Development and Use of a Quantitative Method for

Specification of Interior Illumination Levels

on the Basis of Performance Data

By H. RICHARD BLACKWELL

INTRODUCTION

An eight-year program of research is reported here which has led to the development of a general method by which illumination levels may be determined for various practical tasks, based upon visual performance criteria. During these years, the author had the friendly guidance of the Technical Advisory Committee on Light and Vision of the Illuminating Engineering Research Institute, and he wishes to acknowledge his indebtedness in particular to Dr. Glenn A. Fry, Professor Everett M. Strong, Dr. Sylvester K. Guth, and Mr. Willard Allphin of this committee for many helpful suggestions. Mr. C. L. Crouch, Secretary of the Institute and Technical Director of the Illuminating Engineering Society, has been a strong motivating force in the conduct of this research, and has provided many extremely valuable ideas over the years. The lighting specification method was discussed on several occasions with the IES Committee on Recommendations for Quality and Quantity of Illumination, the members of this committee contributing various worthwhile suggestions. Similarly, Kirk M. Reid, then President of the Illuminating Engineering Society, contributed helpful concepts. Finally, the Basic Research Advisory Committee of the IERI provided valuable counsel. Of course, the author must accept full responsibility for the research program and for the present report, but in all fairness the many contributions of these active friends of lighting research should be acknowledged.

The first report of the method was made in a detailed presentation at a Symposium sponsored by the IERI at Dearborn, Michigan on March 3-4, 1958.* Subsequently, a summary report of the method was presented at the National Technical Conference in Toronto on August 19, 1958. These reports not only described the basic elements of the method, but also recommended specific procedures to be followed in applying the method at the present time. The selection of procedures to be used currently was based upon all available relevant knowledge. The present report describes the method in its most general form, indicating the procedures recommended for current use. It goes beyond all earlier reports, however, by describing in addition what may well be the ultimate procedures for using the method, and by indicating the kinds of research needed to develop these procedures.

The method for specifying lighting levels reported in the present paper is obviously intended to supersede the less well-developed methods described earlier by the present author,[1,2] which depended upon performance data utilized in part for the present method.

The description of the general features of the method will reveal that we have much to learn concerning the details of visual performance. It should be emphasized, however, that the new studies reported here, together with the many important studies of the past, provide us with sufficient insight into the problem so that it is both wise and necessary for available performance data to be used now for the specification of lighting levels for various visual tasks.

The present report contains the following sections:

I. Characteristics of Visual Performance
II. Laboratory Performance Data for Standard Disc Targets
III. Field Factors
IV. The Visual Task Evaluator
V. The Standard Visual Performance Curve
VI. The Standard Lighting Specification Procedure
VII. Evaluation of Sample Visual Tasks
VIII. Future Developments of the Method

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*Minutes of the Symposium may be obtained by addressing the Illuminating Engineering Research Institute at IES National Headquarters in New York.

I. CHARACTERISTICS OF VISUAL PERFORMANCE

THE visual system is primarily an information-assimilation system and visual performance should refer, therefore, to the rate at which information is assimilated. It is well known that the level of illumination of a visual task influences the capacity of the visual system to assimilate information, as do characteristics of the task such as the size and contrast of the "critical detail." The problem is to find some index of the capacity to assimilate visual information for use in specifying the lighting requirements of various visual tasks.

The visual system is not usually a passive information assimilator, but normally follows a complex adjustment procedure designed to extract information from the environment. The eyes normally fixate one point in the visual field, then the two eyes change accommodation and vergence so that clear images are produced in each eye and binocular fusion occurs for the two eyes. During the fixational pause, information is assimilated from the visual field. This information directs the eyes to a new position in space, with appropriate signals being sent to the oculomotor adjustment mechanisms to insure appropriate accommodation and vergence changes. New information is assimilated during this fixational pause which guides further adjustment of the oculomotor mechanisms, and so on. Under these conditions, the visual system is obviously a self-pacing servo-mechanism, the information assimilation capacity of which depends upon the efficiency of the oculomotor mechanisms as well as upon the characteristics of the task and the luminous environment.

Records of eye movements during self-pacing information assimilation reveal that the eyes do not scan the visual field in a simple orderly manner even when the material is simply ordered. For example, eye movements in reading continuous prose do not proceed regularly across the lines of words in the appropriate word order for the language involved. Instead there are repeated glances at some words, and fixation skips over other words. The skips are undoubtedly related to inferences which are drawn in some instances which make detailed examination of some words unnecessary; the repetitious glances are presumably related to the need for confirmation or assimilation of further information in other cases. The existence of these complex patterns of eye movements emphasizes the fact that the information assimilated by the visual system consists of many items which are complexly related and difficult to specify.

Measurements of the detailed characteristics of dynamic patterns of eye movements during reading agree in demonstrating that the eyes usually pause for a duration of about 0.225 second. Ginsburg[3] has shown that the eyes usually make four fixational pauses of this duration per second during continuous reading.

It is difficult to imagine reading through a pair of tubes which limit the field of view to a small zone immediately surrounding the fixational center. Thus, it seems apparent that information is assimilated from a sizable area of the visual field surrounding the fixational center during each fixational pause.

Clearly, then, informational assimilation is a complex process during normal dynamic use of the eyes. We have no easy way to specify the amount of information assimilated, since we cannot define the usual meaningful visual material in unambiguous informational units. Even if we could define the total information extracted during a complex visual task, we would have no way of defining the amount of information extracted in a particular fixational pause. Thus the rate of visual information-assimilation could not be specified independently of the speed and accuracy of oculomotor adjustment processes.

In order to specify lighting levels for various visual tasks, we need a quantitative index of visual capacity to assimilate information. It seems desirable to begin by simplifying the problem by considering the eyes to be incapable of motion. Under these circumstances, a controlled informational input can be supplied and the information-assimilation capacity measured unambiguously. The visual task must be capable of specification in terms of informational content. With this requirement in mind, a test object consisting of a luminous disc, presented on a background of generally uniform luminance, has been selected. When employing the test object, the observers are required only to indicate whether or not the presence of the disc has been detected. They are not required to identify other aspects of the target such as its size, shape, or color. Awareness of the presence or absence of the disc may be considered to be one item of information. (The term "bit" is avoided because of its precise significance in modern information theory; we have no evidence that the information concerning the presence or absence of our luminous disc

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may be defined in this specific manner.) The number of items assimilated per second is considered to measure the visual capacity, in units of assimilations per second (APS).

In actual experimentation, the time during which the disc target is presented is varied. The capacity of the visual system to assimilate the information represented by the disc target is derived from the time during which the information had to be presented for it to be assimilated. Thus, if the disc has to be presented for an entire second, the visual system is operating at a level of capacity corresponding to the assimilation of one item of information per second. If, on the other hand, the disc need be presented for only $^1/_{30}$ second, the visual system is operating at a level of capacity corresponding to the assimilation of 30 items of information per second. If the item of information can be assimilated in $^1/_5$ second or less, then it will be possible for assimilation to occur within one fixational pause. If, however, more than $^1/_4$ second is required for assimilation to occur, then the eye will have to spend more than one fixational pause assimilating the information. It may be considered extremely undesirable for a self-pacing servo-system, such as the visual system, when the level of visual capacity is reduced so that the item of information cannot be assimilated within one fixational pause. Use of repeated fixational pauses may be expected to disrupt the ordinary dynamic information-assimilation activity of the system.

A visual capacity to assimilate the item of information in less than $^1/_5$ second presumably means that the system can assimilate more than one item during a single fixational pause. It is difficult to imagine how the servo-system can operate unless it assimilates a considerable number of items of information during each fixational pause. For example, in reading, the system requires considerable information during each fixational pause to direct the movements of the eyes and the oculomotor adjustment processes.

It is not at present possible to describe the information-assimilation activity of the self-pacing visual system with any accuracy. However, studies conducted in the Vision Research Laboratories at the University of Michigan are suggestive in this connection.

Recently W. C. Clark and the author[4] attempted to evaluate the number of items of information which the visual system can assimilate per second from a single point in the visual field. The experiment involved disc targets which consisted of two very brief pulses, separated by a longer interval. The eyes were motionless during the presentation of the targets. The pulses were each only 0.0025 second long, and the separation between them was varied in different experiments from 0.0040 to 0.4750 second. In each case, the observers were required merely to detect the presence of the target and they were not required to recognize that two pulses had made up the target, much less to correctly estimate the length of the interval separating the pulses. The familiar temporal forced-choice method was employed, in which a target is presented in only one of four possible temporal intervals, each of two seconds duration. The observer had to indicate that he had discriminated the presence of the target by correctly identifying the interval in which it appeared. The contrast of the double-pulse target was varied from trial to trial and the accuracy of correct identification recorded. The contrast was determined at which the target is detected 50 per cent of the time, after correction for chance successes; this quantity is known as the threshold contrast.

The threshold contrast was measured for a number of different double-pulsed targets. It was found that when the two pulses were sufficiently close together in time, the threshold contrast was precisely one-half that which was required for one of the pulses. Thus, a single- and a double-pulse target of equivalent total energy are equally detectable. The existence of perfect temporal summation, as this is called, implies the absence of temporal resolution. (The situation is parallel to the more familiar situation in the spatial dimension, in which perfect spatial summation is revealed whenever two targets of different size but the same shape have equal total energy thresholds. As reported elsewhere[5] the presence of perfect spatial summation implies the absence of spatial resolution or visual acuity.) Perfect temporal summation was found whenever the double-pulses were separated by less than 0.02 second. As the temporal separation between the pulses was increased, the contrast required for detection increased continuously until, when the separation was 0.05 second, the threshold for the double-pulsed target was the same as the threshold for a target consisting of only one of the pulses. This situation revealed that there was no temporal summation between the two pulses. When the temporal interval between the two pulses was increased beyond 0.10 second, there was a small reduction in threshold contrast. This reduction may be explained quantitatively by assuming that the visual system succeeds in detecting the presence of the target whenever it detects the presence of either of the two pulses. Thus, the two pulses improve target detectability by what may be called probability summation. This suggests that the visual system is capable of re-cycling every 0.10 second. Information assimilated in one brief cycle is separated from the information assimilated in a second brief cycle.

It is worth noting that clearly visible double-pulse targets in which the two pulses are separated by 0.10 second are usually seen as double. Thus, there are two rather different bases for believing that the visual system can resolve two items of information at the same point in space in $^1/_5$ second, providing there is at least $^1/_{10}$ second separating them. These data suggest that the visual system can assimilate two items of information from one point in space within the time usually devoted to a fixational pause. Since in self-pacing ocular activity there are normally four fixational pauses per second, it seems reasonable to suppose that at least eight items of simple information can be assimilated per second at a single point in the visual field. The fact that the human can recognize the presence of light flicker at rates up to 50 cycles per second certainly suggests that the visual system is capable of assimilating a great deal more than eight items of simple information per second, even from one location in the visual field. Of course, the successive items of information represented by the flickering light are not independent, and it is not possible for the human to determine the number of pulses per second beyond approximately 10 per second.

Another staff member of the Michigan group, E. R. Harcum, has recently reported the number of items of information which can be assimilated from different parts of the visual field, within the duration of a normal fixational pause. The eye was motionless for these studies, and spatial arrays of information were presented, consisting of multiple elements each of which could have one of two possible forms. These "binary" elements were used so that the target arrays would not have any meaning to the observers, in order to avoid ambiguities as to the amount of information actually assimilated. Provided the task elements had sufficient contrast and the general level of luminance was sufficient, arrays of information consisting of 8-12 elements could be correctly recognized. This means that the capacity of the visual system must be at least 10 items per fixational pause, or 40 items in the four fixational pauses the system normally makes per second.

The data of these studies suggest strongly that the visual system scans across space over time, so that first one and then another point in space is "interrogated" by a neural mechanism in the brain. The scan is repeated perhaps as many as 10 times per second. Thus, during a fixational pause, the entire visual field may be scanned at least twice with items of information being assimilated from various points in visual space during each neural scan.

It is not entirely justifiable to combine the Clark and the Harcum results quantitatively to evaluate the total number of items of information which can be assimilated from all portions of the visual field in a second. Direct use of both sets of data would suggest that at least 80 items of information can be assimilated per second. Of course, items of information may interfere with each other, thus reducing the total informational capacity. On the other hand, items may be related to each other in such a way that the informational capacity will be greater than the value suggested by these studies. Precise evaluations of the information-assimilation characteristics of complex time-space arrays of information must await further research. However, it would not seem unreasonable to suppose that the visual system can assimilate 30 simple items of information per second. In continuous reading, for example, surely the system extracts at least eight items of information during each fixational pause.

There is one further aspect of this conception of the visual system which deserves mention. If the eyeball remains fixed and an object moves rapidly across the visual field, the object is known to be more visible than if it had not moved. We believe that the visual system has auto-correlation sensitivity, so that regular time-space sequences, such as those produced by an object whose image moves across the retina, are unusually detectable. This aspect of the system is probably produced by the existence of spatially interconnected elements of the visual system.

There will usually be sufficient information present in the visual field so that the visual system can work at maximum capacity without assimilating all the information present. However, situations will occur in which the information is reduced to a level where the system cannot work at maximum capacity. It is, of course, a simple matter to produce conditions in the laboratory in which there is a severe limitation on informational content. Consider, for example, the situation in which a disc target is presented on a background field of otherwise uniform luminance. If the observer is required merely to detect the presence of the disc, we may limit the informational content to one item and we may prolong the presentation of the disc as long as we wish without adding information. Thus, presentation of a disc for a full second represents restriction of informational content to one item per second, which must certainly be considered a level of information far below the maximum capacity of the system. The item will usually be assimilated during a single fixational pause, and there will be no further information gained during the next three fixational pauses which will normally be made during the one-second exposure of the disc. Under these circumstances, it is as though the information-assimilation system is idling. It is possible, of course, to reduce the visibility of the disc by reducing either its size or contrast until the disc will not be detected in less than a full second. Under these circumstances, we may surmise that all four of the fixational pauses to be expected during the one-second exposure of the target will be used for examination of the expected location of the disc. Studies by Clark and the author[4] suggest that disc targets exposed for durations longer than $^1/_5$ second are visible due to the probability summation mechanism described above, with separate fixational pauses representing the separate statistical events needed for this mechanism to operate.

Visual performance may also be limited by the requirement that a non-visual motor response be performed as an essential element in the information-assimilation sequence. For example, in some assembly-line inspection tasks, there is a sequence involving visual scanning of the objects to be seen, followed by some selective action with respect to the objects seen. The inspector may be required, for example, to reach out and remove objects which do not meet production standards. No matter how efficiently the inspector arranges his sequences of searching and removing, his capacity to assimilate information from the objects to be inspected may be reduced by the requirement that he respond appropriately to the objects being examined. This situation is to be contrasted with that encountered in continuous reading, in which the information may be assimilated as rapidly as the visual information-assimilation system can operate. It will be of interest, perhaps, to note that the performance data of Weston[7] represent visual performance under conditions in which there was an obvious response limitation. The observers had to cancel certain broken circles when they were seen. The inclusion of this non-visual motor response in the sequence of activities being studied undoubtedly had the result that the observers were unable to perform up to their maximum capacity to assimilate information.

There are different types of non-visual motor response requirements of visual tasks which will limit visual performance to various extents. For example, there are instances in which the observer will have to stop assimilating information completely until the motor response has been performed. Weston's task is probably of this type. Many inspection tasks, however, do not require that information-assimilation be completely stopped while the non-visual motor response is made. For example, it is often possible for the inspector to continue examining additional objects while he takes the requisite action with respect to an object which has already been examined. This can be accomplished whenever the non-visual motor response can be made without guidance by foveal vision. The selection of choice peaches from among large numbers of such fruit spread out on a moving belt is an example of an activity in which the non-visual motor response can be accomplished without foveal guidance once the select peaches have been located by foveal viewing.

II. LABORATORY PERFORMANCE DATA FOR STANDARD DISC TARGETS

The analysis of the preceding section has described the visual information-assimilation process and has introduced the concepts of visual capacity to assimilate information, informational limitation, and response limitation. This analysis has suggested the desirability of "freezing" the eye so that the basic capacity of the visual system to assimilate information may be studied without involvement of the speed and accuracy of the ocular adjustment mechanisms of accommodation and vergence. In studying visual information assimilation, the capacity of the visual system needs to be investigated both when there is an informational limitation and when there is not. Response limitations on the capacity of the visual system should not be present. Visual capacity needs to be investigated at various luminance levels, for various simple visual tasks in which the informational content can be clearly specified.

Laboratory studies have been conducted since 1950 to provide the requisite basic performance data. The target consisted of a luminous disc, presented against an extended background of otherwise uniform luminance. Both target and background were "white light" of about 2850K color temperature. The observers were required to detect only the presence or absence of the disc, and were not required to report on other attributes of the targets such as size, shape, or color. In different series of experiments, the duration of the target presentation was varied from $^1/_{1000}$ second to 1 second, and the angular diameter of the disc was varied from about 1 to 60 minutes of arc. In each series of experiments, the background luminance was varied from zero to several hundred footlamberts. In each experiment, the visibility of the target was varied and an accuracy curve obtained.

Selection of the disc target was based on a number of considerations. It can be argued that the simple brightness discrimination involved with this test object is the most basic discrimination, upon which other more complex discriminations are based. The information contained in the target can be confidently specified as a single item, since the only choice open to the observer is whether the target is present or absent. The target may readily be varied in difficulty over a range from easy to most difficult. Finally, previous experiments have shown that the accuracy data obtained with this target are easily handled by standard statistical methods.

The basic experiments were conducted between 1950 and 1952 and are reported fully elsewhere.[1] Series of experiments were conducted at exposure durations of 1, $^1/_3$, $^1/_{10}$, $^1/_{30}$, $^1/_{100}$, $^1/_{300}$, and $^1/_{1000}$ second. In each series, discs were studied with diameters of 0.802, 3.20, 12.8 and 51.2 minutes. Background luminance was varied from zero to 100 footlamberts in each series. Two well-trained observers made a total of 81,000 observations in experimental sessions lasting more than 12 months.

The basic task of the observers may be described briefly as follows:

The observers were seated before the open face of a lighted cube, as shown in Fig. 1. College students with entirely normal eyes were employed. They used normal binocular vision throughout the experiments. The cube was illuminated by frosted incandescent lamps arranged around the square aperture in the face of the cube at locations not visible to the observers. Direct illumination from these lamps fell upon the wall of the cube opposite from the observers, which served as the observation screen. This screen was approximately uniform in luminance for at least 30 degrees in all directions from the center, which was indicated by a diamond configuration of four orientation points clustered around it. Since the walls of the cube were coated with sphere paint, there was a considerable amount of diffuse illumination of the screen from the walls of the cube. The luminance of the screen was varied among experiments by varying the number and wattage of incandescent lamps. For very low luminances, special diffuse light-boxes were used with provision for the insertion of neutral absorbing filters to reduce the luminance of the sources without altering the geometry of illumination.

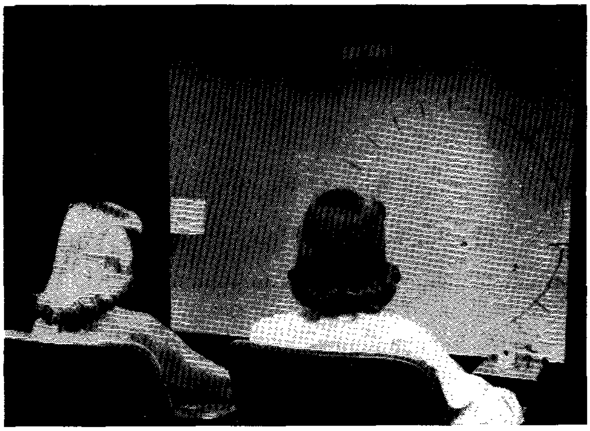

Figure 1. Observers seated in the basic laboratory testing room. The observation screen may be varied in luminance. The standard disc target is produced by transillumination of the screen from behind.

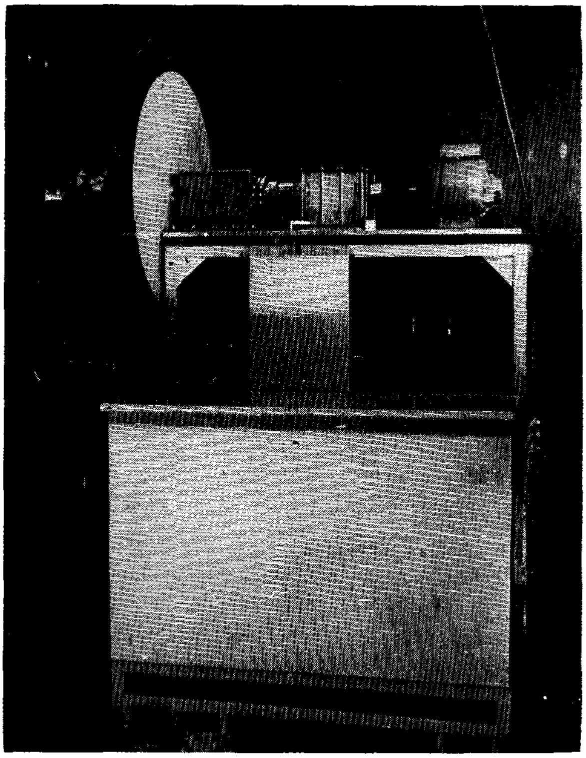

Figure 2. Projection apparatus and timer used to produce the standard disc targets.

The disc targets were produced by transillumination of the center of the observation screen, which consisted of a paper-thin translucent plastic coated with a very thin layer of sphere paint to reduce surface gloss. A special projector was used, as shown in Fig. 2, which consisted of an illumination system and a mechanical sector-wheel timer. The duration of the target pulse was determined by the size of an opening in the sector wheel. The size of the luminous disc was determined by the size of the aperture in a metal plate pressed against the rear of the screen. The luminance of the disc was adjusted by neutral absorbing filters mounted in the projection beam. Following the convention established by the author in 1946[5] contrast is defined by:

$$C = \frac{B_T - B}{B}$$

in which B_T = luminance of the target; and B = luminance of the background. In the present case in which the target is brighter than its background:

$$C = \frac{\Delta B}{B}$$

in which ΔB = the luminance increment produced by transillumination. The value of C varies between zero and infinity.

Observations were made by the temporal forced-choice psychophysical method.[8] With this method, the observers are required to indicate when they can detect the presence of a target by correctly identifying the temporal interval, of four possible intervals, in which it may have occurred. The observers are required always to select the most likely interval even when they are not confident of the correctness of their choice. In the present experiments, the temporal interval occupied by the target, and the precise luminance increment of the disc target were controlled by mechanical and electrical components of an automatic presentation equipment.[9] The scheduling of target presentations, and the recording of responses from the observers were accomplished by the timing equipment and relay racks shown in Fig. 3. Each experimental session consisted of 250 presentations of the target, 50 at each of the five values of target contrast.

The observers were given full knowledge of the size and duration of the target and of the moment during each temporal interval when the target would occur. Since the target was always presented in the precise center of the configuration of orientation points, the observers also had full knowledge of where the target would appear.

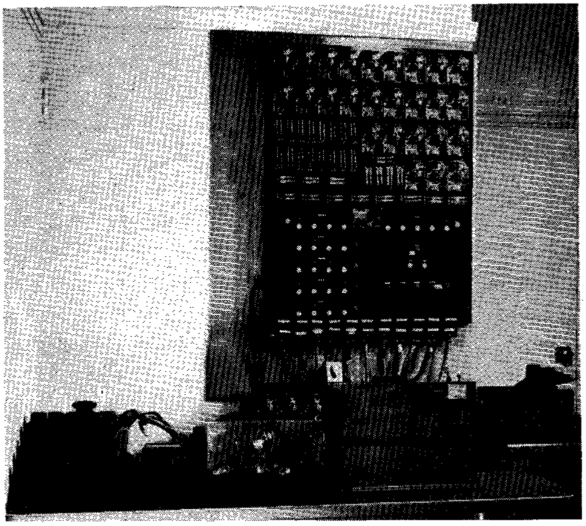

Figure 3. Automatic apparatus used to control the presentation of the standard disc targets and to record the responses made by the observers.

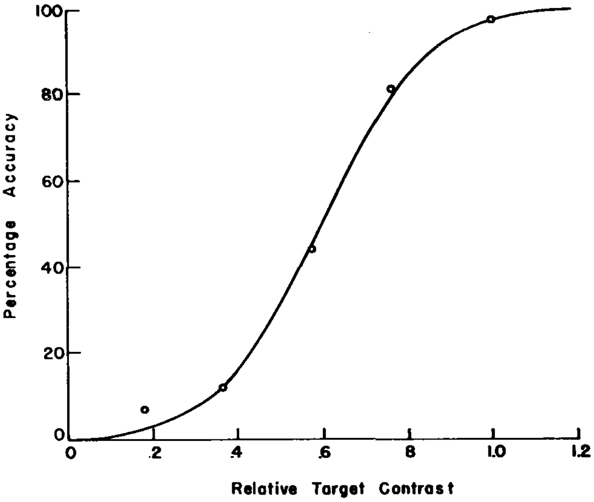

Figure 4. Sample accuracy curve: Response probability data fitted by a normal ogive.

It is to be emphasized that the observers became very proficient in using the forced-choice procedure through extensive practice, and were able to detect the presence of targets of exceedingly small contrast.

The basic data recorded were the number of times each observer correctly identified the interval occupied by the target for each of five values of target contrast for a given set of conditions of target size, exposure duration, and background luminance. These data were analyzed in terms of the probability of correct response, p. Then, correction was made for the presence of correct responses due to guessing by the relation

$$p' = \frac{p - 0.25}{0.75}$$

in which p' = corrected proportion; and p = raw proportion. The relation between p' and target contrast is described by a normal ogive under all conditions.[10] The appearance of a sample set of data is illustrated in Fig. 4, in which percentage accuracy refers to values of p'. The solid curve drawn through the data points is a suitable normal ogive. The range of values of target contrast which result in less than 100 per cent and more than 0 per cent accuracy is known as the threshold range.

The process of data analysis consisted of fitting a normal ogive to the set of experimental values of p' obtained by each observer in each single experimental session by the probit analysis.[11] This analysis of each set of data yields the following:

$\dot{C}$ = the contrast corresponding to $p' = 0.5$
σ = the standard deviation of the ogive
$VR = \sigma / \dot{C}$
$\sigma_{\dot{C}}$ = standard error of $\dot{C}$
σ_{σ} = standard error of σ
σ_{VR} = standard error of VR.

The value of $\dot{C}$ represents the threshold contrast, the index of discrimination normally reported in psychophysical studies of this sort. The value of VR represents the change in contrast required to represent different accuracy levels with respect to 50 per cent accuracy level represented by the threshold. We will have occasion to utilize an accuracy level of 99 per cent for specification of lighting levels to provide adequate visual performance, since no one is interested in an accuracy level of 50 per cent in everyday seeing. The method of converting data from an accuracy level of 50 per cent to a level of 99 per cent will be discussed subsequently. As reported in the 1952 paper,[1] the value of VR was found to vary significantly as a function of target duration. Thus, when we wish to express our data at different accuracy levels, this variation in VR must be taken into account.

The raw threshold data are reported fully in graphical form in Figs. 2-8 of the 1952 paper. There is a separate graph for each of the seven exposure durations. In each graph, there are four curves relating threshold contrast to background luminance, one for each of the four target sizes. The raw data are shown, and empirical curves fitted through the data for purposes of identifying the general form of the relations found among the experimental variables.

Examination of the data points presented in the 1952 paper reveals that, in spite of the substantial number of experimental observations, there is considerable latitude in the shape of the curves which may be fitted through the points. Accordingly, considerable effort was devoted to the development of smooth curves to represent the functional relations more adequately than do the raw data. Consideration was given to the possibility of using simple analytical functions to describe the relations between threshold contrast and background luminance, since these relationships are directly related to the lighting specification problem, a procedure utilized some years ago by Moon and Spencer.[12] This suggestion was finally rejected because there is good reason to believe that the relations between threshold contrast, $\dot{C}$, and background luminance, B, obtained under our experimental conditions cannot be described by simple analytical functions. It is to be remembered that our observers utilized normal viewing with natural pupils. Thus, as B was varied, the pupillary area varied due to the photo-pupillary response. Not only does pupillary area influence the illumination falling on the retina, affecting visual performance, but changes in pupillary area also influence the effectiveness of illumination due to the well-known Stiles-Crawford effect. It is entirely apparent that the effect of B upon $\dot{C}$ cannot be expected to be a simple analytical function under these conditions. It may also be argued that the effect of B upon $\dot{C}$ may not be described by a simple analytical function even when a fixed pupil is used. The value of B presumably influences the concentration of photosensitive pigment which in turn influences visual performance by altering the effectiveness of the pigment in converting incremental light quanta into incremental neural impulses. In addition, the value of B influences the steady state neural noise in terms of which the neural incremental signal produced by the incremental light quanta must be discriminated. There is no reason to expect these two processes to be describable by a simple analytical function. In fact, careful measurements by Bouman[13] with a fixed pupil reveal that $\dot{C}$ and B are not related by a simple analytical function at all, but are related by a complex function which is not at all smooth. Thus, there appears to be no possibility of fitting smooth curves of $\dot{C}$ versus B to the data, unless we are prepared to do marked violence to the data.

Fortunately, there is a functional relationship which can be shown to be described by a simple analytical function which provides a rational foundation for data smoothing. This is the relation between disc diameter, α, and $\dot{C}$, for given conditions of exposure duration and background luminance. As discussed in detail elsewhere,[14] $\dot{C}$ may be related to angular disc diameter, α, by an element contribution function. This function predicts the condition that $\alpha^2 \dot{C} = K$ for values of α small with respect to image blurring on the retina. At larger values of α, C decreases continuously with increases in α, but at a rate progressively less than the rate implied by the condition that $\alpha^2 \dot{C} = K$. The element contribution function is a reflection of known spatial summative mechanisms in the visual system.

The smoothing of the relations between $\dot{C}$ and α for each set of values of exposure duration and background luminance has been described in detail in the 1955 paper[2] and need not be repeated here. We need only remark that contribution functions were found which fitted each set of data adequately. Changes were needed in the parameter of the contribution function for different values of luminance and exposure duration. It was required,

TABLE I — Smoothed Values of Log Threshold Contrast: Original Experiments.

α (minutes)	Log B (fL) 2.00	1.00	.00	—1.00	—2.00	—3.00
			t = 1 second			
1	−.798	−.631	−.256	.376	1.276	2.276
2	−1.400	−1.233	−.858	−.226	.674	1.674
4	−1.892	−1.743	−1.400	−.777	.123	1.123
10	−2.064	−1.958	−1.746	−1.179	−.279	.721
60	−2.128	−2.057	−1.960	−1.506	−.606	.394
			t = 1/3 second			
1	−.639	−.502	−.139	.466	1.331	2.326
2	−1.241	−1.104	−.741	−.136	.729	1.724
4	−1.750	−1.613	−1.287	−.687	.178	1.173
10	−1.979	−1.85	−1.665	−1.111	−.246	.749
60	−2.127	−2.039	−1.952	−1.469	−.604	.391
			t = 1/10 second			
1	−.461	−.236	.140	.764	1.629	2.616
2	−1.063	−.838	−.462	.162	1.027	2.014
4	−1.581	−1.375	−1.010	−.401	.464	1.452
10	−1.835	−1.704	−1.420	−.889	−.024	.964
60	−2.028	−1.943	−1.786	−1.407	−.542	.446
			t = 1/30 second			
1	−.170	.097	.554	1.182	2.032	3.027
2	−.772	−.505	−.068	.580	1.430	2.405
4	−1.287	−1.051	−.622	.029	.879	1.854
10	−1.576	−1.428	−1.061	−.473	.377	1.352
60	−1.835	−1.773	−1.511	−.989	−.139	.836
			t = 1/100 second			
1	.282	.542	1.012	1.712	2.532	3.482
2	−.320	−.060	.410	1.110	1.930	2.880
4	−.835	−.604	−.145	.543	1.363	2.313
10	−1.117	−.988	−.594	.049	.869	1.819
60	−1.414	−1.357	−1.068	−.461	.359	1.309

however, that these parameter changes be regular with respect to both luminance and duration, a rather stringent requirement. It was further required that plots of $\dot{C}$ versus exposure duration be smooth for various values of *B*. Meeting all these requirements left very little latitude in the data smoothing process, and led to curves relating $\dot{C}$ to *B* which were smooth, although by no means simple analytical functions.

Data which resulted from the smoothing process are presented in Table I. Data for exposure durations of $^1/_{300}$ and $^1/_{1000}$ second are not included, since our analysis of visual capacity in Section I suggested an upper limit of less than 100 APS for normal use of the eyes. Also only data for the five target sizes are included. Data for a number of other values of target size are included in the tables presented in the more complete report of these experiments.[15] The data obtained in the smoothing process represent the most adequate form of the experimental data first reported in 1952. Whenever the present tabular data disagree with raw data points or the empirical curves presented in the 1952 paper, the present data should be utilized. Incidentally, the tabular values presented here for the first time were utilized in constructing the curves contained in the 1955 paper.

During 1956 and 1957, additional experiments were performed to verify the form of the relationships between $\dot{C}$ and *B*, in the crucial range above 0.1 footlambert luminance, and to extend the data to somewhat higher values of luminance than were originally studied. The apparatus and procedures utilized were identical with those used in the earlier experiments. The original observers were no longer available. Six new college student observers with normal eyes were utilized in various of the experiments, following a moderately extended training with the forced-choice procedure. These experiments were conducted by Stanley W. Smith of the Michigan staff, who also served as one of the observers.

Series of experiments were conducted at each of three exposure durations: 1, $^1/_{10}$, and $^1/_{100}$ second; these durations were considered to cover the entire range of interest in connection with the specification of interior lighting levels. At each duration, five disc diameters were studied, as follows: 1, 2, 4, 10 and 60 minutes of arc. These values of target diameter were selected to be the same as those for which smoothed data were presented in Table I. Background luminance was varied in each series from about 0.1 to 300 footlamberts. The same group of four observers was used in all the experiments in a given series, but it was necessary to use different groups of observers in different series.

The results of these experiments are presented in Figures 5, 6 and 7 for 1, $^1/_{10}$, and $^1/_{100}$ second exposure durations respectively. Although the data never extended to luminances greater than 350 footlamberts, smoothed empirical curves have been fitted to the data which extend up to 3160 footlamberts. While this may seem to be a considerable

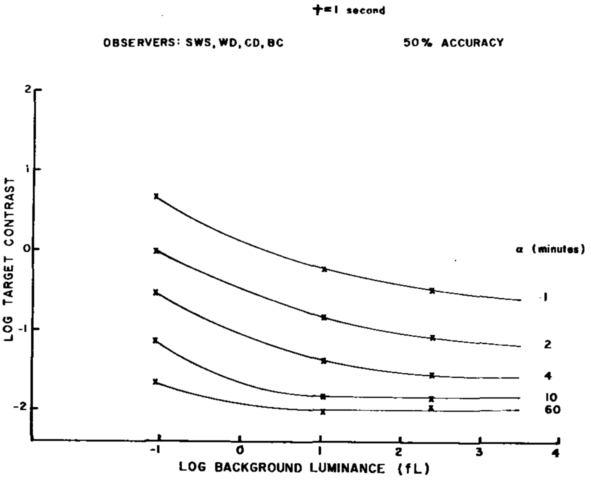

Figure 5. Threshold contrast data from the 1956-1957 experiments for a one-second duration. Each curve represents a standard disc target whose diameter is indicated in minutes of arc.

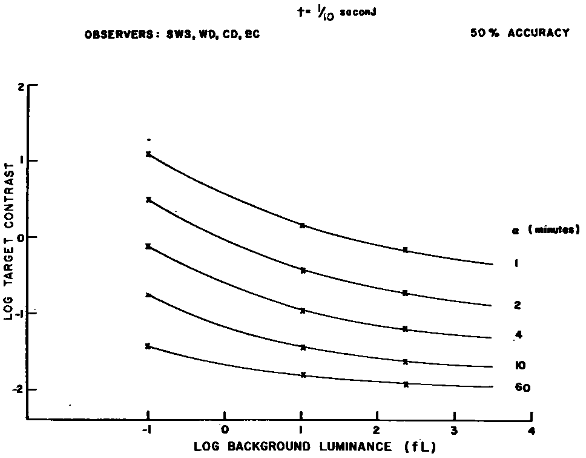

Figure 6. Threshold contrast data from the 1956-1957 experiments for a 1/10-second duration. Each curve represents a standard disc target whose diameter is indicated in minutes of arc.

extrapolation of the experimental data, it would appear from the figures that the extrapolations are not likely to be grossly inaccurate.

Comparison of these data with the data presented in the 1952 paper reveals that the functional relations between $\dot{C}$ and B are quite similar in the two series of experiments, as are the absolute values of $\dot{C}$ obtained at each value of B. (In making these comparisons, allowances must be made for the different values of α involved in the two studies.) The present data exhibit considerably less variability about the smooth curves fitted through them, as would be expected from the use of four rather than two observers.

The new data were used to extend the original data presented in Table I above, to background luminances up to 3160 footlamberts. The method involved determining the relative changes in $\dot{C}$ as a function of B beyond the 100-footlambert upper limit of the original data, and using these relative changes to extrapolate the data from the original study to higher luminances. Values of the log threshold contrast, relative to the value of $B = 100$ footlamberts, are presented in Table II for each of the five disc sizes, at each of the three exposure durations. When these values are added to the values of log threshold contrast presented in Table I, we have the extrapolated data for higher luminance level for the three exposure durations studied in the new experiments. It is possible, of course, to interpolate between the values presented in Table II, for intermediate values of exposure duration. Such interpolations were made for exposure durations of $^1/_3$ and $^1/_{30}$ second and are presented in Table III.

This procedure involves extrapolating the data on the original two observers to higher luminance levels, based upon the form but not the absolute values of the threshold data obtained with the six observers used in the more recent studies. This

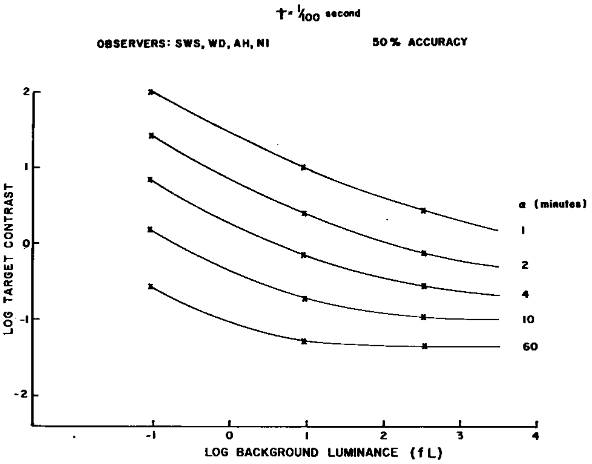

Figure 7. Threshold contrast data from the 1956-1957 experiments for a 1/100-second duration. Each curve represents a standard disc target whose diameter is indicated in minutes of arc.

TABLE II — Relative Log Threshold Contrast Values for High Background Luminance Levels.

Log B (fL)	α (minutes) 1	2	4	10	60
			$t = 1$ second		
2.00	.000	.000	.000	.000	.000
2.50	−.073	−.048	−.039	.000	.000
3.00	−.147	−.121	−.059	.000	.000
3.50	−.202	−.154	−.064	.000	.000
			$t = {}^1/_{10}$ second		
2.00	.000	.000	.000	.000	.000
2.50	−.102	−.095	−.070	−.052	−.030
3.00	−.194	−.177	−.126	−.094	−.040
3.50	−.272	−.247	−.163	−.122	−.050
			$t = {}^1/_{100}$ second		
2.00	.000	.000	.000	.000	.000
2.50	−.155	−.140	−.093	−.043	−.010
3.00	−.302	−.251	−.165	−.091	−.020
3.50	−.422	−.333	−.223	−.101	−.020

TABLE III — Relative Log Threshold Contrast Values for High Background Luminance Levels.

Log B (fL)	α (minutes) 1	2	4	10	60
			$t = {}^1/_3$ second		
2.00	.000	.000	.000	.000	.000
2.50	−.088	−.072	−.054	−.026	−.015
3.00	−.170	−.149	−.092	−.047	−.020
3.50	−.237	−.200	−.114	−.061	−.025
			$t = {}^1/_{30}$ second		
2.00	.000	.000	.000	.000	.000
2.50	−.128	−.118	−.082	−.048	−.020
3.00	−.249	−.214	−.146	−.092	−.030
3.50	−.347	−.290	−.193	−.112	−.035

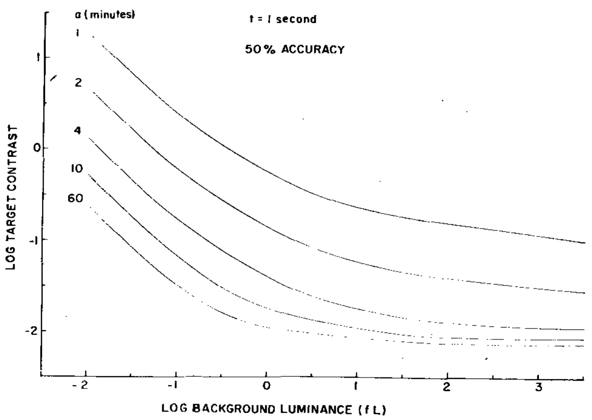

Figure 8. Smoothed threshold contrast curves for a one-second duration. Each curve represents a standard disc target whose diameter is indicated in minutes of arc.

procedure is necessitated by the fact that there are not sufficient data on any other observers under enough different experimental conditions to be useful. The fact that the data were not combined without regard to the specific observers involved in each set implies that the different observer groups gave data with somewhat different absolute values. The observers used in the 1956-57 study gave higher thresholds, a fact which is probably attributable to the fact that they had undergone considerably less training in the forced-choice procedure than had the two observers utilized in the original experiments.

The results of our manipulations of the data from the two studies consist of functional relations between $\dot{C}$ and B for the five exposure durations. These are shown graphically in Figs. 8-12. These

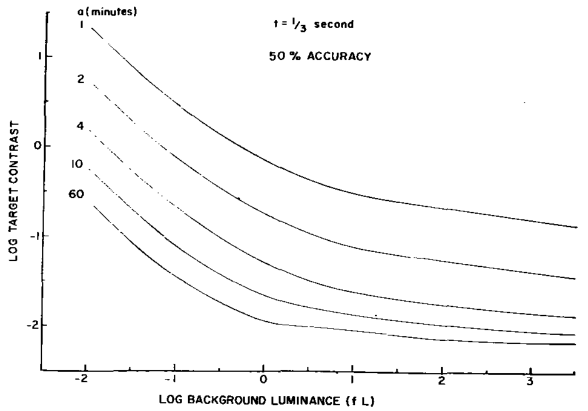

Figure 9. Smoothed threshold contrast curves for a 1/3-second duration. Each curve represents a standard disc target whose diameter is indicated in minutes of arc.

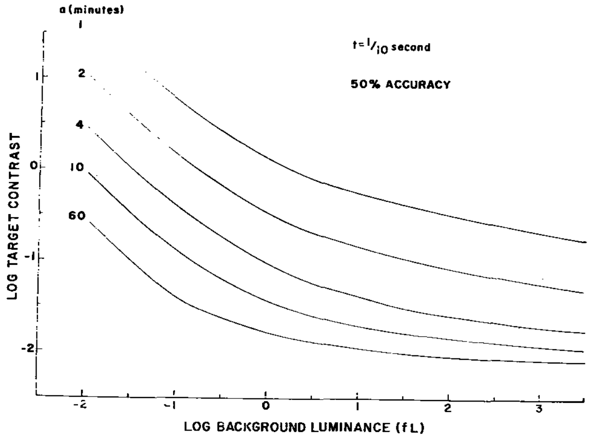

Figure 10. Smoothed threshold contrast curves for 1/10-second duration. Each curve represents a standard disc target whose diameter is indicated in minutes of arc.

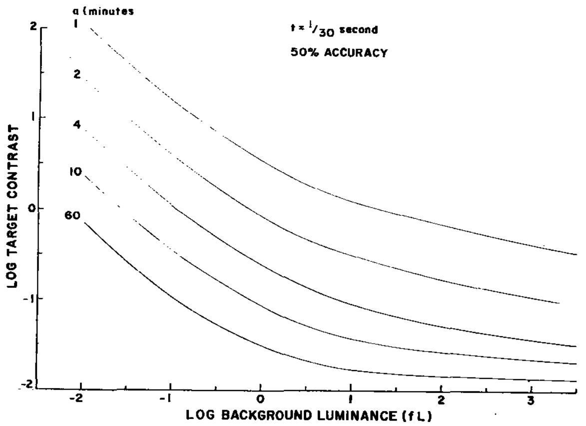

Figure 11. Smoothed threshold contrast curves for a 1/30-second duration. Each curve represents standard disc target whose diameter is indicated in minutes of arc.

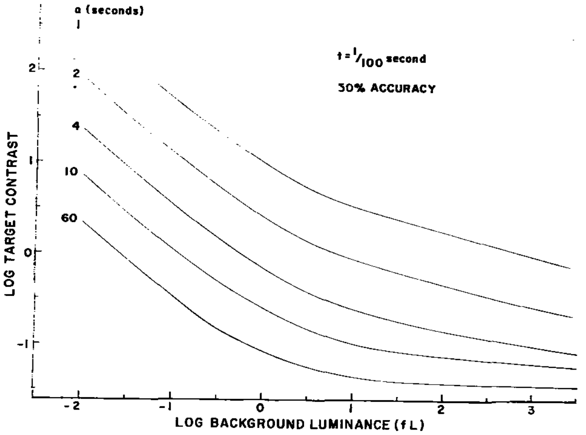

Figure 12. Smoothed threshold contrast curves for a 1/100-second duration. Each curve represents a standard disc target whose diameter is indicated in minutes of arc.

represent the final form of the laboratory visual performance data which will be used to provide the basis for the method of specification of lighting levels for various practical tasks.

III. FIELD FACTORS

It should be apparent from the description of the conditions under which the laboratory performance data were obtained that very favorable conditions were used for observing. The observers were highly skilled in using the forced-choice psychophysical technique, they had extraordinarily complete advance information about the target, and they had more than adequate time in which to align their lines of sight with the target and to adjust ocular accommodation and vergence. These conditions led to extraordinarily fine visual performance. For example, we may compute from Fig. 8 that the threshold contrast was 0.0073 for a 60-minute disc presented at high luminance for one second. Comparable data reported by the author in 1946 reveal that similar laboratory observing conditions give a threshold contrast value of 0.0028 for the 60-minute disc presented at high luminance for a period of from 8-10 seconds. These values are much smaller than values customarily assigned to the lower limit of threshold contrast, the value of 0.05 being a common value for example in the field of outdoor visibility. Clearly, it would be inappropriate to utilize these data directly as a basis for specifying lighting to provide adequate visual performance under the less ideal conditions of everyday seeing. The basic approach has involved studying the effects of the various differences between the conditions employed in the laboratory and those normally encountered in everyday use of the eyes, so that "field factors" can be developed to use in interpreting the laboratory data for practical problems.

A number of studies have been conducted since 1950 in which single variables differing between laboratory and everyday seeing have been studied. The results of these studies will be summarized to provide a basis for adopting reasonable values to use for field factors in applying the laboratory data reported in Section II to the problem of lighting specification.

Two separate experiments were concerned with what might be called the observing criterion. These experiments have been reported fully elsewhere[16] in another connection, so that a brief summary should suffice.

The first experiment involved comparing detection probabilities obtained with the forced-choice method with those obtained with the "yes-no" method, in which the observers indicated by "yes" or "no" whether or not they had detected the presence of the target. Data were obtained on four unusually experienced observers. These observers utilized the forced-choice and the "yes-no" procedures alternately from day to day in a series of daily experiments extending over more than 10 months. The target and background conditions were maintained constant during this period so that these observers had a staggeringly large amount of experience with this one detection situation. The general luminance was 4.71 footlamberts. The target subtended 18.5 minutes of arc, and was presented always seven degrees from the line-of-sight for about 0.072 second.

These observers had every opportunity to develop confidence in their forced-choice responses and to attach the verbal symbol "yes" to the experiences of dim and vague targets which led to correct forced-choice responses. Under these conditions, the difference between the probabilities of detection obtained with the forced-choice and the "yes-no" methods should be minimal. On the average the threshold contrast was 1.20 times as large with the "yes-no" method as with the forced-choice method.

The second experiment involved an evaluation of the extent to which the probabilities of detection with the "yes-no" procedure improve with practice. For this purpose, data were obtained under somewhat different experimental conditions on an entirely different group of observers. A group of 70 observers was used in several series of experiments in which different methods of training were evaluated. In all cases, a point source target was employed in known location on the line-of-sight. The exposure duration was 1.5 seconds. Background luminance varied in the different experiments from 17.9 to 18.7 footlamberts.

Each observer was introduced to the experimental situation with a set of instructions intended to elicit what might be called a "common sense criterion" of seeing. The observers were told: "We are going to turn on a light from time to time. If you see a light, say 'yes.' If you don't, say 'no'." (We did not inform the observers that we were presenting blank trials to evaluate their criteria.) If the observers asked, "How will I know?" we told them: "Oh, you'll know when you try it." These instructions were intended to keep the observers as naive as possible and to prevent them from developing a laboratory frame of reference.

Subsequently, these observers were divided into groups which were given different instructions and training. Some of these led the observers to improve their detection probabilities a great deal more than others. In order to assess the relation between the common sense criterion and the usual laboratory criterion, we have compared the results of all the observers in the initial experimental session with results from the observers who utilized the most effective regimes of instructions and training. Large enough groups of equivalent observers are involved so that this comparison is not seriously affected by sampling differences. It was found that, on the average, the initial "yes-no" threshold was 2.00 times as large as it was after practice.

We may safely assume that the four highly experienced observers who participated in the first experiment were at least as effective in using the "yes-no" method as were any of the groups used for the much shorter time periods of the second experiment. On this basis, we can assume that the contrast threshold for naive observing with the "yes-no" method is at least 2.40 times as large as the threshold obtained by skilled observers utilizing the forced-choice method.

Common sense seeing is still seemingly quite different from laboratory observing, even when the "yes-no" method is used without practice. Common sense seeing does not usually occur in the threshold range where targets are sometimes seen and sometimes not seen. Of course, we can make quantitative corrections for different levels of accuracy and as noted above, in practical use of performance data, an accuracy level of 99 per cent is to be used. We may wonder to what extent common sense seeing is equivalent to laboratory observing at an accuracy level of 99 per cent. It would seem reasonable to suppose that the contrast threshold for common sense seeing would be still higher than the laboratory threshold, even for 99 per cent accuracy. It is, therefore, undoubtedly conservative to utilize a contrast multiplier of 2.50 to take account of the criterion difference between common sense seeing and laboratory performance with the forced-choice method.

The necessity for developing a conversion factor to correct our data from the criterion represented by the forced-choice psychophysical method to that of common sense seeing might suggest the desirability of having conducted our performance studies with a common sense criterion in the first place. Evidence reported elsewhere[16] indicates that the forced-choice procedure is a very desirable one for use in systematic and prolonged experimental work because of its reliability and independence from the effects of irrelevant psychological variables. Use of a common sense criterion makes repeatable data very difficult to obtain, since the observers are unduly influenced by their own opinions and by suggestions others make to them during the experiments.

A second important aspect of the difference between laboratory observing and commonplace seeing concerns the fact that the laboratory observers were able to direct their line-of-sight at precisely the location to be occupied by the target, and were able to adjust their ocular accommodation and vergence for optimal seeing. In a real sense, the visual field utilized effectively by the laboratory observers was reduced almost to a single point in space. In normal use of the eyes, there must be a considerable "receptive field" within which objects are visible, both because an observer cannot align his eyes exactly with an object of interest, and because a fairly sizable receptive field is necessary for sensory guidance of ocular accommodation and vergence. Even when an observer knows precisely where to look for an object, he normally has to move his eyes from point to point in visual space. The necessity for eye movements implies that objects must be visible off the line-of-sight, as well as on the center of fixation. It is not possible to evaluate precisely how large a receptive field is needed to promote sensory guidance for ocular accommodation and vergence, nor is it possible to specify how precisely an observer will normally be able to direct his line of sight. However, it would not seem unreasonable to require that the receptive field should normally extend two degrees in every direction from the fixation center.

In this connection, information is needed to determine how much greater the threshold contrast must be for an object to be visible two degrees from the fixation center, as well as at the fixational center.

Moldauer and the author[17] have recently reported a series of studies of the threshold contrast for targets presented in various locations with respect to the fixational center. The apparatus and procedures described in conjunction with the basic studies of visual performance in Section II were used with a few minor modifications. Provision was made that the orientation points could be moved with respect to the location of the target at the center of the observation screen. Thus, visual performance could be studied when the target was presented various distances away from the line of sight. A luminous disc target with a diameter of one minute was used throughout, and the exposure duration was $^1/_{100}$ second. At each of nine background luminance levels, studies were made of the threshold contrast both at the center of fixation, and at distances away from the fixational center measuring up to 12 degrees, along various meridians of the visual field. The luminances studied were 75 footlamberts, 1 footlambert, and seven values below .1 footlambert.

The relation between threshold contrast and dis-

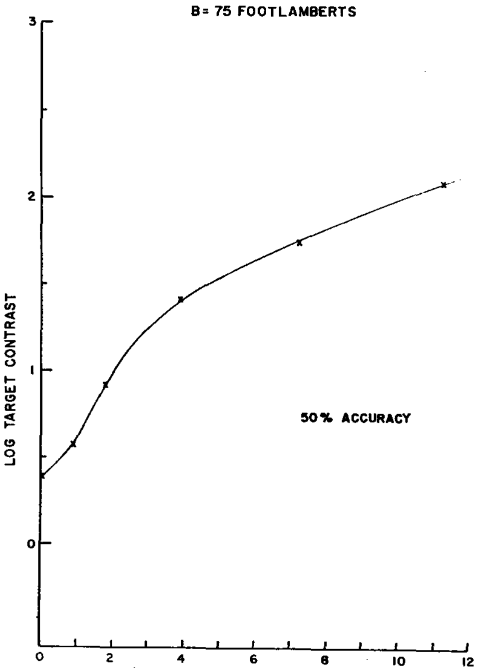

Figure 13. Threshold contrast data for a one-minute diameter disc target viewed at various distances from the fixational center.

tance from the fixational center, obtained at a 75-footlambert background luminance, is shown in Fig. 13, since this luminance level is most appropriate for our consideration here. It is apparent that the contrast threshold increases rapidly as the object to be seen is separated from the line-of-sight. In order to increase the receptive field over which an object may be seen, we must increase the contrast by a factor which represents the ratio of the threshold contrast for objects viewed at the edge of the desired receptive field to the threshold contrast for objects viewed on the light of sight. Sample values of this factor read from the curve in Fig. 13 are presented in Table IV. It is apparent that providing a reasonable receptive field requires a considerable increase in task contrast over the value which suffices when the object of interest need only be seen at a single point in the visual field. On the basis of the assumption made earlier that a receptive field of two degrees radius should be provided, we would need to use a contrast multiplier of 4.00 to accomplish this enlargement of the receptive field.

TABLE IV — Factors for Enlargement of the Receptive Field.

Radius of Receptive Field (Degrees)	Factor
1	1.66
1.5	2.57
2	4.00
3	7.41
4	11.0

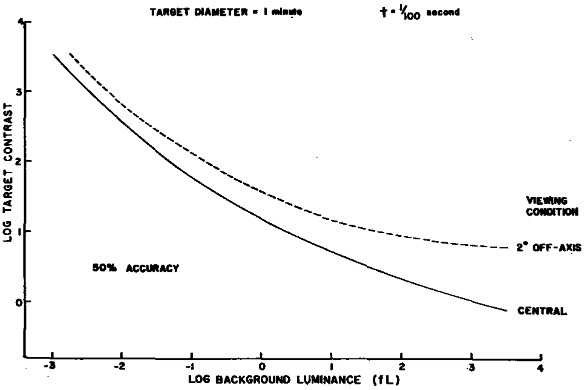

Figure 14. Threshold contrast curves for a one-minute diameter disc target for central viewing and for viewing two degrees off-axis.

The factor required to produce a given receptive field is not the same at all values of background luminance. To illustrate this point, data are presented in Fig. 14 for central viewing and for viewing off-axis by a fixed amount of two degrees. The experimental data do not extend beyond 100 footlamberts; accordingly, the curve for central viewing has been extended by means of the values presented in Table II. The curve for two-degree off-axis viewing has been extended by visual extrapolation. Fig. 15 contains values of the log factor representing the difference between the two curves in Fig. 14, at various values of background luminance. The factor varies sharply with luminance, having a value of four for a luminance level of 75 footlamberts.

Although this analysis suggests that the factor required to provide an adequate receptive field varies with the value of *B*, we shall have to ignore this complication in order to provide a workable system of field factors.

A series of studies has also been conducted to evaluate the influence of various psychological factors which differ between the conditions of the

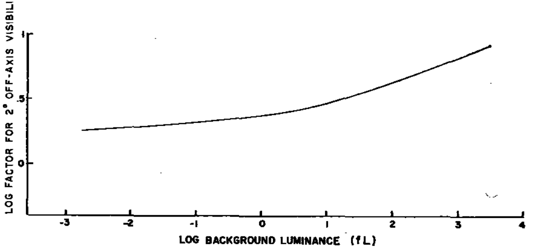

Figure 15. Values of the contrast factor relating thresholds for central viewing and thresholds for viewing two degrees off-axis.

laboratory and everyday use of the eyes. These studies have recently been reported elsewhere,[18] so that a brief summary should suffice. In one group of experiments, the effect of providing the observer with advance information as to the moment of occurrence of the target was assessed. Threshold measurements were made both with and without advance warning as to the moment of presentation of the target. It was found that the threshold contrast was 1.40 times higher when the observers were not given advance warning that a target was to be presented.

In a second group of experiments, the influence of the knowledge the observer possessed concerning the precise location to be occupied by the target was assessed. There were only two possible locations in which the target could occur. These positions were located equidistant from the center of fixation on either side. Different separations between the two possible locations in which the target might appear were investigated, varying from 0.25 degree to 8 degrees. The experiment compared the threshold contrast when the observers were not informed of which location the target would occupy, with the threshold contrast when they were informed of the eccentric target location in advance. The threshold contrast was always greater when the observer was not informed in advance of the location to be occupied by the target, the effect being greater the greater the separation between two possible locations. With the two locations each separated from the line-of-sight by three degrees or more, the threshold contrast was 1.31 times higher when the observer was not given advance knowledge of the target location.

Finally, a group of experiments was conducted to evaluate the effect of the frequency with which target objects occur. In the usual laboratory procedure, a target object is presented regularly each 10-30 seconds. In some inspection jobs, "targets" may occur with considerably less frequency than this. Studies were made in which the frequency of targets was reduced from one every 30 seconds to one on the average of every 15 minutes. (In neither case were the observers warned in advance when the targets were to be presented.) The threshold contrast was 1.19 times higher when the frequency was reduced. Of course, the existence of only one target object every 15 minutes may be considered rather extreme, so perhaps a factor of 1.10 would be more representative of the conditions to be expected in actual everyday use of the eyes.

There is no really satisfactory basis upon which the joint effect of various of these factors related to the psychological conditions of observing can be assessed. Perhaps all we can do is to estimate that the existence of some of these differences will produce an increase in contrast threshold of at least 1.50, and that the existence of them all may be expected to increase threshold contrast by at least 2.00.

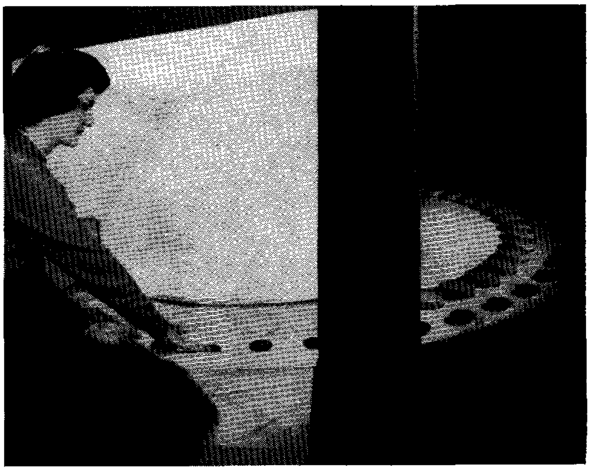

Figure 16. Observer seated in the observation booth of the Field Task Simulator. The wooden platform is shown with the circular plaques and the adjacent indicator buttons.

These studies of the effects of various differences between laboratory observing and everyday seeing are not entirely definitive, but they do assist us in identifying the variables differing between laboratory and everyday use of the eyes, and they provide estimates of the numerical effects which these variables produce. Before attempting to develop field factors for use in specifying lighting for various tasks, we decided to attempt to evaluate the field factor as a whole for some task representing realistic use of the eyes. For this purpose, we developed a "Field Task Simulator," and studied a visual task which could be directly compared with the laboratory task which had been previously subjected to extensive study.

The Field Task Simulator is shown in Fig. 16. The observer is seated in a small light booth, illuminated from overhead through a translucent ceiling. She looks downward at a series of circular plaques, each four inches across. There are 50 of these plaques, mounted around the circumference of a seven-foot wooden platform. The platform extends under the observation booth and considerably behind it, as shown in Fig. 17. The platform may be set into motion, revolving about the shaft shown behind the observation booth in Fig. 17. As the platform revolves, the plaques are moved across the observation booth beneath the eyes of the observer. The walls of the observation booth, the surface of the wooden platform, and the top surfaces of the plaques were painted with sphere

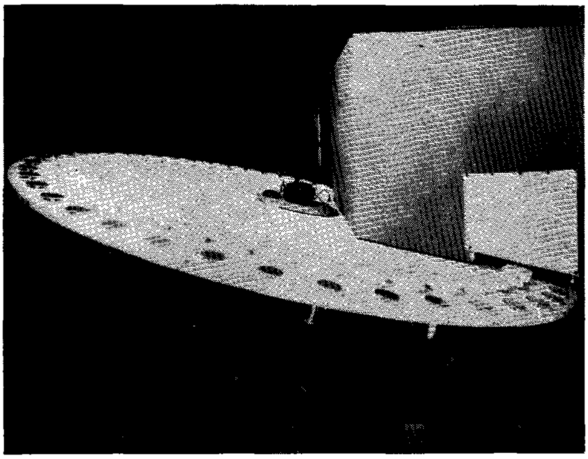

Figure 17. Over-all view of the Field Task Simulator. Wooden platform is made to rotate about the centrally located shaft, thus moving the plaques through the observation booth.

paint. The plaques actually were composed of paper-thin translucent plastic, which could be transilluminated to produce luminous disc targets such as were used in the original laboratory experiments. Metal apertures behind the plastic determined the size of the circular luminous disc targets. Illumination of the target discs was provided by lamps mounted in metal receptacles beneath the plaques. In the absence of transillumination, the plaques appeared to be uniformly bright and were regarded as "perfect." When the lamp below a given disc was turned on, the small spot of light produced in the center of the face of the plaque was considered to be an imperfection in the plaque. The experimenter could vary the size of a luminous disc target by changing the metal aperture placed beneath the plastic. The luminance increment, and hence the target contrast, could be varied by moving the lamp closer or farther from the metal aperture, and by the use of gelatin and glass neutral absorbing filters.

The task of the observer was to inspect all 50 of the plaques for the presence of "imperfections." In a given series, the entire 50 plaques were made to pass beneath the observer's eyes. Discrimination of the presence of a bright spot on the face of a plaque was indicated by the observer depressing the gray button located adjacent to the plaque possessing the imperfection. The experimenter could turn on the lamp beneath any of the plaques. There were usually two or three of the luminous discs turned on at any one time. On occasion, the number was as small as one or as large as six. Since the discs were set for the threshold range, the observer almost never detected the presence of more than two or three discs.

It is important to emphasize that the observer did not have to respond to an imperfect plaque before she could begin to examine the next plaque. She could easily depress the indicator button with the visual guidance provided by peripheral vision. Thus, the observer tended to begin to examine a plaque as soon as it entered the observation booth from the left-hand margin. Because of the larger angular movement of each plaque, the observer had to track the plaque while examining it. The observer had to perform her examination of each plaque quite rapidly in order not to miss some of the plaques. At the same time, she had to successfully depress the button adjacent to any imperfect plaques before the plaque disappeared from the observation booth on the right-hand margin. Six plaques were visible to the observer within the observation booth at one time.

Measurements were made with two speeds of revolution of the wooden platform. In the slower speed, the platform completed a full rotation in 50 seconds. In the faster speed a full rotation was accomplished in only 20 seconds. The observers were able to learn to operate the Simulator at both speeds without response limitation of their visual performance.

Measurements were made at each of a number of levels of luminance of the wooden platform as viewed from within the observation booth. At each luminance level, the contrast of the luminous discs was varied to provide variable accuracies within the threshold range. The actual luminance increment of each disc target was measured with a photoelectric photometer which was calibrated in terms of a visual photometer used to measure the intensity of small sources by measuring the illumination produced by the source on a standard test plate. The luminance increment produced by each disc was computed from the intensity and the measured size of the disc.

The observers made so few errors by depressing buttons corresponding to perfect plaques that the probabilities of correct response can be analyzed without concern for corrections for successes due to "chance." The response data were analyzed by fitting normal ogives to the values of accuracy probability, expressed in terms of a scale of disc contrast. Because of the relative paucity of experimental data, the ogives were fitted by eye and only values of the threshold contrast were obtained, corresponding to an accuracy level of 50 per cent. Three well-trained observers were used in all.

The results obtained with the slower rate of rotation of the wheel are presented as the data points in Fig. 18. Since there were 50 plaques to be examined in 50 seconds, these data are considered to

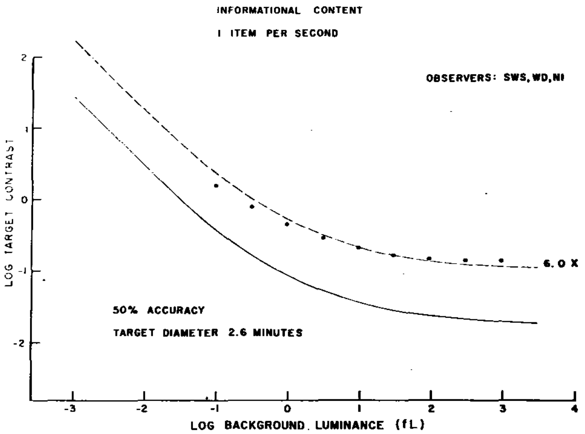

Figure 18. Threshold contrast data from the Field Task Simulator, for a rotational speed yielding plaques at the rate of one per second. The solid curve represents a threshold curve interpolated from the basic laboratory data. The dashed curve represents the laboratory contrast values multiplied by a factor of 6.0

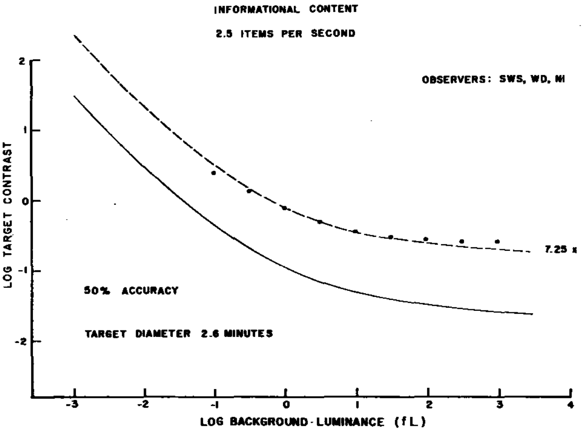

Figure 19. Threshold contrast data from the Field Task Simulator for a rotational speed yielding plaques at the rate of 2.5 per second. The solid curve represents a threshold curve interpolated from the basic laboratory data. The dashed curve represents the laboratory contrast values multiplied by a factor of 7.25.

represent an informational content of one item per second. The angular size of the discs used in this experiment was 2.6 minutes. Note that the values of threshold contrast vary with background luminance in the approximate manner to be expected from our earlier performance data. In fact, the solid curve represents results from the original laboratory studies reported in Section II, in which $\alpha = 2.6$ minutes and in which the exposure duration of the single flashes was one second. Comparison between the simulator data and these particular laboratory data should reveal the over-all effect of the many differences between the laboratory and the simulator, when the informational content was the same. As expected, the simulator data occur at higher values of target contrast, representing the fact that visual performance is inferior in the simulator.

The dashed curve fitted through the data points was constructed by multiplying each value on the solid curve by a constant equal to 6.0. (Since the scale of contrast in the figure is logarithmic, this is accomplished simply by moving the solid curve vertically by an amount equal to the logarithm of 6.0.) The dashed curve provides a fairly reasonable fit to the data, revealing that on the average 6.0 times as much contrast was needed in the simulator as in the laboratory experiment.

The data obtained in the study with the more rapid rotation of the platform are presented in Fig. 19. In this case, the informational content is considered to be 2.5 items per second. The solid curve in this case represents data from the original laboratory study, corresponding to an exposure duration of single target flashes equal to 0.4 second. These data were interpolated from the families of smooth curves produced by the data-smoothing process described in Section II. The dashed curve fitted through the simulator data in this case was constructed by multiplying each value on the solid curve by a constant equal to 7.25. As before, the dashed curve provides a reasonably adequate fit to the data points.

These data suggest that the over-all field factor required to compensate for all the many differences existing between the laboratory conditions and those of the simulator varies between 6.0 and 7.25. It is interesting to relate this to the values suggested by the series of studies of the variables which might be expected to contribute to a field factor. It is to be emphasized at once that the criterion factor is not involved since in both the simulator and the laboratory study trained observers utilized what amounted to a forced-choice procedure. The factor of from 6.0 to 7.25 can be understood as due to a factor of perhaps 4.0 to provide a receptive field of suitable size, and a factor of from 1.5 to 1.8 for psychological factors such as lack of knowledge when and where the target objects would appear. It is interesting to note that factors for lack of knowledge as to when and where the target would appear would equal 1.83 if multiplied together, a value which agrees remarkably well with the values actually obtained. Of course, this agreement could be easily lost had we selected a different value for the factor used to enlarge the receptive field. Still, this comparison provides some understanding of what might go to make up field factors required under actual field conditions.

IV. The Visual Task Evaluator

The basic philosophy of the method for specifying lighting levels on the basis of the visual performance data summarized in Section II involves determining the standard disc target which is equivalent in visual difficulty to each practical task of interest. Once this equivalence has been established, the performance data for standard discs may be used to determine the lighting required to provide a desired criterion level of visual performance. The Visual Task Evaluator is an optical device designed for establishing the equivalence of practical tasks and standard disc targets.

The original Visual Task Evaluator (VTE) was designed to permit several different modes of operation, for evaluating their relative merits. The design of this device is to be credited primarily to my associate, Benjamin S. Pritchard. Design considerations of instruments of this sort will be discussed in a forthcoming paper, so that a brief description of the operating procedure will suffice here. The present model is clearly a research model, and is in no sense supposed to be a practical device for production and widespread usage. The optical diagram is presented in Fig. 20. A photograph of the device is presented in Fig. 21. The optical components are mounted on a rigid aluminum table in individual mounting units which made it a comparatively simple matter for modifications to be made in the optical design.

The operator of the VTE first views the practical visual task through one optical system and adjusts it until it is barely visible. He then views a standard disc target through another optical system and adjusts it until it is barely visible. Equivalence of the two tasks is established by the fact that both are set for threshold visibility. The method by which this operation is accomplished will be described in some detail.

With reference to Fig. 20, when the practical visual task, *P*, is viewed, the removable mirror is removed and the operator views the task through one of two possible objective lenses. The task is seen within the inner field of a photometric comparator cube consisting of inner disc and outer annulus fields. The task is reduced to threshold visibility by means of a partially silvered circular mirror of variable optical properties, kindly provided for our use by Professor D. M. Finch of the University of California. The transmittance of the mirror varies continuously "around the clock." The reflectance varies "around the clock" in the opposite direction. This variable "wedge" is so designed that the sum of its transmittance and reflectance are approximately equal at all points. The wedge is used to reflect a uniform light veil over the practical task. Thus, as the wedge is turned, the contrast of the task is varied continuously while the luminance remains constant. Finch has reported on the detailed characteristics of these wedges elsewhere,[19] so that a detailed description of the wedge is not required.

The design of the VTE employs a single internal lamp for a variety of related purposes. As shown in Fig. 20, the lamp provides the light veil, *V*, for

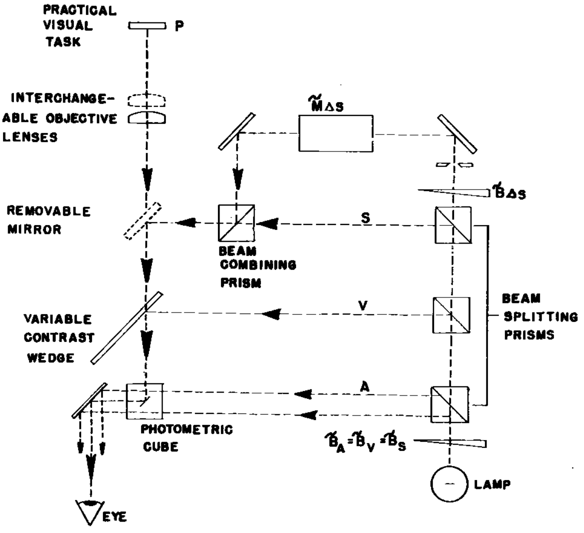

Figure 20. Optical schematic diagram of the Visual Task Evaluator (VTE). See text for explanation.

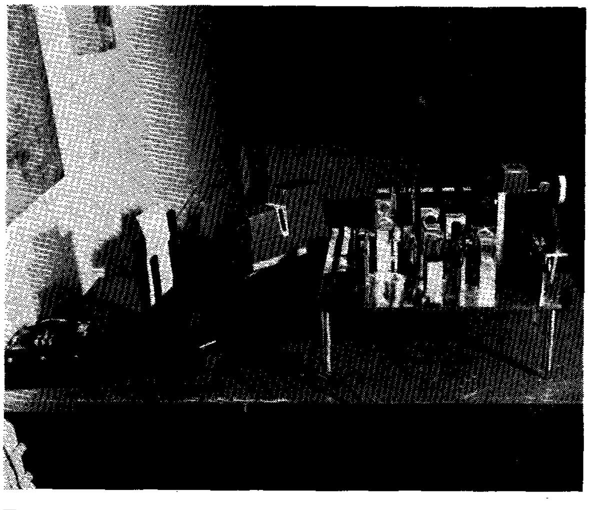

Figure 21. Photograph of the Visual Task Evaluator (VTE). A sample reading task is mounted before the device, lighted by a 35 mm slide projector. The Macbeth Illuminometer is used to measure the average task luminance.

reducing the contrast of the practical visual task. It also provides light for illuminating the annulus, which appears around the inner photometric field occupied by the practical task. The value of V was set equal to A with the wedge turned to 100 per cent reflection when the VTE was originally calibrated and this equivalence is not disturbed in any way by the use of the device.

The actual operating procedure has a further complication. As we shall see, it is necessary for the value of V to be set equal to the average luminance of the visual task. This was originally accomplished by having the operator set the luminance of the annulus, A, equal to the luminance of the inner field containing, as it did, a complex object and its background of non-uniform luminance. The precision of these settings was unsatisfactory. Accordingly, it was decided that the inner field should be defocused to facilitate the photometric match. A second objective lens was obtained which focused the visual task in the plane of the pupil of the operator's eye. Such a Maxwellian-view system provides a perfectly uniform inner field so long as the eye is centered with respect to the optical system. Under these circumstances, it was possible to match A to the inner field with satisfactory precision. Thus, the procedure involved: (a) inserting the blurring lens and setting A to match the inner field; (b) inserting the imaging lens and adjusting the contrast wedge until the task was barely visible.

The next step in the procedure involved leaving the contrast wedge in the position at which it was set to bring the practical task to threshold visibility, and interposing the removable mirror. This mirror is used to replace the view of the practical task in the inner field of the photometric comparator with a view of a standard disc target. The background for the standard target, S, is uniform in luminance and is produced by the lamp used to produce V and A. The luminance increment representing the standard target, ΔS, is also produced by the same lamp but there is an independent control over the luminance of the increment by a neutral density wedge, ground to varying thickness from a piece of Chance neutral glass. Adjustment of the luminance increment, ΔS, varies the initial contrast of the standard disc target. When the standard target is viewed through the variable contrast wedge, the initial contrast of the disc is reduced by the wedge to an extent dependent upon the position of the wedge.

One method of operation of this stage of the VTE involved fixing the size of the standard disc and adjusting the value of ΔS to threshold visibility, with the contrast wedge set for the value previously used to reduce the practical task to threshold visibility. The initial contrast of the standard disc represents the equivalence value desired from the VTE procedure. That is, the initial contrast of the standard disc together with the angular size of the disc, define the standard disc of visibility equivalent to the practical task.

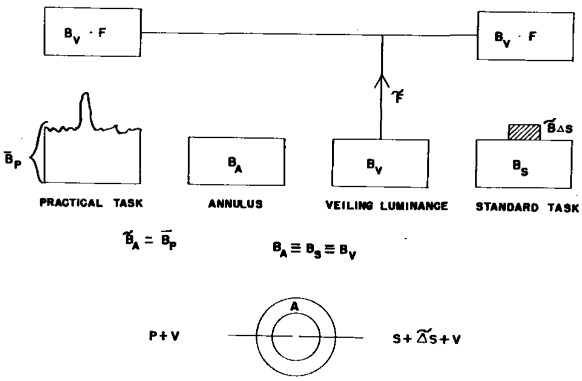

Figure 22. Conceptualization of the operating principles of the Visual Task Evaluator. See text.

The basic operations implied by this procedure for using the VTE are represented schematically in Fig. 22. The practical task, P, has an average luminance, $\overline{B}_p$, which represents an average of the non-uniform luminance of the critical detail and immediate surround of the task. The luminance of the annulus, B_A, is set equal to this average luminance in the first step in the procedure. Then $\widetilde{B}_A = \overline{B}_p$, where ~ implies that the quantity may be adjusted to any desired value. The adjustment of B_A to equal $\overline{B}_p$ implies that $B_V = B_S = \overline{B}_p$ since $B_A \equiv B_S \equiv B_V$. The setting of the contrast reduction factor, F, of the wedge varies the amount of veiling luminance interposed over $\overline{B}_P$ and also over B_S and $B_{\Delta S}$, the luminance increment of the standard disc. Then, the luminance, $B_{\Delta S}$, is varied until the standard task is at threshold luminance when viewed through the amount of veiling luminance required to reduce the practical task, P, to threshold. It is assumed that the practical and standard task which are equally visible at threshold are also equally visible in the absence of the veiling luminance. Standard and practical tasks, set equivalent with the veiling luminance, have been examined in the absence of the light veil. It is difficult to evaluate the degree of equivalence of tasks both of which are well above threshold but, to the extent that such judgments can be made, there does not appear to be any violation of this assumption.

(Incidentally, the diagram in the lower section of Fig. 22 illustrates the appearance of the photometric comparator. It shows that only the annulus A occupies the outer portion of the photometric field. First $P+V$, the practical task and the veiling luminance, and then $S+\widetilde{\Delta}S+V$, the standard background, the standard target and the veiling luminance occupy the central portion of the photometric field.)

At the outset, it was not apparent to what extent it would be preferable to adjust the contrast or the size of the standard disc target to reach the visibility threshold. Accordingly, provisions were made for both means of adjustment. The size of the standard disc target was varied by a telescopic zoomar system, based upon two lenses whose position with respect to an aperture, and whose positions with respect to each other, could be varied mechanically so as to provide continuous variation in magnification without loss of focus. The telescopic zoomar system performed satisfactorily.

An evaluation was made of the relative precision of determining equivalent standard discs by varying size or contrast. Seven observers were used, each of whom made 10 settings with each system. The percentage errors were slightly smaller when contrast, rather than size, was varied. Of course, the variable contrast device is considerably simpler and requires less care in use. For these and other reasons, it was decided to adopt a procedure of varying contrast rather than size. It was arbitrarily decided to adopt a four-minute luminous disc as the target of standard size, and to vary the contrast of this disc to establish equivalence with various practical tasks.

Once an equivalence has been established between a given practical visual task and a standard luminous disc target with the VTE, it is possible to establish the lighting required to provide a criterion amount of visual performance, utilizing a standard curve representing the desired level of visual performance of the four-minute luminous disc target. The next section will describe the development of a standard visual performance curve for this purpose.

V. Standard Visual Performance Curve

As is indicated in Section IV, we require a standard visual performance curve representing a level of visual performance to be provided for various visual tasks by the use of suitable lighting levels. It is to be emphasized that the standard performance curve to be developed is recommended for current use, based upon our current knowledge of visual performance. Subsequent information may lead in time to other standard performance curves, as is suggested in Section VIII. It should be remembered that the method being described in this report is considerably more general than any specific standard performance curve recommended at a particular time.

In developing a standard performance curve, we must first decide upon the units in which performance should be described. It was decided on the basis of experiments described in Section IV that the contrast of the standard target would be varied in the process of determining equivalence between various practical tasks and the standard luminous disc target. Accordingly, the standard performance curve should represent the functional relation between target contrast and background luminance. Thus, the standard performance curve will be analogous to the performance curves presented in Figs. 8-12, in which each curve represents a fixed level of visibility, specified by an accuracy level of 50 per cent at threshold, and by a level of visual capacity implied by the exposure duration of the target. We need to select a suitable level of visual capacity, a suitable level of accuracy, and a suitable field factor. The general discussion of the previous sections provides the basis for the selection of these constants.

The analysis of the basic characteristics of visual information assimilation presented in Section I has suggested the desirability of insuring that information assimilation can occur within a single fixational pause. To insure this level of performance we must provide a level of visual capacity sufficient to permit assimilation of at least five items of information per second. A level of five assimilations per second (5 APS) does not appear to be nearly the upper limit of visual capacity. As indicated in Section I, studies of visual performance for multiple items presented successively at one point in the visual field, and of multiple items presented simultaneously at different points in the visual field, suggest that a visual capacity of at least 30 APS is possible. Nonetheless, it was decided that the standard performance curve to be used at the present time should be based upon only a 5 APS level of visual capacity. Selection of this level is surely conservative, since it provides the capacity to assimilate only a single item of information per fixational pause. It is perhaps wise to be conservative at this time since the proposed method is new and we have had no experience with its use. Furthermore, we cannot claim that we fully understand, at present, the visual capacity to assimilate multiple items of information in a fixational pause. The experiments we have conducted are limited to instances in which the multiple items either reinforced each other (the Clark experiment) or at least did not contradict one another (the Harcum experiment). There will surely be instances in which multiple items of information which should be assimilated within a fixational pause will interfere with each other. We require considerable further study of the assimilation of multiple items of information within a fixational pause before we can begin to utilize standard performance curves based upon visual capacity levels in the range from 5-30 APS.

It is probable that ultimately we will have to recognize that different levels of visual capacity should be provided for different visual tasks. This concept is considered in some detail in Section VIII, and the basic groundwork is established for development of the lighting specification method in this direction once we have a solid factual basis upon which to proceed. For the present, it seems wise to base our standard performance curve upon a level of visual capacity which is surely the minimum required for all visual tasks.

As we noted in Sections II and III, it would scarcely be suitable to establish a 50 per cent accuracy level under conditions of laboratory seeing as the standard level of visual performance. Instead, we wish to use an accuracy level of 99 per cent, and a field factor to represent the conditions of everyday seeing.

In both the 1952[1] and the 1955[2] papers, the method of converting the performance data from one level of accuracy to another was described. We can allow for a change, for example, from 50 per cent to 99 per cent accuracy by multiplying the values of threshold contrast on a particular graph by a constant multiplier. The multiplier varies with exposure duration. For $^1/_3$-second exposures the multiplier is 2.05, whereas for $^1/_{10}$-second exposures the multiplier is 1.87. A multiplier for use with the $^1/_5$-second data, which represent the 5 APS level of visual capacity, was determined by linear interpolation on a logarithmic scale of exposure duration. A value of 1.98 was obtained for the multiplier.

The discussion of field factors presented in Section III above suggests that different visual tasks may well require different field factors, due to differences in the amount of sensory guidance required by the oculomotor adjustment functions and differences in the amount of knowledge the observer will have concerning the nature of the visual task. This concept is considered at some length in Section VIII. Of course, we have no factual basis at the present time for assigning different field factors to various tasks. It seems proper, therefore, to use a single field factor for all tasks until we have a defensible procedure to use in assigning field factors to different tasks.

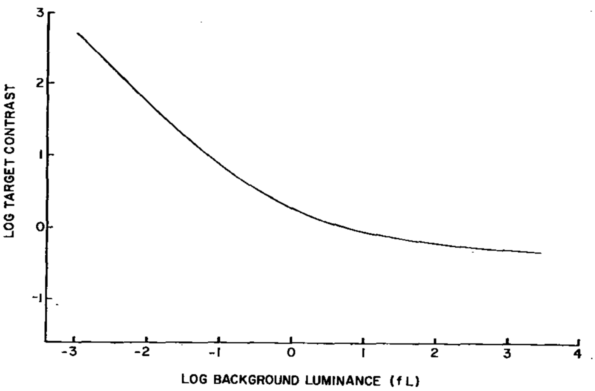

Figure 23. Standard visual performance curve based upon a four-minute standard disc target for a visual capacity level of five assimilations per second (APS). The field factor is 15; accuracy is 99 per cent.

It was decided that a field factor of 15 would be recommended for use at the present time. In selecting FF 15 as the one value for use with all tasks, heavy reliance was placed upon the fact that the assessment of the field factor in the Field Task Simulator resulted in values of FF between 15 and 18.1. Thus, selection of FF 15 was considered conservative on the basis of the only actual field determination of a field factor we had. In terms of the analysis presented in Section III, selection of FF 15 means that we are providing for a four-degree receptive field, and for a moderate loss in information concerning the visual task. Based upon our analysis of field factors, we might conclude that FF 15 is somewhat large for tasks in which either a smaller receptive field than four degrees is required, or in which there is very little loss in information. On the other hand, FF 15 is probably somewhat small for tasks in which either a larger receptive field than four degrees is required, or in which there is a considerable loss in information. Thus, from the point of view of the analysis of field factors, FF 15 may be considered generally representative of all tasks. It must be emphasized, of course, that at the present time heavy reliance cannot be placed upon the analysis of field factors. The only actual determination of a field factor we have comes from the Field Task Simulator study. As indicated above, a value of 15 is the lower limit of the range of values obtained in this study. Thus, selection of a field factor of 15 must be considered a conservative estimate on the basis of our present knowledge.

The standard performance curve for the 5 APS level of visual capacity, adjusted to 99 per cent accuracy and to FF 15, is presented in Fig. 23. It is recommended that this curve be used for the current specification of lighting levels for various visual tasks. This curve was constructed from a threshold curve for a $^1/_5$-second exposure duration obtained in the following way. First, values of threshold contrast were obtained for various luminance levels up to 100 footlamberts from the smooth curves of the original laboratory data described in Section II. Values of threshold contrast for higher luminance levels were computed from values of relative threshold contrast values at various luminance levels, obtained in the recent experiments reported in Section II. These values of relative threshold contrast were obtained by linear interpolation between the values presented in Tables II and III, when exposure duration was plotted on a logarithmic scale. (A quantitative description of the method used to construct the threshold curve for $^1/_5$-second is contained in Section VIII, and the actual threshold curve is exhibited in Fig. 33, which will be described later.)

VI. The Lighting Specification Procedure

Now that we have described the operation of the Visual Task Evaluator and have developed the standard performance curve, it will be possible to describe the entire lighting specification system. Fig. 24 represents the operation of the specification system graphically, utilizing the standard performance curve developed in Section V, presented in the figure as the solid curve. Now, let us suppose that we have two practical tasks to be evaluated. In our example, we assume that we have advance knowledge of the threshold performance curves for these tasks, so as to illustrate the procedures and assumptions of the method. We assume that if we reduced the over-all contrast of these tasks, the relation between threshold contrast and the overall luminance would be identical in form to that actually found by measurement with the four-minute standard disc target. That is, the threshold performance curves for Tasks 1 and 2, shown in Fig. 24, are parallel to the standard performance curve, which is itself constructed parallel to the threshold curve for a four-minute disc presented for $^1/_5$-second duration.

Now, let us suppose that we evaluate Tasks 1 and 2 with the VTE at an arbitrarily chosen level of luminance equal to 100 footlamberts. We assume that the actual contrast of Task 1, before reduction by the wedge in the VTE is of the value C_1, represented by a horizontal line drawn at a real value of log target contrast. The reduction of contrast of Task 1 to the visibility threshold is represented in the figure by the arrow with a single crossmark, extending down from the line C_1 to intersection with the threshold performance curve of Task 1, which is the upper dashed curve. Note that this line is drawn vertically over the value of log background luminance = 2, corresponding to 100 footlamberts. The length of the arrow represents the amount of contrast reduction which must be introduced by the contrast wedge; it corresponds to the degree of rotation of the wedge. The second operation in the VTE involves determining the value of initial contrast of the standard four-minute disc which is also at threshold visibility when the contrast wedge is left untouched after the setting made to reduce Task 1 to threshold. The contrast value labeled 0 is intended to represent the threshold contrast of the observer for a four-minute target with a 100-footlambert background luminance under the conditions of setting the VTE. (This value will normally fall below the standard performance curve because time is virtually unlimited in the VTE measurements.) The operation of adjusting the initial contrast of the four-minute disc until it is at threshold when viewed through the contrast wedge therefore involves moving up from the point 0 a distance on the log target contrast scale equal to the distance moved down in reducing the contrast of Task 1 to threshold. The literal accuracy of this statement is apparent if it is remembered that a fixed distance on the log contrast scale is equivalent to a fixed percentage contrast change, which is precisely what a given setting of the contrast wedge provides to all tasks. Thus, the other single-marked arrow measuring up from the contrast level 0 reaches to a value of initial contrast which is the contrast for the four-minute standard target equivalent to Task 1. (This arrow should, of course, also be constructed along a vertical line representing log background luminance = 2, since the setting of the standard disc target is extending down from the line C_1 to intersect with the threshold performance curve of Task 1, For ease of construction, the arrow was arbitrarily displaced to the left of the first arrow.)

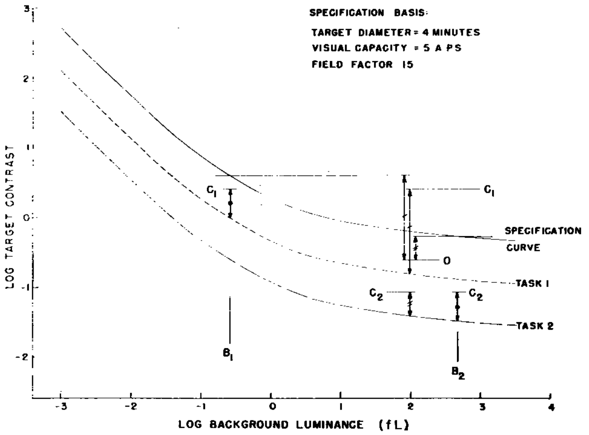

Figure 24. Illustration of the operating principles of lighting specification system. Explanation in text.

The lighting specification system proceeds by defining the level of luminance for Task 1 as the level at which the contrast of the standard disc equivalent to Task 1 will fall on the standard performance curve. Thus, the operation involves extending a horizontal line from the head of the second single-marked arrow until it intersects the standard performance curve. The specified luminance level for Task 1 is B_1 which is shown in the figure to be a level between .1 and 1 footlambert.

We may well inquire to what extent this level of luminance will provide more task contrast than required for threshold visibility. The extent to which the threshold contrast is less than the value C_1 measures the extent to which our specification system has resulted in a condition of supra-threshold visibility for the task. The arrow with the central black dot located above the luminance B_1 measures the distance from the threshold contrast for Task 1 at luminance B_1 to the actual contrast C_1. Since this measures a distance on the log target contrast scale, the length of this arrow measures the supra-threshold visibility factor of 2.51.

Consider next the case of Task 2. The lower dashed curve is the threshold performance curve and the actual task contrast is represented by the level C_2. As before, the VTE evaluation is assumed to have occurred at 100 footlamberts background luminance. The double-marked arrow represents the extent of reduction in task contrast required to bring Task 2 to threshold visibility. As before, the operation of setting the contrast of the standard disc target involves moving up on the log contrast scale from the contrast value 0 a distance equal to the distance the value of C_2 had to be reduced to bring it to threshold. The double-marked arrow constructed upwards from 0 represents this operation. (This arrow should also be constructed vertically along the log background luminance scale at 2, but it was moved arbitrarily to the right to avoid confusion.) The value of contrast corresponding to the top of this arrow represents the contrast of the standard disc corresponding to Task 2. This value of contrast is continued across horizontally until it intersects the standard performance curve. The luminance corresponding to this point of intersection is labeled B_2; it represents the luminance level at which Task 2 should be performed to provide the supra-threshold level built into our standard performance curve. As before, the extent to which luminance B_2 will provide a supra-threshold level of performance for Task 2 is measured by the extent to which C_2 exceeds the threshold for Task 2 at luminance B_2. This extent is measured by the arrow with the central black dot located above luminance level B_2. The length of this arrow indicates that Task 2 will also have a supra-threshold visibility factor of 2.51 at luminance B_2.

Inspection of the construction of Fig. 24 reveals that this system will always result in supra-threshold visibility factors which are equal so long as the threshold curves for various tasks are parallel to the standard performance curve. The placement of the threshold curves on the log contrast scale, and the initial contrast values of the tasks do not alter the supra-threshold factor obtained for all tasks. The absolute placement of the standard performance curve alters the luminances specified, and the magnitude of the supra-threshold factor obtained for all tasks. Obviously, the higher the standard performance curve on the log contrast scale, the greater will be the supra-threshold visibility factor for all tasks.

The level of the observer's threshold for the standard disc also affects the luminances specified and the supra-threshold visibility factor obtained, if this quantity varies while the thresholds for Tasks 1 and 2 do not vary. The null-comparison method adopted as the standard procedure in the VTE was intended to minimize this possibility, since the thresholds for the practical and standard tasks are measured in rapid succession. Actually, this precaution does not appear to be necessary when highly skilled operators are used. It is possible to compare settings made on the standard disc in the VTE at various times, by plotting the contrast values $B_{\Delta S/B_S}$ as a function of the setting of the variable contrast wedge. It has been found that data collected in different observing sessions separated by months were in very good agreement, provided the VTE measurements were made at the same luminance level. The setting of the annulus provides a means of establishing the average luminance at which the VTE measurements are made. If the measurements are made at different luminance levels, the operator's threshold for the standard discs will, of course, be different. Use of the null-comparison method cancels out this variable. It should be apparent from the construction of Fig. 24 that the luminance level at which the VTE measurements are made does not affect the result obtained, provided the threshold contrast curve of the operator for the standard disc target is parallel to the standard performance curve. As suggested by the above discussion, it is convenient to make all VTE measurements at a single luminance level, since it is possible to pool the data obtained on various settings of the standard targets to increase the precision of each individual equivalence setting.

There is, however, a separate argument which suggests that it would be preferable to evaluate various tasks at luminance levels near the ones which will be eventually specified. The errors introduced in the specification process due to nonlevel at which the contrast of the standard disc equivalent to Task 1 will fall on the standard performance curve. Thus, the operation involves extending a horizontal line from the head of the second single-marked arrow until it intersects the standard performance curve. The specified luminance level for Task 1 is B_1 which is shown in the figure to be a level between .1 and 1 footlambert.

We may well inquire to what extent this level of luminance will provide more task contrast than required for threshold visibility. The extent to which the threshold contrast is less than the value C_1 measures the extent to which our specification system has resulted in a condition of supra-threshold visibility for the task. The arrow with the central black dot located above the luminance B_1 measures the distance from the threshold contrast for Task 1 at luminance B_1 to the actual contrast C_1. Since this measures a distance on the log target contrast scale, the length of this arrow measures the supra-threshold visibility factor of 2.51.

Consider next the case of Task 2. The lower dashed curve is the threshold performance curve and the actual task contrast is represented by the level C_2. As before, the VTE evaluation is assumed to have occurred at 100 footlamberts background luminance. The double-marked arrow represents the extent of reduction in task contrast required to bring Task 2 to threshold visibility. As before, the operation of setting the contrast of the standard disc target involves moving up on the log contrast scale from the contrast value 0 a distance equal to the distance the value of C_2 had to be reduced to bring it to threshold. The double-marked arrow constructed upwards from 0 represents this operation. (This arrow should also be constructed vertically along the log background luminance scale at 2, but it was moved arbitrarily to the right to avoid confusion.) The value of contrast corresponding to the top of this arrow represents the contrast of the standard disc corresponding to Task 2. This value of contrast is continued across horizontally until it intersects the standard performance curve. The luminance corresponding to this point of intersection is labeled B_2; it represents the luminance level at which Task 2 should be performed to provide the supra-threshold level built into our standard performance curve. As before, the extent to which luminance B_2 will provide a supra-threshold level of performance for Task 2 is measured by the extent to which C_2 exceeds the threshold for Task 2 at luminance B_2. This extent is measured by the arrow with the central black dot located above luminance level B_2. The length of this arrow indicates that Task 2 will also have a supra-threshold visibility factor of 2.51 at luminance B_2.

Inspection of the construction of Fig. 24 reveals that this system will always result in supra-threshold visibility factors which are equal so long as the threshold curves for various tasks are parallel to the standard performance curve. The placement of the threshold curves on the log contrast scale, and the initial contrast values of the tasks do not alter the supra-threshold factor obtained for all tasks. The absolute placement of the standard performance curve alters the luminances specified, and the magnitude of the supra-threshold factor obtained for all tasks. Obviously, the higher the standard performance curve on the log contrast scale, the greater will be the supra-threshold visibility factor for all tasks.

The level of the observer's threshold for the standard disc also affects the luminances specified and the supra-threshold visibility factor obtained, if this quantity varies while the thresholds for Tasks 1 and 2 do not vary. The null-comparison method adopted as the standard procedure in the VTE was intended to minimize this possibility, since the thresholds for the practical and standard tasks are measured in rapid succession. Actually, this precaution does not appear to be necessary when highly skilled operators are used. It is possible to compare settings made on the standard disc in the VTE at various times, by plotting the contrast values $B_{\Delta S/B_S}$ as a function of the setting of the variable contrast wedge. It has been found that data collected in different observing sessions separated by months were in very good agreement, provided the VTE measurements were made at the same luminance level. The setting of the annulus provides a means of establishing the average luminance at which the VTE measurements are made. If the measurements are made at different luminance levels, the operator's threshold for the standard discs will, of course, be different. Use of the null-comparison method cancels out this variable. It should be apparent from the construction of Fig. 24 that the luminance level at which the VTE measurements are made does not affect the result obtained, provided the threshold contrast curve of the operator for the standard disc target is parallel to the standard performance curve. As suggested by the above discussion, it is convenient to make all VTE measurements at a single luminance level, since it is possible to pool the data obtained on various settings of the standard targets to increase the precision of each individual equivalence setting.

There is, however, a separate argument which suggests that it would be preferable to evaluate various tasks at luminance levels near the ones which will be eventually specified. The errors introduced in the specification process due to non-

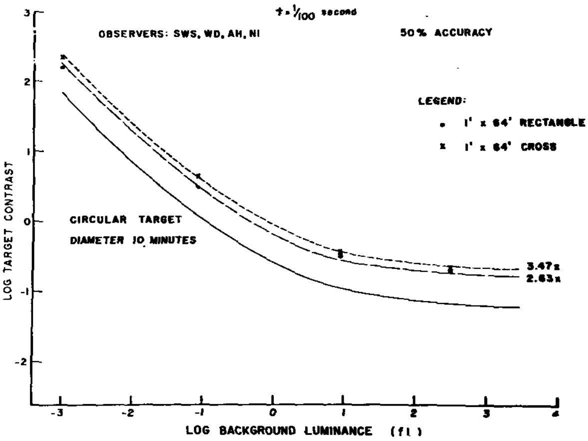

Figure 25. Threshold contrast data for a rectangle and a cross target presented for a 1/100-second duration. The solid curve represents a threshold curve interpolated from the basic laboratory data. The dashed curves represent laboratory contrast values multiplied by factors of 2.63 and 3.47, respectively.

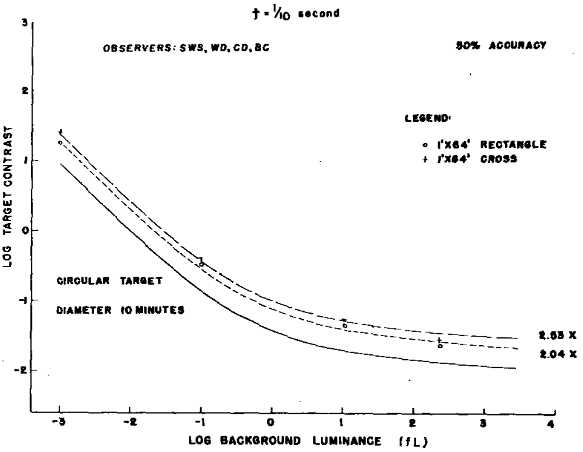

Figure 26. Threshold contrast data for a rectangle and a cross target presented for a 1/10-second duration. The solid curve represents a threshold curve interpolated from the basic laboratory data. The dashed curves represent laboratory contrast values multiplied by factors of 2.04 and 2.53, respectively.

parallelism of the threshold curves for various tasks will be minimized if the assessment of each task is made at a luminance level near the value which ends by being specified. This argument may suggest the use of an iterative procedure for arriving at the final lighting specification.

We well may wonder to what extent the threshold performance curves for various tasks are parallel to one another. During 1956-1957, Stanley W. Smith of the University of Michigan staff studied threshold curves for two tasks which were selected to be markedly different from the luminous disc used as the standard target. One target was a long thin rectangle, subtending 1 minute by 64 minutes. The other target was a 90-degree cross made from two 1-minute by 64-minute rectangles. The apparatus and procedures were identical with those of the main laboratory studies reported in Section II. Groups of four observers were used for each target, at each of the three exposure durations: 1, $^1/_{10}$, and $^1/_{100}$ second. Measurements were made in each case to define the functional relation between log threshold contrast and log background luminance, for comparison with the functional relations obtained with circular targets of equal area. The results for the $^1/_{100}$-second exposure duration are presented in Fig. 25. The solid curve is for a circular disc with a 10-minute diameter. The results for the rectangle and the cross are shown as data points. The two dashed curves represent the solid curve adjusted with respect to the contrast scale so as to provide the best fit to the data for each target. The contrast multiplier used to adjust the curve is indicated in each case. The curves in each case fit the data points well, revealing that the threshold curve has very much the same shape for the noncircular and circular targets viewed at an exposure duration of $^1/_{100}$ second.

Similar data for the $^1/_{10}$-second exposure duration are presented in Fig. 26. As before, the solid curve is for a disc target and the dashed lines represent the curve for the circular target adjusted so as to best fit the data on the rectangle and the cross targets. The curve fit seems quite adequate for the rectangle target. The data point obtained with the cross target at the highest luminance falls well below the upper dashed curve, suggesting that there may be a difference in the functional relation between threshold contrast and background luminance in this case.

The data for 1-second exposure duration are presented in Fig. 27. In this case, the curves fitted through the data points for the rectangle target fit the curve derived from the disc target fairly well, but the data points for the cross target depart markedly from the curve fitted to them. Clearly, the functional relation between threshold contrast and background luminance is different for the cross target and disc target of equal area.

Of course, an examination of the curves which are shown in Figs. 8-12 reveals differences in the functional relation between threshold contrast and background luminance as great as these differences, when disc targets are varied in size over a large range. These data make it clear that there will be errors introduced into the lighting specification method due to non-parallelism of the threshold curves obtained with various visual tasks. However, in a broad sense, the threshold curves bear great resemblance to each other. As indicated

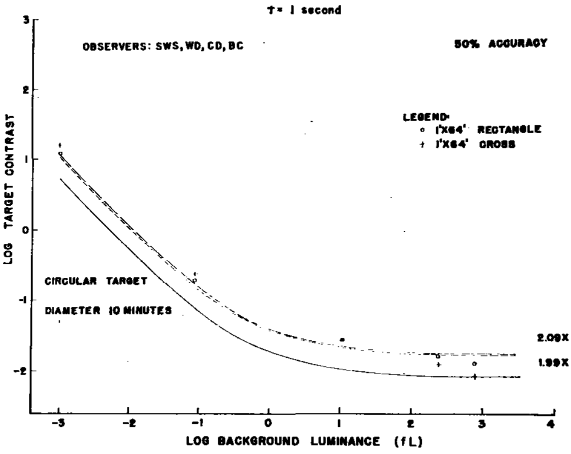

Figure 27. Threshold contrast data for a rectangle and a cross target presented for a one-second duration. The solid curve represents a threshold curve interpolated from the basic laboratory data. The dashed curves represent laboratory contrast values multiplied by factors of 1.99 and 2.09, respectively.

above, differences in the form of these curves can be minimized by evaluating each task at a luminance level as close as possible to the one specified by the system.

It is worth noting that our selection of a four-minute standard disc, rather than a one- or 60-minute disc target, serves to minimize the effect of non-parallelism of the threshold curves, since the curve for the four-minute disc is of roughly intermediate form with respect to those shown in Figs. 8-12 and in Figs. 25-27.

The above account completes our description of the lighting specification process as it is recommended that it be utilized currently. Before reporting the lighting levels recommended for a sample of practical visual tasks, it will be well to discuss two general problems concerned with this method. The first of these concerns the application of the method to visual tasks for which there is luminance non-uniformity in the visual field. The second concerns the applicability of the performance data reported here to the population as a whole.

Application of the Method to Visual Tasks Involving Luminance Non-Uniformity In the Visual Field

It is important to indicate to what extent the present method of specifying lighting levels assumes that the visual field of practical tasks is uniform in luminance. It should be emphasized that the laboratory studies on disc targets were conducted with extended fields of uniform luminance, as were the studies in the Field Task Simulator and the analytical studies of field factors. Thus, the standard performance curves presented in Fig. 23 represent extended fields of uniform luminance.

The VTE has an inner photometric field whose diameter is 2.3 degrees. Thus, when the operator evaluates the difficulty of a practical visual task, luminance non-uniformity of the background in the vicinity of the task influences the task difficulty as it would in actual performance of the task. When the standard disc is viewed within the VTE, it is presented on a field of uniform luminance. Determination of the value of the equivalent contrast of each task thus takes full account of luminance non-uniformities in the vicinity of the practical task, and correctly relates each task to the standard performance curve for the four-minute disc, based upon fields of uniform luminance.

If there are areas in the surround of the task of higher luminance than the task and its immediate background, the task will be more difficult than the VTE measurement indicates it to be, due to the effect of disability glare. Furthermore, the presence of areas in the surround having lower luminance than the task and its immediate background will probably make the task more difficult than the VTE measurement indicates, due to transient adaptational effects. We do not have at present any quantitative method of dealing with the transient adaptational effects, but we do have a quantitative method for dealing with the disability glare effect.

The method of allowing for the deleterious effects of disability glare was described in principle in the author's 1955 article.[2] It was shown that curves relating log contrast and log background luminance can be generated to represent various ratios between the veiling luminance produced by all the sources of disability glare in the surround, and the luminance of the task and its immediate background. Curves representing different ratios between these quantities may be generated from the standard performance curve presented in Fig. 23, using the method described in the earlier article. Once these curves are available, we require a method of establishing the value of veiling luminance actually produced by the surround of a given task. It is possible for the veiling luminance to be computed from the familiar disability glare formulation of Moon and Spencer,[21] provided a considerable number of photometric measurements are made first. A much simpler procedure involves use of the proposed Fry Disability Glare Meter,[22] which yields direct values of the ratio of the veiling luminance to the luminance of the task and its immediate background. These ratios may be used with the new families of performance curves, to compute lighting levels to be used when there is an appreciable amount of disability glare.

Non-uniformity of the distant surround of the task will also alter the difficulty of many visual tasks, due to reflected glare. This effect is properly assessed by the present method if the VTE measurements are made with the task in its realistic environment. As will be reported in Section VII, our measurements of sample visual tasks were made in the laboratory with simple directional illumination which was shown to be generally equivalent to completely diffuse illumination. Thus, the light levels specified in the present paper assume the absence of reflected glare as well as the absence of disability glare. Recent measurements by Finch[23] and by Chorlton and Davidson[24] reveal the presence of considerable losses in task contrast when the tasks are measured under actual room conditions. These results imply that the tasks are considerably more difficult than our measurements indicate, due to the effects of reflected glare. If reflected glare cannot be eliminated, considerably more lighting must be utilized than is indicated in the present paper, to compensate for its deleterious effects. The extent to which a reduction in task contrast by reflected glare will increase the required lighting may be determined directly from the performance curve presented in Fig. 23. The slope of this curve, on the log-log plots, indicates directly the percentage increase in luminance, and hence illumination, required to compensate for a one per cent decrease in task contrast due to reflected glare. It is apparent that the performance curve becomes flatter at higher luminances. This means that greater percentage increases in lighting are required to compensate for a one per cent loss in task contrast, the higher the initial level of lighting.

Sample calculations will prove revealing. Assume, based upon the Chorlton and Davidson study, that a 13 per cent contrast reduction can often occur due to reflected glare in actual classrooms. The standard performance curve presented in Fig. 23 may be used to compute the illumination levels required to compensate for this contrast loss. For the purposes of these calculations, a task reflectance of 0.70 was assumed. The results are presented in Table V. It is apparent that large increases in illumination are required to compensate for a 13 per cent loss in task contrast due to reflected glare.

TABLE V — Illumination Levels Required to Compensate for a 13 Per Cent Loss in Task Contrast Due to Reflected Glare.

Glare-free Illumination	Illumination Needed in the Presence of Reflected Glare
(Footcandles)	(Footcandles)
10.	18.9
20.	45.2
30.	73.5
40.	101.
50.	140.
60.	193.
70.	202.
80.	238.
90.	286.
100.	299.

Comments on the Population Sample Involved in the Present Researches

It should be apparent from the descriptions of the experiments given above that only a few observers were used. The major part of the basic laboratory data depend primarily, in fact, upon only two observers. We may well wonder to what extent these observers represent the population as a whole. It must be emphasized at once that these observers do not at all represent the population as a whole; they were selected to represent the best possible visual performance to be found. These two observers, and the others used throughout the present study, were young adults in the age range from 18-32 years. They were all examined ophthalmologically and were known to have excellent sensory and oculomotor functions of every sort. Those observers needing slight refractive corrections were provided with the corrections during the experiments. All observers were intelligent enough to be successful as university undergraduate or graduate students, and all were well motivated.

Under these circumstances, the data reported here may reasonably be supposed to represent optimal performance. Presumably, older and younger observers may be expected to perform less well, as will most persons with mild or severe ocular deficiencies, as well as persons with less intelligence and motivation than our observers. Presumably, higher lighting levels will be required for the less-than-optimal performance to be expected from the bulk of the population. Extensive further experiments will be required to establish quantitative lighting needs for various segments of the population differing from our observers in the ways indicated. It is hoped that these experiments will in fact be conducted in the next few years.

VII. EVALUATION OF PRACTICAL VISUAL TASKS

During January of 1958, various technical committees of the IES selected what they considered important visual tasks encountered in various everyday activities and sent them to the University of Michigan for evaluation and computation of lighting specifications for them, based upon the quantitative method described above. In our evaluation of the tasks, we mounted them in front of the VTE as shown in Fig. 21. We arbitrarily decided to illuminate each ordinary task with the 35 mm slide projector shown in the figure, with the illumination striking the tasks at 45 degrees from normal to their surfaces. This illumination method was intended to eliminate specular reflection. There were a few tasks which are normally seen by specular reflection; for these a specular highlight was deliberately provided. In most cases, the illumination was adjusted to provide a background luminance of 100 footlamberts in order to increase the precision of measurements by making it possible to pool all measurements made on the standard disc targets.

Initially VTE readings were made by three trained photometrists and illumination specialists: Benjamin S. Pritchard of the University of Michigan staff; Arthur A. Eastman of General Electric Co., Nela Park; and C. L. Crouch, Technical Director of IES. Fourteen tasks were evaluated by all three operators. Operator Pritchard was found to give readings on the average less than two per cent different from the grand average obtained on all three operators. In order to simplify subsequent data collection, studies on the remaining 42 tasks were made by Pritchard alone. Pritchard's data are used for the tasks he alone measured; the average data for the three operators were utilized for the fourteen tasks studied by all three. The basic result in every case is a value of the contrast of the four-minute standard disc target of difficulty equivalent to the task. These values, known as equivalent contrasts and symbolized by $\widetilde{C}$, may be utilized directly with the standard performance curve of Fig. 23 to compute luminance levels for the desired performance criteria. From reflectance measurements made at the time of evaluation, illumination levels may be computed.

Before presenting the data, it will be well to report a supplementary study carried out to ascertain to what extent the measurements obtained with the projector were equivalent to results obtained under fully diffuse illumination. A hemisphere was constructed from half of a 12-inch world globe, and coated inside with magnesium oxide. A shielded source of light was added. Measurements were made with the VTE under this condition of illumination for comparison with measurements made under 45-degree directional illumination with the projector. The samples that were studied represented type, pencil, and ink writing on matte paper. The contrast values obtained with diffuse illumination were divided by the corresponding values obtained with the 45-degree diffuse illumination. The average ratio was 1.01, suggesting that at least "non-specular" tasks, such as those selected for study, yielded equivalent values under the two types of illumination.

Footcandle values assigned on the basis of the presently recommended standard performance system are presented in Table VI. This system, and these values, were utilized by the IES Committee for Recommendations of Quality and Quantity of Illumination in preparing their report of the present research to the IES Technical Committees.[20]

In May 1958, the Joint Committee on School Lighting submitted a number of samples of schoolroom visual tasks for assessment on the VTE. Nineteen samples of spirit-duplicated material were made available from Massachusetts schools, as were five samples from Michigan schools. Since these samples all represent work sheets and are very much alike, it does not seem necessary to present the results obtained with each sample. The samples were graded in difficulty into two categories, with values of log equivalent contrast equal to .185 and −.215, respectively. Using the currently recommended standard performance curve, footcandle values of 2.14 and 141. were obtained for the 12 easy tasks and the 12 more difficult tasks.

There is, of course, no simple way to evaluate the accuracy of the lighting recommendations made with this system. At least for the present, it may have to suffice to evaluate to what extent these lighting values agree with our total experience with various visual tasks. The adequacy of low footcandle levels for reading high contrast print certainly agrees with some evidence of the illumination needs of this task. The need for very high illumination levels for certain very difficult garment and textile tasks certainly agrees with our experience of wanting to take these tasks to the window or out-of-doors. The present data should stimulate considerable careful assessment of accumulated experience with various visual tasks.

A method for checking the internal consistency of the system, suggested by S. K. Guth and A. A. Eastman, has been investigated. This suggestion involves determining the equivalent contrast for the standard four-minute disc for each of a number of non-specular tasks, then using a performance curve, such as the one presented in Fig. 23, to establish illumination levels for all these tasks. The next step involves illuminating each task to the level specified in this way. If the method is internally consistent, it should now be possible to show that

TABLE VI — Values of Illumination or Luminance for 99 Per Cent Accuracy. Field Factor 15 Visual Capacity 5 APS

Task No.	Task Description	Log $\tilde{C}$	R	E (fc)	B (fL)
1.	Reading while writing: sample of ink-writing, one 6th grade student	.273	.76	1.38	
2.	Reading while writing: samples of No. 2 pencil writing, twelve 6th grade students with poorest writing in class of 31	**–.167**	**.76**	63.0	
3.	Reading: 8-point Bodoni type	.228	.70	1.87	
4.	Reading: 6-point textype	.144	.70	2.98	
5.	Reading: 8-point textype	.333	.70	1.13	
6.	Reading: 10-point textype	.372	.70	0.94	
7.	Reading: 12-point textype	.478	.70	0.60	
8.	Reading while transcribing: sample of shorthand copy with No. 3 pencil	–.181	.79	76.5	
9.	Reading: typed original, good ribbon	.397	.62	0.97	
10.	Reading: typed original, extremely poor ribbon	–.338	.62	3140.	
11.	Reading: typed carbon, fifth copy	–.194	.53	133.	
12.	Reading: dark blue mimeograph stencil, with clear plastic overlay	.498	.11	3.54	
13.	Reading: Thermofax copy, poor quality	–.278	.63	589.	
14.	Reading: No. 2 pencil on tracing paper over blueprint	.050	.59	6.58	
15.	Cutting: white chalk mark on blue serge cloth	.664	.020	10.4	
16.	Inspection: dot defects on dark blue cloth	.562	.017	17.8	
17.	Inspection: gray line defect on black cloth	.369	.024	27.5	
18.	Inspection: darned blemish on gray cloth	–.022	.10	74.1	
19.	Inspection: brown stitching on brown silk		**.12**		
a.	vertical stitching	–.398		>10000.	
b.	horizontal stitching	–.022		61.7	
20.	Inspection: gray stitching on gray silk		.076		
a.	vertical stitching	–.268		4160.	
b.	horizontal stitching	–.468		>10000.	
21.	Cutting: orange chalk on light brown tweed	–.168	.18	266.	
22.	Cutting: white chalk on gray cloth	–.018	.33	21.0	
23.	Inspection: light stitching on blue serge cloth		.018		
a.	vertical stitching	.915		5.05	
b.	horizontal stitching	1.191		2.22	
24.	Inspection: pattern threads, men's silk and wool suiting	–.021	.22	32.9	
25.	Inspection: dark brown raised threads on silk	–.180	.035	1680.	
26.	Inspection: blue-gray raised threads on silk	–.283	.046	9650.	
27.	Inspection: pattern threads, white handkerchief	–.045	.91	9.86	
28.	Inspection: pocket stitching, tan shirt	–.318	.53	1890.	
29.	Reading: price tag, pencil	–.236	.63	241.	
30.	Reading: price tag, ink	.127	.76	3.10	
31.	Inspection: broken white wool thread on spinner bobbin		.66		
a.	30° illumination	.302		1.26	
b.	normal illumination	.042		6.32	
32.	Inspection: broken black thread on spinner bobbin, 30° illumination	–.174	.018	2920.	
33.	Inspection: broken gray thread on spinner bobbin, 30° illumination	.295	.079	11.8	
34.	Inspection: broken white nylon thread on spinner bobbin, 30° illumination	–.279	.78	487.	
35.	Inspection: skip defect, viewed from 16 feet	–.080	.19	71.0	
36.	Inspection: tight sound edge knot, viewed from 16 feet	.121	.19	12.9	
37.	Inspection: bark wave, viewed from 16 feet	–.193	.19	381.	
38.	Inspection: small decay spot, viewed from 16 feet	–.443	.19	>10000.	
39.	Inspection: chip grain, viewed from 16 feet	–.323	.19	6470.	
40.	Inspection: small seasoning check, viewed from 30 inches	–.181	.19	317.	
41.	Inspection: small skip defect, viewed from 30 inches	–.148	.19	187.	
42.	Inspection: chip grain, viewed from 30 inches		.19		
a.	no specular	–.243		1030.	
b.	specular	.114		13.4	
43.	Inspection: brown color difference in cloth	–.211	.12	870.	
44.	Reading: proofed type	–.442			>3160.
45.	Reading: unproofed type	–.283			447.
46.	Reading: vernier calipers, non-etched	–.300			631.
47.	Reading: new micrometer, etched	–.022			7.41
48.	Reading: old micrometer				
a.	specular on numbers	–.233			148.
b.	specular on division	.030			4.62
49.	Reading: white line on blueprint, tracing paper overlay	–.558	.59	>5090.	
50.	Inspection: brown thread stitching on brown silk tweed	–.593	.12	>10000.	
51.	Cutting: white chalk on tan cloth	–.561	.24	>10000.	
52.	Inspection: rolled-edge defect on white handkerchief	–.725	.91	>3470.	
53.	Inspection: seasoning check, viewed at 16 feet	–.545	.19	>10000.	
54.	Inspection: brown stain on gray cloth	–.523	.12	>10000.	
55.	Inspection: brown spot on red necktie	–.545	.084	>10000.	
56.	Inspection: brown spot on tan necktie	–.694	.18	>10000.	

each task has an equal supra-threshold visibility level. This condition may be readily evaluated by reducing each of the specially illuminated tasks to threshold, using the amount of contrast reduction required to bring each task to threshold as a measure of supra-threshold visibility.

This check of internal consistency was conducted for illumination levels based upon the present system for tasks Nos. 4, 7, 8, 9, 11, 29 and 30. The predictions of illumination levels were based upon the performance curve for 7 APS. (The performance curve used is of no importance to this check except insofar as the various performance curves differ in shape from one to another. The curve for 7 APS, in fact, appears very similar in shape to the standard performance curve of Fig. 23.) The supra-threshold visibility factors for the seven tasks were averaged and the ratio of the factor obtained with each task to the average was computed. These ratios give a direct measure of the extent to which predicted illumination levels from the lighting specification system resulted in equivalent supra-threshold visibility factors for the various tasks. The ratios for the seven tasks were, in order: .94, .97, 1.03, .90, 1.00, 1.04, and 1.13. The average departure from a ratio of 1.00 was only .05, an average deviation of only five per cent. It is to be emphasized that the illumination levels specified for the various tasks varied from .4 to 339 footcandles. This evaluation certainly suggests that the standard lighting specification system has internal consistency. It suggests that the threshold performance curves for the seven tasks must be essentially parallel to that for the standard four-minute disc, presented for $^1/_7$ second.

VIII. FUTURE DEVELOPMENTS OF THE METHOD

As indicated in Section VI, it is recommended that the lighting specification system for current use should be based upon a level of visual capacity of 5 APS and a field factor of 15 for all visual tasks. These performance criteria represent conservative estimates for current use, based upon our best current knowledge of visual performance. However, it was also pointed out in Section VI that it is entirely likely that different visual tasks actually require different levels of visual capacity, and that the conditions under which these tasks are performed suggest that different field factors should be used when specifying lighting levels for the various tasks. Of course, at present, there is no satisfactory factual basis upon which levels of visual capacity and field factors can be established for different tasks. Considerable further research will be required before it will be possible to make these assignments on a satisfactory basis, and it is hoped that suitable studies will be conducted during the next few years. A lighting specification system in which different levels of visual capacity and different field factors are used for different visual tasks is obviously more complex than the system presently recommended. Its advantage is presumably that this form of application of the lighting specification method will provide lighting levels for individual tasks with greater precision than is possible with the present system. As lighting technology advances, this precision may well be needed.

It seems appropriate to develop, in this report, as many as possible of the basic tools which will be needed to utilize the lighting specification method in this way. Whereas it is not at present possible to describe the procedures to be used in assigning levels of visual capacity and field factors to individual tasks, it is possible to develop the visual performance curves which will be needed for various levels of visual capacity and various field factors. Performance curves for a wide range of levels of visual capacity and a wide range of field factors will be developed. Then, in order to illustrate the procedures to be used with this application of the lighting specification method, lighting levels will be determined for the 56 visual tasks described in Section VII, based upon values of visual capacity and field factors selected by the author as intuitively reasonable.

Obviously, these selections of visual capacity levels and field factors cannot be considered factually established, although all relevant factual material will be used in a general way. Accordingly, the lighting levels specified for the various tasks on this basis cannot be considered factually determined. Nonetheless, it will be instructive to follow through the determination of lighting levels for various tasks. Comparison of the lighting levels obtained in this way and the lighting levels established with the system recommended for current use will provide valuable insights into the general method being used for specifying lighting levels.

Let us begin by constructing visual performance curves for various levels of visual capacity and for various field factors. As in the case of the standard performance curve recommended for current use, we will begin by adjusting our performance data to correspond to 99 per cent accuracy, rather than 50 per cent. As indicated in Section V, this adjustment may be accomplished by the use of contrast multipliers, which are different for different levels of visual capacity. The contrast multipliers to be used for the different capacity levels are obtained from the earliest account of the laboratory per-

TABLE VII — Values of the Contrast Multiplier to Convert from 50 Per Cent to 99 Per Cent Accuracy.

t (Seconds)	Contrast Multiplier	Log Contrast Multiplier
1	2.13	.328
$^{1}/_{3}$	2.05	.312
$^{1}/_{10}$	1.87	.272
$^{1}/_{30}$	1.86	.270
$^{1}/_{100}$	1.84	.265

formance data.[1] These values are presented in Table VII, for convenience, in terms of the exposure duration of the target. Log factors are presented, since we may allow for the effect of a contrast multiplier by adding the logarithm of this multiplier to each value of log target contrast. This amounts to sliding the contrast scale of graphs like those in Figs. 8-12 by an amount equal to the log factor.

The analytical discussion of field factors contained in Section III provides a basis for determining the range of field factors which may ultimately be needed to describe all visual tasks. In this account, it was argued that a field factor of 2.50, which allows for the criterion difference between laboratory and common sense seeing, would always be needed. It was further argued that the requirements for visual guidance of the ocular adjustment mechanisms of accommodation and vergence would normally necessitate a receptive field extending two degrees in each direction from the fixational center, which requires an additional contrast multiplier of 4.0. Thus, the field factor would be expected to be 10.0, provided the observer has rather complete information concerning the task, and provided the task occurs with reasonable regularity. When knowledge concerning the task is reduced, the field factor would have to be increased. Some reduction in knowledge, whether of the time of occurrence or the location of the task, would presumably increase the field factor to 15.0. Considerable reduction in knowledge would presumably increase the field factor to 20.0.

There may be conditions in which the observer has complete knowledge about the task and may not require an appreciable receptive field because he is able to concentrate on no more than a few objects in the visual field. In these cases, the field factor may be reduced below 10.0 by reducing the factor needed to enlarge the receptive field. A total field factor of 7.5 would represent a factor of 3.0 for enlargement of the receptive field. This would provide a receptive field somewhat greater than 1.5 degrees in every direction from the fixational center. A field factor of only 5.0 would represent a factor of only 2.0 for enlargement of the receptive field, which would give a receptive field measuring approximately 1.25 degrees in all directions from the fixational center. Field factors of 5.0 and 7.5 probably represent values to be expected for tasks in which the usual receptive field is not required.

TABLE VIII — Values of the Log Factors to Convert from 50 Per Cent to 99 Per Cent Accuracy and to Allow for Various Field Factors (FF).

	Log Factor				
t (Seconds)	FF 5	FF 7.5	FF 10	FF 15	FF 20
1	1.028	1.204	1.329	1.505	1.630
$^{1}/_{3}$	1.011	1.186	1.312	1.488	1.613
$^{1}/_{10}$	.971	1.147	1.272	1.448	1.572
$^{1}/_{30}$	.968	1.144	1.269	1.445	1.570
$^{1}/_{100}$	.964	1.140	1.265	1.441	1.566

On the basis of the preceding considerations, it was decided that field factors of 5.0, 7.5, 10, 15 and 20 may be expected to cover the range to be expected for various visual tasks. The threshold curves for the four-minute standard target presented in Figs. 8-12 were adjusted to the 99 per cent accuracy level, and allowance was made for the five field factor values. The contrast multipliers to allow for the accuracy correction were multiplied by the various field factors. The resulting constants were converted into logarithms, which may be applied directly to the threshold curves presented in Figs. 8-12. The factors are summarized in Table VIII.

The visual performance curves obtained by applying these factors to the threshold curves are presented in Figs. 28-32. Each figure presents a family of curves for a given field factor. The various curves are expressed in terms of visual capacity (APS), which is the inverse of the exposure duration in seconds. Note that of the above exposure durations, only the 1-, $^{1}/_{10}$- and $^{1}/_{30}$-second

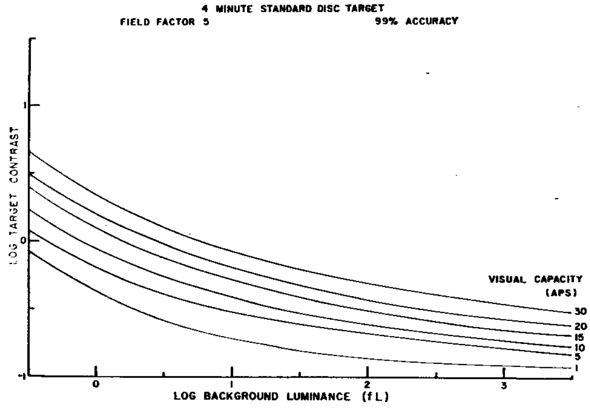

Figure 28. Visual performance curves based upon a four-minute standard disc target. Field factor is 5. Each curve represents a level of visual capacity, indicated in units of assimilations per second (APS).

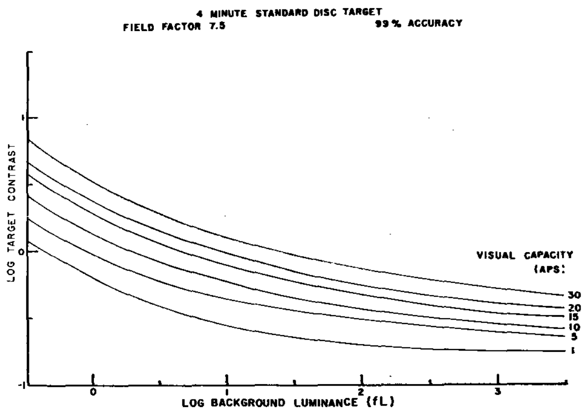

Figure 29. Visual performance curves based upon a four-minute standard disc target. Field factor is 7.5. Each curve represents a level of visual capacity, indicated in units of assimilations per second (APS).

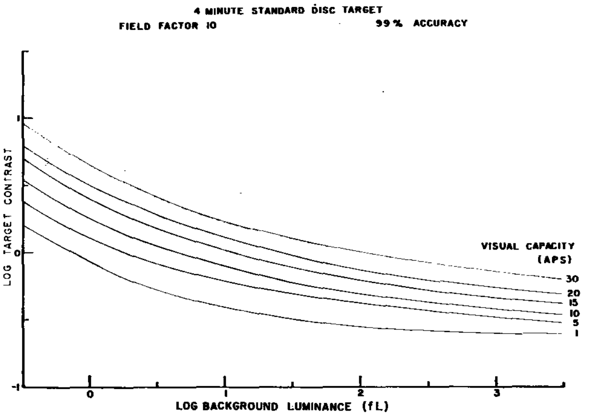

Figure 30. Visual performance curves based upon a four-minute standard disc target. Field factor is 10. Each curve represents a level of visual capacity, indicated in units of assimilations per second (APS).

curves have been utilized. When the curves were being constructed it became apparent that the $^{1}/_{3}$-second curve was too similar to the 1-second curve to be worthy of plotting. The $^{1}/_{100}$-second curve was omitted, since our analysis of visual capacity in Section I suggested that perhaps 30 APS, corresponding to a $^{1}/_{30}$-second exposure duration, was the maximum level of visual capacity under conditions of normal use of the eyes. The data for the $^{1}/_{100}$-second exposure duration are presented in this paper so that they will be a matter of record in the event that future investigations reveal the need for levels of visual capacity greater than 30 APS.

In each of the figures, curves representing the additional levels of 5, 15, and 20 APS levels have been included. (The method of deriving these curves will be described in detail subsequently.) The 5 APS level of visual capacity is included because this level corresponds to the capacity to assimilate about one item of information per fixational pause. The 5 APS curve appearing in Fig. 31, representing FF 15, is the curve which is presented earlier in Fig. 23 as the standard performance curve recommended for current use. The 15 and 20 APS levels are included because of the presumed importance of the range of visual capacity between 5 APS, which represents the assimilation of one item of information per fixational pause, and 30 APS, which may well be the maximum level of visual capacity with normal use of the eyes.

In order to construct performance curves corresponding to the 5, 15 and 20 APS levels of visual capacity, it was necessary to obtain corresponding threshold data and conversion factors. Threshold contrast values for a four-minute disc, for exposure durations of $^{1}/_{5}$, $^{1}/_{15}$ and $^{1}/_{20}$ second were obtained by interpolation from the smooth curves relation log threshold contrast to log exposure duration de-

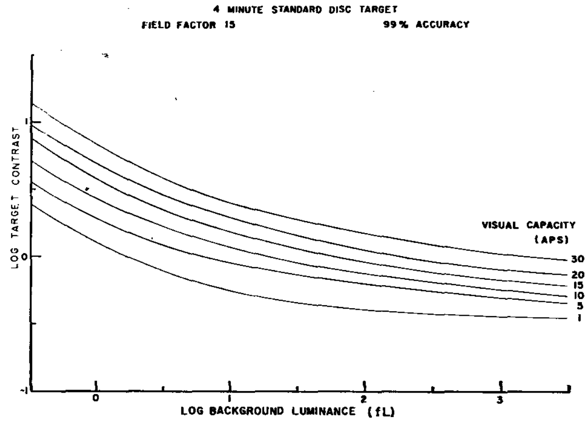

Figure 31. Visual performance curves based upon a four-minute standard disc target. Field factor is 15. Each curve represents a level of visual capacity, indicated in units of assimilations per second (APS).

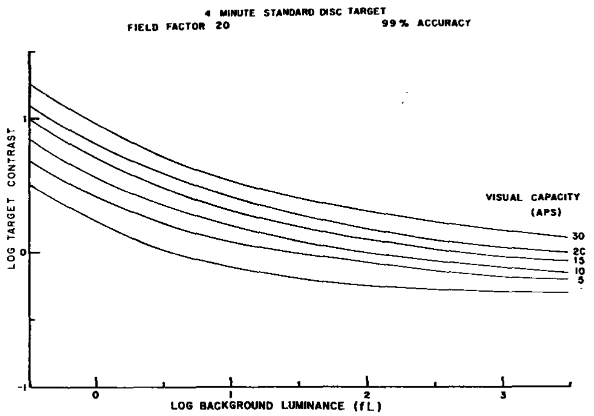

Figure 32. Visual performance curves based upon a four-minute standard disc target. Field factor is 20. Each curve represents a level of visual capacity, indicated in units of assimilations per second (APS).

TABLE IX — Relative Log Threshold Contrast Values for High Background Luminance Levels for a 4-Minute Disc Target.

	Exposure Duration (Seconds)		
Log B (fL)	1/5	1/15	1/20
2.00	.000	.000	.000
2.50	−.060	−.074	−.077
3.00	−.106	−.132	−.138
3.50	−.134	−.172	−.181

veloped during the process of data smoothing described in Section II. These curves were extended to luminances beyond 100 footlamberts on the basis of the recent data obtained at higher luminances. Relative log threshold contrast values were interpolated from the values presented in Tables II and III, with the results shown in Table IX. These resulting threshold data are presented in Fig. 33, together with threshold data for durations of 1, $^1/_{10}$ and $^1/_{30}$ second. It is apparent that the interpolation process resulted in smooth appearing curves of $\dot{C}$ versus B for these exposure durations.

The next step involved determination of contrast multipliers appropriate to correct from 50 to 99 per cent accuracy. Multipliers were interpolated from the values presented in Table VII, with the results shown in Table X. The total log factors needed to convert from 50 to 99 per cent accuracy, and to allow for various field factors, are presented in Table XI. Use of the log factors contained in Table XI permits construction of performance curves for 5, 10, and 15 APS levels of visual capacity. These curves have been plotted in Figs. 28-32, along with the curves for other levels of visual capacity. The families of performance curves contained in these figures will make it possible, at a later date, for different levels of visual capacity and/or different field factors to be utilized in systems of lighting specification.

As noted above, there is no adequate factual basis for assigning levels of visual capacity and field factors to actual practical tasks at this time. However, in order to illustrate the use of the families of performance curves presented in Figs. 28-32, an effort will be made to evaluate the 56 tasks described in Section VI in terms of levels of visual capacity and field factors which *may* be applicable to each task. This evaluation will be intuitive, based upon the general understanding of visual performance which has been developed in preceding sections of this report.

Evaluation of the 56 tasks began with an attempt to estimate a reasonable value of FF to assume in each case. It was decided that the tasks all represented FF 10 and FF 15. All the tasks selected seemed to involve sufficient uncertainty

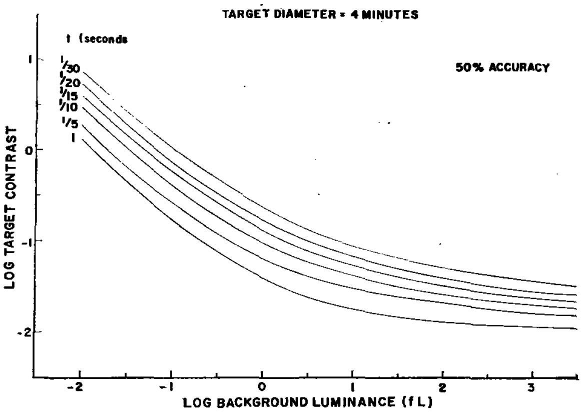

Figure 33. Smoothed threshold contrast curves for a four-minute diameter standard disc target. Each curve represents a different exposure duration in seconds.

as to where the task would appear, or a sufficient need for sensory guidance of the oculomotor adjustment mechanisms so that the enlargement of the receptive field represented by values of the field factor equal to 10 or more was indicated. The tasks where there was complete knowledge of the location of the task, such as reading, were considered to require FF 10. The tasks involving some lack of information as to the exact location or time of occurrence of the task, such as inspection of garments for pattern threads, were considered to require FF 15.

It was assumed that a visual capacity of 30 APS should be provided in each case, unless there were evidence of either information limitation or response limitation in the task. Continuous reading tasks involving no overt response component were considered to be capable of performance at a 30 APS level. However, such tasks as reading while transcribing shorthand were considered to be responses limited to the 15 APS level. Tasks in which there is comparatively little information available, such as reading price tags, were consid-

TABLE X — Values of the Contrast Multiplier to Convert from 50 Per Cent to 99 Per Cent Accuracy.

t (Seconds)	Contrast Multiplier
$^1/_5$	1.98
$^1/_{15}$	1.87
$^1/_{20}$	1.86

TABLE XI — Values of the Log Factors to Convert from 50 Per Cent to 99 Per Cent Accuracy and to Allow for Various Field Factors.

t (Seconds)	FF 5	FF 7.5	FF 10	FF 15	FF 20
$^1/_5$	.996	1.172	1.297	1.473	1.597
$^1/_{15}$	.970	1.146	1.271	1.447	1.572
$^1/_{20}$	.969	1.145	1.270	1.446	1.571

ered to be information limited to the 15 APS level. Inspection tasks in which there is very little information, such as looking for pocket stitching on a shirt, were considered to be information limited to the 10 APS level. Inspection tasks, such as looking for a broken thread on a spinner bobbin, were considered to be severely information-limited to a level of visual capacity of only 5 APS.

In order to establish lighting levels for each task, the value of log $\widetilde{C}$ for each task was entered on the performance curve representing the estimated level of visual capacity and field factor. A log luminance value was determined for each task. Requisite luminance levels for the specular tasks were obtained directly from these values, whereas requisite illumination levels for the non-specular tasks were obtained by allowing for the task reflectance.

Illumination values for the non-specular tasks,

TABLE XII — Non-Specular Visual Tasks Requiring Field Factor 10. Values of Illumination (Footcandles) for 99 Per Cent Accuracy.

Task No.	Task Description	Log $\widetilde{C}$	R	Visual Capacity (APS) 30	20	15	10	5	1
1.	Reading while writing: sample of ink-writing, one 6th grade student	.273	.76	RL	RL	2.40			
2.	Reading while writing: samples of No. 2 pencil, twelve 6th grade students with poorest writing in class of 31	–.167	.76	RL	RL	69.0	22.4		
3.	Reading: 8-point Bodoni type	.228	.70	*13.7*					
4.	Reading: 6-point textype	.144	.70	*27.8*					
5.	Reading: 8-point textype	.333	.70	*6.70*					
6.	Reading: 10-point textype	.372	.70	*5.38*					
7.	Reading: 12-point textype	.478	.70	*3.12*					
8.	Reading while transcribing: sample of shorthand copy with No. 3 pencil	–.181	.79	RL	RL	*76.4*	23.6		
9.	Reading: typed original, good ribbon	.397	.62	*5.22*					
10.	Reading: typed original, extremely poor ribbon	–.338	.62	*>5100.*	>5100.	1090.	244.	67.3	7.04
11.	Reading: typed carbon, fifth copy	–.194	.53	*3600.*	360.	128.	37.7		
12.	Reading: dark blue mimeograph stencil, with clear plastic overlay	.498	.11	*18.0*					
13.	Reading: Thermofax copy, poor quality	–.278	.63	*>5020.*	1480.	355.	79.5	28.2	
14.	Reading: No. 2 pencil on tracing paper over blueprint	.050	.59	*81.2*	26.2				
15.	Cutting: white chalk mark on blue serge cloth	.664	.020	RL	RL	*17.7*			
21.	Cutting: orange chalk on light brown tweed	–.168	.18	RL	RL	*292.*	92.1	30.6	
22.	Cutting: white chalk on gray cloth	–.018	.33	RL	RL	*38.2*			
29.	Reading: price tag, pencil	–.236	.63	IL	IL	*205.*	47.9		
30.	Reading: price tag, ink	.127	.76	IL	IL	*5.36*			
49.	Reading: white line on blueprint, tracing paper overlay	–.558	.59	IL	IL	*>5360.*	>5360.	>5360.	141.
51.	Cutting: white chalk on tan cloth	–.561	.24	RL	RL	*>10000.*	>10000	>10000.	417.
	School tasks		.76						
a.	12 easier	.185		RL	RL	3.78			
b.	12 more difficult	–.215		RL	RL		33.7		

TABLE XIII — Specular Visual Tasks Requiring Field Factor 10. Values of Luminance (Footlamberts) for 99 Per Cent Accuracy.

Task No.	Task Description	Log $\widetilde{C}$	Visual Capacity (APS) 30	20	15	10	5	1
44.	Reading: proofed type	–.442	RL	RL	*>3160.*	1260.	302.	12.6
45.	Reading: unproofed type	–.283	RL	RL	*245.*	57.5		
46.	Reading: vernier calipers, non-etched	–.300	IL	IL	*331.*	79.5		
47.	Reading: new micrometer, etched	–.022	IL	IL	*12.9*			
48.	Reading: old micrometer							
a.	specular on numbers	–.233	IL	IL	*120*	28.8		
b.	specular on division	.030	IL	IL	*8.32*			

and luminance values for the specular tasks obtained in this way are presented in Tables XII, XIII, and XIV. In each case, the log equivalent contrast, $\tilde{C}$, is given. The task reflectance is given for the non-specular tasks. The illumination or luminance value corresponding to the level of visual capacity considered to be required by each task is italicized. Reduction of the required level of visual capacity to less than 30 APS by response limitation and information limitation is indicated

TABLE XIV — Non-Specular Visual Tasks Requiring Field Factor 15. Values of Illumination (Footcandles) for 99 Per Cent Accuracy.

Task No.	Task Description	Log $\tilde{C}$	R	Visual Capacity (APS)					
				30	20	15	10	5	1
16.	Inspection: dot defects on dark blue cloth	.562	.017	IL	IL	IL	IL	*17.8*	
17.	Inspection: gray line defect on black cloth	.369	.024	IL	IL	IL	IL	*27.5*	
18.	Inspection: darned blemish on gray cloth	–.022	.10	IL	IL	IL	IL	*74.1*	18.4
19.	Inspection: brown stitching on brown silk		.12						
	a. vertical stitching	–.398		IL	IL	IL	*>10000.*	>10000.	692.
	b. horizontal stitching	–.022		IL	IL	IL	*193.*	61.7	15.3
20.	Inspection: gray stitching on gray silk		.076						
	a. vertical stitching	–.268		IL	IL	IL	*>10000.*	4160.	155
	b. horizontal stitching	–.468		IL	IL	IL	*>10000.*	>10000.	>10000
23.	Inspection: light stitching on blue serge cloth		.018						
	a. vertical stitching	.915		IL	IL	IL	*8.45*		
	b. horizontal stitching	1.191		IL	IL	IL	*3.66*		
24.	Inspection; pattern threads, men's silk and wool suiting	–.021	.22	IL	IL	IL	*102.*	32.9	
25.	Inspection: dark brown raised threads on silk	–.180	.035	IL	IL	IL	IL	*1680.*	143.
26.	Inspection: blue-gray raised threads on silk	–.283	.046	IL	IL	IL	IL	*9650.*	281.
27.	Inspection: pattern threads, white handkerchief	–.045	.91	IL	IL	IL	*31.9*		
28.	Inspection: pocket stitching, tan shirt	–.318	.53	IL	IL	IL	*>5960.*	1890.	39.4
31.	Inspection: broken white wool thread on spinner bobbin		.66						
	a. 30° illumination	.302		IL	IL	IL	IL	*1.26*	
	b. normal illumination	.042		IL	IL	IL	IL	*6.32*	
32.	Inspection: broken black thread on spinner bobbin, 30° illumination	–.174	.018	IL	IL	IL	IL	*2920.*	264.
33.	Inspection: broken gray thread on spinner bobbin, 30° illumination	.295	.079	IL	IL	IL	IL	*11.8*	
34.	Inspection: broken white nylon thread on spinner bobbin, 30° illumination	–.279	.78	IL	IL	IL	IL	*487.*	16.6
35.	Inspection: skip defect, viewed from 16 feet	–.080	.19	IL	IL	IL	IL	*71.0*	13.2
36.	Inspection: tight sound edge knot, viewed from 16 feet	.121	.19	IL	IL	IL	IL	*12.9*	
37.	Inspection: bark wave, viewed from 16 feet	–.193	.19	IL	IL	IL	IL	*381.*	28.9
38.	Inspection: small decay spot, viewed from 16 feet	–.443	.19	IL	IL	IL	IL	*>10000.*	2900.
39.	Inspection: chip grain, viewed from 16 feet	–.323	.19	IL	IL	IL	IL	*6470.*	123.
40.	Inspection: small seasoning check, viewed from 30 inches	–.181	.19	IL	IL	IL	IL	*317.*	26.4
41.	Inspection: small skip defect, viewed from 30 inches	–.148	.19	IL	IL	IL	IL	*187.*	20.7
42.	Inspection: chip grain, viewed from 30 inches		.19						
	a. no specular	–.243		IL	IL	IL	IL	*1030.*	48.8
	b. specular	.114		IL	IL	IL	IL	*13.4*	
43.	Inspection: brown color difference in cloth	–.211	.12	IL	IL	IL	IL	*870.*	56.2
50.	Inspection: brown thread stitching on brown silk tweed	–.593	.12	IL	IL	IL	IL	*>10000.*	>10000.
52.	Inspection: rolled-edge defect on white handkerchief	–.725	.91	IL	IL	IL	IL	*>3470.*	>3470.
53.	Inspection: seasoning check, viewed at 16 feet	–.545	.19	IL	IL	IL	IL	*>10000.*	>10000.
54.	Inspection: brown stain on gray cloth	–.523	.12	IL	IL	IL	IL	*>10000.*	>10000.
55.	Inspection: brown spot on red necktie	–.545	.084	IL	IL	IL	IL	*>10000.*	>10000.
56.	Inspection: brown spot on tan necktie	–.694	.18	IL	IL	IL	IL	*>10000.*	>10000.

TABLE XV — Comparative Values of Illumination or Luminance for 99 Per Cent Accuracy.

Task No.	Task Description	Method Involving: Selected FF and APS E (fc)	Method Involving: Selected FF and APS B (fL)	Recommended Method: FF 15 E (fc)	Recommended Method: 5 APS B (fL)
1.	Reading while writing: sample of ink-writing, one 6th grade student	2.40		1.38	
2.	Reading while writing: samples of No. 2 pencil writing, twelve 6th grade students with poorest writing in class of 31	69.0		63.0	
3.	Reading: 8-point Bodoni type	13.7		1.87	
4.	Reading: 6-point textype	27.8		2.98	
5.	Reading: 8-point textype	6.70		1.13	
6.	Reading: 10-point textype	5.38		0.94	
7.	Reading: 12-point textype	3.12		0.60	
8.	Reading while transcribing: sample of shorthand copy with No. 3 pencil	76.4		76.5	
9.	Reading: typed original, good ribbon	5.22		0.97	
10.	Reading: typed original, extremely poor ribbon	>5100.		3140.	
11.	Reading: typed carbon, fifth copy	3600.		133.	
12.	Reading: dark blue mimeograph stencil, with clear plastic overlay	18.0		3.54	
13.	Reading: Thermofax copy, poor quality	>5020.		589.	
14.	Reading: No. 2 pencil on tracing paper over blueprint	81.2		6.58	
15.	Cutting: white chalk mark on blue serge cloth	17.7		10.4	
16.	Inspection: dot defects on dark blue cloth	17.8		17.8	
17.	Inspection: gray line defect on black cloth	27.5		27.5	
18.	Inspection: darned blemish on gray cloth	74.1		74.1	
19.	Inspection: brown stitching on brown silk				
a.	vertical stitching	>10000.		>10000.	
b.	horizontal stitching	193.		61.7	
20.	Inspection: gray stitching on gray silk				
a.	vertical stitching	>10000.		4160.	
b.	horizontal stitching	>10000.		>10000.	
21.	Cutting: orange chalk on light brown tweed	292.		266.	
22.	Cutting: white chalk on gray cloth	38.2		21.0	
23.	Inspection: light stitching on blue serge cloth				
a.	vertical stitching	8.45		5.05	
b.	horizontal stitching	3.66		2.22	
24.	Inspection: pattern threads, men's silk and wool suiting	102.		32.9	
25.	Inspection: dark brown raised threads on silk	1680.		1680.	
26.	Inspection: blue-gray raised threads on silk	9650.		9650.	
27.	Inspection: pattern threads, white handkerchief	31.9		9.86	
28.	Inspection: pocket stitching, tan shirt	5960.		1890.	
29.	Reading: price tag, pencil	205.		241.	
30.	Reading: price tag, ink	5.36		3.10	
31.	Inspection: broken white wool thread on spinner bobbin				
a.	30° illumination	1.26		1.26	
b.	normal illumination	6.32		6.32	
32.	Inspection: broken black thread on spinner bobbin, 30° illumination	2920.		2920.	
33.	Inspection: broken gray thread on spinner bobbin, 30° illumination	11.8		11.8	
34.	Inspection: broken white nylon thread on spinner bobbin, 30° illumination	487.		487.	
35.	Inspection: skip defect, viewed from 16 feet	71.0		71.0	
36.	Inspection: tight sound edge knot, viewed from 16 feet	12.9		12.9	
37.	Inspection: bark wave, viewed from 16 feet	381.		381.	
38.	Inspection: small decay spot, viewed from 16 feet	>10000.		>10000.	
39.	Inspection: chip grain, viewed from 16 feet	6470.		6470.	
40.	Inspection: small seasoning check, viewed from 30 inches	317.		317.	
41.	Inspection: small skip defect, viewed from 30 inches	187.		187.	
42.	Inspection: chip grain, viewed from 30 inches				
a.	no specular	1030.		1030.	
b.	specular	13.4		13.4	
43.	Inspection: brown color difference in cloth	870.		870.	
44.	Reading: proofed type		>3160.		>3160.
45.	Reading: unproofed type		245.		447.
46.	Reading: vernier calipers, non-etched		331.		631.
47.	Reading: new micrometer, etched		12.9		7.41
48.	Reading: old micrometer				
a.	specular on numbers		120.		148.
b.	specular on division		8.32		4.62
49.	Reading: white line on blueprint, tracing paper overlay	>5360.		>5090.	
50.	Inspection: brown thread stitching on brown silk tweed	>10000.		>10000.	
51.	Cutting: white chalk on tan cloth	>10000.		>10000.	
52.	Inspection: rolled-edge defect on white handkerchief	>3470.		>3470.	
53.	Inspection: seasoning check, viewed at 16 feet	>10000.		>10000.	
54.	Inspection: brown stain on gray cloth	>10000.		>10000	
55.	Inspection: brown spot on red necktie	>10000.		>10000	
56.	Inspection: brown spot on tan necktie	>10000.		>10000.	
	School tasks				
a.	12 easier	3.78		2.14	
b.	12 more difficult	123.		141	

by the abbreviations RL and IL, respectively. Table XII contains values for the non-specular tasks for which FF 10 was considered appropriate, whereas Table XIII contains data for the specular tasks for this value of the field factor. Table XIV contains data for non-specular tasks for which FF 15 was considered appropriate. Illumination and luminance values have also been determined for levels of visual capacity less than the level considered to be required by the task. These determinations were made for progressively smaller levels of visual capacity down to 1 APS, until all illumination levels for the non-specular tasks were less than 50 footcandles, and all luminance levels for the specular tasks were less than 100 footlamberts. These data make it possible to assess the level of visual capacity provided various tasks by levels of lighting less than those specified on the basis of levels of visual capacity and field factors considered appropriate to each task.

It may be of interest to compare the lighting levels established for each task from these estimates of appropriate levels of visual capacity and field factors with the levels based upon the lighting specification system recommended for current use. The values are presented for comparison in Table XV. In most cases, the differences are not large. The method based upon selected levels of visual capacity and selected field factors specifies illumination levels for ordinary reading tasks which are more in line with past recommendations. On the other hand, tasks 10, 11, and 13 seem to give extremely high footcandle values with the method of selected levels of visual capacity and field factors. It is not worthwhile speculating on the significance of these differences until further studies have been made of the processes of assimilating multiple items of information in each fixational pause, and of the field factors required for various visual tasks.

In order to evaluate the feasibility of a lighting specification system which requires selection of a level of visual capacity and a field factor for each task, we need information on the extent to which lighting levels depend upon the precise values selected. It may be noted from the curves in Figs. 28-32 that the variation in field factor from 5 to 20 has approximately the same effect upon the standard disc data as a variation in APS from 1 to 30. It should also be apparent from the curves in the figures that the effect of variations in FF or APS is greater, the lower the value of the equivalent contrast of the task.

A more quantitative assessment of the effect of the selection of FF and APS levels may be made by reference to Table XVI. Values of the luminance required for performing a given task were computed for each of the FF and APS values represented by the curves in Figs. 28-32, for each of five values of log equivalent contrast of the task. "Light factors" were computed, representing the ratios of the luminances required for given values of FF and APS to the luminance required for the FF 15; 5-APS condition recommended as the current standard. These factors illustrate, most simply, the effect of the choice of FF and APS level upon the illumination level required for non-specular tasks and the luminance level required for specular tasks.

TABLE XVI — Light Factors for Various FF and APS Values.

A. Log $\widetilde{C} = -.300$; Values relative to 549. footlamberts

FF	APS					
	30	20	15	10	5	1
5	.151	.0419	.0190	.00741	.00315	.00132
7.5	1.90	.295	.105	.0318	.0102	.00282
10	>5.75	2.46	.575	.129	.0450	.00589
15	>5.75	>5.75	>5.75	5.75	1.00	.0345
20	>5.75	>5.75	>5.75	>5.75	>5.75	.525

B. Log $\widetilde{C} = -.150$; Values relative to 32.7 footlamberts

FF	APS					
	30	20	15	10	5	1
5	.542	.211	.107	.0494	.0244	.0121
7.5	3.24	.929	.412	.156	.0597	.0244
10	22.3	3.36	1.27	.421	.145	.0437
15	>96.9	>96.9	16.9	3.70	1.00	.124
20	>96.9	>96.9	>96.9	40.4	10.7	.422

C. Log $\widetilde{C} = 0$; Values relative to 5.76 footlamberts

FF	APS					
	30	20	15	10	5	1
5	.975	.473	.262	.138	.0735	.0389
7.5	3.80	1.45	.722	.328	.155	.0758
10	14.5	3.98	1.79	.720	.300	.126
15	208.	27.3	9.55	3.02	1.00	.274
20	>550.	230.	53.6	12.3	4.35	.563

D. Log $\widetilde{C} = +.200$; Values relative to 1.47 footlamberts

FF	APS					
	30	20	15	10	5	1
5	1.26	.673	.435	.244	.136	.0795
7.5	3.16	1.65	.934	.495	.255	.139
10	7.76	3.36	1.76	.851	.436	.219
15	44.8	13.3	5.92	2.45	1.00	.454
20	223.	41.3	17.0	6.09	2.21	.762

E. Log $\widetilde{C} = +.400$; Values relative to .562 footlamberts

FF	APS					
	30	20	15	10	5	1
5	1.45	.773	.540	.310	.184	.116
7.5	2.91	1.61	1.05	.591	.322	.191
10	5.56	2.85	1.71	.938	.515	.288
15	17.1	7.66	4.12	2.03	1.00	.535
20	47.8	17.6	8.52	3.78	1.82	.855

It is apparent from Table XVI that varying FF from 5 to 20 or varying APS level from 1 to 30 can vary the light factor by as much as 1000. The range of values of log $\widetilde{C}$ contained in Table XVI includes approximately two-thirds of the values obtained in VTE assessment of the 56 practical tasks, so that the light factors presented in the table give a reasonable estimate of the effect of FF and APS levels for all the tasks studied. This analysis suggests that it is going to be necessary to develop fairly precise procedures for selecting values of the visual capacity level and the field factor, if the system is to have reasonable precision.

Of course, the light factors presented in Table XVI may be used to estimate the lighting levels which would have been recommended for the 56 tasks, had different levels of capacity and/or a different field factor been selected.

For example, consider task 9, for which $\log \widetilde{C} = +.397$. The illumination level specified by the FF 15, 5 APS-system is 0.97 footcandles. Suppose the illumination level were desired corresponding to the FF 10, 30 APS condition. The value of $\log \widetilde{C} = +.400$ in Table XVI is the most similar to the $\log \widetilde{C}$ value of the task. The light factor for FF 10 and 30 APS is 5.56. The estimated illumination level is $0.97 \times 5.56 = 5.38$ footcandles. The illumination level actually computed for the FF 10, 30 APS-condition is presented in Table XII as 5.22 footcandles. Similarly, task 45 has a value of $\log \widetilde{C} = -.283$. We may estimate the luminance for this specular task for the FF 10, 15 APS-condition from the value for the FF 15, 5 APS-condition given in Table VI as 447. footlamberts. The light factor for $\log \widetilde{C} = -.300$ is nearest the $\log \widetilde{C}$ value for the task; it is given in Table XVI as .575. The luminance is, therefore, $447. \times .575 = 257.$ footlamberts. The value obtained by precise calculations, and presented in Table XIII, is 245. footlamberts. Use of the light factors presented in Table XVI results in a close approximation in these cases, since the value of $\log \widetilde{C}$ for the task in each case so nearly approximated a value contained in the table. Since there are five values of $\log \widetilde{C}$ presented in Table XVI, it will usually be possible to come reasonably close by applying the light factor corresponding to the most nearly equivalent value of $\log \widetilde{C}$.

Of course, it will be possible to come even closer by use of linear interpolation between the light factor values contained in Table XVI. The following are illustrations of this technique. Consider task 48a, for which the value of $\log \widetilde{C}$ is $-.233$. The luminance for this specular task for the FF 15, 5 APS-condition is given in Table VI as 148. footlamberts. The light factors for conversion to the FF 10, 15 APS-level are 1.27 for $\log \widetilde{C} = -.150$ and .575 for $\log \widetilde{C} = -.300$. The light factor value obtained by linear interpolation is .885. Luminance is therefore estimated as $148. \times .885 = 131.$ footlamberts. The value obtained by precise calculations is presented in Table XIII as 120. footlamberts. Similarly, for task 30, the value of $\log \widetilde{C} = +.127$. The illumination for this nonspecular task for the FF 15, 5 APS-condition is given in Table VI as 3.10 footcandles. The light factors for conversion to the FF 10, 15 APS-level are 1.79 for $\log \widetilde{C} = 0$ and 1.76 for $\log \widetilde{C} = +.200$. The light factor obtained by linear interpolation is 1.77. The illumination is therefore estimated as $3.10 \times 1.77 = 5.48$ footcandles. The value obtained by precise calculations is presented in Table XII as 5.36 footcandles. These examples illustrate that use of interpolation between the light factors presented in Table XVI leads to satisfactory estimates of illumination and luminance levels for different values of FF and APS than those for which calculations have been reported.

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