Brightness Discrimination Data for The Specification of Quantity of Illumination

By H. RICHARD BLACKWELL

Introduction

ONE OF THE BASES for specifying quantity of illumination is visual performance. For example, Report No. 5 of the Committee on Standards of Quality and Quantity for Interior Illumination of the Illuminating Engineering Society[1] is devoted to this approach to the problem of quantity of illumination. The primary experimental data upon which Report No. 5 is based are those of Weston. This investigator determined the speed and accuracy of visual performance involving identification of the orientation of Landolt broken rings for each of a number of illumination levels. The subjects were required to identify all rings with breaks in a given orientation from among a large collection of rings. The proportion of rings corectly identified was used as the accuracy score. Speed was measured by the inverse time required to perform the visual task, allowance having been made for the time required for the mechanical manipulations. The simple product of speed and accuracy was taken as a measure of "performance." Weston expressed his data at each illumination level as a proportion of the maximum "performance" which was obtained at the highest illumination studied. The size of the breaks in the Landolt rings and the brightness contrasts between the rings and their background were varied in different experiments.

The Weston data are generally conceded to be useful for specifying the quantity of illumination. The data were obtained with this particular objective in mind, unlike many sets of visual data which might be employed for this purpose. The visual task demanded of the subjects seems representative of visual tasks which may be required of workers in practical situations.

The principal shortcoming of the data is the ambiguity of the measure of "performance" which Weston has used. As we shall see, speed and accuracy each bear complex relations to the quantity of illumination. A simple product of speed and accuracy indices will therefore depend upon each of the constituent indices to a different extent at different illumination levels. Thus, increments of "performance" represent increases in either speed or accuracy or both, in indeterminate amounts. This means that one per cent increments of relative "performance" may be very unequal in their visual significance and that the use of "performance" levels may be very misleading. The only completely unambiguous procedure is to specify speed and accuracy separately so that the illuminating engineer can ascertain the extent to which each of these aspects of visual performance increases as the quantity of illumination is increased.

There is abundant experimental evidence revealing that different visual tasks require different levels of illumination. Thus, specification of the quantity of illumination for a particular lighting installation requires diagnosis of the visual task involved and application of appropriate visual performance data. It is here proposed that ultimately the specification of quantity of illumination from performance data should be based upon systematic data representing the relations between speed and accuracy and illumination for various *fundamental* visual tasks. Once such a body of data exists, the illuminating engineer need only develop a method for diagnosing the appropriate set of data for *fundamental* visual tasks to apply to the actual visual task at hand. At the time of writing, it seems likely that satisfactory methods of diagnosis of visual tasks will be developed, in the form of visibility or contrast meters.

The present paper reports a set of experimental data which were collected to provide a basis for specifying the quantity of illumination, when the visual task is that of discriminating brightness differences. Separate measures of speed and accuracy of brightness discrimination have been obtained for each of a number of illumination levels. Methods are suggested for utilizing these data to specify the necessary quantity of illumination for various levels of speed and accuracy.

Apparatus and Procedures

The experimental data to be reported here have been described elsewhere in detail[2] so that a com-

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paratively brief description of the apparatus and procedures will suffice.

The basic experimental task of the subjects was to detect the presence of a disc target which was produced by adding a brightness increment to a small portion of a screen of uniform brightness. The screen constituted 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 subjects were situated 10.25 feet from the screen. The screen of uniform brightness thus subtended approximately 40 degrees at the eyes of the subjects. 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 subjects used normal binocular vision with natural pupils. Two subjects 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 subjects, 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 brightness of the screen, direct illumination from the lamps was shielded. The apparent color temperature of the screen brightness 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 1, 4, 16 and 64 minutes of arc at the subjects' eyes.

The target brightness 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 subjects 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 subjects 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 brightness difference threshold. Previous experiments reported elsewhere[2] indicated that fixation lights of this intensity will have minimum influence upon the discriminability of nearby targets.

The subjects 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 subjects 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 subjects then had 2 seconds in which to prepare themselves for the next presentation of the target.

It has been shown elsewhere[3] that requiring subjects 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 brightness increments intended to elicit from nearly zero to nearly 100 per cent correct discrimination. Each experimental session was divided into five sub-sessions, each of which contained 10 presentations of each of the five target brightness increment values. Each sub-session lasted about 17 minutes. At the end of each sub-session, the subjects were allowed a 5-10 minute rest and relation 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.[2] 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 presentions depended upon a synchronous motor and a system of cam contacts situated on the drive shaft of the motor. The magnitude of the target brightness 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 subject 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 subject 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 subject for each target brightness 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 subject, at each of the five target brightness increments. There is, of course, a probability of .25 that the subject will get the correct answer by chance alone. The effect of chance successes may be eliminated by the formula:

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

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 an 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 brightness was always a negligible fraction of the target duration.

The two subjects 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 exced 20/20. Two other subjects were used for a portion of the same experiments. These subjects were undergraduates whose interest in the experiments was reasonably great but not exceptional as was the interest of the graduate students. As is reported elsewhere,[2] the data from all four subjects appear to be very similar. Only the data for the two graduate student subjects are presented here since only these subjects observed under all the experimental conditions.

Photometry of the screen brightnesses 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 brightness of the opal disc was measured routinely with the Macbeth. From the transmission of the opal disc and the inverse square law, the intensity of the transilluminated target could be determined. From known size of the transilluminated target, the brightness of the target could be computed. Two "candlepower boxes" were used, one for each of the two smallest targets.

The target brightness 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.

Results

In all, 162 experimental sessions were conducted in which background illumination, target size and duration were varied, in each of which brightness discrimination was measured.

We may well begin by considering the basic form of the data obtained by each subject in a single experimental session. The basic data are proportions of correct discriminations, after correction for chance successes, and the contrast between target and background, defined as follows:

$$\text{Contrast} = \frac{\Delta B}{B}$$

where ΔB = brightness increment of the target
B = brightness of the screen in the absence of the target.

The proportions of discrimination give us a direct measure of the *accuracy* of brightness discrimination.

In Fig. 1 we have exhibited a theoretical curve which has been found to adequately represent the experimental data of all the present experiments. We note that the probability of discrimination 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 distribu-

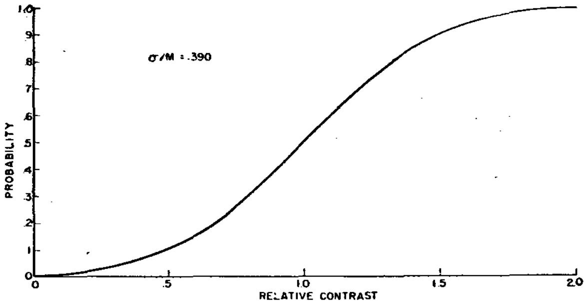

Figure 1. The relation between probability of brightness discrimination and target contrast found in all the experimental data. The curve is an integral of a normal frequency distribution, with parameter values: $M = 1$ and $\sigma = .390$.

tion. Our data analysis procedure involves determining the particular ogive which best fits the five experimental points obtained by each subject 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,[2] 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. Curve fits for all the present data were entirely acceptable.

Values of M varied over a million to one as illumination 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. There is considerable evidence for this relation in earlier experiments, as is indicated elsewhere.[4] As we shall see, the existence of this simple relation between M and σ enormously simplifies the problem of reporting and using the present experimental data.

TABLE I.—Average Values of σ/M

Target Size (Minutes of arc)							
	1	4	16	64			
	.373	.417	.396	.385			
***B* (footlamberts)**							
.001	.1	.3	1	3	10	30	100
.419	.421	.389	.386	.387	.380	.374	.355
Duration (seconds)							
1	1/3	1/10	1/30	1/100	1/300	1/1000	
.485	.450	.374	.370	.361	.361	.332	

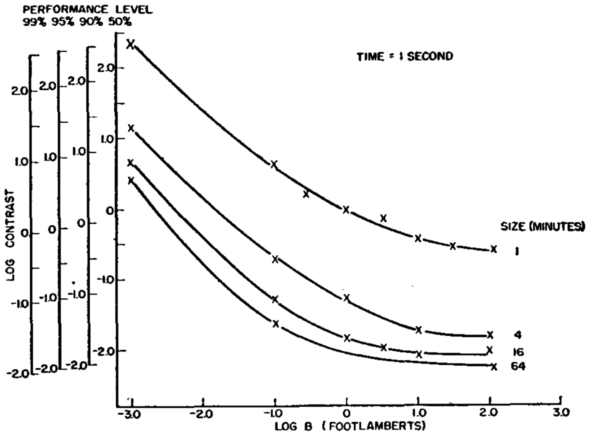

Figure 2. Data obtained with a time of exposure of 1 second. Each point represents at least 500 responses by two subjects.

The average values of σ/M for all the experimental data were .384 for one subject and .396 for the other. The theoretical curve in Fig. 1 represents $\sigma/M = .390$, the average value for the two subjects.

We have obtained average values of σ/M for both subjects 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 B increases, although the effect is small. The values of σ/M appear to decrease as duration decreases, although the effect is still comparatively small. Before indicating the use to which these values will be put, let us consider the functional relations between values of M and the three basic experimental variables.

Values of M are plotted as a function of B for each of four sizes and for each of seven target durations in Fig. 2-8. In each case, values of M refer to the ordinate marked 50 per cent performance level. These are threshold contrasts, where as usual the threshold is defined by 50 per cent discrimination. All plotted points represent averages of the data from the two subjects. In most cases, the points are based upon one experimental session but in several cases, two experimental sessions were conducted under essentially the same conditions. The experimental data presented in Fig. 2-8 represent a total of 81,000 observations by the two subjects. The experiments required daily experimental sessions for more than 12 months.

We note that M decreases systematically as B increases and as duration is increased. These general results were expected on the basis of existing experimental data.[5] The exact nature of the relations could not, however, be predicted from existing data.

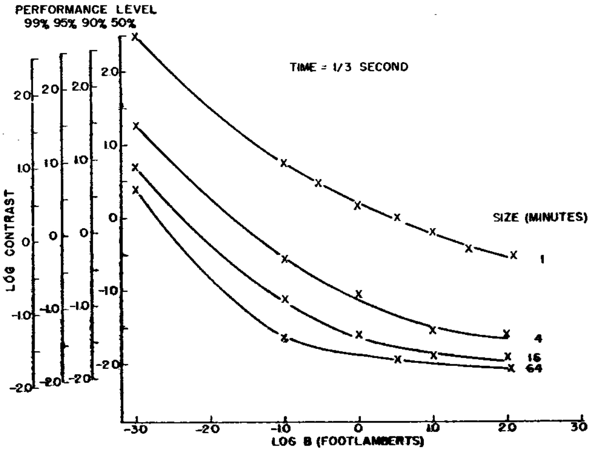

Figure 3. Data obtained with a time of exposure of 1/3 second. Each point represents at least 500 responses by two subjects.

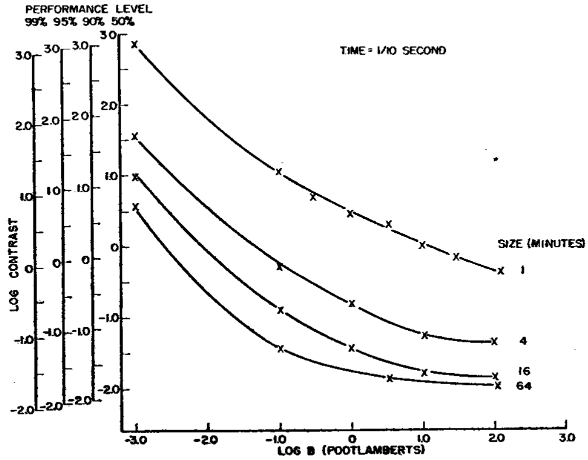

Figure 4. Data obtained with a time of exposure of 1/10 second. Each point represents at least 500 responses by two subjects.

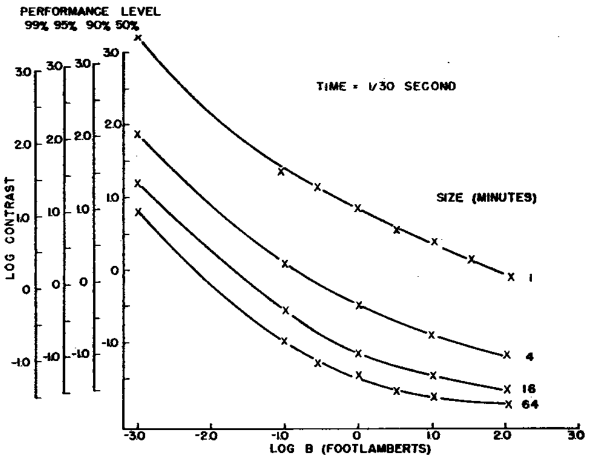

Figure 5. Data obtained with a time of exposure of 1/30 second. Each point represents at least 500 responses by two subjects.

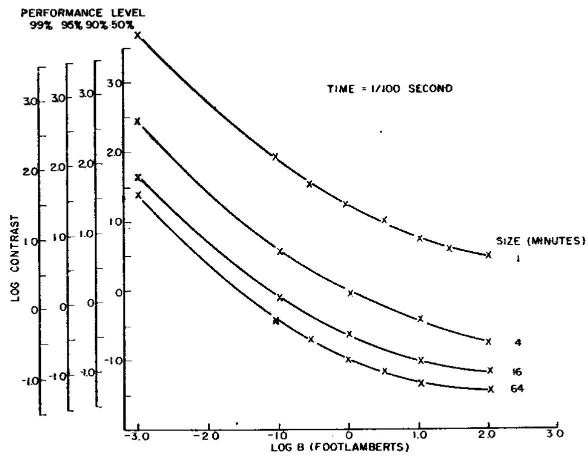

Figure 6. Data obtained with a time of exposure of 1/100 second. Each point represents at least 500 responses by two subjects.

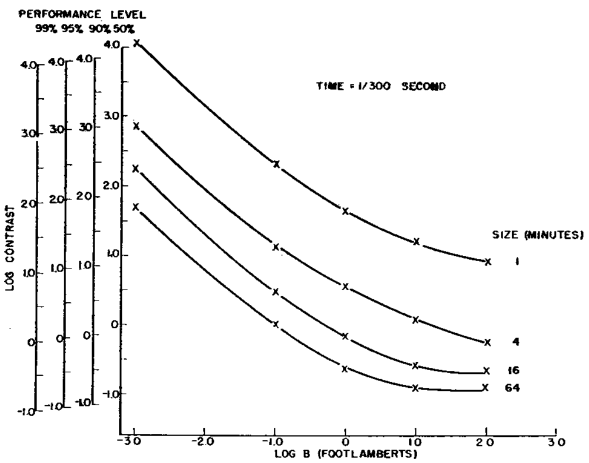

Figure 7. Data obtained with a time of exposure of 1/300 second. Each point represents at least 500 responses by two subjects.

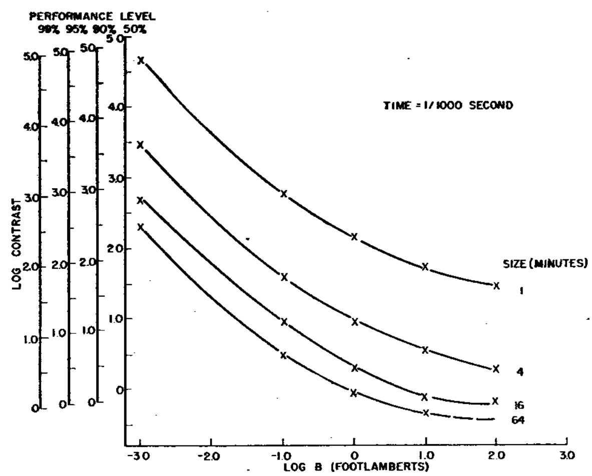

Figure 8. Data obtained with a time of exposure of 1/1000 second. Each point represents at least 500 responses by two subjects.

TABLE II.—Values of Z

Target Size (Minutes of arc)			
1	4	16	64
1.87	1.97	1.92	1.90

B (footlamberts)							
.001	.1	.3	1	3	10	30	100
1.98	1.98	1.91	1.90	1.90	1.88	1.87	1.83

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

If we content ourselves for the moment with 50 per cent accuracy, we note that the experimental data permit us to evaluate the effects of target size and contrast and background illumination upon *speed* of performance, where *speed* is given by the inverse of target duration. We can discover the extent to which *speed* of performance increases with an increase in background brightness by noting the relation between B and target duration, given target size and contrast.

Let us now consider the most convenient manner in which to evaluate *accuracy* of discrimination. We have plotted values of M, corresponding to an accuracy of 50 per cent. We wish to know the correction to make in M to allow for a different level of accuracy than 50 per cent. Let us define Z, a conversion factor which will correct M to any desired level of accuracy as follows:

$$Z = 1 + f_a \cdot \sigma/M \tag{3}$$

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

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

f_a	per cent accuracy
1.29	90
1.65	95
2.33	99

If we assume $\sigma/M = .390$ as in Fig. 1, values of Z are as follows:

Z	per cent accuracy
1.50	90
1.64	95
1.91	99

This means that, when $\sigma/M = .390$, a value of target contrast 1.50 times M, the threshold, will give 90 per cent accuracy; 1.64 times M will give 95 per cent accuracy; and 1.91 times M will give 99 per cent accuracy. These values may be verified by inspection of Fig. 1, 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 99 per cent accuracy 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 ± 2.5 per cent; among the eight brightnesses by only ± 4 per cent; and among the seven durations by ± 10 per cent. Variations in Z for accuracy levels less than 99 per cent will vary less. It is concluded that variations in Z as a function of either size or background brightness are negligible. Variations in Z as a function of target duration are small, but should 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 *accuracy* by different scales of log target contrast, displaced by a constant amount representing log Z. In Fig. 2-8, the four ordinates have been computed by allowing for Z in this way. Each figure has been constructed with different values of Z, representing the fact that Z is not constant for different target durations. Within each figure, the same values of Z apply since we concluded that Z does not vary significantly as a function of either size or background brightness.

Use of the Data to Specify Quantity of Illumination

To utilize these data to specify the quantity of illumination, we have merely to specify the target size and contrast. We may then investigate the influence of quantity of illumination upon (a) *accuracy* and (b) *speed* of brightness discrimination. For example, let us assume the visual task involves brightness discrimination of a 1 minute circular bright spot whose brightness is twice that of its background. Contrast = 1.0; log contrast = 0. Values of B (footlamberts) for various target durations at each of four levels of *accuracy* are obtained as follows:

	Accuracy (per cent)			
Duration	50	90	95	99
1	1.0	2.5	3.6	4.8
1/3	2.8	8.3	10.	17.
1/10	10.	28.	33.	58.
1/30	69.	>100.	>100.	>100.

We can see from these values how *speed* and *accuracy* increase as B increases. Knowing the reflectance of the background material in question, we may compute the quantity of illumination required to provide desired levels of *accuracy* and *speed*.

Summary and Conclusions

A comprehensive study of brightness discrimination for uniform circular targets has been made. The accuracy of discrimination has been related to target contrast, target size, target duration, and brightness of background. If the target contrast and size are known, the *speed* and *accuracy* of brightness discrimination can be readily related to the quantity of illumination.

Acknowledgments

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DISCUSSION

DOMINA EBERLE SPENCER*: For several years, Dr. Blackwell has been telling the members of the Committee on Standards of Quality and Quantity for Interior Illumination about the extensive experimental work he has been carrying on. We have been awaiting the publication of his data with great interest. The paper "Brightness Discrimination Data for the Specification of Quantity of Illumination" represents the first tangible fruit of this work. Needless to say, this type of visual research is very important to the Illuminating Engineering Society.

However, before the results of Dr. Blackwell's experiments can provide a suitable experimental basis for recommendations of the Q and Q Committee, certain modifications and extensions of the work are needed:

(1) The results of this paper are based on observations by *only two observers* who visual acuity exceeded 20/20. No indications of discrepancies between the two observers are given. Yet the lack of coherence of the various sets of curves to the family patterns found in more extensive experimental investigations by other researchers leads one to question the significance of the curves drawn by Dr. Blackwell. Would these same peculiarities appear if a larger number of observers were used? How accurate are the data given? Could we not draw sets of curves of simpler shape which would represent the data with sufficient accuracy and yet be more significant than those drawn by Dr. Blackwell?

The illuminating engineer may also wonder if his rooms should be designed only so that two particular observers with above normal vision can see to perform tasks with a given accuracy. What about the typical occupant of the office or drafting room whose eyes are not above normal but are average or, as is more common, far below average? Will data for these two observers have any meaning in the practical case?

(2) If it is possible (and there is every indication that it *is*, according to numerous other experimental investigations) the results should be expressed *analytically*. If the data can be summarized by a single equation, meaningless irregularities will be smoothed out and the results will be placed in the most convenient form for application. Dr. Blackwell has taken, implicitly if not explicitly, a step in the right direction in his use of the S-curves. But his inhomogeneous families of graphs are far from the most convenient form for the presentation of the results.

(3) We have here a large quantity of information on the detection of small round spots of low contrast. But not many of us are called upon to perform this type of visual task. Such work will become much more useful to the illuminating engineer when it is extended to tasks more closely related to those found in practical situations.

(4) Dr. Blackwell is to be commended for having obtained a reasonable approximation to a uniform surround. The fact that his curves have a continued downward trend at large quantities of light is indicative of the fact that the visual surround is adequately uniform.

An important extension of these researches would be to repeat them for non-uniform surrounds. We would like to be able to assess the effect of the moderately non-uniform surround encountered in the best contemporary lighting practice — say one which satisfies the 3:1 ratio. It would also be valuable to be able to determine the effect of glare sources such as are found, either in direct view or reflected from our work, in most artificially lighted luminous environments.

It is to be hoped that Dr. Blackwell can extend his research to cover some of these suggestions without causing the U. S. Treasury to run dry or bankrupting the I.E.S. Research Fund.

*University of Connecticut, Storrs, Conn.

SYLVESTER K. GUTH*: Dr. Blackwell's comprehensive study of brightness discrimination considerably extends the scope of our knowledge of the relationships among the four fundamental factors of seeing. Not since the early work performed by Cobb and Moss has anyone undertaken such a thorough investigation. His study provides us with additional fundamental data for determining the speed and accuracy of performance for one type of simple visual task. As the author points out, when similar data are available for a variety of basic visual tasks, we will be able to apply visual performance data to actual work-world tasks. I hope that Dr. Blackwell and other investigators will extend such researches to include other tasks.

It may be desirable for Dr. Blackwell to amplify his very brief discussion of contrast. By expressing this factor always in terms of the background brightness, he obtains values of contrast in excess of 100 per cent (log contrast greater than 2.0). While his method is logical, convenient and useful, it may be confusing to those who usually express contrast in terms of the brighter of two adjacent surfaces and, thus are limited to a maximum of 100 per cent.

I believe that the extremely short exposure times of 1/300 and 1/1000 are of only academic interest in most lighting situations. However, it is well to extend experimental variables beyond the practical range to avoid inaccurate extrapolations. On the other hand, I wonder if at least one exposure time longer than one second would not be useful. Many tasks are such that time is of little importance, but the utmost in accuracy is required.

A word of caution may be in order for those who will want to apply these data immediately and directly. Dr. Blackwell's results establish general relationships for one specific type of visual task. Before they can be used on an absolute basis we will need data from more than two experienced observers and with more complex tasks. We need to know how various workers respond. That is, slow, average, superior, young, old, experienced, inexperienced workers and those with various degrees of visual abilities should be

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included as subjects. Our objective is to provide the proper seeing conditions for all the workers and not only for the best workers. Furthermore, considerable weight must be given to ease of seeing or the effort involved, and the degree of manual or mental dexterity required. In other words, lighting requirements are dependent upon many factors. Thus, this paper must be considered as but one more important step along the road toward complete knowledge of the effectiveness of light and lighting.

C. L. CROUCH*: I cannot pass up the opportunity of putting in a word in behalf of the I.E.S. Research Fund.

This paper represents the first step in the Fund's planned approach to establish a performance method of determining footcandles. It further represents the outcome of many hours of ardent discussion in the Standards of Quality and Quantity Committee where the vision researchers and the practicing engineers have wrestled with the problem of "how much illumination should be recommended."

You are acquainted with the Weston method of evaluating the illumination to obtain a given percentage of maximum performance based upon the output of work of cancelling Landolt rings having differing size and contrast. This method has received considerable study and respect from the S.Q.Q. Committee. But we have also come to realize its limitations — a question of validity of applying results from Landolt rings to other configurations in the work world, a question as to the scatter of Weston's experimental point to establish statistical significance and the question as to the significance of Weston's empirical accuracy factor. As a result it has been felt that this type of approach should be studied in this country and an attempt be made to separate out the pure functions of size, contrast, time for seeing, and accuracy. Having done this for a pure type of test object, "a circular disc," then studies can be made of the variations due to other types of configurations. Dr. Glenn Fry has proposed seven configurations as representing individually or in combination all those found in the field. Thus with the research continuing until all these configurations have been tested, you can see that there would become available a series of graphs similar to the results of this paper which would allow the practicing engineer to pick out the one applying to his configurations, size, contrast, time for seeing, and degree of accuracy desired, and find the illumination necessary. We realize that such a comprehensive program may require the "U. S. Treasury" but we hope that the I.E.S. Research Fund may do its share in making this worthy objective become a reality.

H. RICHARD BLACKWELL**: I very much appreciate the suggestions which have been made by Dr. Spencer, and by Mr. Guth and Mr. Crouch. I can agree with most of these suggestions without qualification. The experimental data we have collected represent only a beginning in the task of providing visual performance data upon which the specification of illumination levels should be based. We have studied only one visual capacity, brightness discrimination. Similar studies to ours should certainly be made of the other fundamental visual capacities. We are not entirely sure how many fundamental visual capacities there are. Studies of various visual capacities, which may seem to visual theorists to represent different fundamental capacities, will establish the extent to which these capacities are indeed fundamental and distinct from one another. At such time as all such studies have been completed, it will be possible for illumination levels to be specified on an entirely rational basis. The achievement of this goal is not to be expected soon, but we should keep working toward it with all possible dispatch. Even as far as brightness discrimination is concerned, our experiments are admittedly incomplete. The influence of non-uniform surrounds must be evaluated. As a matter of fact, we have requested funds from the I.E.S. Research Fund to carry out such a study. We should not content ourselves with data on two observers. I propose that we study brightness discrimination for several conditions of background luminance and target duration with a large number of observers. We do not expect the functional relations among these variables to vary greatly among observers. If this is true, then population data under a few experimental conditions, and complete data on a few observers, will suffice to give us good estimates of brightness discrimination as a function of background luminance for the general population.

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I believe Mr. Guth is quite correct in remarking that exposure durations of 1/300 and 1/1000 second are of "only academic interest." However, I agree with Mr. Guth that it is desirable to study experimental variables beyond the limits of practical interest. As far as longer durations are concerned, we may utilize the data I published in 1946, representing durations as long as 16 seconds. If we compare the 1-second data with these earlier data, we find very little difference, suggesting that the 1-second data represent durations this long, or longer, with reasonable accuracy.

The one suggestion with which I cannot agree is that made by Dr. Spencer that we find a single analytic function and fit all the curves relating brightness discrimination and background luminance to it. I may remark that we are very eager to find *theoretical* arguments which will rationalize all our experimental data. It is apparent from examining the data, however, that no single analytic function adequately fits all the data. We cannot attribute this apparent perversity of the data to experimental errors. The factors which lead to the form of the brightness discrimination curves just do not happen to be so few that a single analytic function will describe all the experimental data. We hope to identify all the factors eventually and describe all the data with mathematical functions. As a matter of principle, I object to *force-fitting* all the data by a single analytic function. As a matter of practice, I believe that empirical curves which really fit the data are much preferable to a standard analytic function which does not really fit the data.

Finally, I must comment on the definition of contrast, first adopted in the 1946 report. Contrast was defined so as to simplify the comparison between the bright and dark targets investigated in the study which was reported. If we define contrast as $\Delta B/B$, where ΔB is either the brightness increment or decrement, the experimental data for bright and dark targets become virtually identical. Other definitions of contrast lead to large differences between the data for bright and dark targets, a situation which we believe to be artifactual. In the case of the bright targets, contrast may go to infinity. A value of ΔB twice that of B gives a contrast of unity. Such contrast is usually referred to as a 100 per cent contrast. In his discussion, Mr. Guth refers to 100 per cent contrast, and notes that the logarithm of this contrast equals 2.0. According to our definition, log contrast will in this case be zero.