The first part of this lecture, published in the May 1957 issue of ILLUMINATING ENGINEERING, reviewed British and other European work which has been completed or published since the C.I.E. Meeting at Zurich in 1955. The second part of the lecture, given here, includes new work on glare recently completed or still in hand at the Building Research Station, Garston, Watford, England.

The basic formula for the evaluation of glare discomfort is reviewed and some of its many limitations discussed. Cross-checks undertaken during the last few years at the Building Research Station show that nevertheless it still serves a valuable purpose for practical lighting engineering, provided too great a precision is not sought. The additivity of glare is discussed, in relation to the saturation characteristics of the adaptation mechanism. It is suggested that the simple addition of the glare effects of a number of sources can never give a "true" solution, but that it often yields a result of adequate precision for most present-day lighting problems. The greatest need for further research is in the study of the discomfort caused by very large sources of moderate luminance, such as occur in daylighting or in the use of "overall" ceiling lighting.

Evaluation of Glare

By R. G. HOPKINSON

Basic Glare Formula

RECENT WORK AT THE Building Research Station on glare discomfort followed on informal meetings which were arranged at Stockholm in 1951 in conjunction with the C.I.E. Congress.

At these meetings, agreement was reached by all that the main factors which govern glare discomfort are the following:

(1) Luminance of the light sources.

(2) Apparent size of the sources.

(3) General level of adaptation.

(4) Position of the sources relative to the direction of viewing.

(5) Luminance of the immediate surrounds to the sources.

It was further agreed that glare discomfort could be assessed on the basis of an expression of the form:—

$$\text{Glare constant} \quad G = \frac{f(B_s) \cdot f(Q) \cdot}{f(B_b) \cdot f(B_i) \cdot f(\theta)} \qquad (1)$$

where B_s = source luminance

Q = apparent size of the source

B_b = adaptation luminance

B_i = luminance of immediate surround to the source

θ = angle between direction of source and direction of viewing

The higher the value of G, the greater is the degree of discomfort. Thus greater source luminance and apparent size make for worse glare; greater adaptation level, immediate surround to the source or angle between direction of source and direction of viewing make for less glare.

To a first approximation the formula (1) can be expressed as:

$$G = \frac{B_s^2 \cdot Q}{B_b} \quad \text{or} \quad G = \frac{B_s \cdot E_s}{B_b} \qquad (2)$$

where E_s is the illumination on the eye *from the sources.*

This modified formula was put forward by the British National Committee at the C.I.E. 1955 conference as a basis for the derivation of a set of international glare tables.

Part II of a lecture given at Cornell University, Ithaca, N. Y., September 1956, to a symposium on Visual Research held by the Illuminating Engineering Research Institute of the U. S.A.

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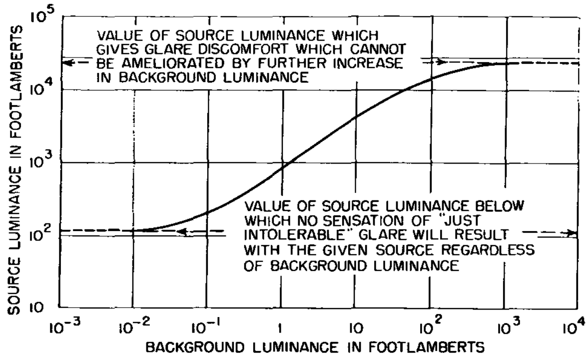


Figure 1. The sigmoid nature of the relation between source and surround luminance for constant degree of glare discomfort.

Exponents in the Basic Glare Formula

The basic glare formula breaks down in a number of ways and cannot be regarded as more than an approximation which is convenient for some purposes.

(1) At very high adaptation luminance levels, of the order of 5000 footlamberts and above, the visual adaptation mechanism begins to saturate. If a glare source is so bright and large that glare discomfort has not been eliminated even though the surround luminance has been raised to 5000 footlamberts, no further increase in surround luminance will produce any amelioration. On the contrary, the surround itself will begin to cause discomfort. There is no longer any question of a balance between the source and the surround luminance. This implies therefore that the exponent of the term B_b in the glare formula as given above with B_b in the dedenominator decreases as the values of Q and B_s increase, and becomes negative when Q is very large and B_s is about or above 5000 footlamberts (the exact value of the changeover depending on the visual characteristics of individual subjects).

(2) The basic glare formula embraces a simple power law between the source luminance B_s and the surround luminance B_b. This simple relation breaks down under certain circumstances. First, especially if the source is very large, there is a level of source luminance above which the source is glaring no matter what the value of the surround luminance. There is also a level of source luminance below which the source causes no glare even if seen in total darkness. The relation between the logarithms of the source luminance and surround luminance is therefore a form of sigmoid, and not linear. (Fig. 1.) It is an approximation, but a reasonable one, to consider it linear over a limited range.

(3) If we accept the approximation to a linear relation between the source and the surround luminance on a logarithmic scale, it might be expected that the exponents of B_s and B_b will depend on the apparent area of the source, since as this area increases, the area of the surround must necessarily decrease since the total area of the visual field is constant. It might be deduced, therefore, that the influence of the source luminance would become greater as its area increased. This has been shown to be the case experimentally. There are three quite separate sets of data available from my own studies. Originally, in the course of the study on glare in lighted streets, it was shown that, as the source area increased, the exponent of the source luminance also increased relative to that of the surround luminance. With point sources the ratio of the two exponents (of source and of surround) was 1.0, with large sources

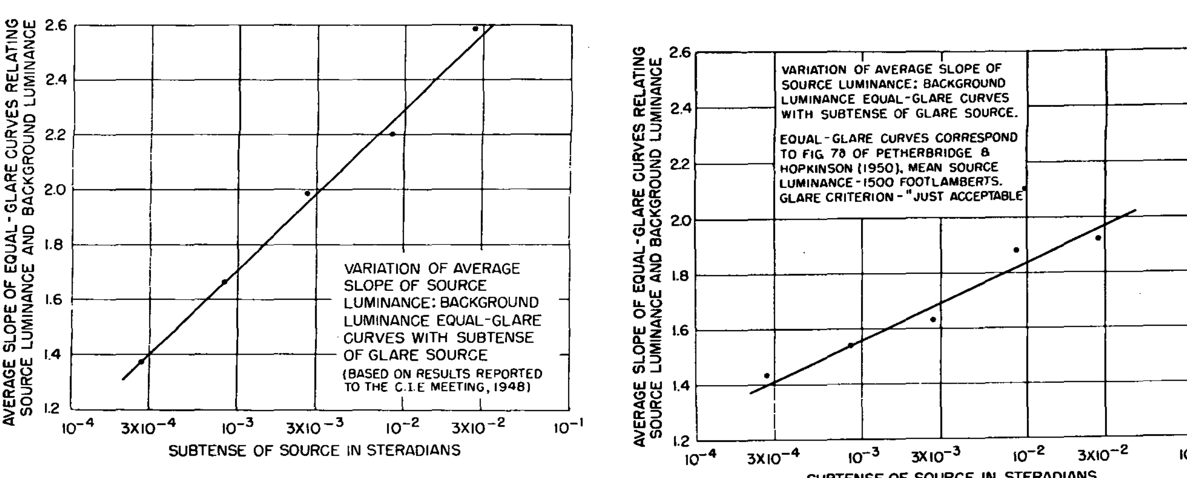


Figure 2. Relation between apparent size of glare source and average shape of source/background luminance curves, (left) determined by four observers (Hopkinson 1948), (right) determined by six observers (Petherbridge & Hopkinson 1950).

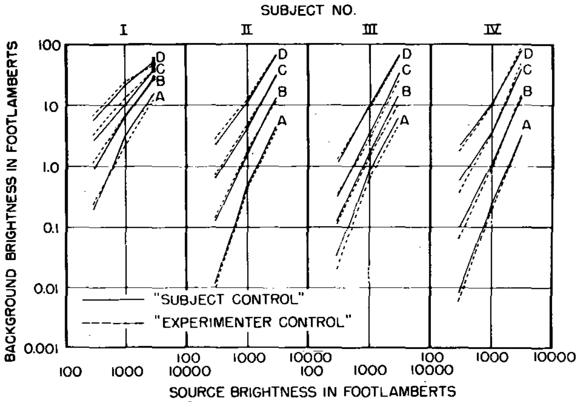


Figure 3. Relation between source and surround luminance for four constant degrees of glare: A, just intolerable; B, just uncomfortable; C, just acceptable; D, just perceptible. The shape of the relation for A is steeper than that for D. The borderline between Comfort and Discomfort (BCD) lies between Criterion B and Criterion C. (The curves also show that the same judgments apply whether the subject himself or the experimenter exercises control of the physical variable.)

it approached 3.0. Next, when the work was first resumed in 1947, a similar relation was found, and was reported in a paper to the C.I.E. in 1948. (Fig. 2.) Finally, the more extensive work with a larger number of observers (Petherbridge, Hopkinson (1950)) confirmed the same trend, but to a less marked degree.

(4) The θ function again depends on the area and the luminance of the source. Consequently the θ function, or Position Index as it is called by Luckiesh and Guth, is not independent of the other factors in the glare formula.

(5) The B_i function (the influence of the immediate surround to the source) cannot be expressed in any simple form. The influence of the luminance of the immediate surround to the glare source depends on the size of the source and the size of the immediate surround. Clearly if this immediate surround is very large, it begins to influence the adaptation to a marked extent. If it is very small, a mere annulus around the glare source, it has little influence on the degree of glare. If it is of a size as to influence glare, this influence is exercised only over a limited range of luminance. As the luminance of the immediate surround begins to approach that of the glare source, glare increases rather than decreases. The exponent of the B_i term therefore changes from a positive to a negative value, in the position in which it is shown in the denominator of equation (1).

(6) The matters discussed in (1) to (5) above apply equally to determinations of glare expressed in terms of the borderline between Comfort and Discomfort (BCD) and to determinations expressed in terms of other criteria of discomfort. The BCD does not tell us all we need to know about the sensation of glare, however, and for this further information we need a scale of glare sensation such as that provided by the Multiple Criterion system, in which all the many studies, both the early work and that at the Building Research Station, have been conducted. The relations expressed in formula (1) above are then found to be not the same for different criteria, *e.g.*, "just perceptible" glare, or "just intolerable" glare. Broadly, the influence of the surround or adaptation luminance on "just perceptible" glare is less relative to that of the source luminance than it is on the BCD, and still less than it is on "just intolerable" glare. (Fig. 3.)

By working with the BCD only, these additional complications can be escaped, but it is the escape of the ostrich, for they are there all the same, and they are important in practical lighting.

(7) So far the simple conditions of one glare source in the field of view have been considered. If there are many sources, we need to know how can their effects be assessed. This problem will be discussed again later.

The first stages of the work at the Building Research Station showed that the glare effect of a number of sources of the same luminance was the same as that of one source, in the same mean position, of the same apparent area as the sum of the apparent areas of all the sources. In practice it has been found that simple additivity on this basis works, but only over a limited range of conditions. If we think about the situation, we could not reasonably expect otherwise. Simple additivity of large bright sources cannot apply if the relation between source and surround luminance shows saturation characteristics, as we have already seen that it does. The departure from simple additivity will be more serious the larger and brighter are the sources being added, and the higher the surround luminance consequently necessary to "balance out" the glare which they cause. These conditions apply in practical lighting in the U.S.A., but to a less extent in Europe, where levels of lighting are generally much lower. The departure from simple additivity is a problem which has concerned you more than it has us, but it is one which we ought to settle in the course of achieving international agreement.

The above summary does not exhaust the discrepancies in the simple basic glare formula, but it is sufficient to offer such a gloomy picture that we might well ask, of what use is the formula anyway?

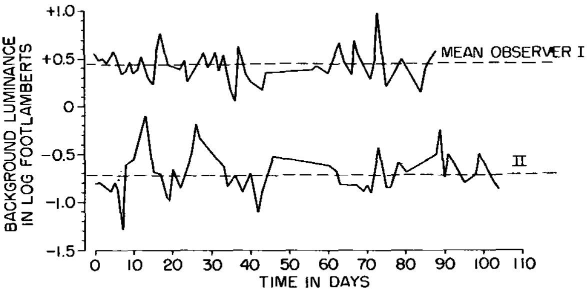


Figure 4. Day-to-day assessments made by two experienced observers of the background luminance necessary to balance out the source luminance to the criterion of "Just Uncomfortable" glare. The mean is steady over a period of three months, but the actual values differ considerably.

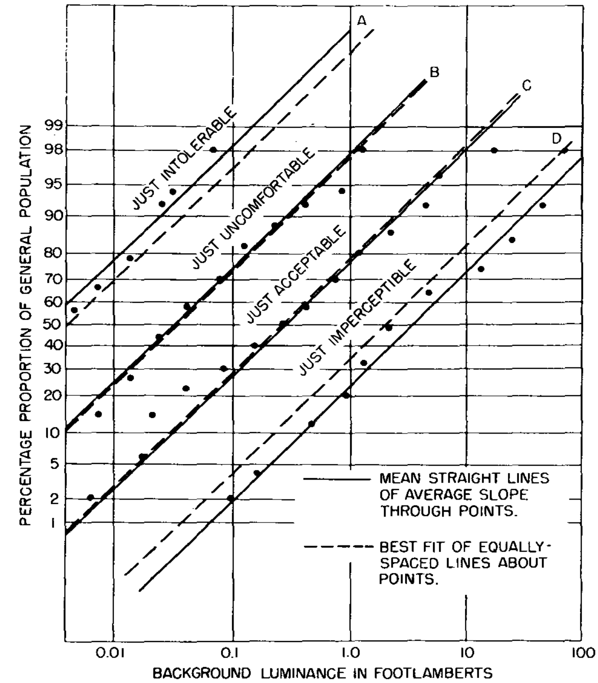


Figure 5. Variation with background luminance of the percentage of general population who would assess glare discomfort in a particular environment at the given level or less uncomfortable than the given level. Source luminance: 300 footlamberts.

Observer Variance

The answer to this question depends on the level of precision to which we aspire. If we are making a study of vision by the aid of subjective judgments of glare discomfort, all these discrepancies are important because they may reveal the working of some parts of the visual mechanism. If, however, our purpose is to devise a working tool to enable designers to avoid glare in lighting installations, we can decide arbitrarily the precision to which we all agree to work. The precision must depend on the variability of the judgments on which the various expressions are based.

In our studies at the Building Research Station most of the judgments were made by a small team of six observers; the same applies to my original studies on glare in lighted streets. Guth also employed a small team for the majority of his detailed studies. Within each of these small teams there were wide variations in the individual judgments of discomfort. In our own studies we had sufficient observations over a long period to study the consistency of these judgments. It was clear that each observer maintained his criterion over many weeks, even though this criterion was different from that of each of his colleagues. (Fig. 4.) These results all demonstrate that there are real differences in the sensitivities to glare of different individuals, that these differences are large, not negligible, and that they were maintained throughout the weeks during which the subjects made their extensive series of observations.

Wide though the variations are between the sensitivities to glare of individual subjects in our main team, the variations between individuals in the general population are wider still. We obtained series of judgments from 50 subjects selected very much at random from the staff of the Building Research Station, including a large proportion of non-scientific people. The variations were very considerable. Included in this group of 50 were some who did not understand what was demanded of them, and some whose over-anxiety to obtain the "right" answer affected their judgment. The variations were far greater than those obtained by Guth, or those which I obtained myself in the course of the street-lighting study, but in the latter case, and perhaps in the former, the subjects were mostly scientifically trained people who quickly grasped what was required of them.

These judgments from our 50 random subjects have been analyzed, for what they are worth. They plot well on a probability diagram, where the enormous variances can be readily appreciated. (Figs. 5, 6 and 7). The conclusions to be drawn from these results are as follows:

1. The mean of the observations of the "random" observers is not the same as that of the experienced team of six people. There are consistent differences throughout the series of observations.
2. There is, for example, a relation between the means for the 50 observers and for the six observers, in that the mean judgments differ by approximately one criterion on the multiple-criterion scale (for example, if a given situation is judged on average as "just intolerable" by the six-observer team, it will be judged on average as "just uncomfortable" by the 50-observer team). *The general population is less sensitive to glare than the experienced team.*

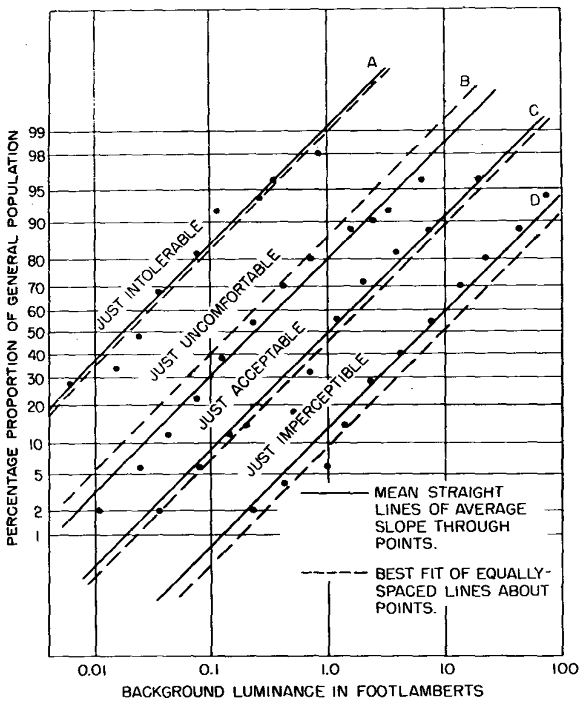


Figure 6. As Fig. 5, with sources at 1000 footlamberts.

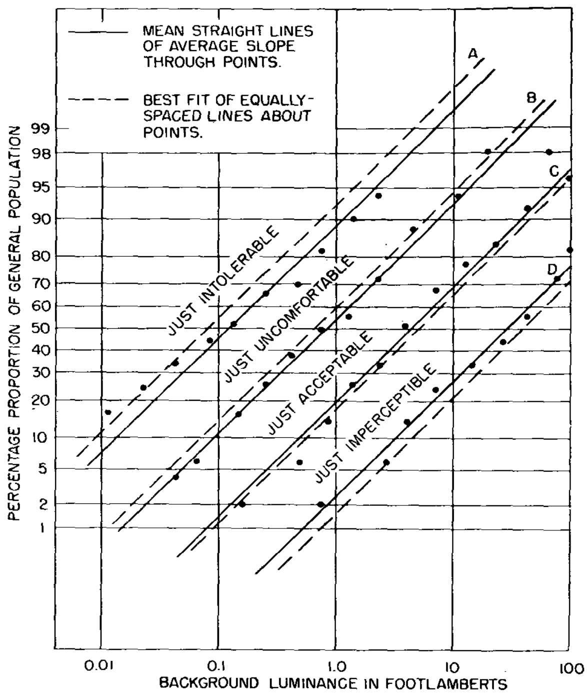


Figure 7. As Fig. 5, with sources at 3000 footlamberts.

3. Approximately 80 to 85 per cent of the general population would experience less glare discomfort in any given situation than the mean observer of the experienced six-man team.

There is therefore available information which enables us to decide the degree of precision to aim for in any practical statement of the glare phenomenon. One the one hand we have information on the variances in the judgments of experienced subjects, the consistent differences in their mean assessments expressed in terms of the standard error of their day-to-day judgments, and finally the variance of the judgments of the general population related to the judgments of the experienced team. The decision on the degree of precision to be aimed at in any international statement on glare must be made by the Working Party appointed by the C.I.E. Later I shall summarize the procedure which we use ourselves at the Building Research Station to evaluate glare.

Influence of Method of Experimentation

So far we have examined the glare formula, the conditions in which it can be expected to break down, and the experimental evidence on which we can base our decision as to the degree of precision which we expect it to perform in practice. The next stage is to consider to what extent the method of experimentation influences the results.

Most of the American work on glare has followed Holladay and Luckiesh's original method of presenting the glare source in one-second "flashes," rather than presenting it continuously in the field of view. We have never followed this practice in Europe, that is to say in England or in Holland, because we argue that in a glare situation, both source and surround are continuously present, and the sensation of discomfort that results is due to the continuous interplay of the relevant mechanisms of vision. The "flash technique" gives reliable results, but they are not necessarily measures of the form of glare discomfort with which we are concerned.

In order to study the effect of the method of experimentation, we undertook an extensive series of observations. Three observers only took part, but unfortunately these three individuals were found, after the results had been analyzed, to differ very considerably in their glare sensitivities. For this reason the results were never published because it was hoped one day to repeat them with other observers, but this has not proved possible. They are offered here with all possible reservations. The body of data is considerable, running to many thousands of observations in the laboratory report. It is at the disposal of any worker in the subject if it is felt to be useful.

The experiments were conducted in our model apparatus and also in a large white cubical space designed to match as closely as possible the apparatus used by Guth. The source was presented both by the "flash" technique and by the "continuous exposure" method. In some sets of experiments the subject varied the surround luminance, and in others he varied the source luminance. In some he judged on the Multiple Criterion scale (A, just intolerable; B, just uncomfortable; C, just acceptable; and D, just perceptible glare), and in others he judged by the BCD scale. A visiting scientist from South Africa acted as one of the subjects. He was not familiar with either the Building Research Station scale or the BCD scale when he commenced his judgments. He judged initially on the BCD scale.

The range of conditions was wide, each variable (source luminance, surround luminance, source (100:1) or greater. The "flash" exposure conditions followed the Luckiesh-Guth 10-second cycle (three one-second "on" periods separated by one-second "off" periods followed by a five-second "off" period before the next "on" period). The results showed:

1. Momentary exposure results in a slightly greater degree of glare than continuous exposure.
2. If the source luminance is varied by the subject, he appears to be slightly more sensitive to glare.

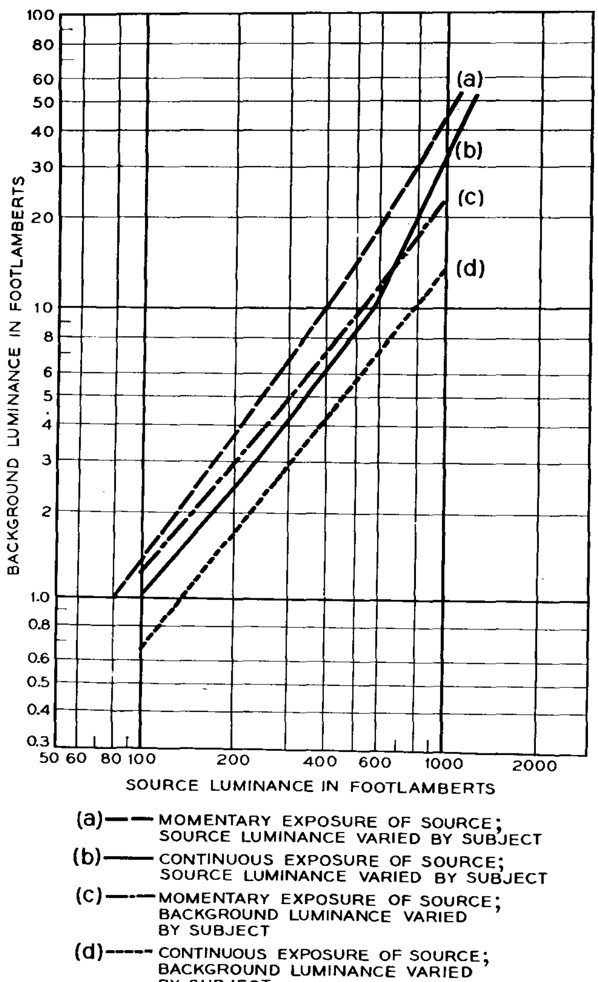


Figure 8. Comparison of glare judgments for four methods of study, using the BCD as criterion. Method (a) is the Luckiesh technique, method (b) the Hopkinson technique.

The greatest difference between the means of the results for the four systems (momentary exposure and variation of source luminance, momentary exposure and variation of surround luminance, continuous exposure and variation of source luminance, continuous exposure and variation of surround luminance) is less, however, than the consistent differences between the three observers. Despite these differences in individual sensitivities, however, all subjects varied in the same sense and in particular showed a higher sensitivity to glare when using the Luckiesh-Guth technique of momentary exposure with variation of source luminance. (Fig. 8.)

It is of interest to note where the BCD criterion lies in relation to the four criteria of the Building Research Station multiple-criterion scale. The visiting scientist, who had no previous experience of glare judgments on either scale, made his first judgments by the BCD and his later judgments by the multiple-criterion scale. He placed the BCD between "just uncomfortable" and "just acceptable," a result which confirmed the comparison which I showed at Stockholm of the entirely independent studies of Luckiesh and Guth on the one hand, and of Petherbridge and myself on the other. In this present study, which of course did not figure in the Stockholm comparison, averaged judgments of our three subjects for the BCD also lay between "just uncomfortable" and "just acceptable" irrespective of the experimental technique being used.

The standard error of the observations using BCD was 0.17, log. luminance units, which compares with 0.16 for a much more extensive series using the multiple-criterion method. These three "skilled" observers therefore managed quite as well with the BCD as with the multiple-criterion method.

A further interesting result from these studies was that for two of the observers the relation between the source area and the source luminance for the BCD criterion followed the slope given by Luckiesh and Guth more closely when the Luckiesh-Guth exposure technique was used. The third subject's observations, however, were consistent throughout with the slope of the original Building Research Station glare formula, no matter what technique was used.

There were many more cross-checks involved in this study, but sufficient has been given to show that, if anyone hopes to resolve the discrepancies between the American and the European work on glare, they will have to employ a very large number of observers and engineer the experiment on the lines of a military operation as Blackwell, to his great credit, has done in his contrast threshold work. Anything less is a waste of time.

We were, however, able to provide sufficient data to afford a reliable comparison between glare judgments made in our model apparatus and those on a full scale. For this study a larger number of observers were employed and we were able to establish that the judgments on a full scale always fell within the relevant confidence limits of the model scale assessments. (Ref. 8.)

Most of the work reported above was completed early in 1952, and I read a paper summarizing the results to the French Association of Lighting Engineers at their congress at Toulouse in May 1952. (Ref. 4.) Glare has been lying dormant at the Building Research Station since then, until last month we were able to take some time from our other work to study some of the effects of additivity. These results are still coming off, and we have not analyzed or assimilated them yet.

The Additivity of Glare

This work was started as a result of the C.I.E. meeting at Zurich in 1955, where it was clear that workers in the U.S.A. were unwilling to accept the *simple additivity function advocated by the British* delegation, yet did not offer any alternative based on sounder principles.

It would be a great mistake if the impression were given that the simple additivity function is believed by us to be fundamentally true. It is not, and clearly cannot be, for many reasons, some of which have already been discussed. It was advanced as a simple and practical expedient, which could be shown to agree reasonably well with the experimental facts, within the limited degree of precision which the British proposals as a whole set out to attain.

In any discussion on the additivity of glare, it is important to distinguish most carefully between the addition of the stimuli and the addition of the sensations. To abide by this precept is something which even the great have often failed to do. But if this distinction is not made both in thought and in the expression of thought, much of what is written is meaningless, however erudite it may at first appear to be.

The work on glare in street lighting (Hopkinson 1940) showed that, within the limits of the luminances and sizes of the sources, and the luminances of the background then under study, glare was additive. The expression there used for the additivity function was, that the background luminance necessary to balance the glare from a large number of sources (for a given criterion of discomfort) was equal to the arithmetic sum of the separate background luminances necessary to give the same criterion of discomfort with each of the sources seen separately. In other words, if:

$$B_b' = \frac{f(B_s')\cdot f(w')}{G} \qquad \text{for one source}$$

$$B_b'' = \frac{f(B_s'')\cdot f(w'')}{G} \qquad \text{for another source}$$

and so on,

then the background B_b for all sources seen together $= \Sigma\, B_b' + B_b'' + B_b'' + \ldots\ldots$ for the same criterion of discomfort throughout.

This was established experimentally.

The later work (Petherbridge and Hopkinson 1950) showed that this simple additivity of background luminances did not apply to low luminance sources, though it did to high luminance sources (such as had been studied for the street lighting investigation), but that to a reasonable degree of accuracy it could be accepted as a practical method for the calculation of glare effects. A summation more in accord with the experimental facts was given, *i.e.* that "the glare effect from a number of sources is the same as that from a single source of the same total apparent area in the same mean position." This has subsequently been shown to be an acceptable statement for most conditions met in practice.

The most recent work has been conducted:

(a) to show the probable extent of the error involved in the assumption of a simple additivity function in situations likely to be met in practice,

(b) to show whether the way in which a number of sources are disposed in the field of view affects the additivity of the discomfort effects,

(c) to determine whether a more complete picture of the mechanism of glare can be obtained, which would yield a more fundamental and more acceptable basis for the simplifications to be introduced for practical lighting calculations.

With the limited resources at our disposal, this work advances slowly. An interim report must necessarily be unsatisfactory, because it leaves unanswered so many questions which later results may resolve.

No useful purpose is ever served by erecting hypotheses to explain experimental findings unless these findings embrace the whole problem. On glare we have not the body of knowledge to justify the advancement of a hypothesis — we still do not know just why discomfort is caused by bright sources and exactly what visual and mental process are involved in the relation between stimulus and glare sensation. Nevertheless we can avoid a great deal of unnecessary work if we search for a limited explanation of our empirical results, even if this explanation does not constitute a hypothesis.

Two distinct situations at least seem to create a condition which gives rise to discomfort. First, the eyes may be dark-adapted (or partially dark-adapted) and the presence of bright sources acts as an "emotional affront." These sources may not, however, be so bright that the eye could not adapt to their luminance alone, *i.e.* the retinal stimulation is not maximal, it is simply that their presence in the darker field is the cause of the discomfort. This is the kind of situation met in lighted streets for example. The second situation arises when the whole field or a large part of it is extremely bright, and the eyes are fully light-adapted, but still unable to adjust themselves to the high luminance. Luminances of the order of, or brighter than, snow in full sunshine are in this category.

Practical situations can involve one or the other or a combination of these basic situations. Consider a simple case of the former. If a small source of, say, 500 footlamberts *(i.e.* approximately 1 candela/sq. inch), is seen in a dark surround, it will cause some discomfort if it is bigger than about 10^{-4} steradians. Yet a total field of 500 footlamberts is quite comfortable (it is the luminance of an average overcast sky). In fact, if the size of the source is steadily increased from 10^{-4} steradians, the glare discomfort first increases, reaches a maximum, and then decreases until, when it covers the whole field, it is causing no discomfort whatever.

(1) If, therefore, we neglect boundary and position effects (but we cannot always do so) we would expect that the addition of small sources of 500 footlamberts luminance to increase discomfort *up to a point,* and then to reduce discomfort. Hence we can only assume simple additivity over a limited range.

(2) Now, if we consider a source of 20,000 footlamberts *(i.e.* about 40 candelas/sq. inch), we can establish that such a source causes distinct discomfort when seen in a dark surround, when its size is about 10^{-6} steradians. If such a source is increased in size, it becomes steadily more "uncomfortable" and no amount of adaptation time causes any amelioration. Hence we might expect that the addition of small sources of 20,000 footlamberts would produce a progressive increase in discomfort. Simple additivity might possibly be valid for such bright sources.

These two deductions are in accord with the experimental findings of the Petherbridge-Hopkinson (1950) investigation. The relation between the size of a source, its luminance and the degree of glare discomfort for conditions of zero field (surround) luminance has recently been determined at the Building Research Station but, since the relation needs many more observations from many more subjects to validate it, it is, I think, wiser to leave it in the laboratory files at the moment.

When the effect of a surround field is included, the situation becomes more complicated. But if we can look forward a little, we may find that:

(a) For the greater body of present-day lighting practice, the glare from a number of sources can be evaluated by the addition of the effects of the individual sources, on the basis of equivalent source area (Petherbridge and Hopkinson (1950)).

(b) For conditions involving the addition of large sources of low luminance, the glare effects of a number of such sources can be expected to be less than simple additivity of the individual effects would indicate.

(c) For conditions involving the addition of sources of high luminance, the glare effects of a number of sources will be greater, in some cases much greater, than simple additivity of the individual effects would indicate.

It would perhaps be unwise to go further than this at the moment. It may be useful, however, to report the results of two studies which are ancillary to the investigation. In one experiment, the aim was to simulate a situation similar to that of an installation consisting of a series of large laylight sources which taken together occupy a large part of the upper visual field. Five rectangular sources, arranged in a perspective pattern were employed, whose angular subtense varied from 0.0009 steradians for the smallest to 0.013 steradians for the largest. The angular subtense of the five sources together was 0.026 steradians. The smallest source lay 6° and the largest 14° above the direction of viewing.

Assessments of glare were made on two occasions by each of three experienced subjects, viewing each of the sources singly and in three combinations, *i.e.* sources 2 and 4 together; 1, 3 and 5 together; and all five sources together. The assessments demanded settings of surround luminance to give, in turn, the four B.R.S. criteria of glare at each of three source luminance levels (300, 1000, and 3000 footlamberts) with each source or combination of sources.

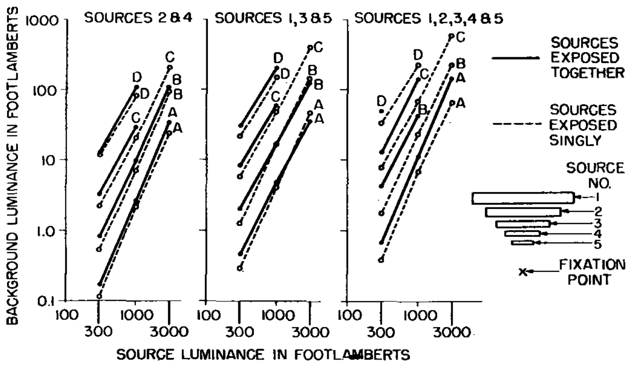
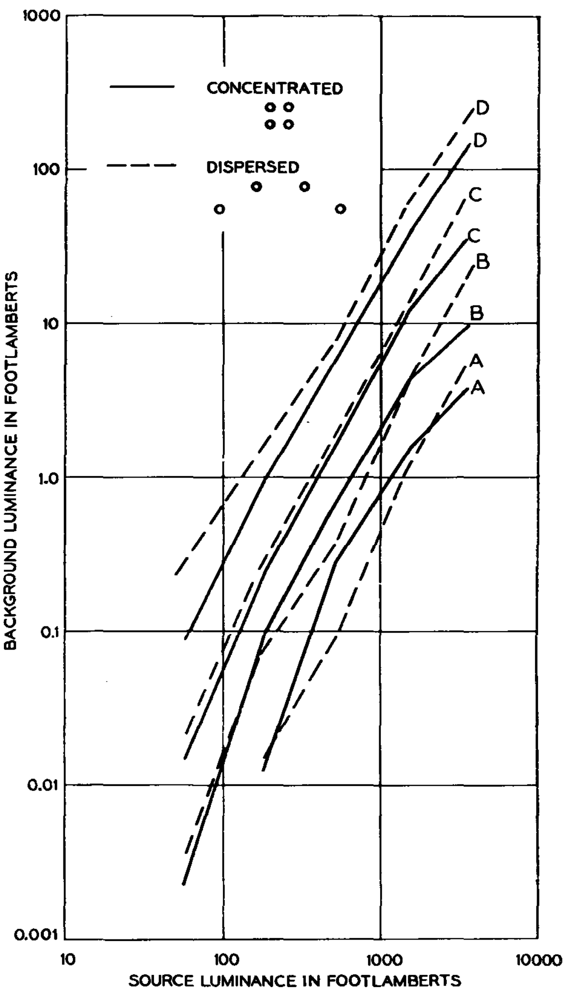


Figure 9 (above). Equal-glare curves showing additive effect/ glare from those combinations of sources.

Figure 10 (right). Equal-glare curves for four small circular sources with concentrated and dispersal groupings.



The averaged surround luminance settings for individual sources were added together for each of the three combinations of sources studied and compared with the corresponding averaged settings actually obtained for the combination of sources. The results are shown in Fig. 9.

In general, under these particular conditions, the surround luminance needed to "balance out" the glare from a combination of sources is rather greater than that deduced by adding the luminances needed to balance out the glare from each individual source. This is, of course, the effect reported by Harrison from observations in actual installations.

These results show to some extent the errors that can occur of the assumption of simple additivity of "glare constants." The greatest error, when all five sources are considered, amounts to half the difference between "just uncomfortable" and "just acceptable."

Another study just completed has as its aim to see if the inhibition of one part of the retina by stimulation of an immediately adjacent part might have some bearing on the additive nature of glare sources grouped in close proximity. To check on this, appraisals were made of the relative discomfort produced by two groups of glare sources, one group having the sources concentrated together and the other having the sources relatively widely dispersed. (Fig. 10.) Twelve observers viewed each of the groups of sources and were asked to say which group appeared to be most glaring when the source and background luminances were set at twelve predetermined levels.

Of the 144 appraisals which were made, 53 indicated the concentrated grouping to be more glaring while 42 indicated the dispersed grouping to be more glaring. Forty-three appraisals gave no difference in the relative degrees of discomfort. An analysis of these results showed that the actual appraisals were not distributed significantly differently from a theoretical distribution which divided the appraisals equally between "concentrated more glaring than dispersed," "dispersed more glaring than concentrated" and "no difference in glare."

Three observers used the multiple criterion technique to determine equal-glare curves relating source and background luminances for the two groups of sources when the background luminance was made variable and the source luminance was set at five predetermined levels. The average curves for two sets of appraisals from each of the three observers all confirmed the previous finding that there was no significant difference in the relative degree of glare produced by the two groups of sources. (Fig. 10.)

The two studies therefore established that if any mutual inhibition arose with the concentrated grouping then it was not sufficiently great to be detected by either of the two experimental techniques described above, under the conditions of the experiment.

Studies of this kind, though valuable pointers, do not enable a systematic modification in the "glare formula" to be made, although they do give a practical result which can be made use of in lighting design. It would evidently be wise, for example, to recommend a more than proportional increase in surround luminance if sources are added to an installation of the kind simulated by the experiment of Fig. 9. Such installations are more common in the U.S.A. than in Europe. Every effort should be made to continue the work in the form of a comprehensive study designed to reveal the missing features of the glare phenomenon, following the outline given earlier in this paper.

The final stage of this review is to summarize for you our present practice in evaluating glare.

We use our Glare Formula

$$G = \frac{B_s^{1.6}\, Q^{0.8}}{B_b^{1.0}} \qquad (3)$$

as our basic measure. Although we were responsible for the proposal to use the formula

$$G = \frac{B_s^2\, Q}{B_b} \qquad (2)$$

at the C.I.E. at Zurich, and although we have gone to considerable trouble to evaluate the best values of Glare Constant G to enable the new formula to give a good fit to the actual observations, we prefer to use equation (3) until international agreement is obtained, because it accords more closely with our experimental findings.

For situations where the sources are small and of uniform luminance, no major difficulties arise. The apparent size of the source is worked out, or gauged by a "steradian gauge," to give Q, and its mean luminance taken as the B_s term. The value of B_b is taken as numerically equal, when expressed in footlamberts, to the illumination in footcandles on a plane perpendicular to the direction of viewing, excluding the direct illumination from the glare sources. The Position Index may be ignored, or it may be given the values of Luckiesh and Guth. The effect of the immediate surround is ignored for first-order appraisals, or is estimated empirically from the experimental data. The glare constants for each source are worked out separately, and added arithmetically to give the Glare Constant for the whole installation.

Thus the glare constants G', G'' etc. are calculated for each source separately, for the same background luminance B_b.

$$G' = \frac{f(B_s')\cdot f(Q')}{B_b}$$

$$G'' = \frac{f(B_s'')\cdot f(Q'')}{B_b}$$

Then the "glare constant" G for the whole installation would be given by:

$$G = \Sigma\, G' + G'' + G'' + \ldots\ldots$$

Although the "glare constants," which are related to the degree of glare discomfort, have been added, this does not amount to an addition of *sensations*. It is merely an addition of $[f\cdot(B_s)\cdot f\cdot(Q)]$ terms over the common denominator B_b, and is therefore an addition of stimuli.

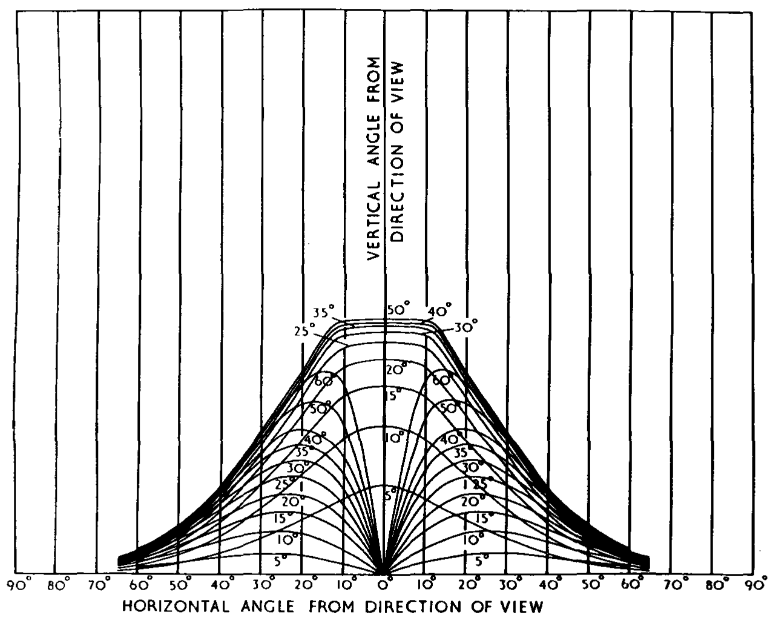


Figure 11. Petherbridge's projection for evaluating angular subtense of glare source, taking the Luckiesh-Guth Position Index into account. Droop lines are shown defining horizontal edges in planes at right angles and parallel to direction of view.

Figure 12. Luminance measurements are transferred to Petherbridge's diagram, and the combined source luminance, source size, and position factors determined together.

If the glare source is large or of irregular shape, it may be evaluated on a diagram which Petherbridge prepared, in which a cylindrical equal-area projection is modified to take into account the Luckiesh-Guth Position Index. (Fig. 11.) The diagram gives in one operation both the Q and the $f(\theta)$ terms in the Glare Formula (1). The normal droop-line diagram or a Sanson's net diagram can be used also to evaluate the average luminance B_b in a complex situation.

A vexed question arises in daylight studies or in artificial lighting by luminous ceilings or laylights, where the source luminance may be not much greater than the surround luminance. How is the adaptation term B_b to be evaluated?

It is not a question which has occupied much of my thought, for the reason that in those situations where it is important, the glare formula is known to break down. I am therefore more concerned to find a better relation between the variables than to find a modus operandi for the existing relation. In practice, in situations such as that shown, (Fig. 12), we decide by inspection. If the "source" occupies more than about a third of the field of view, we determine B_b as the average luminance of the whole environment including that of the "source." Otherwise it would probably be taken as the average of the environment excluding that of the source. In actual practical cases very little *significant* difference in the value of the Glare Constant results. If the Glare Constants obtained by one or the other system of evaluation differ substantially, it is almost certain that both are in error, and that the situation is one in which the glare formula is invalid (*i.e.* a situation where "saturation" effects are important, or where the exponent of the B_s term should be greater, and of the B_b term less than those of the formula, for reasons discussed earlier).

The glare constants so evaluated can then be

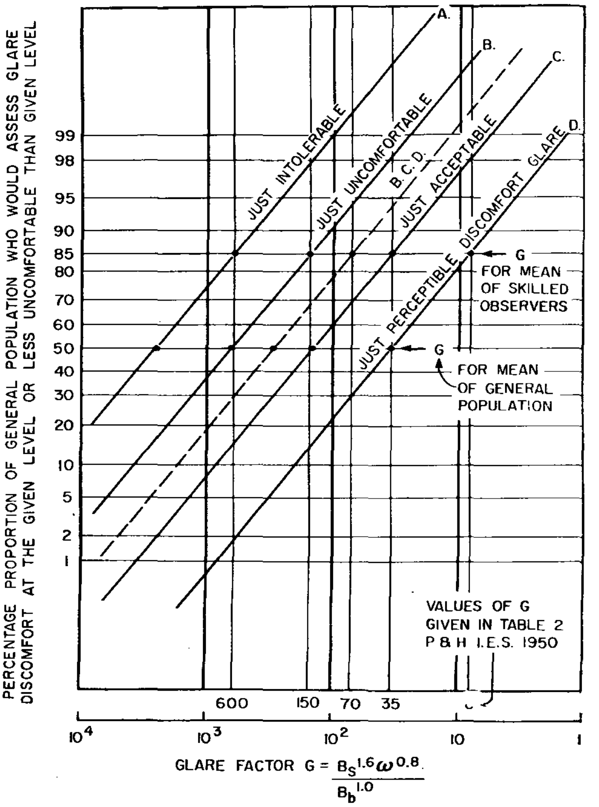


Figure 13. Mean probability diagram to enable proportion of general population satisfied by a given glare criterion to be related to the B.R.S. "Glare Factor."

examined on a mean probability diagram (Fig. 13). This diagram is derived from the results of the 50-observer study referred to earlier, but it is not a mathematical average of those results. It is based on the findings (a) that the means for the experienced six-man team on whose judgments the glare constants are based correspond to the 85 per cent probability level on the 50-observer study, and (b) that the mean judgment of glare for the general population in a given situation is one "criterion" less glaring than that of the six-man team.

With the aid of the diagram an estimate can be made of the percentage of the general population who will receive any given sensation of glare in the given situation whose glare constant has just been evaluated. The changes necessary to the glare constant to enable any given percentage of the general population (80 per cent was suggested to the C.I.E. as a reasonable figure) to achieve any given standard (*e.g.* the BCD) can thence be determined from the diagram. It so happens, quite by accident, that a Glare Constant of 100 from the B.R.S. formula enables 80 per cent of the general population to achieve the BCD or better.

Conclusion and Acknowledgments

The purpose of this review is to summarize ideas and work on glare discomfort at the Building Research Station, and to give a rather less formal presentation than customary in order that work could be discussed which is incomplete or which rests on insufficient evidence for a formal publication. There are many advantages in holding meetings at which ideas can be exchanged freely without the fear that adverse criticism must be anticipated by an array of cross-checks on all the results.

The end to which we are all working is to achieve a useful measure of international agreement on our findings, in order to promulgate an agreed method for the estimation of glare discomfort in practical lighting situations. It is clear that the problem, while simple at first glance, is riddled with second and third order complexities. A decision must be reached as to how far we can let these complexities hold up our agreement. The matter is urgent, because, certainly in Britain, if the experts do not agree, the engineers will go ahead themselves, as to a large extent they already have done.

In making this informal presentation of the work, I have committed myself perhaps further than I could in a formal paper from the Building Research Station, but I acknowledge the permission of the Director of Building Research to present the paper, though I cannot commit the Station in any way to the personal opinions I have expressed. I also acknowledge the help of my colleagues in these studies, especially Mr. Petherbridge who has been associated throughout with the Building Research Station work, and Mr. S. J. Richards and Miss W. M. Godfrey who have shared the work at different stages.

Finally I would like to thank the Illuminating Engineering Research Institute, Mr. C. L. Crouch and Professor E. M. Strong, for affording me the opportunity to attend the Cornell Symposium and present the paper.

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