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# A New Look at the Research Basis for Lighting Level Recommendations

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# A New Look at the Research Basis for Lighting Level Recommendations

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# Contents

# A New Look at the Research Basis for Lighting Level Recommendations

G. T. Yonemura and Y. Kohayakawa*

The validity of using threshold studies as the basis for lighting level recommendations is questioned. The performance of the eye at suprathreshold levels was investigated with sine- and square-wave gratings. The results of the study indicate that the behavior of the eye is significantly different at suprathreshold levels as opposed to threshold levels. For threshold studies, when contrast is plotted against luminance, the function is a monotonically decreasing function. At suprathreshold levels the function indicates the existence of a definite minimum, luminances greater or less requiring more contrast to appear subjectively equal. It is recommended that lighting levels be based on laboratory studies that appraise visual requirements and performance simulating conditions encountered in real world environments.

Key words: Gratings; illuminating engineering; lighting; modulation transfer function; suprathreshold visibility; visibility; vision.

## 1. Introduction

The determination of the quantity of illumination required for visual task performance should be based on empirical data obtained from the user. To this end, the Illuminating Engineering Society (IES) has adopted a Visibility Reference Function to serve as a standard or reference base for the determination of recommended levels of illumination [1].[1] See the solid curve in figure 1. The Visibility Reference Function was obtained under controlled laboratory conditions and is defined as the contrast required to *detect* a 4 min diameter luminous disk presented for 1/5 s, as a function of background luminance (L). The threshold contrast is the contrast required to detect the luminous disk 50 percent of the time using a forced choice technique. Contrast (C) is defined as:

$$C = (L_b - L_t)/L_b, \qquad (1)$$

where the subscripts $t$ and $b$ stand for target (luminous disk) and background, respectively. Usually the larger of the two areas constitutes the background luminance and is often referred to as the adaptation luminance. Equation (1) is often expressed as:

$$C = |\Delta L|/L_b, \qquad (1a)$$

the numerator being the luminance difference between target and background regardless of whether the target or background luminance is greater.

The detection threshold is the borderline between visibility and invisibility. Most routine visual tasks are not performed at this borderline of visibility and invisibility. The next higher order of visual performance requires the observer not only to detect the presence of an object, but also to recognize it as a member of a group. This level will generally require shape or form discrimination and is called the *acuity threshold*. Classical examples of this task are the Landolt *C* and the Snellen Chart. In an acuity test the observer is not only required to detect the presence of an object, but in addition is required to detect the orientation of the gap in the landolt *C* or recognize the perceived image as a specific alphabet member in the Snellen Acuity Test. But in the majority of realistic task conditions, the task is significantly above the acuity threshold. For example, in reading we see (detect) some things on the page and recognize (acuity) them as specific

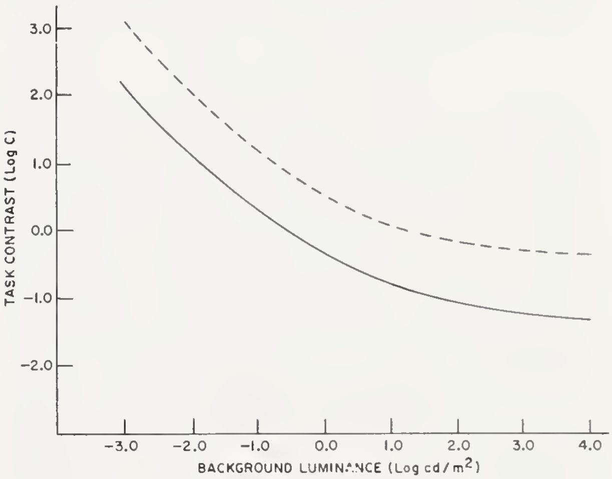


FIGURE 1. *The visual performance reference base used by the Illuminating Engineering Society for recommending levels of illumination.*

The solid curve is the Visibility Reference Function and the dashed curve is the Visual Performance Criterion Function.

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[1] Figures in brackets indicate the literature references at the end of this paper.

members of the alphabet. That is, under most realistic conditions, the visual tasks are significantly above threshold. We generally see the task—the only remaining question is, "how well can we see it?". Is it better under condition A rather than B? In the IES system, extrapolation from detection to realistic levels is accomplished by the concept of visibility level.

The Visibility Reference Function is called $VL1$ (visibility level 1). Higher levels of visibility (suprathreshold) are defined as $VLi$ (visibility level $i$). In terms of its physical correlates, contrast and luminance, $VLi$ is defined as:

$$C_i(L) = i[C_1(L)]; \tag{2}$$

where $C_i(L)$ is the suprathreshold contrast at $VL_i$ and $C_1$ is the contrast threshold as given by the Visibility Reference Function for a given background luminance level ($L$). The contrast threshold, $C_1$, is the just noticeable difference (jnd). Therefore $VLi$ is $i$ number of jnd steps above threshold, that is:

$$C_i(L)/C_1(L) = VLi(L). \tag{3}$$

The IES in its handbook (5th ed.) [1] defines $VL8$ ($i=8$) as the Visual Performance Criterion Function, shown by the dashed curve in figure 1. That is, $VL8$ is the luminance contrast required at different levels of task background luminances under conditions of "realistic visual work," or alternately, the luminance required for a task of a given contrast to meet the criterion for visual task performance.

$VL8$ was obtained by considering three aspects of realistic conditions that differed from those existing in the detection experiments: (1) threshold detection for a moving rather than a stationary target, (2) redefinition of the threshold as detecting the presence of the target 99 percent of the time instead of 50 percent, and (3) the threshold for detecting a target whose apparent location was unknown as opposed to knowing exactly where the target was going to appear. Experiments conducted with moving targets indicated that the contrast required to detect a moving target was 2.8 times greater than that required to detect a stationary target. Similarly the contrast multiplier required to change from 50 percent probability of detection to 99 percent probability of detection was found to be 1.9. The contrast required to detect a target whose appearance location was unknown was 1.5 times greater than that required to detect a target whose appearance location was known. The product of these three contrast multipliers, $(2.8)(1.9)(1.5) = 8.0$, is the factor by which the Visibility Reference Function ($C_1$) has to be multiplied in order to approach realistic conditions. The dashed curve in figure 1 is the Visual Performance Criterion Function ($VL8$), discussed earlier, and is obtained by multiplying the Visibility Reference Function (solid curve in fig. 1) by 8. The assumption is that since $VL1$ represents contrasts that are subjectively equal (equal detectability) $VL8$ also represents physical contrasts that are subjectively equal:

$$C_8(L_i) = C_8(L_j), \tag{4}$$

or the physical contrast for $VL8$ at luminance $i$ *is matched by* physical contrast for $VL8$ at luminance $j$. That is, for any given $VL$ all points falling on the curve of contrast plotted against luminance have equal visibility. For a more complete description of the Reference Visibility Function and Visual Performance Criterion Function see Blackwell [2].

There are two points in the extrapolation to higher visibility levels that should be validated. First, all the data, including the contrast multipliers for correspondence to realistic conditions, were obtained at *threshold levels*, therefore direct experiments at suprathreshold levels (100% seeing) should be conducted. Second, is the linear extrapolation (contrast multipliers) to higher visibility levels, eq (2), justified? Bodmann anticipated this difficulty, when he suggests that eq (3) be defined as contrast factor, as "the term contrast factor would not anticipate its interpretation and might therefore be preferred by the reader" [3]. Cases can be cited from the literature where predictions of suprathreshold performance from threshold data did (can) lead to erroneous predictions. Poppel and Harvey [4] found that subjective brightness as a function of retinal eccentricity predicted from threshold data differed significantly from the empirical data obtained by experiments performed at suprathreshold level. An example of this difference in photometry is the spectral luminous efficiency function. We can discuss spectral luminous efficiency in terms of retinal location, rods and cones, etc., but for purposes of this discussion, the primary interest is the brightness sensitivity as a function of radiant energy evaluated wavelength by wavelength. The function describing the sensitivity of the eye to radiant energy from different parts of the visible spectrum is different when obtained at the detection (threshold) levels [5] as opposed to equal brightness contours obtained for suprathreshold stimuli [6]. In both examples, experiments conducted at suprathreshold levels indicate the inappropriateness of predicting suprathreshold functions from threshold data.

The grating (alternating light and dark bars) has been in use for a long time as a resolution power test in lens evaluation and as a target for psychophysical studies in vision. The resolution threshold as a function of pertinent parameters has been extensively investigated for several forms of visual targets: Landolt $C$, single lines, disks, etc., as well as gratings [7]. Bryndgdahl [8] investigated subjective contrast of gratings at suprathreshold levels, but his range of luminances was limited, 5 to 20 cd/m$^2$. Watanabe et al. [9] had subjects make equality of contrast judgments for gratings at mean luminances of 17 to 171 cd/m² for many spatial frequencies, but only at a single low contrast level, 0.032. The purpose of the present experiment was to determine whether the function obtained under visibility conditions significantly higher than detection or acuity thresholds would be similar in form to that obtained at threshold levels. The present study will investigate visibility at suprathreshold levels over a large range of luminances, 0.06 to 630 cd/m², and contrasts, 0.08 to 0.7.

## 2. Experiment I. Sinusoidal Gratings

Two identical sinusoidal (luminance distribution of dark and light bars follows a sinusoidal pattern) grating transparencies were projected through separate projectors.[2] The luminous intensities of the projectors were controlled by neutral density filters and neutral density wedges and balances. Each grating subtended a visual angle of 7.5° (0.13 rad), and the gratings were projected adjacent to each other on a vertical (frontal) plane with the bars oriented horizontally. The gratings were seen against a dark surround and the viewing distance was 145 cm. The contrasts of the gratings were varied by defocusing the images. The contrast change was accompanied by a slight change in magnification and luminance of the grating, but these changes were below threshold for the contrast ranges used in a given experimental run; consequently, they were ignored when the data were analyzed. The modulation of the projected pattern, defined as

$$M = (L_{max} - L_{min})/(L_{max} + L_{min}), \qquad (5)$$

was measured for every new condition. $M$ will be used to denote contrast defined by eq (5) and $C$ for contrast as defined by eq (1). The spatially averaged luminance, defined as:

$$L_m = (L_{max} + L_{min})/2, \qquad (6)$$

is the counterpart of $L_b$ in eq (1). Since a sinusoidal distribution retains its sinusodial form after defocusing, nothing in the image changes except the contrast. The modulation was evaluated by measuring the luminances at the centers of the dark and light bars with a modified spot photometer.

### 2.1. Procedure

The reference grating of fixed spatial frequency, contrast and spatially averaged luminance was presented in the left visual field. The test target presented in the right field was in all cases of the samc spatial frequency as the reference field. In the first trial, the luminances of the two fields were the samc. The Observer (O) was asked to vary the contrast of the test field until both fields appeared to be of equal "clarity" or "distinctness." These adjustments were made by changing the focus of the test field. When making these adjustments, O was asked to look at the center of thc grating patterns and not near the edge separating the test and reference gratings. Since both fields were of the same luminance and frequency, the average contrast obtained for the test field should be the same as that for the reference field. If O did not mcet a 1 percent criterion—that is, if the average of 10 match settings of the test field was not within 1 percent of the reference stimulus contrast—O was given a practice session. In all cases but one, practice sessions were not required as the test matches were within 0.5 percent of the reference field contrast under identical frequency and luminance conditions.

During the next phase of the study, a neutral filter of density ($D$) 0.5 was added to the test field. O was asked to vary the contrast of the now dimmer test field until the clarities of both gratings were subjectively equal. After O made a setting, the experimenter changed the contrast of the test field. In half of the cases the experimenter increased the contrast over the level set by O, and in the other half the contrast was decreased. O was asked to make another match. This procedure was repeated for a total of 10 settings. The mean of these 10 test field contrast settings was computed, the test field was set to this mean value and the contrast for this mean setting was measured with a modified spot photometer. The luminance of the test field was then decreased by an additional 0.5 $D$ (a total of 1.0 $D$), making the luminance of the reference field 10 times greater than that of the test field. O was again asked to make 10 "equality of clarity" matches, and the average setting was measured with the photometer. For the next trial, the spatially averaged luminance and contrast of the reference field were changed to the luminance and mean contrast value of the test field based on the previous run and the same procedure was followed again and again as described above. This cascade technique, whereby the reference stimulus replaced the previous test field, was continued in 1.0 $D$ steps until the apparatus limitations were reached. When the mean luminance level of either field was less than 1.0 cd/m², the O was dark adapted for 5 minutes prior to the run.

Either two or three starting reference contrasts were used for each frequency. The contrast values ranged from 0.7 to 0.08. Three spatial frequencies: 1.8, 3.9 and 7.7 cycles per degree (cpd) were investigated for spatially averaged luminances between 0.06 and 630 cd/m².

### 2.2 Results

The results of the experiment with sinusoidal gratings are presented in figures 2–4. Each datum

[2] The gratings transparencies were furnished by the Optics and Micrometrology Section, Institute for Basic Standards, NBS.

point represents the mean value of 10 settings. Each curve in these graphs represents a contour of constant clarity, with the datum point at 630 cd/m$^2$ being the reference starting contrast. The outstanding feature of the most of these curves is the existence of an optimum luminance level, at which a minimum amount of contrast is needed to achieve a given degree of clarity. Obtaining the same clarity at either a higher or lower mean luminance requires more contrast than is needed at this optimum luminance. This finding applies to gratings presented at suprathreshold levels only. These

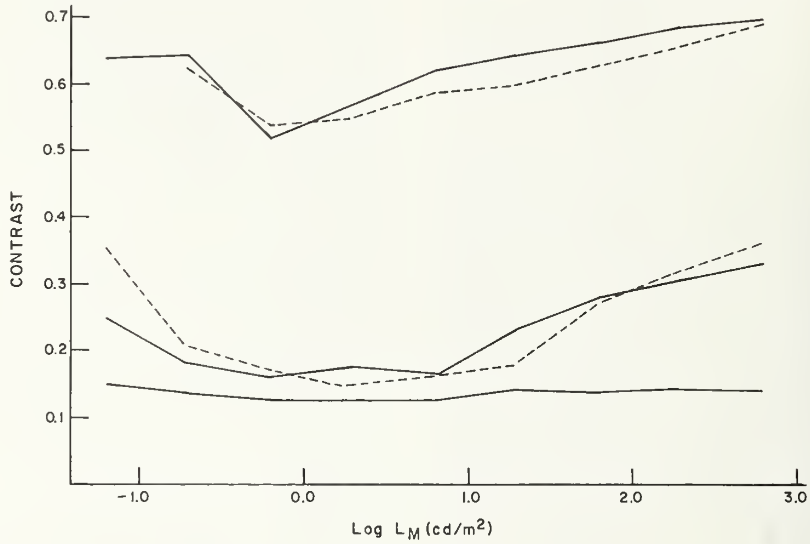


FIGURE 2. *Equal-clarity contours as a function of mean spatial luminance for a sine-wave grating of frequency 1.8 cpd.*

The solid and dashed curves represent the results for two different observers.

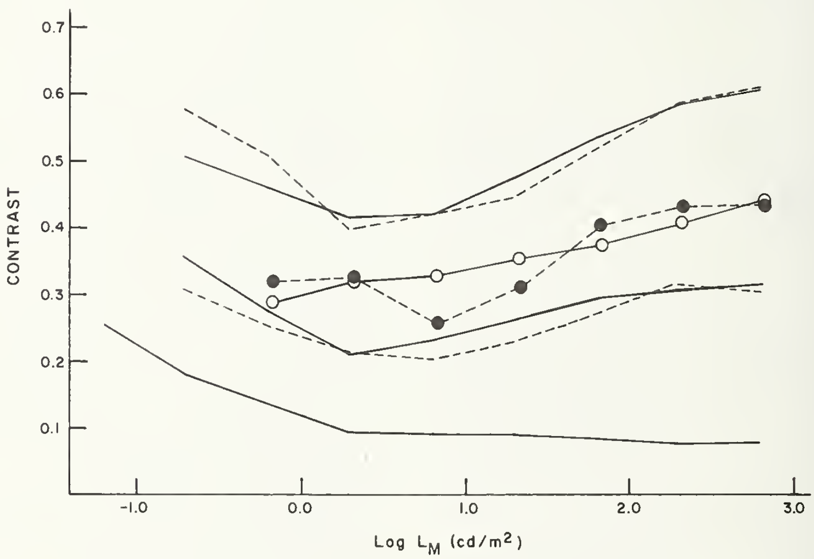


FIGURE 3. *Equal-clarity contours as a function of mean spatial luminance for a 3.9 cpd sine-wave grating.*

The solid and dashed curves represent the results for two different observers. The curves with the circled data points are for surround luminaces maintained at the mean spatial luminance of the grating with the higher luminance.

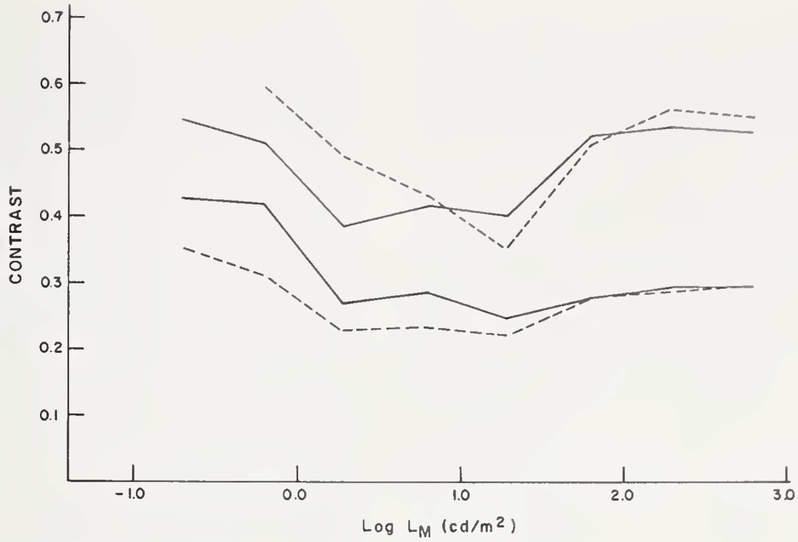


FIGURE 4. *Equal-clarity contours as a function of mean spatial luminance for a 7.7 cpd sine-wave grating.*

The solid and dashed curves represent the results for two different observers.

optimum luminance levels appear to depend on the frequency of the grating, shifting toward higher luminance values as spatial frequency (fineness of detail) increases. When the reference (starting) contrast approaches a level near the resolution threshold, the equal-clarity contours assume a monotonically decreasing form similar to that obtained at resolution thresholds. This is clearly seen in the lowest equal-clarity contour for 3.9 cpd, figure 3.

The dark surround used in the experiment may have had an important effect on the results. To investigate this possibility, a square surround field, 25.1 deg (0.438 rad) on each side, was presented during the matches. The luminance of the surround was always the spatially averaged luminance of the brighter grating. The results of this experiment are presented in figure 3 as circles. These circles indicate the occurrence of an optimum luminance level. (It can be presumed that the needed contrast must rise at sufficiently low luminance levels, so the optimum for the open-circle data must be below the lowest luminance used.)

## 3. Experiment II. Square-Wave Gratings

Most practical visual tasks involve targets with sharp rather blurred edges. The spatial luminance distribution of the sinusoidal grating has an edge gradient that can be called blurred. Furthermore, when the amplitude of a sinusoidal grating is changed, although the spatial luminance distribution is still sinusoidal, the slope of the edge gradient is different. A square-wave grating by definition has a sharp cutoff separating the dark and light bars. In order to be sure that the results of the experiments with sinusoidal gratings were not artifacts due to specific shape of the spatial luminance distributions, analogous experiments were conducted with a square-wave grating.

### 3.1. Procedure

A single projector displayed a square-wave grating transparency of 3.9 cpd with the light and dark bars running horizontally. The lower half of this grating was projected through a 0.7 *D* neutral density filter and was used as the test field, with the top half being the reference field. The observer was thus presented with two grating patterns physically similar in all respects except for the mean luminances. The contrast of the grating was varied by superimposed veiling lights, since defocusing distorts square-waves. Two additional projectors were used to add homogeneous veiling illumination independently to the top and bottom gratings. The luminous intensities from both veiling projectors were controlled by neutral density filters, wedges and balances. By increasing or decreasing the luminous intensity of the veiling lights, the grating contrast could be varied. The spatially averaged luminance also changed as the contrast was changed.

The reference field was kept constant at a given spatially averaged luminance and contrast. The contrast and mean luminance of the test field were varied by the veiling projector until a match with the reference field in clarity was obtained. The setting of the veiling-light variable-density wedge was recorded and randomly changed to a new setting for the next trial. Ten observations were taken for each condition. The reference field was then changed so that the contrast and mean luminance corresponded to the mean value obtained for the test field on the previous run. Because of apparatus limitations, an exact match for luminance and contrast could not be obtained, but as can be seen in figures 5 and 6 a close approximation was obtained. The mismatches appear as open spaces between ends of straight line segments making up the curve.

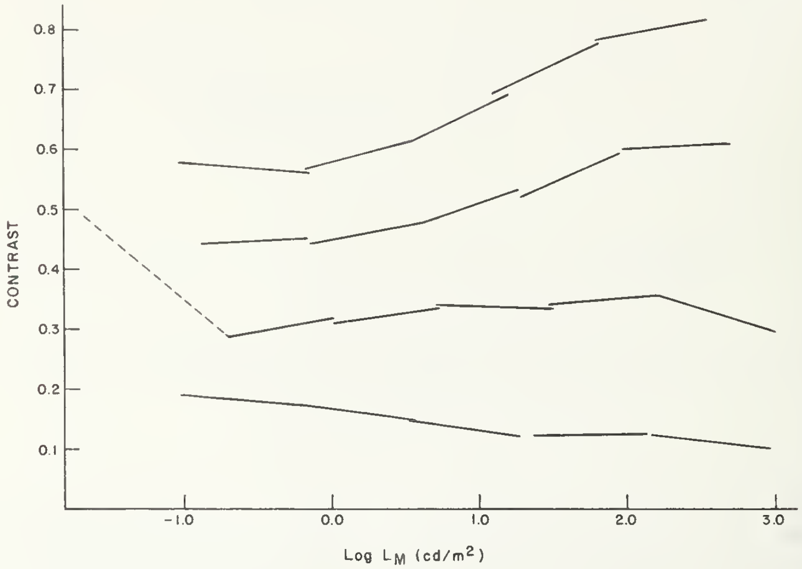


FIGURE 5. *Equal-clarity contours as a function of mean spatial luminance for a 3.9 cpd square-wave grating.*

Observer YK.

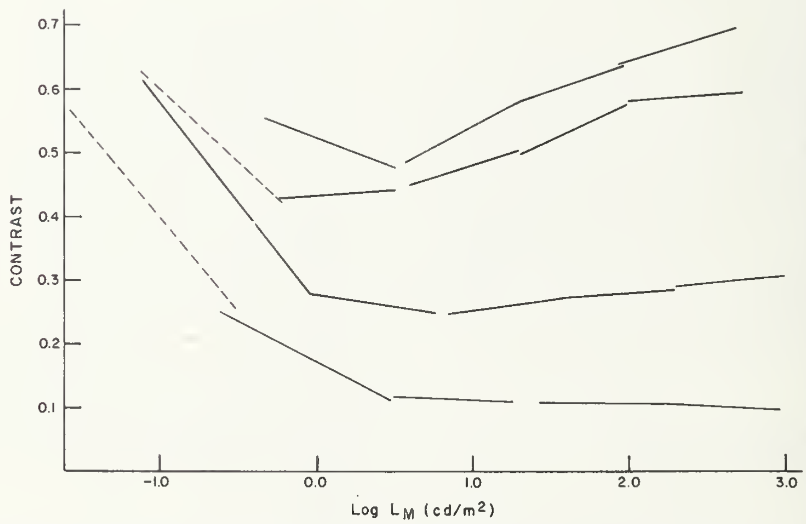


FIGURE 6. *Equal-clarity contours as a function of mean spatial luminance for a 3.9 cpd square-wave grating.*

Observer GY.

### 3.2. Results

The results for the square-wave gratings are shown in figures 5 and 6. The results are similar to those obtained with sine-wave gratings. For contrasts significantly above threshold, there is an optimum mean luminance level at which a minimum amount of contrast is needed to achieve a given degree of clarity. For grating clarities approaching resolution threshold, the classical monotonically decreasing function is obtained. For square-wave gratings, as for sine-wave gratings, the functions obtained at threshold levels are significantly different from those obtained at suprathreshold levels. The left ends of the dashed lines in figures 5 and 6 represent contrasts which were at the maximum levels obtainable with the apparatus for the given condition. The observer felt that this contrast value "almost" gave equal distinctness. That is, the subject felt that a slight increase in contrast would have been sufficient to meet the equality criterion.

## 4. Discussion

The Visibility Reference Function currently used as the standard for recommending levels of illumination states that visibility increases monotonically as luminance is increased. That is, as luminance increases, the contrast required to detect the presence of an object decreases. This study utilizing a different psychophysical technique confirms the above, but only for the special condition where visibility is at or near threshold levels. Near threshold the contrast required to match the same target for clarity at a higher luminance decreases monotonically as luminance is increased. But, when the targets are significantly above detection and acuity thresholds, the form of the equal-clarity contours changes from a monotonically decreasing function to one indicating the presence of a minimum contrast level. There appears to be an optimum luminance level where the target is seen with a given degree of clarity at a minimum contrast level, or with maximum clarity for a fixed value of contrast. The observation that the equal-clarity contours near threshold levels, like the detection function, decrease monotonically as luminance is increased, indicates that the existence of an optimum luminance at suprathreshold levels is not an artifact due to criterion differences or experimental methodology. There appears to be a continuous transition from the "monotonic" to the "optimum" form, and the simple detection or acuity function can be identified with seeing at a minimum level of clarity.

The spatial frequencies used in this study were 7.7, 3.9, and 1.8 cpd; the width of the light or dark bars being 3.90, 7.69, and 16.7 min, respectively. These values can be compared to the 4 min luminous disk used by Blackwell [2], the 2.5 and 1.6 min line thicknesses for numbers used by Bodmann [10] and Weston's [11] 1.5 to 4.5 min gap in the Landolt *C*. All of these earlier data were considered directly or indirectly to derive recommended illumination levels. The results of the present study indicate that for suprathreshold stimuli, the size effect is manifested by changes in the location of the optimum luminance level on the luminance axis. Figures 2–4 indicate that as spatial frequency is increased (or bar-width is decreased) the optimum luminance level is shifted toward higher luminance values. More data will have to be obtained at suprathreshold levels to determine the slope of the function and location of optimum luminance levels as influenced by other variables that affect visual performance.

The present study was not an attempt to define the absolute contrast and luminance required for visual task performance. Is *VL8* the correct visibility level to be used? This study did indicate that whatever visibility level is decided on, extrapolation from threshold data to performance criteria levels by a simple multiplicative constant may not be valid. The most valid technique for determining standard performance criteria is to empirically determine them under work situations, but such determinations may be impractical. This performance test should minimize nonvisual components like motor responses and cognitive factors. An acceptable laboratory technique may be to have the observers choose the contrast level they feel is just acceptable, similar to the criterion used in the concept of borderline between comfort and discomfort (BCD) in glare [12]. The dependent variable would be contrast and not luminance. At a given luminance level, for example, 150 cd/m$^2$, contrast is varied until a *just acceptable* contrast level is obtained. The equi-contrast contour falling on this point will serve both as the Visibility Reference Function and Visual Performance Criterion Function.

Tasks of differing sizes, shapes and edge gradients will be equated to the standard task for equality in subjective contrast and/or clarity. The Visual Task Evaluator (*VTE*) for this purpose will require a modification of Blackwell's [13] *VTE*, since equating two stimuli for contrast will be required rather than bringing a single stimulus to threshold. There may be advantages to asking observers to match two stimuli for equality rather than bringing a single task to threshold. In matching two stimuli for equality the reference stimulus is always present, the observer's task being to vary the test stimulus until it appears to be equal to the reference in the dimension being compared. The advantage is that suprathreshold stimuli can lead to less within observer variability (response variability for a single observer) than threshold stimuli. When observers are asked to color match one field with another, the individual variability in color matches increases as target conspicuity decreases [14, 15]. That is, the standard deviation for color matches serves as an index of color discriminability.

The IES Lighting Handbook, 5th Ed. states: "The illumination levels shown in the table are intended to be minimum on the task . . ." and "in order to assure these values at all times, higher initial levels should be provided . . . ." If the aim of interior lighting is to insure adequate illumination levels for the *most* difficult task encountered, then the present Visibility Reference Function may be the appropriate standard. In a typical visual environment the most difficult task (although encountered infrequently) may be near threshold levels. But, the majority of realistic tasks are not near threshold levels. The results of the present study indicate that, in order to accomodate for this infrequent occurrence a price must be paid. The higher luminance levels recommended to satisfy the requirements for seldom occurring low contrast tasks may bring the luminance level beyond the optimum luminance level for tasks with good contrast. The above is an instance of "less light, better sight" and seriously questions the indiscriminate application, as a working rule, the popular notion "more light, better sight." The monotonically decreasing contrast requirement as luminance is increased dictated by the Visibility Reference Function and the Visual Performance Criterion Function derived from it reinforces the concept more light, better sight. The Visual Performance Criteria Function as the basis for recommending light levels may lead to an unnecessary expenditure of energy as well as a loss in ease of seeing for many realistic tasks. Why should energy be wasted in setting lighting levels high enough to accommodate infrequently occurring difficult tasks, especially if the consequences may be an actual loss in ease of seeing for the many good contrast tasks encountered in everyday visual performance?

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The validity of using threshold studies as the basis for lighting level recommendations is questioned. The performance of the eye at suprathreshold levels was investigated with sine- and square-wave gratings. The results of the study indicate that the behavior of the eye is significantly different at suprathreshold levels as opposed to threshold levels. For threshold studies, when contrast is plotted against luminance, the function is a monotonically decreasing function. At suprathreshold levels the function indicates the existence of a definite minimum, luminances greater or less requiring more contrast to appear subjectively equal. It is recommended that lighting levels be based on laboratory studies that appraise visual requirements and performance simulating conditions encountered in real world environments.


17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Gratings; illuminating engineering; lighting; modulation transfer function; suprathreshold visibility; visibility; vision.

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