

Assessment of Brightness:

What We See

By R. C. HOPKINSON

IT WAS AN honor to be invited to address the Illuminating Engineering Society at its 50th Anniversary Convocation, and one which I deeply appreciated. When I was asked to address the Society I thought of what might be the most suitable subject to choose from the various investigations in which we are engaged at the Building Research Station at the moment. I felt that a Fiftieth Anniversary Convocation was the kind of special occasion which calls either for a review of what has been done in the past, or a description of work which might lead to something new in the future. I decided to try to fulfill the second requirement. The subject I have chosen is the Assessment of Brightness—the problem of the judgment of magnitude of brightness as we see it.

In order to understand what the problem is, try to go back to the days before you became professionally interested in lighting and remember how you used to think of brightness in those days. When I first went to work (on street lighting), it seemed to me that once I had learned to use a photometer it gave me results which did not accord with what I could see. The brightness of a road sign on a lighted street at night, might measure ten foot-lamberts, and yet seem to me to be "as bright as day"; even though I knew that the daylight sky was at least one hundred times as bright. Now what was wrong here? Why was it that the photometer was not telling me the story which my eyes were telling me? It did not make sense. I felt this discrepancy perhaps more keenly than my colleagues did, because my first job as a post-graduate student was to develop a technique for the true representation of street lighting installations. To achieve this it was necessary to represent the brightness seen on the street by the same "apparent brightness" when the photograph was viewed in a room. That is why this work on the apparent brightness was initiated. It has been

going on intermittently for the last twenty years and we certainly have not finished yet.

Figs. 1 and 2 show two pictures of a classroom by daylight and by artificial light. A comparison of the appearance of the classroom by daylight for example, with a similar classroom by artificial light—walls, ceiling and sky, desk tops and so on—shows that the apparent brightness of the walls is about the same as it was by day. Photographs, of course, are not the same as the reality, but perhaps taken together with personal experience of these situations, they do illustrate my point. Luminance measurements made by a physical brightness meter show that in daylight the wall has a brightness of about 72 footlamberts, the sky about 2000 ft-L, desk tops about 40 or 50 ft-L, and so on. Luminance measurements in the room by artificial light show that the walls have a luminance of only about 3 or 4 footlamberts, and yet to the eye they appear to be almost equally bright as they did by day. Now, the photometer clearly is telling a different story than the eye. Why is this? This is the problem. It is a real one for us lighting engineers and for others too, such as the architect, who wants to have a measure of What We See. With this picture in your mind I want to go on and to describe our work.

Lighting is a technology in which the relation between physical energy and the visual sensory reaction is of prime importance. Photometry would be impossible without the basic Relative Luminous Efficiency function for the Standard Observer. This basic stimulus-sensation relation enables us to build a scale of photometric units in terms of the energy of the stimulus. A brightness scale derived in this way fails to take into account certain basic facts of vision.

First, the visual mechanism at any one moment can register as a sensation only a limited range of energy stimulus. Consequently, a finite but small amount of energy reaching the eye may cause no sensation of light. It is below the "threshold of sensation" for the given conditions, and on a true subjective scale it should be rated as zero.

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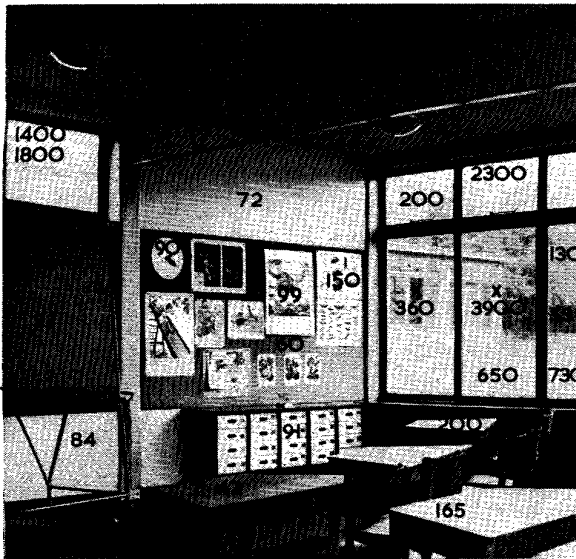


Figure 1. Photograph of a room by daylight, with values of luminance measured by a physical photometer.



Figure 2. Photograph of a room by artificial light, with values of luminance measured by a physical photometer.

Second, the visual mechanism can accept only a limited amount of energy on a given occasion—too much saturates the mechanism, and there is a sensation of blinding light or of pain.

Third, the sensation of brightness which results from a given stimulus depends on the environment in which it is seen. In a dark environment, stimuli seem brighter than they do in a bright environment. There is thus an “adaptation” effect which results in the subjective brightness being determined, not only by the energy of the stimulus, but also by the energy in the surround areas.

Fourth, the increment of energy which causes a given apparent change in brightness varies systematically in a non-linear manner, so that equal changes in luminance do not normally produce equal changes in subjective brightness.

Fifth, there is an uncertainty and a hysteresis in the stimulus-sensation relation which precludes the establishment of a simple and definite statement of the relation.

Need for a Scale of Subjective Brightness

A scale of subjective brightness is necessary whenever we need to interpret the physical constants of a lighting installation in terms of *What We See*. A street lighting engineer, for example, in speaking of a “bright” road surface, has values of the order of one footlambert in mind, whereas these values to a daylight consultant are about the threshold of darkness. Both engineers have built up by experience a subjective scale which they

automatically employ when thinking about their job.

Difficulties arise when the same job may embrace two or more levels of luminance, for example an art gallery in daylight and in artificial light. Some means is needed for ensuring that the effect, the *subjective* effect, is exactly what is required in both sets of conditions.

The first extensive use of the concept of apparent brightness followed on the derivation of a scale of apparent brightness which took adaptation levels into account (Hopkinson 1939, Stevens and Waldram, 1941). This scale was used at first for the solution of problems of photographic reproduction, and later applied to a study of street lighting visibility. Later still for wartime visibility problems (Stevens and Waldram 1946, Hopkinson 1946). After the war, the concept was applied either in general or specific form to the lighting of buildings. (Hopkinson 1948, Bickerdike and Allen 1951, Hopkinson 1951). Waldram (1954) has used the scale as an essential feature of a method of lighting design which he calls “Designed Appearance” in which the architect is expected to specify the brightness sensation to be given by any part of the visual field in terms of apparent brightness, and this, with the aid to the Hopkinson 1941 data is converted into luminance, and thence to illumination, reflection factor and light distribution.

In the work at the Building Research Station it was always borne in mind that the universal validity of the 1941 data could not be assumed, since these data were built up from contrast rather than

brightness estimation, as will be described later. Situations has arisen which showed that a direct application of the 1941 apparent scale would give misleading results. A series of experiments were put in hand in 1949 to investigate these discrepancies, which confirmed the limitations of the data but which unfortunately had to be left incomplete (Hopkinson 1951).

This gives briefly a picture of the historical background to the present work, up to the point where I was able to visit Professor S. S. Stevens at Harvard University in April 1956 and discuss the problem of brightness assessment with him.

Determination of a Scale Of Subjective Brightness

The classical work on the relation between brightness stimulus and sensation is, of course, that of Weber and of Fechner. From the experimental statement by Weber, that just noticeable differences in sensation result from equal ratios of stimulus, came the Fechner deduction that equal intervals in sensation are proportional to equal ratios of the stimulus. There have been attempts to formulate a subjective brightness scale by the Weber-Fechner method. Aribat (1935) produced such a scale in an attempt to solve the problem of true photographic reproduction of luminosities. It was Aribat's scale, and its evident failings, which served as the starting point for the present work.

By far the greater number of early attempts to formulate a working subjective brightness scale derive from the indirect approach of Fechner, which depends on the assumption that all just noticeable differences, wherever or whenever they occur, are equal. More recently this approach has given ground to the multitude of determinations based on methods of doubling, halving, or other fractionation and multiplication, of which one of the earliest examples is that of Merkel (1888, 1889).

Judgments of subjective brightness using a binocular matching method were made by Pitt (1939) from which a subjective brightness scale could be constructed, but the conditions of observation were not comparable with those which arise in normal problems of illuminating engineering. Craik (1938, 1940), made an extensive study of the effects of adaptation on subjective brightness, without formulating an engineering scale. Hunt (1953) derived a set of "characteristic curves of the human eye" from Craik's and other data in order to assist in the solution of photographic reproduction problems. The enormous body of work by S. S. Stevens and his collaborators will be referred to later.

Experimental Methods for Deriving An Apparent Brightness Scale

Method 1 — Contrast Scaling

The need for a subjective brightness scale became acute in the period immediately before the war, when research on photographic reproduction and on street lighting demanded the assessment of brightness in terms which expressed directly the sensation of brightness being received by the observer. The data of Aribat were examined for these purposes, and found to give a general picture which accorded well with practice, but they were too scanty to give an adequate basis for a complete scale of apparent brightness. A new determination was made using a method known as the "Contrast Ladder," or perhaps better called "contrast scaling."

The essential feature of the method was the successive adjustment of two patches, seen in an adapting field, to appear always of equal contrast one with the other. The two square patches, each of 1° side and separated by 1°, were seen in an adapting field covering most of the field of view. The two patches were first set each to appear black to the observer. The experimenter adjusted the luminance on one (say patch B) of the comparison patches until a contrast well above threshold, perhaps about five just noticeable difference steps resulted with the other (black) patch. The subject was asked to note and remember the contrast between the two patches. The subject now himself adjusted the black patch (patch A), raising its brightness until the contrast with the other patch was the same as before, patch A now being the brighter of the two. Thus two steps of the "contrast ladder" had been established, the first given by the experimenter and the second set by the subject himself. The subject was now asked to bring up patch B until it was brighter than patch A by the same contrast as before, and so on. Thus was the "contrast ladder" built up.

Observations were made by this means at several adaptation levels (*i.e.* settings of the luminance of the surround field). The data were in general consistent. The experimental data were paired and compared with the data of Aribat (1935). (At the time that these studies were actually in hand, 1937, the data of Pitt, 1939, and Craik, 1938, 1940, were not available. There was a long gap between the work and its publication, due to the author being caught up in the march of events).

The agreement was good. The curves shown in Fig. 3 were drawn up from the experimental data and from the data of Aribat, taking Aribat's data to determine the basic shape of the curves,

and the experimental data to fill in the gaps. Abribat's data were not really necessary here, but perhaps in those student days there was a certain lack of confidence when working in a field where many pitfalls were only too clearly delineated by more experienced workers.

The scale of Apparent Brightness was an arbitrary one. It was, of course, a scale of contrast, but it was argued that two luminances each of which appeared, for example, five steps on the contrast ladder brighter than black, would have the same apparent brightness. The scale was deliberately not called a scale of sensation, as had been done by Abribat, but it would perhaps have been better if it had been labeled Contrast. The numerical scale was chosen so that one unit represented approximately a "just noticeable" or perhaps more accurately "just certainly perceptible" contrast, under the experimental conditions. At the time that the scale was first made available (in 1937), a warning was given that, since the scale had been built up from contrast and not from brightness judgment, it would not necessarily represent brightness accurately. It was, however, used for a wide range of visibility problems before and during the war, and, provided the conditions in which it was used compared with the experimental conditions in which it was determined, it gave satisfactory assessments of the subjective impressions of the contrast between adjacent areas in the field of view.

Method 2 — Luminosity Photometer

The use of the concept of apparent brightness in the lighting of buildings was described at a Conference on Lighting and Color of the Council of Industrial Design in London (Hopkinson 1948), but already at that time certain difficulties in the use of the scale had become evident. One was that the values of apparent brightness on the scale did not always correlate with subjective judgments of highlight and shadow; the other was that high luminances did not always appear to have the values of apparent brightness given to them on the scale. The fact that these discrepancies had not been detected before was undoubtedly due to the pre-war and wartime work being concerned almost entirely with low luminance and low adaptation levels, where the scale worked well.

Provided one was aware of these discrepancies, the scale could still be useful, and was employed in many practical situations. In the lighting of art galleries, it had been found empirically that pictures could be seen and enjoyed better by giving preferential lighting to the pictures and reducing the brightness of the general surroundings (Bickerdike and Allen, 1951). The magnitude of the effect

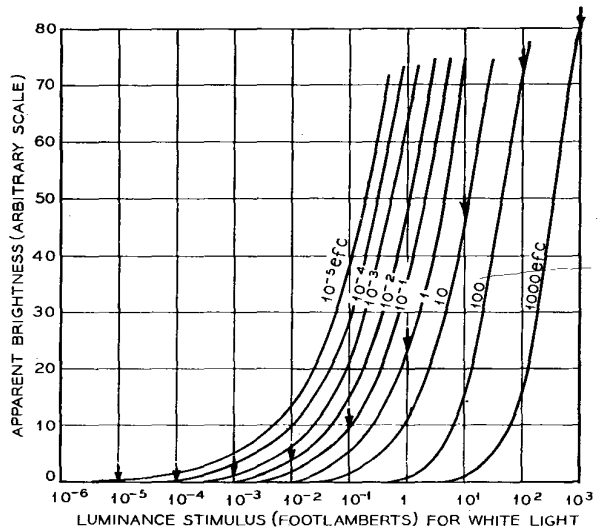


Figure 3. Scale of Apparent Brightness determined from Contrast Scaling Technique (Hopkinson 1939, 1941). Each curve relates the physical brightness stimulus (luminance) with the corresponding subjective brightness magnitude for a given adaptation level.

in different circumstances could be predicted by the use of the apparent brightness scale.

The use of the scale made one more sensitive to brightness relationship in the field of view, and with experience came a greater awareness of discrepancies. It was always realized that a simple dual relation between physical stimulus and sensation could not exist, because of the inherent hysteresis of the sensation-stimulus mechanism, but the discrepancies were often greater than could be accounted for by this explanation.

It was therefore decided to examine the scale by a series of cross-sectional judgments, *i.e.* to see if luminances to which the scale had assigned the same apparent brightness in a range of adaptation conditions were actually judged to have the same apparent brightness. This was therefore a direct check on the basic assumption that an equal number of steps on the "contrast ladder" would always yield the same apparent brightness.

The apparatus used was called the Luminosity Photometer, Fig. 4. It consisted of two identical compartments set side by side with a viewing aperture in each, so that the subject could view the one or the other as he pleased. The interiors of each compartment were white and illuminated uniformly by screened lamps. At the far end of each compartment was a square field patch subtending 3° side at the subject's eyes, and illuminated independently of the surround field. The subject could thus compare the apparent brightnesses of the two field patches, set in different surround luminances,

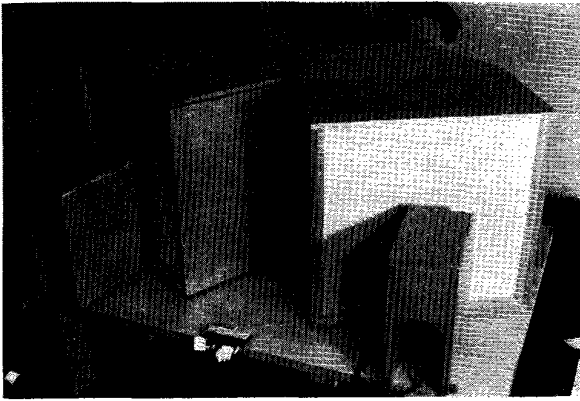


Figure 4. The luminosity photometer. Two identical compartments, side by side, enable the subject to view a patch of light in the one or in the other. The adapting conditions in the two compartments are different, and the task of the subject is to set one of the patches to appear of the same brightness magnitude as the other.

using normal binocular vision, much as he would be able to compare the luminosities of two pictures in adjacent galleries when standing in the communicating door between. The disadvantages of the method were appreciated, especially the need to pause to adapt when changing the view from one compartment to the other, but it was felt that the advantages outweighed them. The method of Hess and Pretori (1894) was considered, but it was felt that the visual difficulties associated with the different planes of presentation would influence the results and that the method gave more weight to simultaneous contrast than to adaptation effects.

The task of the subject was to set the apparent brightness of the two test patches to be equal. Several methods of observation were tried, and much time was spent, as an exercise, in the study of these various methods, including that described by von Bekey (1947) and Oldfield (1949).

As a result a great deal of information was gathered about the accuracy of different methods of brightness judgment which has come in useful in many connections, but unfortunately the work had to be abandoned for more urgent matters before sufficient data had been gathered to enable a new scale of apparent brightness to be derived. The results confirmed the discrepancies in the high luminance regions of the Hopkinson 1941 scale, however, and also explained why contradictory estimates of apparent brightness were occasionally given. It was found, for example, that simultaneous contrast could upset the basic relation to a marked degree. Also, if the surround luminance in the left hand compartment was almost a photometric match with the patch, *e.g.* 10 footlamberts

for the surround and 11 footlamberts for the patch, it proved very difficult for the subject to set the patch in the right hand compartment. Suppose the surround luminance in this compartment was one footlambert, the tendency would be for the subject to set the right hand patch for approximate equality with its surroundings. The observations for such settings tended to fall into two groups, the one where the subject had set for equal appearance, and the other where he had resisted the temptation and had tried to set for equal luminosity.

The experiment proved a very valuable exercise in the fundamental problems of brightness sensation-stimulus relations. No further work could be undertaken, however, until 1956. This is the point at which I had a most valuable discussion with Professor S. S. Stevens at Harvard. I came away feeling that here was the key to the problem.

Method 3 — Method of Direct Estimation (S. S. Stevens' Method)

Stevens asks his subjects to estimate a sensation directly by attaching a number to the sensation. For example, in judgments of loudness, a loud tone might be given the number 100, a still louder tone 150. Consequently he avoids all the objections to the indirect methods of the Fechner school.

Stevens has described his method in detail in several publications (1955, 1956). The results which he has obtained, both published and unpublished, are undoubtedly impressive. The mechanism by which people judge a sensation and assign a number to it is not understood, and they themselves seem to have no confidence in it, yet nevertheless the numbers which they assign to the sensations plot well with the stimuli. Whether the numbers bear any fundamental relation to the sensations they purport to describe is, of course, a matter for examination. Nevertheless, I felt the method to be one worthy of study, and accordingly, immediately after my talk with Stevens, while I was still in America, I airmailed back to my laboratory a request to perform an experiment to make a set of determinations under conditions similar to those of Stevens' studies. The experiment was described in detail in my letter, but the purpose of it was not, and the experimenter had no knowledge himself of the background to the study. He therefore had no prejudices or preconceived hypotheses which could have influenced him, and through him, the subjects he employed.

The subjects were to be presented with ten luminances in random order, covering a range of 4×10^5 in luminance. A 2° field in a dark surround was employed. They were asked to put a number on the magnitude of brightness sensation. The

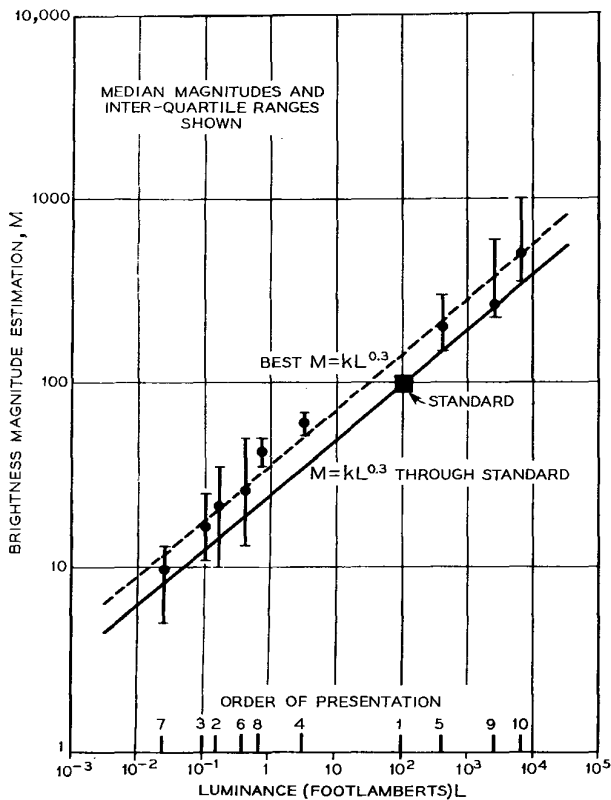


Figure 5. Estimates of brightness magnitude of small source (2° square) related to physical luminance stimulus. 10 observers. Reference standard set at 100 foot-lamberts and called 100.

subjects all complained of the difficulty, in some cases of the imbecility of the experiment, exactly as had Stevens' subjects at their first attempts. They were, however, prevailed upon to complete the task, eleven observers in all making two sets of judgments. The subjects were given a standard, in the first series a luminance of 100 footlamberts was assigned to the number 100 by the experimenter, and in the second series the number 100 was assigned to a luminance of 0.4 footlambert. This setting of a standard was a decision of the experimenter himself. I had not asked for a standard, and did not want one, but he, and the colleagues with whom he discussed the experiment, could not conceive of doing the experiment without a standard. He, as well as the subject, could not muster enough confidence in "direct judgment" to following my instructions to the limit.

The results of these two determinations are shown in Figs. 5 and 6. It will be seen that the relation between the logarithm of the stimulus (luminance) and the logarithm of the brightness magnitude is an approximate straight line. I have fitted the relation $M = kL^{0.3}$ to the points. This is

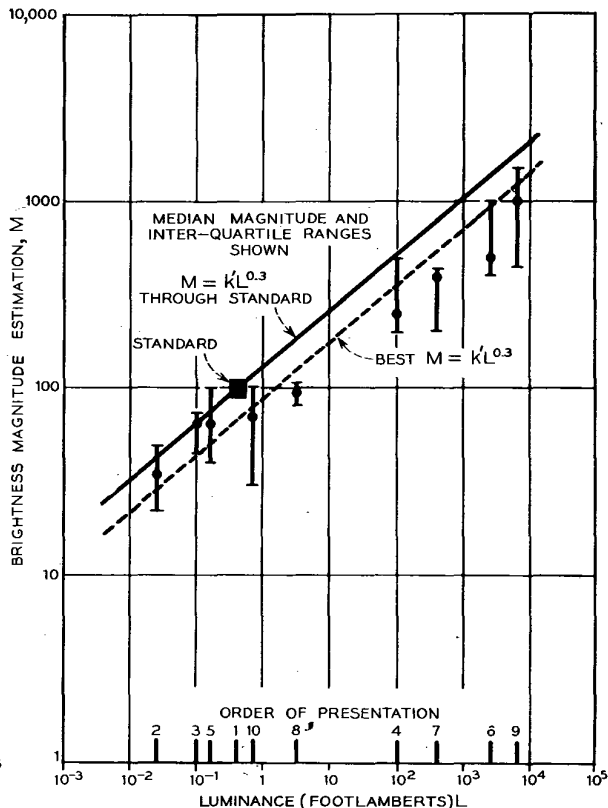


Figure 6. Estimates of brightness magnitude of small source (2° square) related to physical luminance stimulus. 11 observers. Reference standard set at 0.4 foot-lambert and called 100.

the relation which Stevens and his colleagues have found between magnitude of sensation (M) and physical stimulus. The fit is none too bad, but it is not perfect.

These results convinced me that a method of direct estimation offered an alternative for determining a scale of subjective brightness. It was a direct method and one which corresponded closely with the way in which the scale would be used in practice. It avoided the various half-way stages of the other methods—the doubtful Fechner integration of Aribat's method, the unnatural binocular matching of Pitt's determinations, the translation from contrast judgment to apparent brightness scale of my own pre-war determinations, and the tortuous stages of the fractionation and multiplication methods. It was impressive too, that the long-distance experiment with naive subjects and an unbiased experimenter answered some of Stevens' critics, who appeared to suggest that his subjects could only make consistent judgments after long training by a dominant personality who willed them to give the "right answers." My subjects had certainly not been under any such influence.

It is easy to understand the doubts of the critics, because the nature of the experiment is not one to inspire confidence in anyone with a conventional scientific training. It is as well to remember, however, that such doubts were not always entertained. The ancient world often had no means, other than subjective estimates, of expressing the magnitude of many entities which can now be determined by precise measurement, and they have often been shown to have been remarkably accurate in these judgments. Long before photometers existed, Hipparchus deduced a scale of stellar magnitudes, grading visible stars into six groups, the brightest of the first magnitude, and the faintest of the sixth. During the following centuries, this scale was refined, notably by Tycho Brahe and later by Argelander and his co-observers, careful and painstaking observation enabling every star visible to the naked eye, and many telescopic stars, to be assigned a magnitude, often to two significant figures. When eventually accurate photometers became available, which permitted a precise check to be made on these subjective assessments, it was found that they were remarkably consistent, and that a precise mathematical relation between observed magnitude and measured luminous intensity could be formulated.

The mystery still remains, however, why the numbers 1 to 6, and not 1 to 10, or 1 to 100 were used for the stellar magnitude scale, and this doubt applies to our present set of brightness judgments. What have people in their minds when they say that a patch has a brightness of "25," that is, not 25 units, but just "25"? What do they mean when they say that one noise is "twice" as loud as another? What exactly is "twiceness" in this context?

We simply do not know, and as engineers we do better to leave the inquiry to our extra-professional activities (that is to say, I feel that we should pursue it, but as philosophers, not as engineers). We should, however, recall that non-scientific people even nowadays, and the ancient world in general, have and had no difficulty in expressing the magnitude of intangible things. They will tell you confidently how big the moon appears to them. Down on the horizon it is as big as one of your cantaloupe melons—in the English countryside the traditional saying is that the moon is as big as a cheese. Up, in the sky it is as big as an orange. Lucretius asserted that both the sun and the moon were in fact actually no bigger and no less than they appeared to our senses to be. "*Nec nimio solis maior rota nec minor ardor esse potest, nostris quam sensibus esse videtur. . . . lunaque . . . nilo fertur maiore figura quam, nostris oculis qua cer-*

nimus, esse videtur" and then used this assessment as the basis for a discussion of how the sun is able to provide such an immense amount of heat and light from such a small area.

We have, of course, to distinguish between assessments based on comparison, which is what the English countryman makes when he says that the moon is as big as a cheese and assessment expressed in absolute terms, which is what Hipparchus made and what our observers have made. As far as I can tell, however, the processes of thought seem to be the same. Certainly the more highly trained in measurement a subject is, the less confidently can he make these judgments—the best subjects are intelligent but unscientific. One observer was unable to make independent judgments—she had spent all her working life making photometric measurements in lighting installations, and her assessments, unknown to her, followed almost exactly the photometric values—she had, in fact, a scale of "absolute luminance," similar to the scale of "absolute pitch" possessed by some musical people.

On my return from the U.S.A. in May 1956, I set about an intensive program of brightness determination using the direct judgment technique, in order to study the effect of adaptation on apparent brightness. The first stage was to repeat the experiment just described, substituting for the 2° field a large surround luminance covering the whole of the field of view. Seven luminances, covering a range of 6 cycles (100,000-1) were presented in random order, and judgments made as before. These judgments were made without an initial standard.

A 2° aperture was next opened in the center of this field. The luminance of this aperture could be adjusted independently of the luminance of the large surround field. The surround field was set to a given constant value, and the subject was presented, in random order, with a series of different luminances of the 2° patch, to which he assigned numbers for the sensation magnitude. I started by giving him as a standard a number for the adaptation surround derived from the mean plot of the judgments made on the surround alone, but soon abandoned this procedure as it appeared only to confuse him or raise doubts in his mind. The method of free choice proved preferable.

Similar series of judgments were made with the surround luminance at various values from 0.04 footlamberts to 450 footlamberts.

A preliminary set of judgments obtained by three observers proved that the method could give a consistent set of data. Three other observers then made judgments. Their absolute magnitudes differed widely (*i.e.* one observer would assign, for

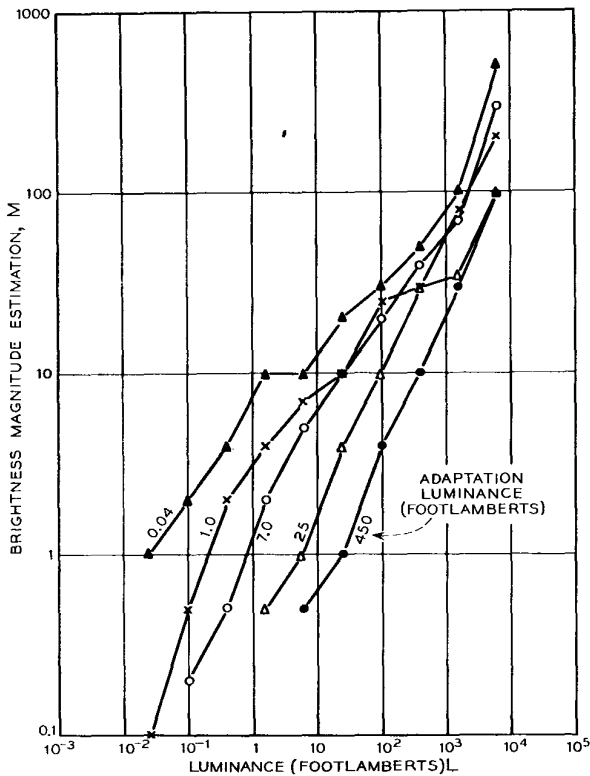


Figure 7. Estimates of brightness magnitude of small source (2° square) in large adapting field, related to physical luminance stimuli presented in random order. One observer.

example, the number 100 to the luminance to which the other assigned 3), but if their determinations were averaged, a consistent plot was obtained which could be compared with other data.

The remarks made by the subjects during the course of the experiment are of interest. Low or high brightnesses could be judged most easily, intermediate values offered the greatest difficulty. This was confirmed by the uncertainty of the plots in these regions.

Data for the highest adaptation levels plotted most consistently. A typical set of observations is given in Fig. 7. All data were paired and compared with the pre-war "contrast-scaling" data, dotted on the same scale (Fig. 8). (Refer also to Fig. 10.)

(1) The slopes of the M/L curves were shown to depend on the adaptation level, the higher the adaptation level, the steeper the slope.

(2) At low adaptations the slope approaches the relation

$$M = kL^{0.3}$$

which had previously been found for a dark surround.

(3) At high adaptation levels the slope approaches

$$M = kL^{1.0}$$

i.e. at high levels apparent brightness and luminance march in step. This is true both for the direct judgment data and the contrast-scaling data.

(4) The adaptation levels themselves from the various curves could be said to fall approximately on a line

$$M = kL^{0.3}$$

if we were trying to prove a case, but the departures from this regression are different for the direct judgment data than for the contrast-scaling data.

(5) The contrast-scaling data assign approximately the same sensation magnitudes to low luminances as do the direct judgment data, but differ widely in the high luminances. The luminosity photometer experiment, it will be recalled, recorded discrepancies with the contrast-scaling data in these regions.

At this stage a decision had to be made whether to continue the work with a very limited number of subjects, or wait until a full research program could be undertaken. The temptation to go a little further could not be resisted, even though we knew that the data we obtained could be of little more permanent value. The subjects by now were gain-

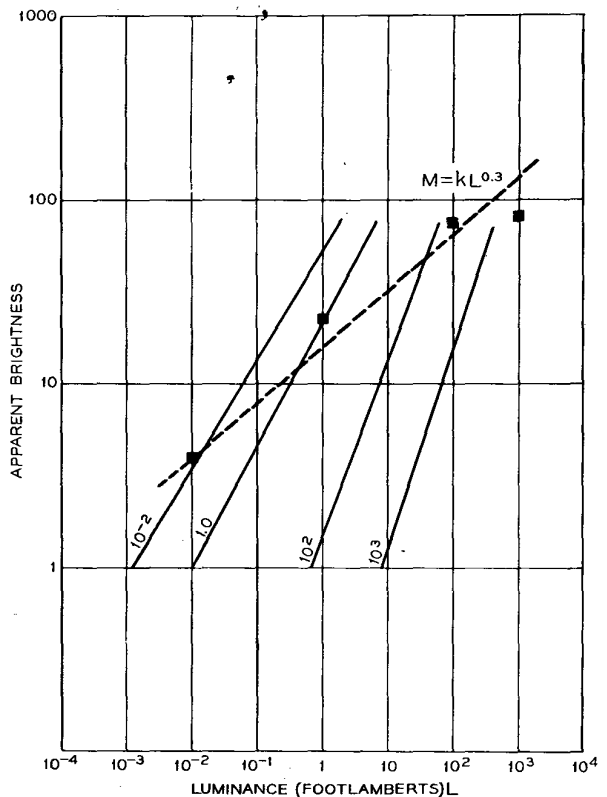


Figure 8. The data of Fig. 1 re-plotted on a log/log scale (data for four adaptation levels only).

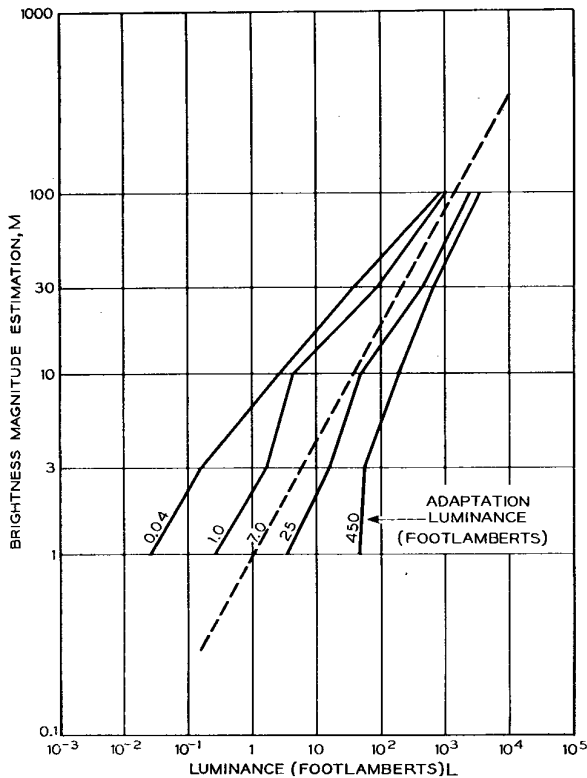


Figure 9. Settings of luminance of 2° source to give constant apparent brightness when luminance is varied. Source pre-set to each of five previously judged levels of apparent brightness at adaptation luminance of 7.0 footlamberts.

ing confidence in their judgments and were less inclined to protest.

One variant was introduced. A series of "cross section" checks of the data was made, in which the subject was asked to remember the apparent brightness of the patch in another surround to this remembered magnitude. This was done at five levels of brightness magnitude, at these levels of adaptation (0.04, 7.0, and 750 ft-L) for datum; data for one observer are shown on Fig. 9. Two observers made these cross-check observations.

Finally a grand average of all the observations was made, for two subjects. The observations of all the subjects could have been included, but were not because they were incomplete and their inclusion would have introduced weighting problems. This average is shown in Fig. 10. The curves as drawn attempt to take into account the fact that at any given adaptation level, there will be a range of luminance which appears "black" to the observer. The determination of this "subjective black" is one which has proved a stumbling block to previous investigators, *e.g.* Pitt (1939), and we decided to avoid the problem at this stage. Since

TABLE I—Percentage of Occasions on which a Given Luminance of a 2° Source Appeared Black under Different Adaptation Luminance Conditions.

SOURCE LUMINANCE (ft-L)	ADAPTATION LUMINANCE (ft-L)			
	0.04	1.0	7.0	25 450
PERCENTAGE OF OCCASIONS				
0.025	0	80	100	100
0.1	0	0	83	100
0.4	0	0	0	40
1.6	0	0	0	0
6.4	0	0	0	0
25.6	0	0	0	0

the luminances of the 2° field which were presented to the observer were in stages of 4:1, it was not easy to deduce from the judgments the value of the maximum luminance which would just appear black. Instead, a table was drawn up as shown, listing the number of occasions on which any given luminance appeared black in the course of the judgments. From this, the highest value which would appear black on 100 per cent of all occasions was estimated, and this was taken as the asymptote for the relevant apparent brightness curve on Fig. 10.

It is a subject of philosophical argument as to whether this value of luminance should be assigned the sensation magnitude 0. "Blackness" is, accord-

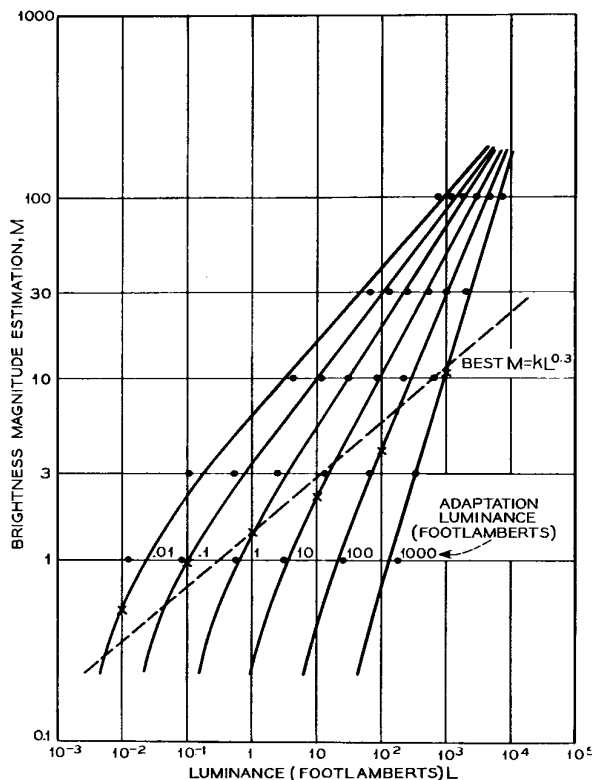


Figure 10. Faired data of all brightness magnitude estimations for two observers. 2° source in large adapting field.

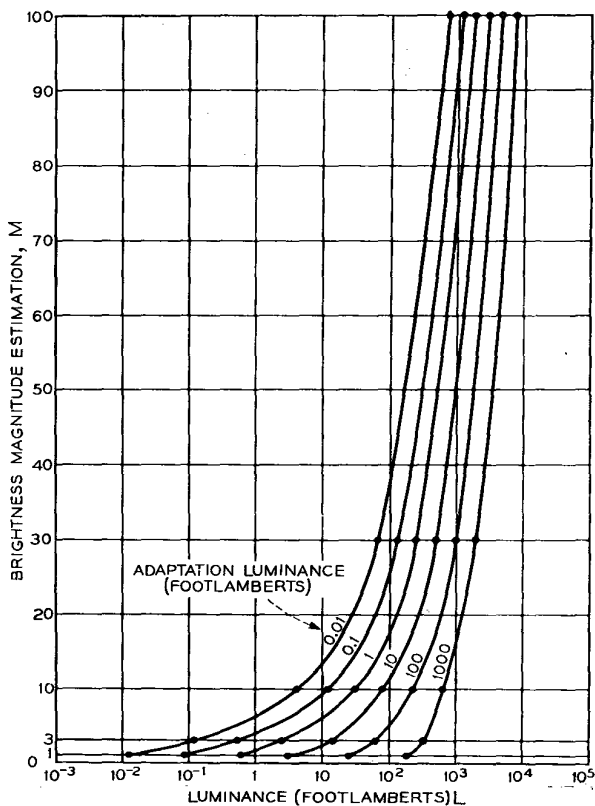


Figure 11. The data of Fig. 10 on a linear scale of brightness magnitude, logarithmic scale of physical luminance.

ing to many, including Hering, a positive sensation, not a zero sensation. Equally the nature of the sensation-stimulus curve in these lower regions is speculative. Some observers did use fractional numbers for their estimates, and one observer never gave "black" as a response at all, using minute fractions instead. He explained his reason for this in the words "I knew there must be something there even though I couldn't see it, so I guessed a small fraction. The whole thing was a guess anyway." When it was explained that on occasions there had in fact been no stimulus presented, the subject shrugged indulgently. Stevens (1955) quotes Robinson (1953) as suggesting "when intensity crosses the threshold, loudness comes on with a jump." Nothing like this happens in brightness. If the 2° patch is black, and its luminance is slowly raised, eventually, as the threshold is passed, a faint glimmer is seen, but there is no "coming on with a jump." At the moment, therefore, it is best to leave the argument until further basic studies of near-threshold sensations can be undertaken.

The data of Fig. 10, or the same data on a linear/log plot (Fig. 11) would, if they had been based on sufficient observations from a sufficient

number of subjects, serve as the basis for a *standard scale of apparent brightness*. Such scales have been proposed before (e.g. the brill scale of Wright (1940), the brill scale of Hanes, Michel, and Helson (1953, 1954) and others). The present scale is more comprehensive than these in that it takes adaptation fully into account, a matter of importance to the lighting engineer. It is in the same form as the original "contrast-ladder" scale, but, being based on direct judgments with free choice, it does not suffer from the criticism that apparent brightness, one type of sensation, has been reached through contrast, another type of sensation. But quite apart from the fact that it is based on the judgments of too few observers at the moment, it is incomplete, in that it applies only to judgments on a 2° patch in a large field. We need to know how the size of the test patch governs the judgment of brightness, and whether as the work of Hanes (1951) suggests, in a comprehensive scale, separate relations are necessary for different areas of stimulus just as they are for different adaptations. We also need to assess the effect of simultaneous contrast, for example, the effect that the presence of the 2° patch has on the judgment of the brightness of the surround. The work is therefore not anywhere near a stage of finality, and it would certainly not be wise to use the data of Fig. 10 as a working scale for any conditions other than those of the experiment. But we have made a step forward.

Two features of the results which have already been pointed out are perhaps worth special attention, features which are common to both the direct-judgment (Fig. 10) and the contrast-scaling (Fig. 8) data. The first is that, at high luminances, the sensation of brightness magnitude bears almost a linear relation to the luminance. This does not mean that a luminance of (say) 30 footlamberts will be assigned the numeral $M = 30$, but it does mean that if the subject judges 30 footlamberts as $M = 10$, he will judge 300 footlamberts as $M = 100$, *i.e.* ten times as great, in the same ratio as the luminances. The need for a subjective scale at high levels of luminance is therefore limited, since the luminance scale itself will accord well with the subject's judgment of brightness magnitude, within the obvious limitations. This does not, of course, mean that the research is wasted effort. Without the investigation we would not know the special properties of the luminance scale, whereas now we can be fairly certain that if the lighting engineer is asked by the layman client to make, say, a ceiling "twice as bright as before," he will achieve the aim by making the luminance twice as great.

The other feature of the results, of more impor-

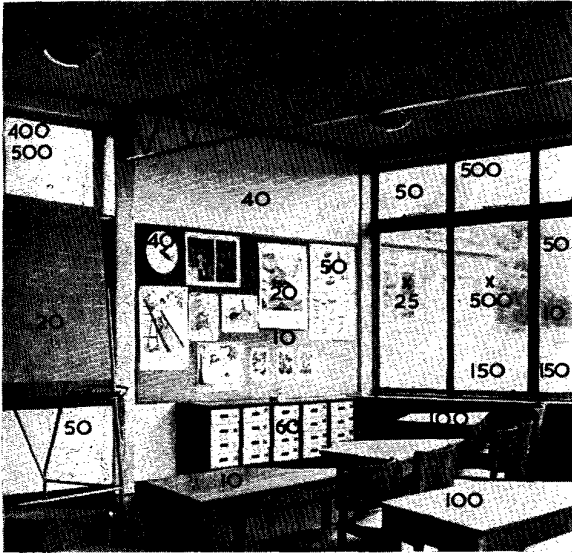


Figure 12. Photographs of the same room as Fig. 1, by daylight, with values of apparent brightness (estimated magnitude).

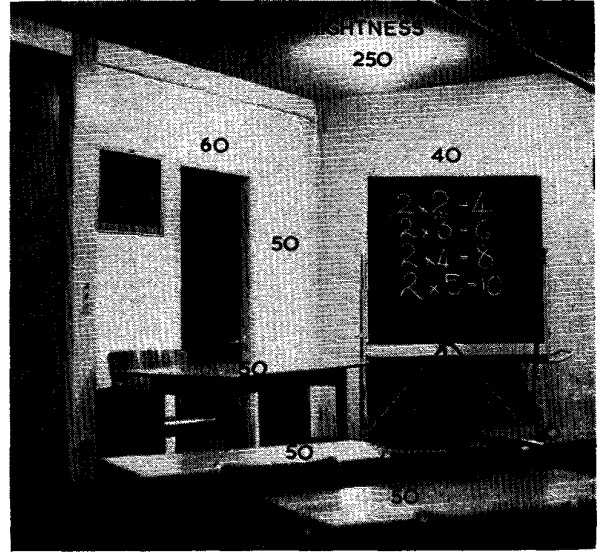


Figure 13. Photograph of the same room as Fig. 2, by artificial light, with values of apparent brightness (estimated magnitude).

tance to the psychologist than to the lighting engineer, is the way in which the relation $M = kL^{0.3}$ crops up. The similarity between the judgments of brightness sensation in a dark surround and loudness sensation in an anechoic room, when each is related to the relevant energy stimulus, may be more than coincidental. If it is real, it follows that the assignment of a numerical magnitude to a sensation is a basic mental process taking place in the higher centers of the brain, and that there is some essential similarity between the visual and aural mechanisms which convert energy into sensation.

We now have our scale of apparent brightness, and we can now examine our school classrooms again. (Figs. 12 and 13.) Instead of the luminance values that we had before, we can work on the apparent brightness values. It is seen that the walls are now given apparent brightness of the order of 50 on the scale, and in daylight they are given a value of about 40 which is just slightly less. If you compare the apparent brightnesses in detail for the daylight and the artificial light scene, you will see that things which look about equally bright to you are assigned equal numbers on the apparent brightness scale. We have in fact a scale now which really accords with What We See.

Conclusion

It is not the purpose of this paper to detail the uses of an apparent brightness scale. That must await another occasion. This paper is clearly the beginning, not the end of a story. It shows, I think, that a useful engineering scale of apparent

brightness can be derived by various methods, including direct estimation. The effects of adaptation can be allowed for. Much more work is necessary before a final scale can be put forward.

Nevertheless I feel that we ought to look forward to this step and I would like the C.I.E. to turn its attention to the problem. The acoustic engineers are well ahead of us here. There is already an American Standard loudness scale and talk of an international standard. If the science of acoustics can do this, with the enormous discrepancies that have occurred between the different determinations, we should be able to do at least as well.

I would put forward as a basis for discussion a suggestion that the *apparent brightness magnitude should be expressed in units which are numerically equal to luminance units when the adaptation luminance is 1000 footlamberts*. When the adaptation luminance is other than 1000 footlamberts, the brightness magnitude expressed in apparent brightness units should be determined from an internationally agreed set of data which might be similar to that of Fig. 10 but which might also include an allowance for the area of the test field and for simultaneous contrast.

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The work reported in this paper covers a long period, from the time when I was working on my thesis under the late Mr. G. H. Wilson, to the post-war period when my colleagues, Dr. Gilbert in 1949-50, and Mr. Longmore in 1956, did the experimental work for me. My acknowledgments to them

and to all the subjects who consented to make observations on experiments which seemed futile to them is gratefully made. My special gratitude is due to Professor S. S. Stevens, whose own studies and enthusiasm for them set me about the latest stage of the work, which I greatly hope will not be the last.

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Display Lighting for New Cars

To display the shiny new automobiles to best advantage, a combination of fluorescent and incandescent has been used in the showroom of Adcock Buick Co., St. Petersburg, Fla. An aluminum louverall ceiling is mounted 11 feet from the floor, with single-lamp 8-foot channels of slimlines mounted on two-foot centers in the white plenum. Average level from this system is 80 ft-c on the horizontal surfaces and 30 ft-c on the vertical. Supplementary lighting over the cars, from PAR-38 floods, is 120 ft-c. These gimbal ring fixtures are

spaced around the sales room to bring out the sparkle of the chrome.

Upper walls are pink, 60% RF; lower walls of natural wood, 60% RF; floor is gray, 40% RF. The area is 38½ feet by 29¾ feet.

Installation designed by David A. Whitson, Florida Power Corp., Clearwater, Fla., and R. Y. Fernandez, Madeira Beach, Fla. Lighting installed by G. S. Grant, Inc., St. Petersburg, Fla.

