the effect is small. The values of σ/M appear to decrease as duration decreases, although the effect is comparatively small.

The fact that σ/M is so nearly constant for the entire range of experimental conditions is of considerable practical value. As noted above, the main results of the present experiments will be presented in terms of the threshold values of contrast, defined for p' = .50. The target contrast needed for other levels of detection probability will often be of interest. Let us develop a convenient method of converting threshold contrast values to the contrasts needed for various other probability levels. Let us define Z, a conversion factor which will correct M to any desired level of detection probability as follows:

$$Z = 1 + f_a \cdot \sigma/M \qquad (3)$$

where f_a = factor to allow for probability level derived from standard tables of the normal frequency function.

We may tabulate values of f_a once for all as follows:

f_a	Detection Probability
1.29	.90
1.65	.95
2.33	.99

If we assume σ/M = .390 as in Figure 2, values of Z are as follows:

Z	Detection Probability
1.50	.90
1.64	.95
1.91	.99

This means that, when σ/M = .390, a value of target contrast 1.50 times M, the threshold, will give a detection probability of .90; 1.64 time M will give a detection probability of .95; and 1.91 time M will give a detection probability of .99. These values may be verified by inspection of Figure 2, where M = 1.

We may inquire to what extent values of Z vary for experiments conducted at different values of the three experimental variables. Values of Z for a detection probability of .99 are tabulated in Table II, based upon values of σ/M presented in Table I and equation (3).

Values of Z vary among the four sizes by only $\pm$ 2.5 per cent; among the eight background luminances by only $\pm$ 4 per cent; and among the seven durations by $\pm$ 10 per cent. Variations in Z for detection probabilities less than .99 will vary less. It is concluded that variations in Z as a function of either size or background luminance are negligible. Variations in Z as a function of target duration are small, but should probably be allowed for in dealing with the present experimental data.

Insofar as Z is a constant multiplier times every value of M, we may represent different levels of detection probability by different scales of log target contrast, displaced by a constant amount representing log Z. We will have occasion subsequently to consider how such allowances may be made conveniently in dealing with the present data.

B. The Raw Threshold Data

The threshold contrast values obtained from the probit analyses of the data for the two observers were averaged, and these average values of $\mathring{C}$ represent the basic data from the present experiment. There were 162 experimental sessions in all, and a total of 81,000 observations by the two observers.

These raw data are presented in Tables III A - III G, as tabular values of log $\mathring{C}$ and log B for each of the seven exposure durations. These data were originally graphed in terms of log $\mathring{C}$ versus log B, with a curve for each target size, with four such curves for each exposure duration. Empirical curves were fitted through the experimental points to describe the functional relations found to exist between $\mathring{C}$ and B for each target studied. The first report of these data (Ref. 1) contained these empirical curves.

Use of these data in the solution of practical visibility problems usually involves the computation of particular values of the three experimental variables, which were not studied directly. These interpolations also usually involved plotting different variables against one another. For example, we plotted log $\dot{C}$ against log target diameter for fixed values of background luminance and exposure duration. We also on occasion plotted log $\dot{C}$ against log exposure duration for fixed values of background luminance and target diameter. Such computations necessarily proceed by interpolation from the existing empirical curves drawn through the experimental data. Use of the original empirical curves in this way soon revealed that the interpolated data did not fall on smooth curves in the "cross-plots" in particular, but appeared to vary in a manner which suggested that our original empirical curve fits were introducing random uncertainties in the data. As a first assumption, it seems reasonable to expect that all the relations of the three variables involved in the experiment should be smooth rather than irregular. Therefore, a considerable effort has been made to develop curve fits to the raw data which lead to generally smooth functional relations in the three main data graphs. The revised curve fitting procedures will be described in the next section.

C. The Data Smoothing Process

The smoothing process began by plotting curves relating log threshold contrast and log target size for each of nine values of background luminance. A family of nine such curves was plotted for each of the seven exposure durations. These curves were found to be highly irregular when they were based upon the original empirical curves.

The smoothing process continued by regularizing these families of curves. Certain restrictions were placed on these curves, on the basis of relations between log target size and log threshold contrast which have been well established in previous studies of visual detection. For example, for small target sizes, the relation known as Ricco's law must be found. This relation states that $\alpha^2 \dot{C} = K$, where α = the diameter of the circular target. The reciprocal relation between target area and threshold contrast is absolutely required for targets small with respect to the resolution of the eye. Manifestly, when the retinal image of a target does not change in size with changes in size of the target, changes in area can be compensated for by changes in contrast, in the quantitative manner known as Ricco's law. All we can safely conclude, however, is that Ricco's law represents the limiting relation to be found when target size is small; we cannot be certain below what target size the law will apply. Ricco's law is represented by a linear relation between log α and log C with slope of -1/2. This slope was constructed as the limiting slope of all the curves relating log threshold contrast and log target size.

As log target size is increased beyond the size where Ricco's law applies, log threshold contrast decreases at a slower rate, but it still decreases as log target size increases. Kincaid, Blackwell, and Kristofferson (Ref. 2) have suggested that this relation may be explained as due to a contribution-function concept, where it is assumed that a unit area of the target always contributes to the detectibility of the target, with the amount of contribution being reduced as the unit area is separated farther and farther from the target center. In an approximate sense, contribution-functions represent first derivatives of the curves relating log threshold contrast to log target size. The details of this construct need not concern us here. Suffice it is to state that curves relating log threshold contrast and log target size may have the requirements placed on them that contribution-functions derivable from them are monotonic, and that changes in contribution-functions proceed in an orderly manner as background luminance is changed. There were nine contibution functions, representing different background luminance levels, for each of the seven exposure durations.

The next step in the data-smoothing process involved replotting these contribution functions so that the graphs for different exposure durations at the same background luminance were brought into direct comparison.

The restriction was placed that the contribution-functions must change in an orderly manner as a function of exposure duration, at a fixed value of background luminance. (This restriction was added to the earlier restriction that the contribution-functions be monotonic, and that changes in contribution-functions be orderly as a function of background luminance, for a fixed target exposure duration.) When these restrictions were simultaneously placed on the data, there remained very little latitude in the determination of the contribution-functions and, hence, in the shapes of the individual curves relating log threshold contrast and log target size.

The absolute placement of these contribution functions on the scale of threshold contrast is indeterminate in terms of the contribution-function concept alone. This placement must depend upon functional relations in which log threshold contrast is a continuous variable. Accordingly, the next step in the smoothing process involved interpolating two classes of graphs. The first of these interpolated graphs presented the relation between log threshold contrast and log background luminance, for fixed values of target size. The target size values selected for the graphs did not correspond to the values studied experimentally, but corresponded rather to values of target size believed to be of the most use for the solution of practical visibility problems. (Since we have continuous graphs relating log threshold contrast and log target size, we may of course interpolate any values of target size of interest, with equal precision. The second class graph presented the relation between log threshold contrast and log exposure duration, for the same values of target size, for various fixed background luminance levels.

Once the curves relating log threshold contrast and log target size are fixed in form, changes can be made in curves of these two classes only by moving all values of log target size at a given exposure duration and background luminance up or down the log C_{o} scale by the same amount.

Furthermore, the same values appear on two graphs, one of each class. We now require that the families of curves of these two types be monotonic and orderly in appearance. It turns out that there remains almost no uncertainty in the form of the smooth curves when all these requirements are met. Work with the present data along these lines demonstrated that changes of the order of 2% were the maximum allowable changes without an obvious violation of one or another of the previously stated requirements.

This process of data-smoothing was carried to completion, with the following results:

(a) A set of seven graphs plotting log threshold contrast against log background luminance, one for each of the seven exposure durations;

(b) A set of nine graphs plotting log threshold contrast against log exposure duration, one for each of the following values of log background luminance: 2, 1, 0, -.5, -1, -1.5, -2, -2.5, and -3.0; and

(c) A set of seven graphs plotting log threshold contrast against log target size, one for each exposure duration.

These graphs were prepared at large scale, suitable for easy reading to three significant figures. Tabular values were read from the graphs, which represent the principal data of the present report. These data are presented in Tables IV A - IV G, with a separate table for the data at each of the seven exposure durations.

Data from these tables have been used to plot Figures 3 - 16, which represent two of the three classes of graphs which were plotted at large scale. Figures 3 - 9 present the plots of log threshold contrast against log background luminance for each of four selected target sizes. The fixed values of target diameter used were selected to cover the range in target diameter from 1 - 60 minutes with reasonably evenly spaced curves. Figures 10 - 16 present the plots of log threshold contrast against log target size for six selected background luminance levels, representing log unit steps in this variable. One graph of each class is presented for each of the seven exposure durations. These graphs are presented primarily to illustrate the general nature of the relations among the experimental variables, and to demonstrate the extent to which the data-smoothing procedures have been successful.

There are additional data in the tables which do not appear in these graphs. Anyone wishing to obtain data by interpolation is urged to plot his own graphs, utilizing all the tabular data. There is generally a sufficient number of points to define a smooth curve for any variable of interest. More precise interpolations may be obtained from the large scale graphs by contacting the senior author.*

*After September 1, 1958 address Dr. H. Richard Blackwell at the Institute for Research in Vision, The Ohio State University, Columbus, Ohio.

All the data presented in the tables and the figures represent a level of detection probability, p' = .50. As indicated above, we may convert these data to represent other probability levels conveniently. If we ignore the variations in σ/M shown in Table I, we may convert our tabular data to other probability levels by simply adding a suitable value of log Z to every value. If we assume σ/M = .390, values of log Z are as follows:

Log Z	Detection Probability
.176	.90
.215	.95
.281	.99

The figures may be modified to correspond to different probability levels by a suitable adjustment of the log $\dot{C}$ scale.

To be more precise, different values of log Z should be used for the different target durations. These may be computed from the values in Table I, and equation (3).

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TABLE I: Average Values of σ/M

Target Size (Minutes of Arc)

1	4	16	64
.373	.417	.396	.385

Background Luminance (foot-lamberts)

.001	.1	.3	1	3	10	30	100
.419	.421	.389	.386	.387	.380	.374	.355

Target Duration (seconds)

1	1/3	1/10	1/30	1/100	1/300	1/1000
.485	.450	.374	.370	.361	.361	.332

TABLE II: Values of Z for p' = .99

Target Size (Minutes of Arc)

1	4	16	64
1.87	1.97	1.92	1.90

Background Luminance (foot-lamberts)

.001	.1	.3	1	3	10	30	100
1.98	1.98	1.91	1.90	1.90	1.88	1.87	1.83

Target Duration (seconds)

1	1/3	1/10	1/30	1/100	1/300	1/1000
2.13	2.05	1.87	1.86	1.84	1.84	1.77

TABLE III A: Raw Threshold Data, 1 second

Diameter (minutes)

.802		3.21		12.8		51.4	
Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$
-3.000	2.338	-3.000	1.140	-3.000	0.659	-3.000	0.412
-.991	0.597	-.985	-.720	-.991	-1.270	-.991	-1.652
-.541	0.203						
.004	-.015	.008	-1.270	-.007	-1.846		
.517	-.139					.510	-1.979
1.009	-.442	1.014	-1.728	1.012	-2.075		
1.477	-.558						
2.045	-.604	2.007	-1.795	2.003	-2.018	2.067	-2.240

TABLE III B: Raw Threshold Data, 1/3 second

Diameter (minutes)

.802		3.21		12.8		51.4	
Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$
-3.000	2.502	-3.000	1.261	-3.000	.699	-3.000	.392
-.991	.737	-.997	-.567	-1.000	-1.112	-.987	-1.646
-.524	.474						
.004	.163	.002	-1.068	.004	-1.604		
.522	.017					.510	-1.939
1.011	-.209	1.016	-1.549	1.009	-1.902		
1.477	-.430						
2.090	-.523	2.004	-1.565	2.006	-1.909	2.065	-2.063

TABLE III C: Raw Threshold Data, 1/10 second

Diameter (minutes)	.802		3.21		12.8		51.4	
	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$
	-3.000	2.849	-3.000	1.556	-3.000	.975	-3.000	.569
	-.996	1.046	-.998	-.283	-.993	-.922	-.991	-1.439
	-.526	.677						
	.004	.444	.008	-.821	.004	-1.416		
	.525	.289					.509	-1.866
	.997	-.003	1.015	-1.268	1.011	-1.789		
	1.477	-.179						
	2.097	-.384	2.005	-1.367	2.011	-1.833	2.069	-1.951

TABLE III D: Raw Threshold Data, 1/30 second

Diameter (minutes)	.802		3.21		12.8		51.4	
	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$
	-3.000	3.214	-3.000	1.845	-3.000	1.190	-3.000	.812
	-1.037	1.371	-.981	.093	-.978	-.554	-1.049	-.974
	-.535	1.149					-.535	-1.289
	.004	.854	.020	-.488	.024	-1.164	-.005	-1.461
	.524	.554					.529	-1.674
	1.050	.386	1.021	-.898	1.023	-1.455	1.025	-1.751
	1.550	.129						
	2.075	-.104	2.025	1.181	2.024	-1.605	2.054	-1.860

TABLE III E: Raw Threshold Data, 1/100 second

Diameter (minutes)	.802		3.21		12.8		51.4	
	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$
	-3.000	3.689	-3.000	2.450	-3.000	1.644	-3.000	1.393
	-1.035	1.926	-.977	.569	-.978	-.115	-1.049	-.436
	-.532	1.537					-.541	-.699
	-.017	1.241	.022	-.041	.021	-.628	-.004	-1.000
	.519	1.016					.521	-1.184
	1.021	.750	1.032	-.417	1.026	-1.045	1.037	-1.370
	1.449	.593						
	2.025	.500	2.024	-.746	2.025	-1.180	2.054	-1.406

TABLE III F: Raw Threshold Data, 1/300 second

Diameter (minutes)	.802		3.21		12.8		51.4	
	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$	Log B	Log $\dot{C}$
	-3.000	4.088	-3.000	2.857	-3.000	2.249	-3.000	1.676
	-.997	2.325	-1.000	1.129	-1.003	.469	-1.004	.005
	.005	1.625	.000	.537	.013	-.170	-.005	-.629
	1.002	1.189	.996	.059	.998	-.581	1.000	-.908
	2.027	.892	2.026	-.249	2.020	-.660	2.011	-.885

TABLE III G: Raw Threshold Data, 1/1000 second

Diameter (minutes)	.802		3.21		12.8		51.4	
	Log B	Log Ċ	Log B	Log Ċ	Log B	Log Ċ	Log B	Log Ċ
	-3.000	4.676	-3.000	3.463	-3.000	2.711	-3.000	2.298
	-1.003	2.774	-.999	1.614	-1.002	.961	-1.001	.485
	-.013	2.186	.000	.973	.004	.321	-.007	-.045
	.995	1.717	.997	.548	1.003	-.107	1.003	-.331
	2.002	1.475	2.001	.291	1.992	-.150		

TABLE IV A: Smoothed Threshold Data, 1 second duration
Values of Log Threshold Contrast

Log Target Diameter (minutes)	Log Background Luminance (foot-lamberts) 2.00	1.00	.00	-1.00	-2.00	-3.00
.000	-.798	-.631	-.256	.376	1.276	2.276
.125	-1.044	-.866	-.501	.131	1.031	2.031
.301	-1.400	-1.233	-.858	-.226	.674	1.674
.447	-1.692	-1.525	-1.150	-.518	.382	1.382
.602	-1.892	-1.743	-1.400	-.777	.123	1.123
.778	-2.002	-1.874	-1.603	-.993	-.093	.907
1.000	-2.064	-1.958	-1.746	-1.179	-.279	.721
1.146	-2.086	-1.992	-1.831	-1.265	-.365	.635
1.301	-2.102	-2.017	-1.880	-1.339	-.439	.561
1.477	-2.114	-2.036	-1.921	-1.410	-.510	.490
1.602	-2.122	-2.045	-1.941	-1.451	-.551	.449
1.699	-2.126	-2.053	-1.952	-1.482	-.582	.418
1.778	-2.128	-2.057	-1.960	-1.506	-.606	.394

TABLE IV B: Smoothed Threshold Data, 1/3 second duration
Values of Log Threshold Contrast

Log Target Diameter (minutes)	Log Background Luminance (foot-lamberts) 2.00	1.00	.00	-1.00	-2.00	-3.00
.000	-.639	-.502	-.139	.466	1.331	2.326
.125	-.884	-.747	-.384	.221	1.086	2.081
.301	-1.241	-1.104	-.741	-.136	.729	1.724
.447	-1.533	-1.396	-1.033	-.428	.437	1.432
.602	-1.750	-1.613	-1.287	-.687	.178	1.173
.778	-1.878	-1.754	-1.496	-.908	-.043	.952
1.000	-1.979	-1.857	-1.665	-1.111	-.246	.749
1.146	-2.024	-1.905	-1.748	-1.204	-.339	.656
1.301	-2.059	-1.947	-1.814	-1.285	-.420	.575
1.477	-2.090	-1.987	-1.875	-1.361	-.496	.499
1.602	-2.108	-2.011	-1.908	-1.412	-.547	.448
1.699	-2.120	-2.027	-1.935	-1.441	-.576	.419
1.778	-2.127	-2.039	-1.952	-1.469	-.604	.391

TABLE IV C: Smoothed Threshold Data, 1/10 second duration
Values of Log Threshold Contrast

Log Target Diameter (minutes)	Log Background Luminance (foot lamberts) 2.00	1.00	.00	-1.00	-2.00	-3.00
.000	-.461	-.236	.140	.764	1.629	2.616
.125	-.706	-.481	-.106	.519	1.384	2.372
.301	-1.063	-.838	-.462	.162	1.027	2.014
.447	-1.355	-1.130	-.754	-.130	.735	1.722
.602	-1.581	-1.375	-1.010	-.401	.464	1.452
.778	-1.722	-1.555	-1.224	-.648	.217	1.204
1.000	-1.835	-1.704	-1.420	-.889	-.024	.964
1.146	-1.890	-1.772	-1.514	-1.018	-.153	.834
1.301	-1.934	-1.827	-1.596	-1.130	-.265	.722
1.477	-1.977	-1.879	-1.680	-1.241	-.376	.612
1.602	-2.000	-1.909	-1.730	-1.313	-.448	.540
1.699	-2.016	-1.929	-1.764	-1.361	-.496	.492
1.778	-2.028	-1.943	-1.786	-1.407	-.542	.446

TABLE IV D: Smoothed Threshold Data, 1/30 second duration
Values of Log Threshold Contrast

Log Target Diameter (minutes)	Log Background Luminance (foot lamberts) 2.00	1.00	.00	-1.00	-2.00	-3.00
.000	-.170	.097	.534	1.182	2.032	3.027
.125	-.415	-.148	.289	.937	1.787	2.762
.301	-.772	-.505	-.068	.580	1.430	2.405
.447	-1.064	-.797	-.360	.288	1.138	2.113
.602	-1.287	-1.051	-.622	.029	.879	1.854
.778	-1.443	-1.253	-.851	-.235	.615	1.590
1.000	-1.576	-1.428	-1.061	-.473	.377	1.352
1.146	-1.645	-1.516	-1.170	-.600	.250	1.225
1.301	-1.709	-1.594	-1.269	-.712	.138	1.113
1.477	-1.768	-1.666	-1.369	-.827	.023	.998
1.602	-1.799	-1.713	-1.431	-.899	-.049	.926
1.699	-1.818	-1.749	-1.476	-.949	-.099	.876
1.778	-1.835	-1.773	-1.511	-.989	-.139	.836

TABLE IV E: Smoothed Threshold Data, 1/100 second duration
Values of Log Threshold Contrast

Log Target Diameter (minutes)	Log Background Luminance (foot-lamberts) 2.00	1.00	.00	-1.00	-2.00	-3.00
.000	.282	.542	1.012	1.712	2.532	3.482
.125	.037	.297	.767	1.467	2.287	3.237
.301	-.320	-.060	.410	1.110	1.930	2.880
.447	-.612	-.352	.118	.818	1.638	2.588
.602	-.835	-.604	-.145	.543	1.363	2.313
.778	-.985	-.801	-.375	.290	1.110	2.060
1.000	-1.117	-.988	-.594	.049	.869	1.819
1.146	-1.188	-1.085	-.709	-.074	.746	1.696
1.301	-1.254	-1.165	-.815	-.187	.633	1.583
1.477	-1.320	-1.244	-.947	-.299	.521	1.471
1.602	-1.361	-1.293	-.985	-.371	.449	1.399
1.699	-1.393	-1.328	-1.031	-.421	.399	1.349
1.778	-1.414	-1.357	-1.068	-.461	.359	1.309

TABLE IV F: Smoothed Threshold Data, 1/300 second duration
Values of Log Threshold Contrast

Log Target Diameter (minutes)	Log Background Luminance (foot-lamberts) 2.00	1.00	.00	-1.00	-2.00	-3.00
.000	.772	1.012	1.502	2.202	3.022	3.972
.125	.527	.767	1.257	1.957	2.777	3.727
.301	.170	.410	.900	1.600	2.420	3.370
.447	-.122	.118	.608	1.308	2.128	3.078
.602	-.345	-.134	.345	1.033	1.853	2.803
.778	-.495	-.331	.115	.780	1.600	2.550
1.000	-.627	-.518	-.104	.539	1.359	2.309
1.146	-.698	-.615	-.219	.416	1.236	2.186
1.301	-.764	-.695	-.325	.303	1.123	2.073
1.477	-.830	-.774	-.430	.191	1.011	1.961
1.602	-.871	-.823	-.495	.119	.939	1.889
1.699	-.903	-.858	-.541	.069	.889	1.839
1.778	-.924	-.887	-.578	.029	.849	1.799

TABLE IV G: Smoothed Threshold Data, 1/1000 second duration
Values of Log Threshold Contrast

Log Target Diameter (minutes)	Log Background Luminance (foot-lamberts) 2.00	1.00	.00	-1.00	-2.00	-3.00
.000	1.282	1.522	2.012	2.712	3.532	4.482
.125	1.037	1.277	1.767	2.467	3.287	4.237
.301	.680	.920	1.410	2.110	2.930	3.880
.447	.388	.628	1.118	1.818	2.638	3.588
.602	.165	.376	.855	1.543	2.363	3.313
.778	.015	.179	.625	1.290	2.110	3.060
1.000	-.117	-.008	.406	1.049	1.869	2.819
1.146	-.188	-.105	.291	.926	1.746	2.696
1.301	-.254	-.185	.185	.813	1.633	2.583
1.477	-.320	-.264	.080	.701	1.521	2.471
1.602	-.361	-.313	.015	.629	1.449	2.399
1.699	-.393	-.348	-.031	.579	1.399	2.349
1.778	-.414	-.377	-.068	.529	1.359	2.309

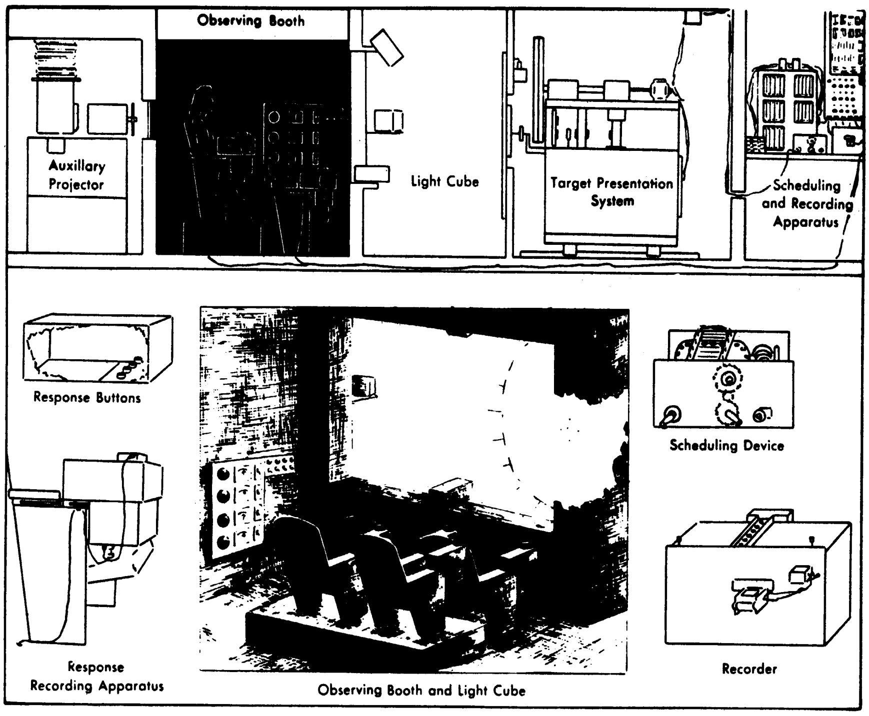

Fig. 1. Artist's conception of the basic psychophysics test facility.

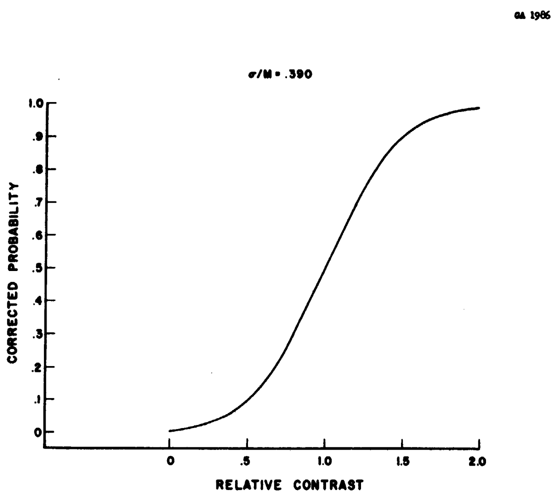

Fig. 2. Normal ogive fitted to experimental data.

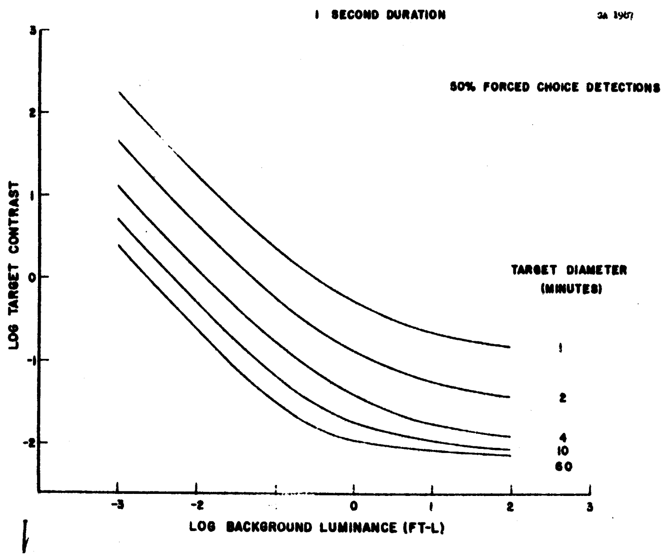

Fig. 3. Target diameter contours, 1 second duration.

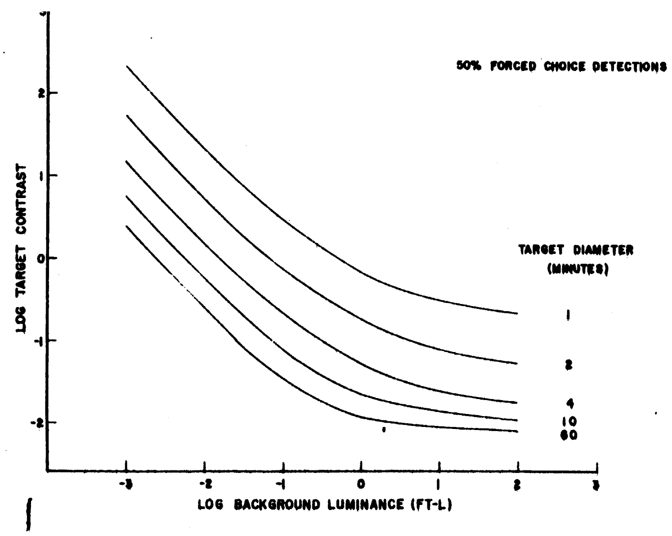

Fig. 4. Target diameter contours, 1/3 second duration.

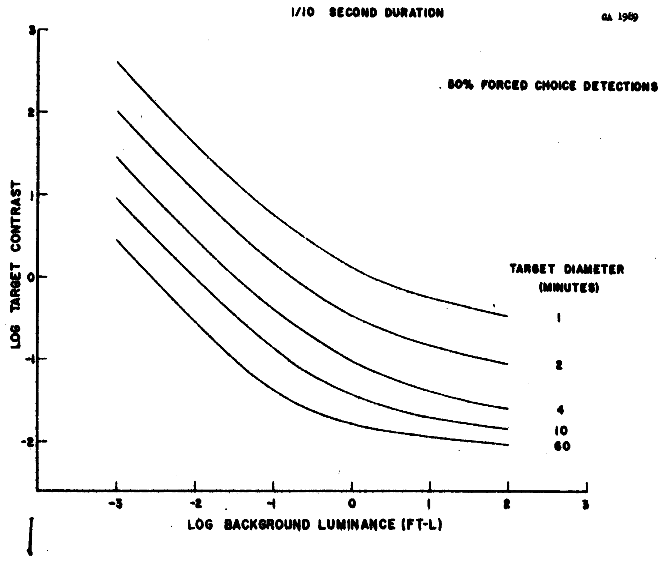

Fig. 5. Target diameter contours, 1/10 second duration.

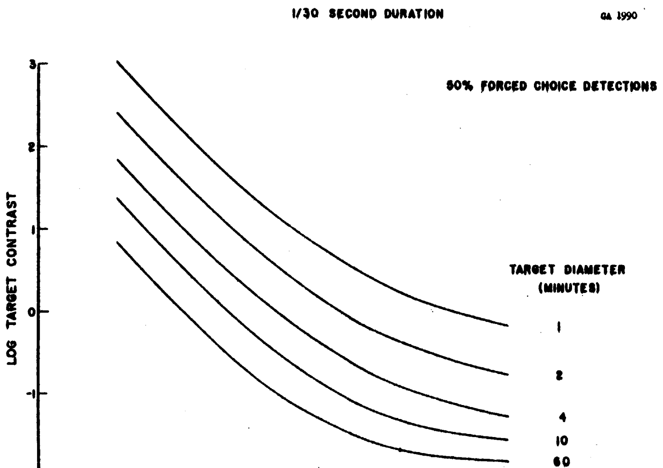

Fig. 6. Target diameter contours, 1/30 second duration.

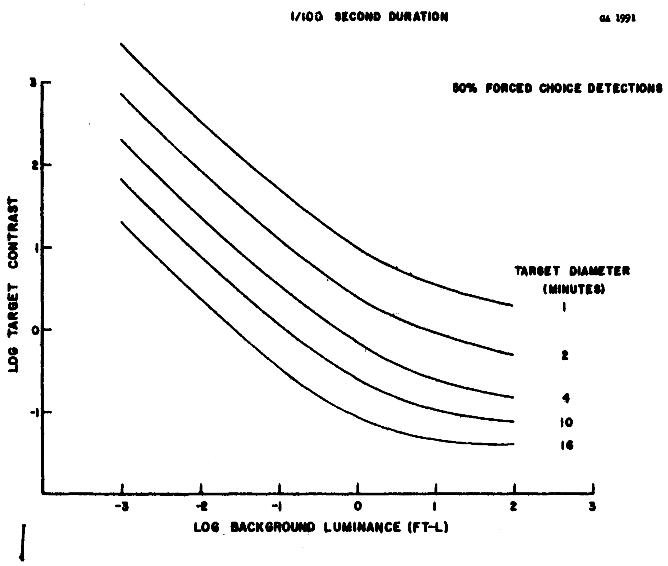

Fig. 7. Target diameter contours, 1/100 second duration.

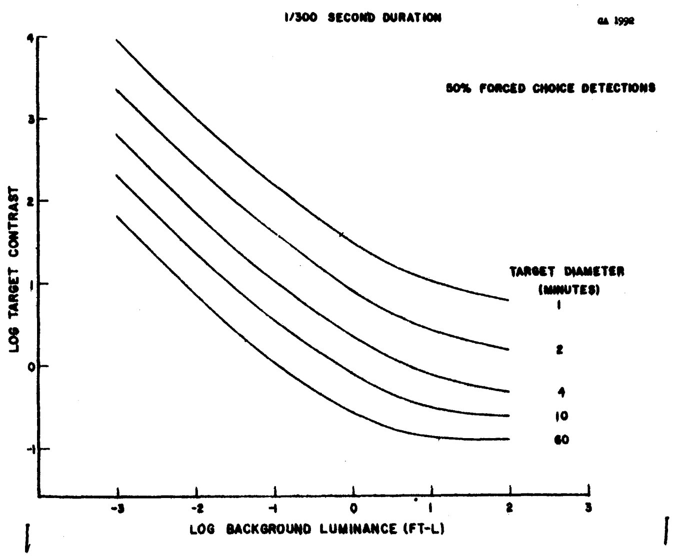

Fig. 8. Target diameter contours, 1/300 second duration.

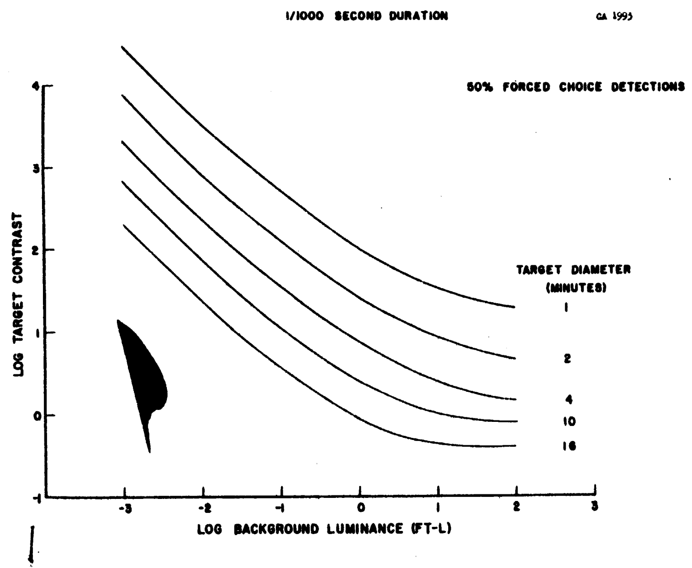

Fig. 9. Target diameter contours, 1/1000 second duration.

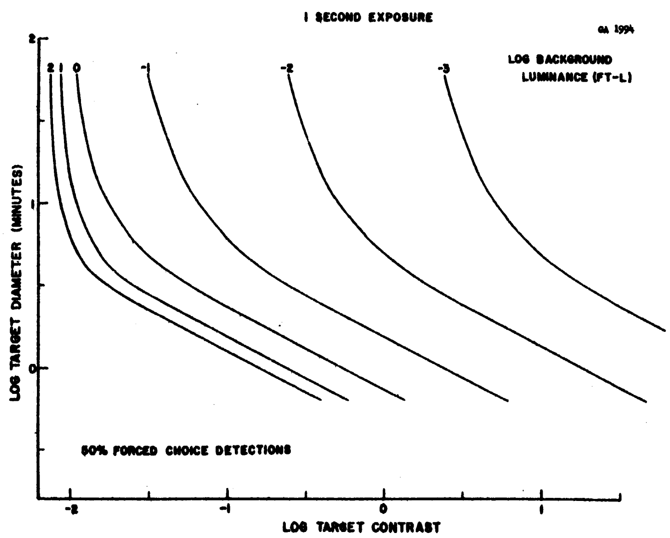

Fig. 10. Background luminance contours, 1 second duration.

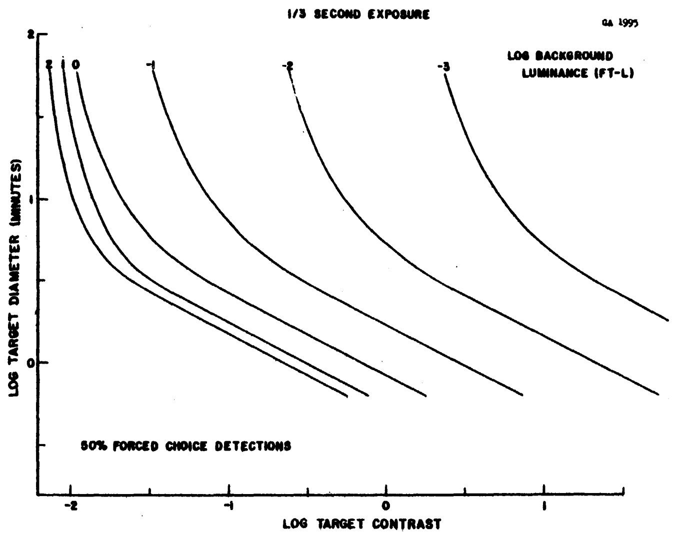

Fig. 11. Background luminance contours, 1/3 second duration.

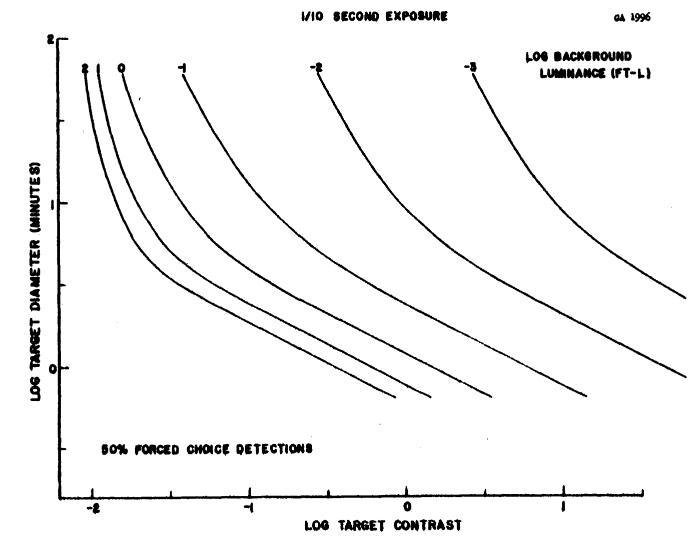

Fig. 12. Background luminance contours, 1/10 second duration.

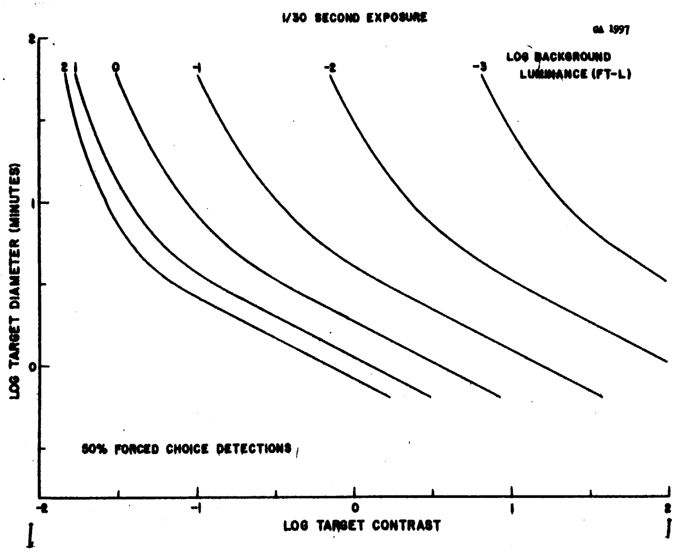

Fig. 13. Background luminance contours, 1/30 second duration.

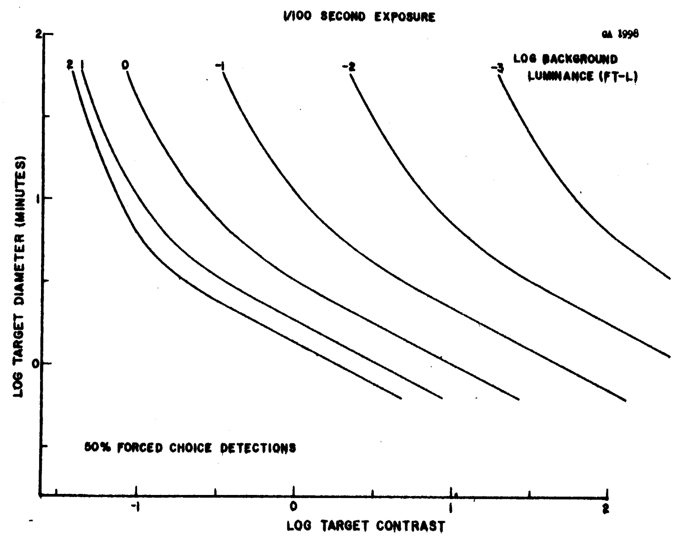

Fig. 14. Background luminance contours, 1/100 second duration.

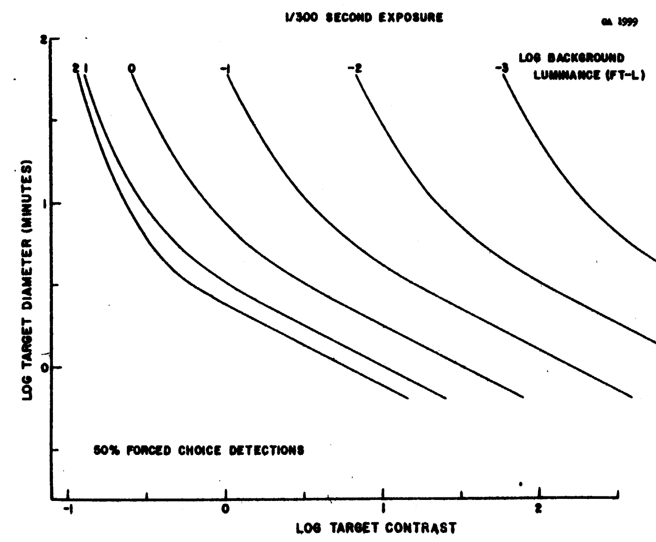

Fig. 15. Background luminance contours, 1/300 second duration.

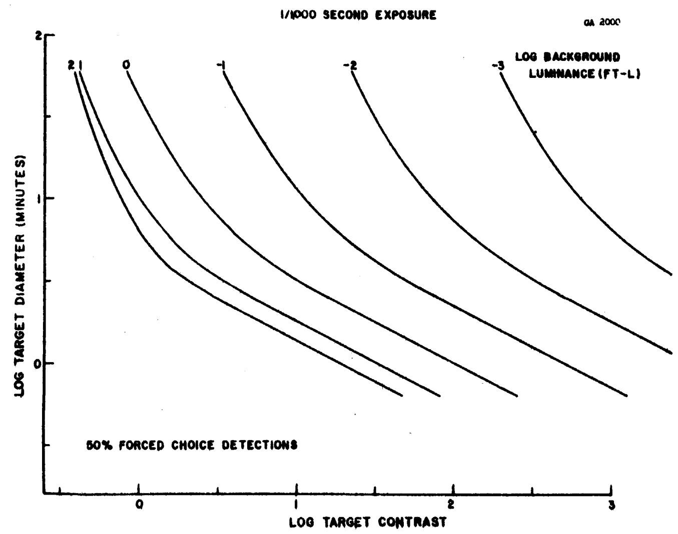

Fig. 16. Background luminance contours, 1/1000 second duration.