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THE CIE VISUAL PERFORMANCE SYSTEM

ANALYZED

by A.W. Levy

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SOMMAIRE

La Commission internationale d'éclairage (CIE) a développé un système d'évaluation des aspects du rendement visuel de l'éclairage. Le système et ses concepts sont présentés en référant particulièrement à l'économie d'énergie par l'éclairage. On y discute de certains problèmes impliqués dans l'application du système CIE et des données nécessaires avant qu'une diffusion massive soit possible.

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Summary The International Commission on Illumination (CIE) has developed a system for evaluating the visual performance aspects of lighting. The system and its concepts are presented with special reference to lighting energy conservation. Some of the problems involved in the application of the CIE system and the data required before widespread application is possible are discussed.

The CIE visual performance system

A. W. LEVY

1 Introduction

In an era of energy conservation it is vital that lighting energy should be used efficiently and effectively. Efficiency can be achieved by suitable control, including automatic dimming techniques, sensible switching arrangements and efficient sources and luminaires. Effectiveness can be pursued in terms of visibility, resulting in the provision of just-adequate illuminance to meet all the visual requirements of specific activities. Adequate illuminance in this context is that which is sufficient for a desired level of visual performance.

It is the purpose of this paper to describe the visual performance approach to effective lighting, as outlined by the International Commission on Illumination (CIE).[1,2] Hereafter this approach will be termed the Blackwell system after its originator, H. R. Blackwell of Ohio State University. Problems associated with the practical application of the Blackwell system will be discussed in an attempt to evaluate the usefulness of the visual performance approach for lighting energy conservation programmes and, more generally, in specifying recommended illuminances. CIE publications describe a framework of methods that enable the illuminating engineer to evaluate the merits of different lighting systems in terms of visual performance for different tasks and different illuminances.

A visual performance approach to lighting deploys both human observers and photometric equipment to establish psychophysical relations. Such an approach to lighting recommendations and standards is a sensible and scientific one but it is not a simple procedure. In general, an observer's response to a visual signal will depend on three factors:

(*a*) the 'photometry' of the lighting installation, i.e. its intensity, directionality etc.;

(*b*) the physiology of the visual system, e.g. accommodation, fixation, adaptation; and

(*c*) the mental condition of the observer, including such factors as intelligence, motivation, pre-information, training, arousal and central nervous fatigue.

The first two factors are much more clearly understood than the third. Although it recognizes the importance of the mental state of the observer, the Blackwell system does not include this factor in the general framework of methods. It is postulated that the mental state of the observer may affect the actual performance of tasks but has no direct effect on the performance potential of the visual mechanism. The various constituents of this factor, however, must be controlled or accounted for in visual performance experiments. This paper describes the application of the system to interior lighting for stationary two-dimensional tasks.

2 Contrast

For an object to be perceived there must be contrast in either brightness or colour between it and its immediate background. For an achromatic task, the task contrast, C, can be defined as the ratio of luminance (objective brightness) difference between task detail, L_1, and background L_2, to the background luminance itself (L_2)

$$C = |(L_1 - L_2)/L_2| \tag{1}$$

This definition permits C to take any value from zero to infinity. In practice L_1 may be the luminance of some detail of a printed ink letter or symbol and L_2 the luminance of the white paper on which it is printed. When the task detail represents a small area seen against a much larger uniform background, the adaptation luminance of the eye is clearly L_2, the background luminance. For the other extreme, consider a grating of equally spaced black and white bars of equal width. Here contrast can be defined as

$$C = |(L_{max} - L_{min})/\bar{L}| \tag{2}$$

where L_{max} = luminance of white bars, L_{min} = luminance of black bars, and $\bar{L}$ = average over task area = $(L_{max} + L_{min})/2$ for equal areas of both

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types of bar. The adaptation luminance in this case is taken as L; in other cases the appropriate value of the adaptation luminance must be established empirically.

Adaptation luminance in this context is extremely important. A value of contrast alone is insufficient to describe the visual difficulty of a task; the adaptation luminance must also be stated.[3] The visual effect of a given task contrast will alter with luminance. For example, the ability to see a task of luminance 100 cd/m^2 on a background of 10 cd/m^2 will be greater than that of a task of 10 cd/m^2 on a background of 1 cd/m^2. Although both tasks have identical contrast values ($C = 9$) the former will be more highly visible because the luminance at which it is seen is greater. (For this reason, some workers use the difference ($L_1 - L_2$) as a measure of contrast. In the example this yields values of C equal to 90 and 9, respectively. Nevertheless, these values do not reflect the subjective effect and reference to the adaptation luminance must still be made).

3 Threshold contrast and contrast sensitivity

Visibility is a word generally used to describe how well a scene or particular object can be seen. In the Blackwell system it takes a more restricted meaning related to visual performance (the term 'visibility level' is discussed in Section 6.2). For the present, however, the word is used in a generalized fashion associated with the perception of objects and visual details of interest.

Visibility also depends on parameters other than task contrast and adaptation luminance; spatial pattern of luminances in the visual field and their magnitude, size of task, task shape, exposure duration, age of observer, and information requirements are all important.

The Blackwell system is useful in that the effect of these variables on visibility and visual performance may be quantified by means of a single psychophysical parameter, threshold contrast $\tilde{C}$. $\tilde{C}$ acts as a 'barometer' of task difficulty, increasing as difficulty increases owing to changes in task shape, information requirements etc. Threshold contrast is the value of contrast when luminance difference between detail and background is so small that detail is barely perceptible; i.e. it is the minimum contrast that can be detected. A number of criteria are suitable for threshold determination, but detection of presence is best for the visibility reference task (see Section 4). In practice, the threshold condition is measured by the value of the stimulus for which the required response is 50% correct. For example, if a black dot against a uniform white background at a given adaptation luminance can be detected correctly in 50% of trials, the observer is at his visibility threshold and the contrast between the dot and the background at the given adaptation luminance is designated the threshold contrast. Justification for using the 50% criterion is that frequency of detection (corrected for rate of guessing) near the threshold as a function of increasing stimulus intensity can be fitted by a normal probability integral (Fig. 1); it is convenient, therefore, to define the threshold condition at a probability of 0.5. The reciprocal of threshold contrast is known as contrast sensitivity, and has been chosen in the Blackwell system as the fundamental measure of seeing ability for a particular lighting situation.

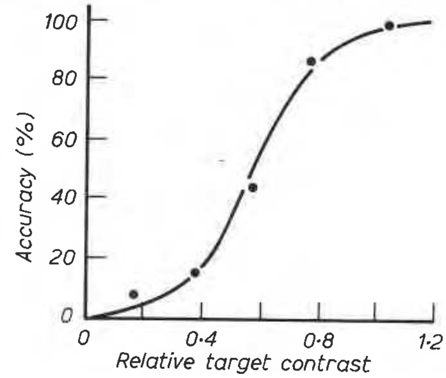

Fig. 1. Sample accuracy curve: response probability data fitted by a normal ogive (reprinted from Illuminating Engineering, June 1959, with permission).

4 RCS function

In general, the higher the light intensity (or luminance) at which the eye is operating, the higher its contrast sensitivity, i.e. a smaller contrast is needed for detail to be visible. Typical curves of threshold contrast as a function of luminance are illustrated in Fig. 2. If contrast sensitivity instead of threshold contrast were plotted on the ordinate, the curve would simply be inverted. The interesting and important feature of these curves is the flattening off at higher luminances. This has important implications for energy conservation and will be discussed separately.

In other experiments the relation between threshold contrast and adaptation luminance has been determined for different target sizes, shapes, exposure durations and perceptual criteria. The results indicate that in all cases tasks of low contrast require a higher luminance for equal visibility (Fig. 2). At low light levels a large contrast is necessary for detail to be visible, i.e. contrast sensitivity tends to zero. Further, when the data obtained from the various experiments are plotted on a double logarithmic grid they are found to be approximately parallel, especially in the photopic range (i.e., luminances in the range of the horizon sky at twilight to snow in bright sunlight, see Fig. 2).

Variation in absolute values of threshold contrast among separate experiments merely reflects the difference in visibility of the variety of visual tasks

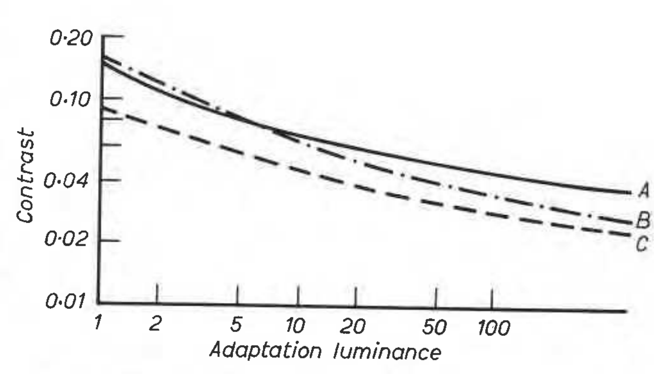

Fig. 2. Threshold contrast relations for the discrimination of detail (B) and detection of presence (C) of a 4' parallel-bar test object compared with that for the detection of a disc (A). Exposure time was 0.2 s. (Reprinted from Illuminating Engineering, January 1968, with permission).

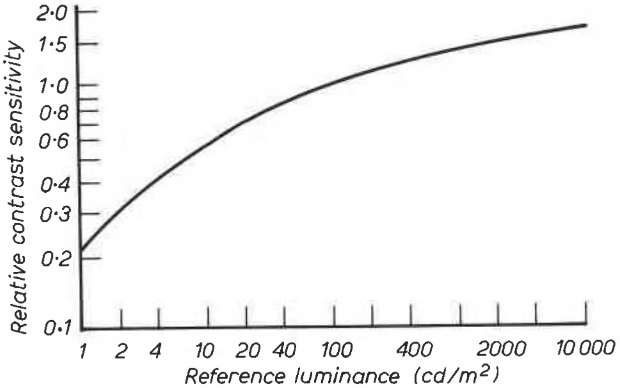

Fig. 3. Relative contrast sensitivity reference function of luminance.

used. The fact that the curves are so nearly parallel is rather significant and leads to the production of a relative contrast sensitivity (RCS) reference function (Fig. 3). It is a reference curve of contrast sensitivity plotted against adaptation luminance normalized to a value of unity at 100 cd/m^2. It is called a reference curve because it is obtained using a visual task, method of lighting, and observer characteristics deliberately chosen as reference standards.

Reference lighting was chosen that is easy to specify and reproduce, integrating sphere illumination where illuminance is diffuse, unpolarized, and there is a completely uniform luminance surrounding the task.

The visibility reference task was a 4' luminous disc presented for 0. 2 s exposure under reference lighting conditions; the information criterion was detection of presence.

The reference population comprised approximately one hundred 20 to 30 year old observers with normal vision. Choice of a 4' luminous disc as the visibility reference task was governed by the fact that it gives absolute values of threshold contrast, which are a good average of the variety of visual tasks investigated. Fortunately, all tasks were investigated under lighting conditions closely approximated by those of reference lighting. This is why all the curves in Fig. 2 can be normalized to fit the RCS reference function.

The RCS reference function directly relates seeing ability (measured in terms of contrast sensitivity) to reference luminance. This function is central to the Blackwell system. It demonstrates that the relative sensitivity of the eye to contrast increases with luminance and is independent to task size, shape and exposure duration. Equally important, the shape of RCS reference curve happens to aid the illuminating engineer to conserve lighting energy. The law of diminishing returns operates (see Fig. 3). As light levels are increased, there is progressively smaller return in terms of visibility. For example, increasing the adaptation luminance by a factor of 10 from 1 to 10 cd/m^2 increases the RCS value by 2. 7; raising luminance from 100 to 1000 cd/m^2 only improves RCS by a factor of 1. 4, little more than half the increase obtained at the lower luminance values. The usefulness of the RCS reference function in this context will be explored in more detail in Section 5, where the features of a lighting installation that directly affect contrast sensitivity are discussed.

5 Effectiveness of various lighting systems

The Blackwell system determines the effectiveness of different lighting systems in terms of their ability to reveal contrast, which can be measured in units of RCS. Any measure that increases the value of RCS at constant luminance is desirable because it improves visibility without having to provide more light. (If this can be achieved at a lower wattage per unit floor area it will also save power.)

The RCS reference curve demonstrates a fundamental property of the visual mechanism: the relation of contrast discrimination to increasing light levels (which are arbitrarily categorized in terms of a reference lighting condition). The visibility of a given task contrast in a particular lighting installation will be affected by a number of characteristics of that installation, apart from illuminance. By considering such effects as altering contrast sensitivity, the deviation of any installation from reference lighting conditions can be found (see Sections 5. 1, 5. 2 and 5. 3). Lighting characteristics include the direction in which the light falls on the task and the spatial pattern of luminance in the field of view surrounding the task. The effects are illustrated in Fig. 4.

5. 1 Contrast rendering

Veiling reflections are the minute specular reflections superimposed on diffuse reflections from an object that partially or totally obscure details by reducing contrast. An extreme condition exists where a luminaire can be seen by reflection in the surface of a visual task; this is reflected glare. The more specular the surface the brighter the reflected image and the greater the reduction in contrast. Unwanted veiling reflections in a visual task that result from a lighting installation are quantified by the contrast rendering factor (CRF).

The contrast rendering factor is a measure of the visibility of a task in a given lighting installation, in

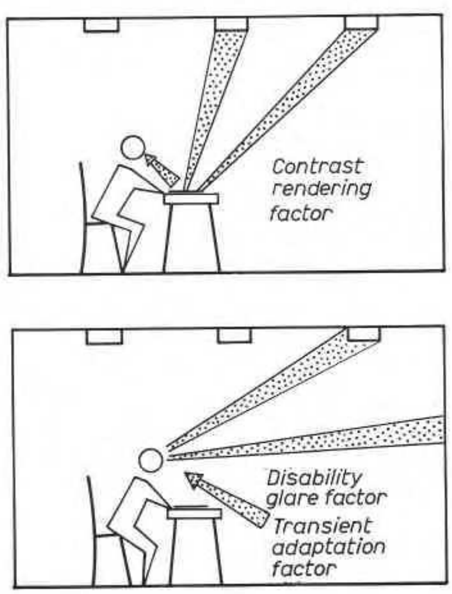

Fig. 4. Lighting installation factors affecting visibility:
CRF contrast rendering factor;
DGF disability glare factor;
TAF transient adaptation factor.

comparison with its visibility under reference lighting conditions. Visibility meters may be used to obtain CRF values by determining values of relative visibility (RV), defined as the extent to which unattenuated task visibility exceeds threshold visibility:

$$\mathrm{RV} = \frac{\text{actual task contrast}}{\text{threshold contrast viewed through visibility meter}}$$

RV in the real environment divided by RV in the reference sphere equals CRF. Visibility meters facilitate the diminution of task visibility by contrast reduction at a constant adaptation luminance. The amount of contrast reduction, determined by the transmittance and reflectance characteristics of the instrument, may be used as a measure of relative visibility. Fig. 5 is a schematic diagram of the operating principle of a visibility meter. The visual task is viewed through either a monocular or binocular viewing system that superimposes a fraction f_1 of focused light from the task with a fraction f_2 of unfocused, diffuse light from a source of veiling luminance V. In setting up the instrument the value of unattenuated V is set equal to the adaptation luminance L. The luminance combining device D has the property that the sum of its reflectance and transmittance is a constant at all settings. The visibility of the task can be reduced by simultaneously varying the fraction f_1 of L and f_2 of V while the sum $(f_1 + f_2)$ remains constant and visual adaptation is unaltered.

CRF quantifies unwanted veiling reflections and takes account of the geometry and polarization of the illumination reaching the visual task.*

These parameters ultimately affect the physical or luminance contrast of the task, suggesting that luminance photometry may be used in place of the visibility meter procedure to obtain CRF. CRF, then, may be defined as the ratio of luminance contrast in the actual luminous environment to the value of contrast obtained in the sphere.

If C_{eff} is the luminance contrast of the visual task in the actual environment and C_{ref} is the luminance contrast under reference lighting conditions,

$$\mathrm{CRF} = C_{\mathrm{eff}}/C_{\mathrm{ref}} \tag{3}$$

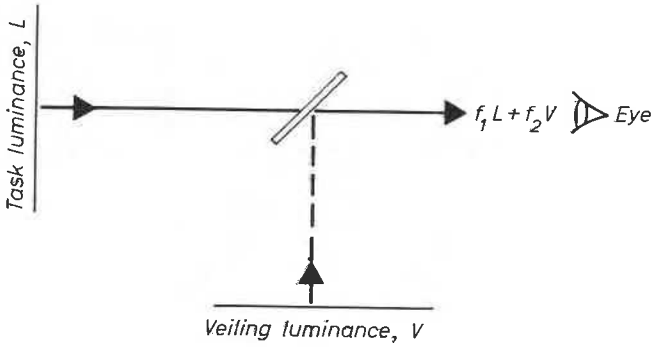

Fig. 5. Operating principle of contrast-reducing visibility meters.

* If discussion were widened to include visual tasks with chromatic contrast, CRF would also account for spectral composition of illuminance.

Values of CRF obtained by luminance photometry will only agree with those from visibility meter readings when tasks are not too specular and lighting geometry not too directional. In addition, special precautions must be exercised in luminance photometry to include optical effects at the boundaries of task details. These can be caused by depression of the surface of the paper during printing.

Alternatively, with precise knowledge of the reflection properties of the task and the geometry and polarization of the illuminance, CRF values may be predetermined by computer calculation. CRF will therefore depend on the particular visual task chosen, how it is illuminated, and the angle at which it is viewed (for a non-matt surface the luminance factor will vary with viewing angle).

Commercial fluorescent lighting systems produce CRF values in the range 0.8 to 1.1 for a pencil handwritten task; values greater than unity are possible because there are some veiling reflections in reference sphere illumination.

To describe the change in visibility of tasks placed in real installations where CRF may deviate from unity, the Blackwell system evaluates the effect on the RCS reference function. This is justified by the assumption, discussed in Section 6, that visibility levels, i.e. curves of constant visibility, are parallel to the threshold visibility curve.

Fig. 6 shows two arbitrary contrast sensitivity curves representing different levels of visibility plotted parallel to one another. Curve x represents threshold visibility and curve y a higher level of visibility. Consider a task viewed under lighting conditions such that CRF is less than unity. If the contrast of the task at threshold visibility is $1/a$ at luminance L_2, contrast sensitivity is a. If the task is placed under reference sphere lighting at L_2, where CRF is by definition unity, its visibility is increased above threshold (there are fewer veiling reflections) and its visibility can be represented by point B on curve y. To bring the task back to threshold visibility the luminance of the sphere must be reduced to L_1, which may be found by determining the intersection of the horizontal line Bb with the curve of threshold visibility x. The value of L_1 corresponds on curve x to an effective value of contrast sensitivity given by b.

If, in fact, curve x is the RCS reference curve the installation providing a background or adaptation luminance of L_2, with its particular low CRF value, is said to have an effective sphere luminance of L_1,

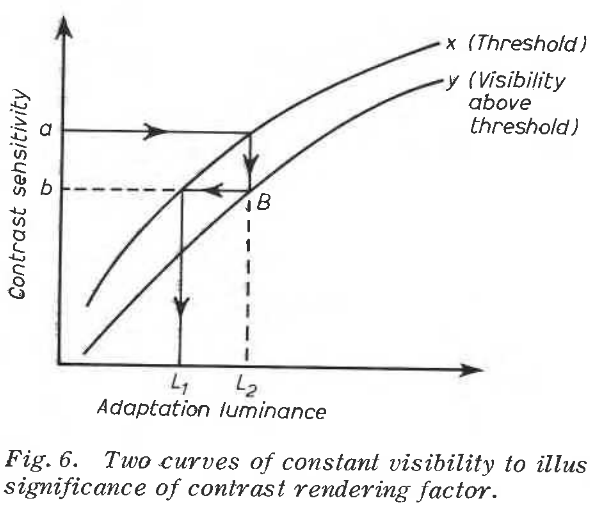

Fig. 6. Two curves of constant visibility to illustrate significance of contrast rendering factor.

which corresponds to an effective RCS of b. In this way

$$RCS_{eff} = RCS_{ref} \times CRF \qquad (4)$$

RCS_{eff} takes into account the level of contrast sensitivity at the background luminance produced by the real environment (RCS_{ref}) and the level of task visibility due to the physical characteristics of actual illuminance in relation to the task surfaces (CRF).

Either effective luminance, L_{eff}, or effective relative contrast sensitivity, RCS_{eff}, may be used in the Blackwell system to designate a figure of merit for a lighting installation. Fig. 7 illustrates three installations, A, B and C, giving CRF values of 0.8, 1.0 and 1.2, respectively, for the same task at a nominal task luminance of 100 cd/m^2. Following eqn. (4) the respective RCS_{eff} values for A, B and C are (1.0 × 0.8), (1.0 × 1.0) and (1.0 ×1.2)

Installation A produces an RCS_{eff} of 0.8, which is available using only 30 cd/m^2 of sphere illumination. Power is therefore wasted since a nominal task luminance of 100 cd/m^2 is equilavent to 30 cd/m^2 of sphere illumination, i.e. L_{eff} = 30 cd/m^2. A better designed installation such as B or C should be sought where CRF and hence RCS_{eff} values are higher. As can be seen from Fig. 7, installation C provides an L_{eff} of 390 cd/m^2 with a nominal task luminance of only 100 cd/m^2.

The varying contrast for a given task under the three lighting systems, at a lighting level of 100 cd/m^2, is equivalent from the visibility standpoint to a range of 13:1 in the amount of light provided.

5.2 Disability glare factor

The pattern of luminance in the visual field surrounding the task gives rise to two separate effects on visual performance. One is the disability glare factor, which quantifies the luminance veil produced in the eye by the surrounding luminance field. Although the veiling luminance increases task luminance, it reduces contrast and therefore visibility. In a correctly designed installation the disability glare factor (DGF) should be small. In the Blackwell system DGF is defined as the ratio of the relative visibility of the task in the actual environment to the value under reference lighting conditions, account being taken of the equivalent veiling luminance of the surround visual field. To date, DGF has rarely been measured according to this definition, but rather calculated using established formulae. DGF values are commonly in the range 1.02 to 1.03 and do not significantly affect visibility to the same extent as CRF.

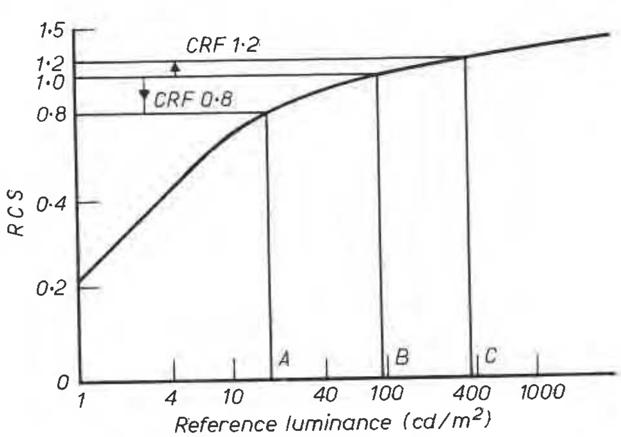

Fig. 7. Effect of CRF on RCS reference function.

For completeness, however, DGF is included in the formula for RCS_{eff}.

$$RCS_{eff} = RCS_{ref} \times CRF \times DGF \qquad (5)$$

5.3 Transient adaptation factor

The transient adaptation factor (TAF) measures temporary loss in contrast sensitivity when the observer moves his line of sight from the task to nonuniformities in the surround luminance of the environment and back to the task again. TAF is the ratio of relative visibility for the practical lighting situation to that for the uniform reference field, and is an important factor when task vigilance is a priority. In this situation

$$RCS_{eff} = RCS_{ref} \times CRF \times DGF \times TAF \qquad (6)$$

The effectiveness of a lighting installation can therefore be expressed in terms of RCS_{eff}, and the higher the value the better the installation. Knowing the actual task luminance, the effective task luminance L_{eff} may be determined in the manner illustrated in Figs. 6 and 7 and described in Section 5.1.

As the illuminating engineer normally works in units of illuminance as opposed to luminance, it is usual for values of L_{eff} to be expressed in units of equivalent sphere illuminance or ESI (this nomenclature may soon be altered to ERI, equivalent reference illuminance). ESI is simply the illuminance required for reference sphere lighting to reach the same level of visibility for a given task as that provided by the real or actual installation.

6 Visual performance

6.1 Static and dynamic viewing

The phenomena and methodology outlined so far have dealt solely with situations in which the observer knows exactly where and when to fixate his vision to determine whether the visual task is visible. Visibility itself has been confined to the procedure of detection, that is to determining whether the task is present or not when displayed for a brief period of time (0.2 s for the visibility reference task). Most visual tasks, however, require more than simple detection processes. Identification and recognition are also important. Further, the majority of visual tasks, by their very nature, require some search and scanning, with fixation performing a vital role in a complicated pattern of other eye-movement behaviour. Such tasks are performed with what is termed dynamic viewing. Visual tasks for which one knows when and where to fixate, such as the visibility reference task, are performed under static viewing conditions. The Blackwell system relates visual performance, a measure of visual work, to units of static viewing called visibility levels (VL). The choice of these units is somewhat arbitrary, but they are the most sensible and useful to employ since so far they have consistently produced interpretable results.

Visibility levels are explained in more detail in Section 6.2 and the parameter α, quantifying dynamic viewing, in Section 6.3. Note that the term visibility level has a confined and strict definition as a measure of visibility for static viewing of brief stimuli. A fuller discussion of the distinction between static and dynamic viewing is available elsewhere; [4] it is mentioned now only so that a more precise understanding of the term visibility level may be appreciated. Values of VL do not completely determine the level of visual performance that can be attained. α, which characterizes the extent to which an observer has to search and scan and view objects off the ocular line of sight, will significantly affect performance level (Section 6.3).

6.2 Equivalent contrast and visibility levels

The relation between contrast sensitivity and adaptation luminance has been discussed in some detail. Relative contrast sensitivity is a powerful tool for distinguishing the relative visibilities of different tasks or of a given task under different lighting conditions. The Blackwell system, however, also enables the illuminating engineer to predict how well an observer will be able to see and perform a particular visual task, in terms of a level of visual performance, as a function of the amount of light provided.

First two new parameters are required, namely equivalent contrast $\tilde{C}$ and visibility level VL. The RCS reference function was constructed in Section 4 using a visibility reference task, a 4' luminous disc presented for 0.2 s exposures, and reference lighting conditions produced by integrating sphere illumination. The Blackwell system postulates that the static visual difficulty of any task may be measured in terms of the visibility reference task. The concept of an equivalent contrast $\tilde{C}$ is used, measured by means of the following procedure.

The visual task, illuminated by reference lighting and at a given adaptation luminance, is viewed through a visibility meter adjusted to bring it to threshold visibility. The task of interest is then replaced by the visibility reference task (4' disc) in the field of view and the luminance contrast of the reference task adjusted (the disc is trans-illuminated) so as to bring it to threshold visibility at the setting of the visibility meter required to bring the real task to threshold visibility. Thus the visibility reference task and the real task are equivalent in visibility (both at threshold) at the adaptation luminance of interest. Numerically, $\tilde{C}$ is the physical contrast of the visibility reference task at the threshold setting of the meter. This procedure for determining $\tilde{C}$ is intended to cancel individual differences in visibility thresholds for different visibility meter operators, since a single operator makes two threshold determinations* for each value of $\tilde{C}$. The concept of an equivalent contrast, $\tilde{C}$, is the stepping stone from the visibility reference task to the real task in much the same way as CRF, DGF and TAF enable one to proceed from reference sphere illumination to actual lighting environment.

Visibility levels, VL, measure units of visibility under static viewing conditions, ie. where no search or scanning takes place. The visibility reference function, VL_1, is a curve representing the luminance contrast required for threshold visibility (50% detection probability) of the visibility reference task for the reference population of observers at different levels of adaptation luminance provided by sphere illumination. It is the inverse of the RCS reference function adjusted to the absolute values of threshold contrast (Fig. 8). Visibility levels are parallel to VL_1. The VL number for any curve is the contrast multiplier required to obtain that curve from VL_1. For example, VL_2 represents a curve obtained by multiplying each

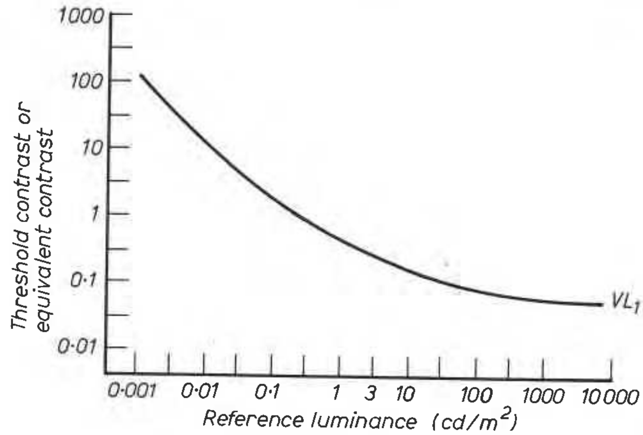

Fig. 8. Visibility reference function of luminance.

value of contrast, designated C_1, on the VL reference curve by a factor of 2. The VL curves are correctly ranked for visibility under static viewing conditions in this fashion, but no significance should be attached to the magnitude of the contrast multipliers; VL_4 does not mean twice the visibility of VL_2. The contrast multiplier is obtained from the ratio of $\tilde{C}$ to C_1, i.e.

$$VL_{ref} = \tilde{C}/C_1 \tag{7}$$

at a given adaptation luminance when $\tilde{C}$ is measured under sphere illumination. For tasks that cannot be placed under reference lighting conditions, but where DGF and TAF have been accounted for, an effective visibility is introduced:

$$VL_{eff} = VL \times DGF \times TAF \tag{8}$$

where

$$VL = VL_{ref} \times CRF \tag{8a}$$

[it would have been more logical to define $VF_{eff} = VL_{ref} \times CRF$ to replace eqn. (8a), but unfortunately the CIE publications have adopted the nomenclature above.]

VL_{eff} is not only an index of merit for different luminous environments (as are RCS_{eff} and L_{eff}) but can also be related to visual performance, see Section 6.3.

* For tasks that cannot be placed conveniently under sphere illumination, for example in a roadway lighting situation, the value of $\tilde{C}$ is a combined assessment of task difficulty and the physical properties of the illumination (in the absence of DGF and TAF). In this case, no separate determination of CRF can be made and lighting levels can only be recommended in terms of effective luminance values rather than reference values. Thus

$$\tilde{C}_{eff} = \tilde{C}_{ref} \times CRF$$

and, in general,

$$X_{eff} = (X_{ref} \times CRF)$$

where $X \equiv L$, RCS, VL, and X_{ref} refers to the value of the parameter X under reference lighting conditions. The terms in brackets cannot be separately identified unless the task can be placed under reference lighting.

6.3 Application to lighting standards

Attention is now turned to the use of visual performance criteria to establish lighting recommendations and standards. Previous parameters such as RCS and VL measure task visibility alone; visual performance, P, takes into account task visibility and the conditions of observation and response required by the visual task situation. Observation in this context means patterns of ocular search and scanning; response refers to visual information processing, i.e. to the processes of detection, recognition, and identification. Existing conditions of motivation, training and fatigue, however, are ignored.

Typical visual performance experiments have involved the identification and marking of Landolt C rings, with breaks in prescribed directions; [5] a search task such as finding a specific two-digit number from among 100 randomly arranged numbers on a test card; [6] the detection or absence of a specific shape (e.g. a square) among a number of different shapes (e.g. circles). [7] The performance score is normally one of speed or accuracy. Most early studies concentrated on the relation between performance and illuminance on the task, varying size, contrast, and exposure duration. Weston in the UK performed numerous pioneering studies in this field mainly using Landolt ring tasks. A family of his experimental curves is shown in Fig. 9. This family of curves can be reduced to a single one by adopting the procedures of the Blackwell system and plotting the chosen index of performance against the effective visibility level (Fig. 10). Values of VL_{eff} were calculated using eqns (7) and (8) and measured values of $\bar{C}$. The system can therefore offer a great advantage in the analysis of visual performance data in that it collects, on a single curve, data points obtained with tasks of different size and contrast, all presented at different adaptation luminances.

Reference 1, which explains the Blackwell system, contains a mean or average curve of relative visual performance (performance as a percentage of the maximum achieved) against effective visibility level. This curve provides a good fit to four quite separate sets of experimental data and is regarded as demonstrating a general relation between visual performance and visibility level. Further work by some of the authors of the CIE document has shown, however, that when proper allowance is made for guesswork and chance success the values of performance are

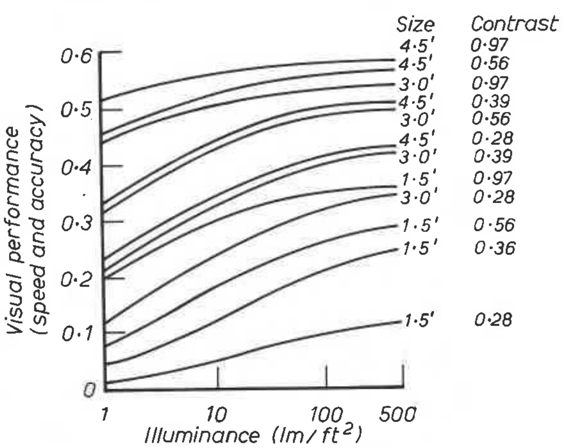

Fig. 9. Family of curves showing relation between speed and accuracy of visual discrimination and illumination on the visual task (reprinted from Light, sight and work, H. K. Lewis, 1962).

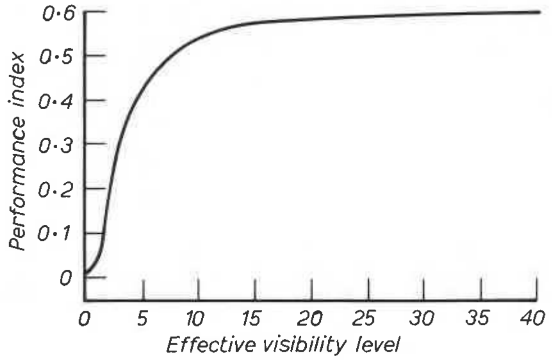

Fig. 10. Reduction of family of curves to single curve by plotting performance data as function of effective visibility level.

considerably different from those used to generate the average curve; no average curve exists.[8] This fact has now been officially accepted.[2]

Current procedure, which is set out in a draft CIE publication[2] as a sequel to publication 19, is to plot visual performance, corrected for guesswork and chance, as a function of the logarithm of VL_{eff} (Fig. 11). It has been found that each set of data plotted in this manner can be fitted by a member of a family of mathematical functions. The basic mathematical function is the ogive or integral of the normal frequency distribution

$$p = \int_{-\infty}^{X} \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-(X-M)^2/2\sigma^2\right\} dX \qquad (9)$$

where p is the probability of occurrence of an effect, X is a physical measure of a cause, M is the mean value of the normal frequency distribution of X, and σ^2 is a measure of variance of the normal frequency distribution of X. For visual performance data, the performance index is set equal to p in eqn. (9) and log VL replaces X. An alternative method of fitting the data to the skew distribution shown in Fig. 11 is to use probit analysis and work to a straight line.

Results obtained so far indicate that four parameters, which separately describe the mean value α, gradient γ, maximum value P_{max}, and variance ν (on the scale of log VL) of the ogive functions, are related to each other by 'locked' linear equations so that the value of any one parameter defines the values of the other three. The parameter α describing M on the scale of log VL has been found to measure the degree of ocular search and scan involved in a visual task. Although different observers seem to generate ogives with the same gradient γ, α varies with a normal frequency distribution of variance ν.

α provides a useful measure of the difficulty of conditions of ocular search and scanning, and of off-axis information processing. The importance of α in the Blackwell system is almost equal to that of equivalent contrast $\bar{C}$. $\bar{C}$ is a measure of intrinsic task difficulty based on size, contrast, configuration and information to be obtained from the task under static viewing conditions. Strictly speaking α is a measure of the dynamic threshold of a visual task and is expressed in units of log VL. Two further parameters describe the proportion of visual component in the visual task and importance of errors, both important for cost benefit analyses.

This latest approach appears to offer considerable insight into the complex components that combine to generate the ogive functions and greater precision in prescribing recommended illuminances. It has become clear that individual differences in performance and differences in the values of equivalent contrast, $\bar{C}$, for various tasks are the variables having the largest effect on relative visual performance. Values of α describing ocular search and scanning are next in importance, followed by the respective parameters describing the proportion of nonvisual component in the task and the importance of errors. Values of reference illuminance have the least effect of all the variables considered.

7. Application of Blackwell system to lighting design and energy conservation

7.1 Areas of continuing research

Some aspects of the Blackwell system require further study before general implementation can be achieved. Of particular concern is the task dependence of the system. Until recently the ESI concept has been limited as a practical design tool to the American IES reference pencil handwriting task. With reflectance data available now for another four tasks the range of visual tasks available for computer programs for ESI computation has been extended,[9] but more data are required. It will be interesting to learn whether the relative magnitudes of ESI at different points in an interior are independent of the task chosen. If the variation is not significant, use of a standard task for assessing lighting installations will become practical and sensible. If it is significant, decisions will be required with respect to the limiting or average representative task characteristics.

Another problem is determination of the correct adaptation or background luminance, L, for practical tasks. In Section 2 it was stated that the appropriate value of L must be established empirically. For energy conservation programmes this situation is not acceptable, since the shape of the RCS reference function demands that the adaptation luminance be known accurately. Consider for example this page. Is the adaptation luminance the luminance of the white paper, the black print, or some weighted average of the two? Lack of information concerning the problem presents a significant drawback in applying the Blackwell system to common written and printed

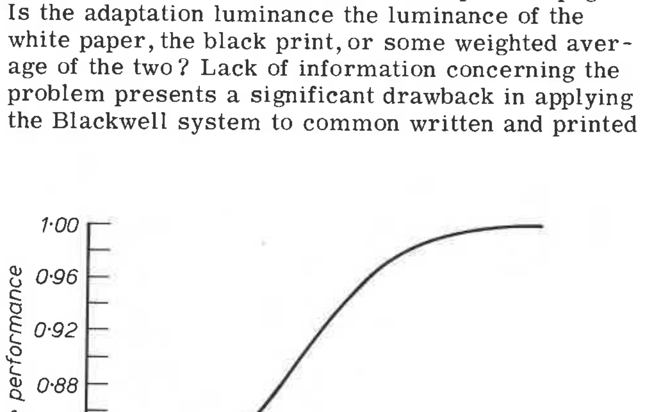

Fig. 11. Logarithmic ogive of relative visual performance against visibility level.

visual tasks, although a possible method of determining the background luminance in a separate experiment has been devised.[10]

The luminance profile, where task detail meets background, is an important factor in determining visibility thresholds.[11] It would be useful to know the relative visibilities of task details with blurred edges (shallow luminance profile) but high contrast and those with sharp edges (steep luminance profile) but low contrast. The parameter α characterizing the search and scanning pattern required for a visual task affects visual performance. At present α can only be obtained from the experimentally determined performance ogive function. A separate measurement of α is needed and although a sophisticated psychophysical measurement technique is under investigation[12] a simple method would be more practical.

Finally, a means of measuring ESI directly would greatly accelerate both the use and acceptance of the Blackwell system. One meter has already been developed, but it is costly and delicate enough to be inconvenient for use in field studies.[13] A more robust, simple meter is under development at the National Research Council of Canada.

7.2 Energy conservation

Sizable savings in the energy used for lighting may be expected if lighting is selected for specific tasks rather than to meet some general specification in terms of a uniform illuminance. The Blackwell system provides a means of achieving selective lighting standards and thereby optimizing lighting energy. In the very near future enough data on different tasks and populations of subjects will have been collected to enable the illuminating engineer to design a lighting scheme on a valid scientific basis.[14] It is suggested[15] that he first consider how critical performance errors are for each task; and secondly decide what level of performance is necessary for its operation and the cross-section of worker population involved. Using the Blackwell system to calculate a visibility level, he can then arrive at a prescribed reference illuminance ESI. His aim is to design a lighting installation so that the ratio of ESI divided by actual illuminance is as large a number as possible and preferably equal to or greater than unity.

Examples follow where the Blackwell system has been used to obtain significant power savings. In all instances the non-uniform lighting concept has been employed, so that illumination of the correct quality and quantity is concentrated at work stations and illuminances in circulation areas significantly reduced in intensity. In this context the local desk lamp becomes a highly attractive proposition. In fact, the Blackwell system has already been used in designing a desk lamp with a light output distribution that has the correct intensity and directionality for good visibility.[16]

Cuttle and Slater[17,18] offer a low energy approach to office lighting by means of local fluorescent desk lamps (each containing a 600 mm, 20 W fluorescent lamp) mounted over the ends of office desks and reducing the level of background lighting, which is automatically switched on and off by a photo-electric control situated outdoors. The original installation of recessed fluorescent ceiling luminaires with flush prismatic panels provided a desk-top illuminance of 550 lux but (using a printed paper task as a standard) only 330 lux ESI. Local desk lights alone give 280 lux on the desk and an ESI of 570 lux. Supplemented by reduced background lighting, these values increase to 410 lux and 740 lux ESI respectively. A trial installation has been metered for 129 working days, July to December, and shows a total lighting energy consumption of 968 kWh. Assuming use at full capacity,* the original installation would have consumed 5625 kWh, indicating that the trial installation reduced consumption by approximately 83% while increasing ESI by a factor of more than 2.

Lange[19] has conducted experiments in a conference room and two offices in the New York City Municipal Building. Existing conventional luminaires were replaced by twin-beam distributions providing high ESI by illuminating tasks from the side, thus minimizing veiling reflections. The power saving is derived from the fact that at luminances typically found in interiors, a 1% loss in task contrast requires an increase in illuminance of between 10 and 15% to maintain the same level of visibility. The results of changing to twin-beam distribution luminaires are as follows:

Conference room: total wattage was reduced from 2000 to 1400 W with ESI on the conference table increasing from 240 to 390 lux;

Large office: a power reduction from 1200 to 600 W was achieved while maintaining ESI at 480 lux;

Small office: a new lighting system reduced power from 400 to 300 W, with ESI on the desk increasing from 140 to 240 lux.

In each area visibility was maintained or increased and a significant reduction in power consumption achieved.

At a recent Federal Energy Agency Symposium in Washington, King[20] of the General Services Administration outlined the non-uniform illumination concept (derived from the Blackwell system), explaining that it conserves energy while providing adequate, comfortable lighting at work stations. Adhering to the GSA 50/30/10 standard, †lamps were removed or de-energized where this standard was obviously exceeded; each room was visited to ensure that the standard was accomplished in such a way as to provide an acceptable environment. The previous uniform illuminance concept in the interior was replaced by a more uniform ESI level throughout the task area. With removal of over 3 million fluorescent lamps in 10 000 buildings, a reduction in energy of 445×10^6 kWh was achieved.

* A pilot study carried out at the UK Building Research Establishment has shown that in large open-plan offices 80% of the maximum possible lighting usage occurs (private communication by D. R. G. Hunt).

† 50 ft-c (approximately 500 lux) in working areas (on the desk top); 30 ft-c (~300 lux) in the general office environment; 10 ft-c (~100 lux) in hallways, corridors and seldom occupied areas.

8 Conclusion

The Blackwell system provides a unified framework of methods in which the relations between illumination and visual performance and visibility can be expressed in a quantitative fashion. Some of the problems of application and the data required before widespread application is possible have been discussed. At present the system permits the monitoring of visibility, an extremely important aspect where lighting energy conservation programs are enacted. Lack of data and convenient means of implementation and application, however, may prevent the use of the system for prescription of recommended lighting levels.

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