Brightness Function: Effects of Adaptation*

J. C. STEVENS AND S. S. STEVENS
Laboratory of Psychophysics, Harvard University, Cambridge, Massachusetts

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The method of magnitude estimation was used to investigate how the level of adaptation affects the power function relating brightness to luminance. With the left eye dark adapted and the right eye light adapted, a test field was presented briefly to one eye. The observers' estimates generated a pair of brightness functions, one for each eye. The validity of these functions was checked by interocular brightness matching. The results are described by the equation $\psi=k(L-L_0)^\beta$, when ψ is brightness, L luminance, and L_0 the absolute threshold. All the parameters—k, L_0, and β—change systematically with light adaptation. The exponent β increases from 0.33 for the dark-adapted eye to 0.44 for the eye adapted to 1 lambert.

A SERIES of experiments, begun in 1953, has demonstrated, by a variety of techniques, that subjective brightness grows as a power function of luminance with an exponent of 0.33.[1] The power function appears to be the universal psychophysical law that governs every sense modality, but each sensory system has its characteristic exponent. The exponent for brightness is one of the lowest values found on the twenty or more continua that have been measured thus far. The sensation from electric current through the fingers has the highest exponent (about 3.5). These findings are reviewed elsewhere.[2] The well-known logarithmic function, proposed a century ago by Fechner, appears to have little relevance to the operating characteristics of sensory systems.

The power law, according to which the psychological magnitude ψ is related to luminance L, can be written $\psi=k(L-L_0)^{0.33}$ where k is a constant and L_0 is the threshold value. If L is measured in mL and ψ is defined as below, the value of k is 10. This equation obtains under what may be called "standard conditions": the observer is dark adapted and views a target subtending a visual angle of 5° for a period of 1 sec. Target size and exposure time are not particularly critical, but the values suggested provide a reasonable base line in terms of which parametric studies can be made. It is also convenient to choose a unit for the psychological scale, called a *bril*, and to define it as the brightness seen under the standard conditions when the target has a luminance of 40 dB *re* 10^{-10} L, or 1 μL.[3] A segment of the brightness function, together with the results of a typical experiment in which 28 observers estimated the apparent brightness of a series of luminances, is shown in Fig. 1.

One of the more interesting parameters affecting the brightness function is adaptation. All the parameters, k, L_0, and the exponent β, change when the eye is light adapted. The purpose of the following experiments was to determine how these parameters change and to specify, if possible, the complete family of functions relating brightness to luminance for any level of adaptation. The results published by Onley[4] have already demonstrated the general form of these functions for a small number of observers.

PROCEDURE

Adaptation can be conveniently studied if we light adapt one eye and dark adapt the other. With the eyes thus differently adapted we can do two kinds of experiments. We can measure the brightness function for each eye separately by the method of magnitude estimation, the method used in Fig. 1, and we can directly compare the operating characteristics of the two eyes by matching the brightness seen in the dark-adapted eye to that seen in the light-adapted eye—an interocular matching procedure used by Hering and many others.[5]

The apparatus is diagrammed in Fig. 2. The observer looked into a pair of contoured rubber goggles mounted in a fixed position. A foam-rubber nose bridge between the left and right chambers of the goggles isolated the two eyes. The right eye looked straight ahead toward a luminous target, 25 mm in diameter at a distance of 25 cm, subtending a visual angle of about 5.7°. Sur-

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[1] Results of some of these experiments have been reported from time to time to the Optical Society of America. See J. Opt. Soc. Am. **48**, 287 (1958); **50**, 1139 (1960); **52**, 598 (1962). For a quasi-historical account of the discovery and development of the psychophysical power law, see S. S. Stevens, "The Surprising Simplicity of Sensory Metrics," Am. Psychologist **17**, 29–39 (1962). The present paper is in part a chapter from an unpublished monograph: S. S. Stevens and J. C. Stevens, "The Dynamics of Visual Brightness," Laboratory of Psychophysics, Harvard University, 1960. For an early attempt to depict the brightness function and the effects of adaptation, see S. S. Stevens, "Sensory Transducers," Convention Rec. IRE, Part 9, 27–33 (1954).

[2] S. S. Stevens, "The Psychophysics of Sensory Function." In W. A. Rosenblith (editor), *Sensory Communication* (John Wiley & Sons, Inc., New York, 1961), pp. 1–33.

[3] The decibel, invented originally to describe losses in the transmission of electromagnetic energy, has invaded several fields because it provides a very convenient logarithmic unit. Applied to luminance it is equivalent to a tenth of a common logarithmic unit. As a measure of attenuation it is equal to a tenth of a density unit. When used in this paper to measure levels of luminance, the reference value (0 dB) is 10^{-10} L which is approximately the absolute threshold. Thus all visible dB values are positive. The values of the most common units are: 1 mL=70 dB, 1 ftL=70.3 dB, 1 nit=65 dB. For further discussion see S. S. Stevens, "Decibels of Light and Sound," Phys. Today **8**(**10**), 12–17 (1955).

[4] J. W. Onley, "Light Adaptation and the Brightness of Brief Foveal Stimuli," J. Opt. Soc. Am. **51**, 667–673 (1961).

[5] J. W. Onley and R. M. Boynton, "Visual Responses to Equally Bright Stimuli of Unequal Luminance," J. Opt. Soc. Am. **52**, 934–940 (1962).

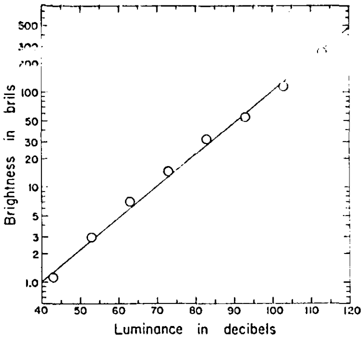


FIG. 1. The straight line is a segment of the bril function. The ordinate values of the points are proportional to the geometric means of the brightness estimates of 28 observers. The instructions were to assign the number 10 to the first stimulus presented and thereafter to assign numbers in proportion to the subjective brightness. The first stimulus was 83 dB for 14 observers and 73 dB for the other 14 observers. All the geometric means were multiplied by the same factor in order to show their conformity to the brightness function.

rounding the target was a large adaptation field, which was constructed of white cardboard and illuminated by projector lamps located to the side of and behind the observer. The aperture in front of the right eye limited the observer's view of the adaptation field to about 58°. The left eye looked through an aperture into a light-tight chamber that isolated the left eye from the stimulation directed to the right eye. A mirror, mounted in this chamber, reflected a second luminous target, also 25 mm in diameter and at an optical distance of 25 cm. Each target was milk Plexiglas illuminated from behind by diffused light from a separate projector (150 W). The luminances of the two targets were separately controlled by means of neutral-density filters and adjustable apertures. When the two targets were set to equal luminance and viewed with the eyes equally adapted, they appeared to be of equal apparent size, color, and brightness.

With this apparatus it was possible, with the left eye dark adapted and the right eye adapted to a constant luminance, to present a "test" stimulus to either eye. In the experiments involving magnitude estimation and brightness matching, the observer's eyes were first dark adapted for 10 min. Then for 3 min the left eye continued to dark adapt, while the right eye adapted to a luminance level that was constant for a given experiment. In order to light adapt the right eye, the observer fixated a small cross on the white cardboard, 3.8 cm northeast of the center of the target opening. When a test stimulus was presented, the adaptation lights were extinguished and the observer looked directly at the test stimulus.

Magnitude Estimation

In four different experiments with the method of magnitude estimation,[6] the observer's right eye was adapted

TABLE I. Conditions used and slopes obtained in log–log coordinates in four experiments. L means left eye; R means right eye. Decibel values are *re* 10^{-10} lambert.

Exp. No.	Adaptation luminance (dB)		Stimulus range (dB)		Standard stimulus (dB)	Obtained slope		Adjusted slope	
	L	R	L	R	L	L	R	L	R
1	dark	dark	44–94	44–104	74,84[a]	0.28	0.28	0.33	0.33
2	dark	63	29–74	44–84	64	0.33	0.35	0.33	0.35
3	dark	79	44–94	54–104	74	0.29	0.33	0.33	0.37
4	dark	97	44–94	69–104	74	0.26	0.35	0.33	0.44

[a] Five observers for each standard.

to 97 dB, 79 dB, 63 dB, or to darkness. In each experiment, test stimuli of various luminances were presented alternately to the right and left eyes. The brightness of the first target (presented to the left eye) was arbitrarily called 10, and the observer was told to assign numbers to subsequent stimuli in proportion to the apparent brightness. (Table I lists, among other information, the ranges of stimulation and the levels of the standards used in the four experiments.) Upon a signal from the experimenter, the observer pressed a key, which simultaneously extinguished the adaptation lights and turned on the appropriate test stimulus for 2 sec. About 10 sec elapsed between stimuli, during which time the condition of differential adaptation prevailed.

Ten observers participated in each of the four experiments. Each observer saw the stimuli in a different irregular order. After the entire set of stimuli had been judged, the standard, called 10, was again identified, and the stimuli were presented a second time in a different order.

The five functions obtained with the dark-adapted eye (four with the left eye, one with the right) turned out to be similar to the functions obtained under "standard" binocular conditions and may therefore be regarded as further corroboration of the psychophysical power law. In all five cases the geometric means determine, in log–log coordinates, straight lines whose slopes range between 0.26 and 0.33 (see Table I). Al-

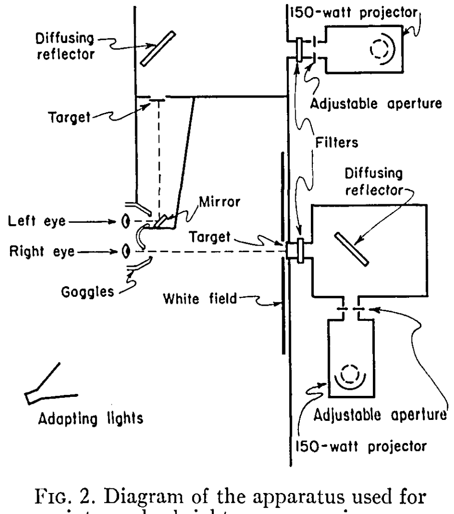


FIG. 2. Diagram of the apparatus used for interocular brightness comparisons.

[6] S. S. Stevens, "Problems and Methods of Psychophysics," Psychol. Bull. 54, 177–196 (1958).

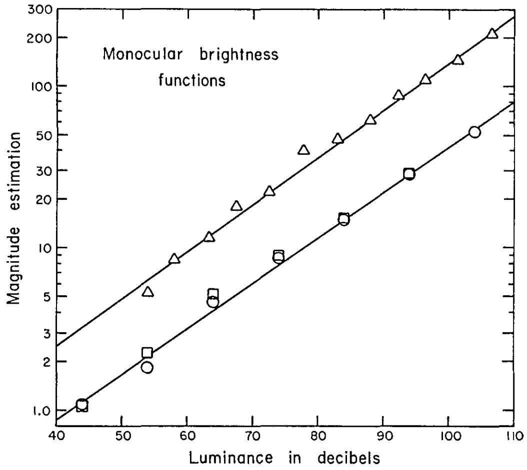


FIG. 3. Monocular brightness functions. With the apparatus used for interocular comparisons, the circles (right eye) and the squares (left eye) were obtained by magnitude estimation. The triangles are from an experiment by Onley. Her 24 observers viewed a 1° target presented for 0.275 sec to the "preferred eye." Each triangle represents the geometric mean of 24 judgments, one by each observer, except that the values 72.6 and 77.7 dB were each used as a standard for half the observers and were not judged by them. Each standard was called 10 by six observers and 100 by the other six. These procedural variations had little or no effect.

though some of these slopes are slightly lower than those obtained by magnitude estimation under binocular viewing in similar experiments, the evidence is probably not sufficient to prove that monocular brightness grows by a different power law.

It is interesting to note, however, that monaural loudness grows with a different exponent (0.54) from the one that governs binaural loudness (0.6). With loudness there is a generous summation under binaural stimulation, so that a moderately intense sound heard with two ears sounds about twice as loud as the same sound heard with one ear. The degree of summation varies with level, and it is only at 90 dB that it is precisely 2 to 1. At higher levels summation is greater, at lower levels it is less.[7] Brightness shows no such dramatic summation when a target is viewed with two eyes. One need only close one eye in order to see that the scene does not look half as bright under monocular viewing. Nevertheless, some degree of binocular summation has sometimes been claimed.[8]

The two functions obtained in the first experiment (both eyes dark adapted) are shown by the circles (right eye) and the squares (left eye) in Fig. 3. The other values (triangles) in Fig. 3 are from an experiment by Onley.[9] The results of the other three experiments are shown in Fig. 4, whose coordinates are explained below. The triangles in Fig. 4 are for the left, dark-adapted, eye (Experiment 2).

In each experiment the function obtained with the dark-adapted eye can be used to evaluate the effects on brightness of light adapting the other eye. Thus, even though the slope of the function obtained for the dark-adapted eye may vary from one experiment to another, for a given experiment it is possible to plot both functions in the same log–log coordinates and to make comparisons between the relative rates at which brightness grows in the dark-adapted and the light-adapted eye. Three main findings have emerged from the examination of such log–log plots.

(1) Brightness in the light-adapted eye grows as a power function of luminance, except near the absolute threshold where the functions are sharply concave downward. If, however, a constant L_0, whose value approximates the threshold, is subtracted from each stimulus, the results approximate a power function throughout. In other words, brightness is a power function of luminance provided luminance is measured as distance above the threshold.

(2) The function obtained with the light-adapted eye has a steeper slope (higher exponent) than the function obtained in the same experiment with the dark-adapted eye. This slope difference increases with increasing level of adaptation (see Table I).

(3) The intercepts of the brightness functions for different levels of adaptation are maximally different in the vicinity of the threshold. Extrapolated upward, the functions appear to converge toward a common point at a luminance of approximately 150 to 160 dB. (It is probably only a coincidence that the luminance of the sun, about 157 dB, falls within this range.)

All these findings can be presented in a single set of coordinates if it is assumed that the growth of bright-

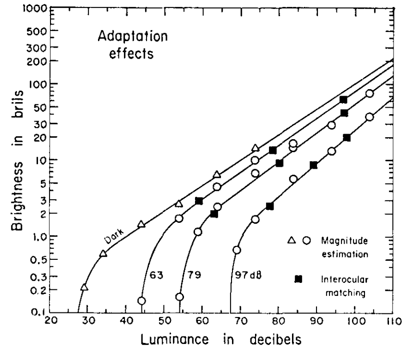


FIG. 4. Results of determining the brightness functions under different states of adaptation. The topmost curve represents the standard bril function together with the results (triangles) from Experiment 2 of Table I. The circles give the results obtained by magnitude estimation, each curve for a different level of adaptation, as indicated. The squares show the results of interocular brightness matching by the method of constant stimuli. All data are plotted so that the *differences* measured in each experiment between the values for the dark-adapted eye and the values for the light-adapted eye are preserved.

[7] G. S. Reynolds and S. S. Stevens, "The Binaural Summation of Loudness," J. Acoust. Soc. Am. **32**, 1337-1344 (1960).

[8] S. H. Bartley, *Vision* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1941); W. Nagel, Appendix in H. von Helmholtz, *Physiological Optics* (Optical Society of America, New York, 1924), 3 Vols. Vol. 2, p. 339.

[9] J. W. Onley, "Brightness Scaling Using Brief Foveal Stimuli," Interim Data Report presented to the Vision Group, University of Rochester (June 14, 1959).

ness in the dark-adapted eye follows the same power law, regardless of the level to which the other eye is adapted. That this assumption is reasonable is shown by the fact that the exponents for the dark-adapted eye do not vary in any large or systematic way when the other eye changes in adaptation. In this connection, Wright[10] observes that ". . .tests by the threshold method or by direct observation of the change in appearance of a test patch viewed in the left eye when the right eye is light adapted show quite definitely that any effect which is produced on the left eye is of a second-order magnitude and in no sense comparable to the much greater changes produced in the right eye. Such effects can therefore be neglected."

Figure 4 and Table I (right-hand column) are based on the supposition that the growth of brightness in the dark-adapted eye follows the standard bril function, i.e., the 0.33 power law. The topmost curve of Fig. 4 represents the standard bril function, together with the results from Experiment 2 (triangles). The other curves represent the functions for the various levels of light adaptation. The open circles, based on the geometric means of the estimates of stimuli presented to the light-adapted eye, are so plotted that they bear the particular relation to the curve for the dark-adapted eye that was found in the separate experiments. The abscissa gives the luminance of the stimulus (in dB *re* 10^{-10} L), and the ordinate gives the equivalent brightness (in *brils*) seen by the dark-adapted eye.

The variability of the estimates over the straight portion of the functions in Fig. 4 was about the same as that normally encountered in magnitude estimation of photopic levels, viewed with dark-adapted eyes. The average quartile deviation was 0.11 log unit. Because of the noticeable color differences produced by differential adaptation of the two eyes, we had anticipated that the observers might experience difficulty in making brightness estimates of all the stimuli in terms of the same subjective scale. The observers noted the color differences, and occasionally complained about them, but the differences were apparently not troublesome enough to alter materially the precision of the judgments.

The results in Fig. 4 show a clear tendency for the exponent of the brightness function to increase with light adaptation. The effect is not, however, a large one—at least not so large as the effects of simultaneous contrast.[11] Thus, the eye adapted to a high level (97 dB) yields an exponent that is only about 33% higher than the exponent of the standard bril function, whereas the interaction effects of simultaneous contrast may increase the exponent by several times.

It should be noted here that some preliminary experiments, previously reported elsewhere, showed no definitive effect of adaptation on the over-all slope of the brightness function.[12] Those earlier experiments also used the method of magnitude estimation, but the procedure used then did not make possible a direct comparison between differentially adapted eyes.

Interocular Matching

A critical test of the validity of the functions in Fig. 4 is their ability to predict the outcome of interocular brightness matching when one eye is dark adapted and the other light adapted. On first thought it may seem that interocular matching should provide the simplest and most straightforward means of mapping the effects of adaptation on the brightness function. In practice, however, the method is tedious and beset by a number of difficulties, with the result that a clear and consistent picture has not emerged from studies heretofore reported. In the present experiments a procedure was evolved by means of which interocular matching could be used to verify the functions obtained by magnitude estimation.

In a preliminary study observers were asked to adjust the brightness of a target presented to the light-adapted eye in order to match a target of standard luminance, viewed simultaneously by the dark-adapted eye. Under this simultaneous viewing of the standard and variable targets, hue differences proved troublesome, and the variability among the observers' settings was quite large. The judgment was especially difficult when one eye was adapted to a high luminance level.

Five observers became adapted to 98 dB with the right eye and then during 2-sec exposures of two targets—one seen by the dark-adapted left eye and one by the light-adapted right eye—they adjusted the luminance of the right-eye target. Matches were made to seven different levels of the left, dark-adapted, target ranging in 10-dB steps from 36 to 96 dB. The dB averages of the settings for luminances of 76 dB and lower lie within 3 dB of the values predicted on the basis of the functions in Fig. 7 below. This is rather good agreement. At the higher levels, however, the observers adjusted the right-eye luminance to values as much as 10 dB too low. The reasons for this are not very clear. The extreme differences among the settings by the five observers ranged from 4.5 to 11 dB.

The method of adjustment was therefore replaced by a procedure that required the observer merely to judge which of the two targets appeared the brighter when they were viewed successively, rather than simultaneously. This method of "constant stimuli" is similar to

[10] W. D. Wright, *Research on Normal and Defective Colour Vision* (The C. V. Mosby Company, St. Louis, 1947), p. 214.

[11] S. S. Stevens and J. C. Stevens, "Brightness Function: Parametric Effects of Adaptation and Contrast," J. Opt. Soc. Am. **50**, 1139A (1960); S. S. Stevens, "To Honor Fechner and Repeal his Law," Science **133**, 80–86 (1961).

[12] J. C. Stevens, "A Comparison of Ratio Scales for the Loudness of White Noise and the Brightenss of White Light," PhD thesis, Harvard University, 1957; S. S. Stevens, "Some Similarities between Hearing and Seeing," Laryngoscope **68**, 508–527 (1958).

TABLE II. Levels used for interocular brightness matches. The last column shows the luminance in the light-adapted eye that matched a given luminance (second column) presented to the dark-adapted eye. Decibel values are *re* 10^{-10} L.

Adaptation luminance (dB)	Luminance of standard (dB)	Range of comparison stimuli (dB)	Luminance found to match standard (dB)
	54	54–66	59.2
63	74	73–85	78.8
	94	92–104	97.0
	49	57.6–70.4	63.2
79	69	73.6–86.4	80.4
	89	91.6–104.4	97.3
	52	71–83	77.9
97	68	84–96	89.2
	79	92–104	98.0

the one that Craik[13] had used with fair success. With this method it was a simple matter to simulate the experimental conditions under which the magnitude estimates had been obtained.

For three separate experiments, each with 10 observers, the right eye was adapted to 63, 79, or 97 dB, the same levels used for magnitude estimation. In each experiment the standard brightness was presented to the left, dark-adapted, eye, followed about 10 sec later by a comparison stimulus to the right eye. Each stimulus lasted 2 sec, during which time the adapting field was turned off. The observer reported whether the comparison stimulus appeared brighter or dimmer than the standard. The same standard preceded each of seven comparison stimuli, presented in random sequence, until every comparison stimulus had been judged twice. A

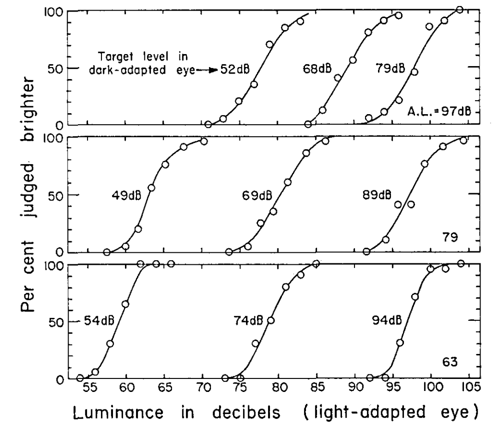


FIG. 5. The poikilitic (scatter) functions obtained in the process of equating a brightness in the light-adapted eye to the brightness in the dark-adapted eye. The right eye was adapted to 63, 79, or 97 dB. Then for each of several levels presented to the left (dark-adapted) eye, various levels were presented to the right eye (abscissa). The percentage of times these levels were seen as brighter than the stimulus in the left eye is plotted on the ordinate. Each point is based on two judgments by each of 10 observers. The 50% point is the value plotted in Fig. 4 (squares).

[13] K. J. W. Craik, "The Effect of Adaptation on Subjective Brightness," Proc. Roy. Soc. (London) B128, 232–247 (1940).

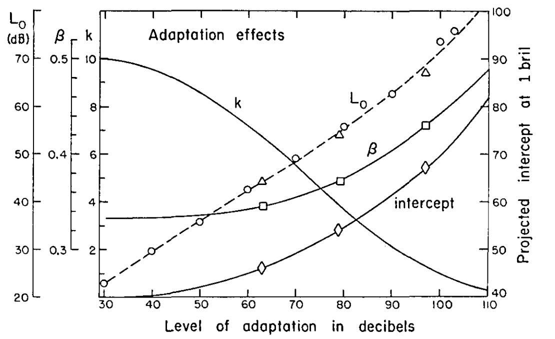


FIG. 6. Parameters of the brightness equation as a function of adaptation level. The values for the 1-bril intercepts (diamonds) and the exponents (squares) were read from Fig. 4. The values of k were then calculated. The values of the absolute thresholds L_0 were estimated from Fig. 4 and plotted as triangles. The circles are measured threshold values.

second standard of higher luminance was then employed to obtain a similar set of judgments, and finally a third standard of still higher luminance. The luminances of the standards are listed in Table II, along with the ranges of luminance spanned by the comparison stimuli. The comparison stimuli were spaced at approximately 2-dB intervals in such a way that the middle stimulus had a value within 1 or 2 dB of the luminance that the earlier magnitude estimates predict for a match.

Figure 5 shows the poikilitic functions obtained. The abscissa is the luminance in dB of the comparison stimuli, presented to the light-adapted eye, and the ordinate is the percentage of times (combined data of 10 observers) that a comparison stimulus was judged brighter than the standard. An S-shaped curve was fitted by eye to each of the nine sets of data obtained. The luminance at which the curve passes through the 50% point was taken as the luminance that matches the standard stimulus. These values are listed in Table II and are plotted as squares in Fig. 4, where the ordinate is the brightness of the standard stimulus in brils, and the abscissa is the luminance obtained for a match. Figure 4 shows that the outcome of matching is in good agreement with the functions obtained by magnitude estimation.

Parameters of the Brightness Function

In terms of the basic equation relating the psychological or subjective value ψ to luminance L, $\psi=k(L-L_0)^\beta$, the level of adaptation has major effects on the values of k and L_0. Light adaptation lowers the value of k and raises the value of L_0. In order to exhibit these relations more clearly, the parameters of the brightness equation have been plotted in Fig. 6. The plotted points were derived directly from Fig. 4, and the smooth curves were drawn through the points in a manner that seemed the most reasonable. The procedure was as follows.

First the intercepts of the straight portions of the curves at the 1-bril ordinate value were determined from

Fig. 4 and plotted as diamonds in Fig. 6. The resulting curve shows the behavior of the "operating point" of the eye, i.e., how the luminance required to produce a brightness of 1 bril grows with increasing level of adaptation. The values of the exponent β were then determined from the slopes of the curves in Fig. 4 and plotted as squares in Fig. 6. The values of k were next calculated by setting $\psi=1$ and raising the intercept value to the appropriate power given by the curve for β. These values of k are based on the assumption that luminance is measured in mL. Finally, the values of L_0 were estimated by determining approximately what number of mL would need to be subtracted from each luminance in order to straighten out the lower end of each function in Fig. 4. These values of L_0, plotted as triangles in Fig. 6, are the effective absolute thresholds under the various levels of adaptation.

It is interesting, and indeed reassuring, to compare the triangles with the circles in Fig. 6. The circles represent the average threshold values measured by Nutting[14] on three observers, with an apparatus not unlike the one used in the present experiments. A large white cardboard, illuminated to various known luminances, was used to "sensitize" the eye, as Nutting phrases it. In the center was a spot (3 cm square) independently controlled. Viewing was from a distance of 35 cm. After the eye was fully adapted, the light on the large field was switched off. The luminance of the spot was adjusted to be "barely visible at the first instant of switching off the light of the large field." The three observers were reported to be in good agreement. Except for the two highest points, at 100 and 103 dB, Nutting's data are certainly in excellent agreement with the values derived from Fig. 4.

One notes that the top curve in Fig. 4, which we have been calling the dark-adapted brightness function, turns down in a manner to suggest that the effective threshold lies at about 27 dB. This is higher than the threshold would be if the eye were fully dark adapted. From the L_0 curve in Fig. 6 we can determine that

TABLE III. Showing the effect of adaptation level on the parameters of the brightness equation $\psi=k(L-L_0)^\beta$. Values were read, or calculated, from Fig. 6. Decibel values are *re* 10^{-10} L. Values of k are for measurements expressed in millilamberts (mL).

Adaptation level				L_0		Intercept at 1 bril	
dB	mL	k	β	dB	mL	dB	mL
	dark	10	0.333	0 (approx)		40	0.001
40	0.001	9.6	0.334	30	0.0001	40	0.0012
50	0.01	8.6	0.335	36	0.0004	42	0.0016
60	0.1	7.2	0.342	42	0.0016	45	0.0032
70	1.0	5.5	0.355	48	0.0079	49	0.008
80	10	3.7	0.38	55	0.032	55	0.032
90	100	2.2	0.41	62	0.16	62	0.16
100	1000	1.0	0.44	72	1.58	70	1.0
110	10000	0.26	0.49	84	25.1	82	15.8

[14] P. G. Nutting, "1919 Report of Standards Committee on Visual Sensitometry," J. Opt. Soc. Am. 4, 55–79 (1920).

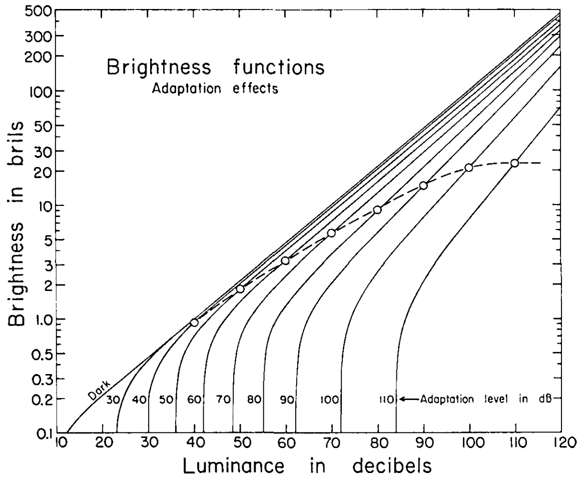


FIG. 7. Brightness functions for various levels of adaptation. The dashed line shows the terminal brightness locus—the level of sensation reached when the eye comes into full equilibrium with the luminance it is viewing.

a threshold of 27 dB characterizes an eye adapted to a level of about 36 dB. Under the conditions of the experiment, where the eye received 2-sec exposures to various luminances at intervals of 10 sec, it is probably not unreasonable to find that the effective level of adaptation was near the bottom of the photopic range. (Note, however, that the evidence for this particular value rests on only one point—the lowest triangle in Fig. 4.) In any case it is important to note that an effective adaptation level of 36 dB has almost no effect on the parameters k and β in the brightness equation (see Fig. 6). At these low levels of adaptation only the value L_0 is altered by changes in adaptation level. (We verified this fact in a separate experiment to be discussed shortly.)

Table III lists various values of the parameters of the brightness equation for different levels of adaptation. With the aid of these values the complete formula for subjective brightness in brils can be written as a function of luminance for a given level of adaptation. For example, when the eye is adapted to 1 mL the formula becomes $\psi=5.6(L-0.0063)^{0.355}$. The constant L_0, which in this case equals 0.0063 mL, is of course negligible for all but very low luminances.

The process of filling in the values in Table III required interpolations and extrapolations of the experimental data. The extrapolations toward the lower values in Fig. 6 seem plausible enough, but greater potential uncertainty attaches to the extension of the curves to adaptation levels above 100 dB. Consequently, the validity of the extrapolations to the higher levels was tested in a separate experiment discussed below.

Family of Brightness Functions

Taking the available evidence into account, we can construct a set of functions showing how apparent brightness grows with increasing luminance for different states of visual adaptation. These functions are shown in Fig. 7. They relate principally, of course, to the apparent brightness of a target subtending a visual angle of about 5° and viewed against a dark surround, although they may be representative of larger target sizes as well.[15] The apparent brightness is that perceived by a normal (median) observer when the target is presented for a 2-sec exposure immediately after the extinction of the adapting field, to which field the observer is presumed to have become fully adapted. The adapting field is assumed to be illuminated by white light and to subtend a visual angle that is large compared to the visual angle of the target. Over a fairly wide range, the exact size of the adapting field is apparently unimportant.[16] Viewing is assumed to be with natural pupils.

These conditions are admittedly arbitrary, but they are not without interest. They can provide a starting point for the experimental construction of other families of functions designed to incorporate whatever parametric changes in the circumstances of observation may prove worthy of study. Conditions of likely interest may include the effects of a fixed pupil, the effects of very short target exposure, the effects of adaptation to different wavelengths, and so forth.

A clear indication in Fig. 7 is the disparity between the effect of light adaptation on the threshold (the vertical asymptote) and its effect on supraliminal brightnesses. For example, adaptation to a luminance of 100 dB shifts the threshold luminance by about 70 dB, but the horizontal displacement of the functions at the 10-bril level shows that adaptation to the same 100-dB level causes only a 23-dB shift in the luminance required to produce a brightness of 10 brils.

Equilibrium Function

In addition to the family of brightness functions, the dashed line in Fig. 7 shows the locus of brightnesses achieved under full adaptation to the target level. This is the terminal brightness, so to speak—the sensation that is reached when the eye comes into complete equilibrium with the luminance of the target itself. The form of this interesting function confirms a finding by Craik,[13] whose data showed that above an adaptation level of about 100 dB there is little or no increase in the terminal or fully adapted brightness. Thus, the upper end of the dashed curve in Fig. 7 becomes horizontal, just as did Craik's functions. Craik pursued this question of the invariance of the terminal brightness up to an adaptation level of 119 dB (75 000 ft-L), which is a rather heroic level to stare at for a long period of time. Craik used a wide visual angle obtained with a Maxwellian view.

[15] For effects of size, see S. S. Stevens, "The Surprising Simplicity of Sensory Metrics," Am. Psychologist **17**, 29–39 (1962).

[16] W. D. Wright, *Research on Normal and Defective Colour Vision* (The C. V. Mosby Co., St. Louis, 1947), p. 230.

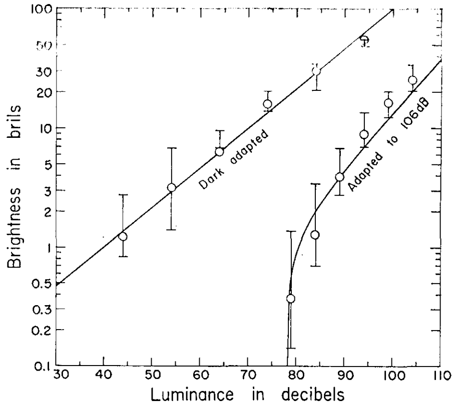


FIG. 8. Brightness functions determined by presenting stimuli in irregular order to the dark-adapted left eye and the light-adapted right eye (adapted to 106 dB). All the points were shifted upward by a constant amount in order to make the dark-adapted curve correspond to the bril scale. The curve through the other points was calculated from the brightness equation, $\psi = k(L-L_0)^\beta$, with the parameters determined from Fig. 6.

At the other extreme, the dashed curve and the circles show that for low-adapting luminances the terminal brightness is very little different from the initial brightness, i.e., the two lowest circles fall close to the brightness function for the dark-adapted eye. This finding is also consistent with Craik's results.

Even though for any given state of visual adaptation apparent brightness is governed by a power law, the over-all curvature of the dashed line in Fig. 7 makes it clear that the terminal or equilibrium brightness does not follow a power law. The changing "operating point" of the visual system that results from different levels of adaptation can thus obscure the basic form of the psychophysical function. When the operating point is held fixed, the power law holds, but in experiments that measure the response of the eye to different stimulus intensities, we may fail to find the power law if we permit the state of adaptation to change sufficiently. Caution may be especially in order when attempts are made to determine the physiological response of the visual system (e.g., by recording nerve action potentials), for in such procedures the state of adaptation may be quite as important as it is in the analogous psychophysical experiments. The terminal or equilibrium brightness function shows that, if the visual receptor is allowed to adapt to the level of the stimulus, the input–output relation may approximate a logarithmic function more closely than a power function, at least over some of the range.

Low-Level Adaptation

Figure 7 contains much other interesting information concerning brightness relations, some of which may impress the reader as strange enough to be questionable. The authors felt that way about the apparently negligible effects of adapting the eyes to a level of about 40 dB. According to Fig. 7 the brightness seen by an eye

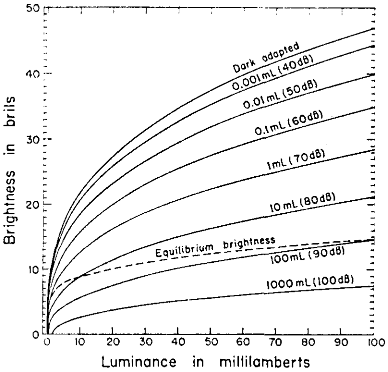


FIG. 9. The brightness functions for different levels of adaptation are here plotted in linear–linear coordinates (brils vs mL). These are the same functions shown in log–log coordinates in Fig. 7.

adapted to 40 dB is almost the same as that seen by a dark-adapted eye. This surprising suggestion was put to direct test in an experiment in which 10 observers made interocular brightness matches. The left eye was dark adapted and the right eye was adapted to 38.5 dB. Every 10 sec the adapting field was turned off, and for 2 sec the observer saw two luminous targets, one with each eye. He adjusted the luminance of the right target to make its brightness equal that of the left target. Despite some interesting differences between the two eyes of a couple of observers, the average settings agreed closely with the predictions of Fig. 7. On the average the observers set the luminance for the right, light-adapted, eye about 0.4 dB higher than the luminance in the left, dark-adapted, eye. The target levels tested were 50, 60, 70, and 80 dB. It should be pointed out that at this low level of adaptation (38.5 dB) the color changes were so slight that the interocular brightness matches were easily made. They showed a quartile range of variability of only ± 1.5 dB.

High-Level Adaptation

Some experiments, done in 1962 by van den Brink,[17] were designed to trace the course of brightness during the process of dark adaptation, and they provided an occasion to test how well the results obtained in 1959 (Fig. 6) would predict the form of the brightness function when the eye was adapted to 106 dB (about 4000 mL).

The right eye of each of 10 observers was adapted for 3 min to 106 dB by means of a floodlighted white cardboard. Stimuli were then presented twice each, in irregular sequence, to the right and left eyes, and the observer estimated the apparent magnitude of the brightness relative to a standard called 10, which was produced by 74 dB presented to the left eye. The standard was presented only once, at the beginning of the session.

The geometric means of the observers' estimates are shown in Fig. 8, along with vertical lines indicating the interquartile ranges of the estimates. The judgments of the stimuli presented to the dark-adapted eye were almost exactly proportional to the standard bril scale, as shown by the upper line. The lower curve was derived by means of the brightness equation given above, with the parameters appropriate to an adaptation level of 106 dB, as determined from the curves of Fig. 6. The disagreement between the calculated curve and the geometric means of the observers' estimates of brightness is in no case greater than the quartile deviation of the estimates.

Linear Plots

The brightness functions of Fig. 7 are plotted in log–log coordinates, a display that permits one to depict the behavior of the functions over wide ranges of values. This indeed is one of the virtues of logarithmic scales, of which the dB scale is merely a convenient form. It is instructive, however, to inquire how the brightness functions look in linear–linear coordinates. The answer, for a representative range of values, is shown in Fig. 9, where we note several interesting features.

Since brightness in brils grows approximately as the cube root of the luminance in mL, it is not surprising that the curves in Fig. 9 are concave downward. The *slope* of a line in the log–log plot (Fig. 7) becomes the *curvature*, so to speak, in the linear plot. Since the slope in the log–log plot is less than 1.0, in the linear plot the growth of brightness follows a path that is a decelerating function of luminance. In this sense the visual transducer behaves as a compressor,[18] a feature that aids, no doubt, in the eye's ability to respond effectively to energy inputs covering a stimulus range of billions to one.

The linear plot of sensation vs stimulus quite clearly shows how light adaptation serves to reduce the absolute apparent brightness produced by a given luminance. The downward displacement of the curves in Fig. 9 with increasing level of adaptation reflects mainly the considerable reduction in the value of k in the brightness equation. The spacing of the curves in Fig. 9 is also interesting. Thus, for a stimulus of 50 mL, the brightness decreases by roughly 5 brils for every 10-dB increase in adaptation level over the range from 50 to 100 dB.

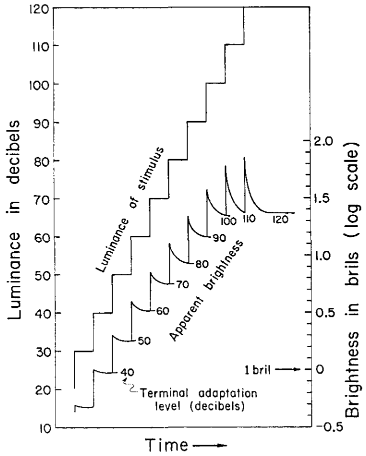
Effects of Changing Levels

An interesting deduction from Fig. 7 concerns the appearance of a field whose luminance is increased periodically in, say, 10-dB steps. By looking steadily at the field at a given level, one becomes, in the course of time, adapted to this level. Then, when the luminance is raised 10 dB, the brightness jumps by a factor of 2 or more, but it declines again as adaptation to the new level takes place. The resulting sequence is illustrated in Fig. 10, which puts into better quantitative per-

[17] G. van den Brink, "Subjective Brightness during Dark Adaptation," Vision Research (to be published).

[18] S. S. Stevens, "Measurement and Man," Science **127**, 383–389 (1958).

FIG. 10. A schematic plot showing how brightness changes when the eye is stimulated by a target whose luminance is periodically increased by steps of 10 dB. The stimulus steps are plotted directly above the resulting brightness steps. The time scale is arbitrary. With each increase in luminance the brightness jumps and then settles back to the equilibrium level that results when the eye is fully adapted to the luminance of the target.



spective a sequence that was diagrammed by Craik. As the luminance is increased by 10-dB steps at intervals of several minutes, the brightness follows the sawtooth curve shown below the staircase curve representing the stimulus. We note, for example, that at low levels a 10-dB jump in luminance approximately doubles the brightness (0.3 log unit), whereas at the high levels a 10-dB increase almost triples the brightness (0.45 log unit). Despite this fact, the rise of the sawtooth function in Fig. 10 fails to keep up with that of the staircase stimulus function. The reason, of course, lies with the greatly increased brightness reduction that takes place in the process of adapting to the higher luminances.

No attempt has been made in Fig. 10 to depict a real time scale. van den Brink,[17] however, has made a series of interocular comparisons designed to trace the exact course of adaptation and its effect on brightness as a function of duration. Regardless of the time scale used, two very useful properties of the visual system can be made obvious by means of a scheme like that in Fig. 10: The system can signal small changes and still respond over a large dynamic range.

Instead of increasing the luminance level by steps, we could, of course, increase it slowly but continuously. In this manner one might test the validity of the widespread belief that the eye is a notoriously poor instrument for judging absolute levels of illumination. Undoubtedly there is much truth in this notion, as most amateur photographers learn to their sorrow. But is it true, as Hardy and Perrin[19] express it, that "the level of illumination in a room could be varied slowly between wide limits without producing any change in the appearance of objects in the room"? The "wide limits" referred to here were thought by Hardy and Perrin to coincide with the range over which relative differential sensitivity is constant. These authors were following the common misconception that sensation grows as the logarithm of the luminance.

Actually, if an observer were dark adapted and placed in a dark room, and if the illumination were slowly increased, the brightness of a light-colored object in the room would seem to grow approximately as the equilibrium brightness function—the dashed curve in Fig. 7 (and in Fig. 9). The apparent brightness would grow continuously as the illumination increased until the luminance of the object approached 100 to 110 dB, at which point the apparent brightness would cease to grow any further. In an unexpected sense, then, the statement by Hardy and Perrin turns out to be correct, for there is indeed a region of intense illumination over which the appearance of the object does not change when the level is slowly increased. But this is not what the authors had in mind, for they believed that the region of invariant brightness embraced the middle ranges rather than the extreme levels.

It is easy to make the mistake of concluding that, because the eye is unreliable in judgments of the absolute level of illumination, it is equally unreliable in judgments of the absolute level of subjective brightness. The eye, or rather the observer using the eye, may well make reliable judgments of brightness without knowing what combinations of stimulus and adaptation level produced the particular brightness he sees. The situation can be clarified with the aid of Fig. 7, where we note that a brightness of 10 brils, for example, can be produced by putting a luminance of 70 dB before a dark-adapted eye or a luminance of 101 dB before an eye adapted to 110 dB. Unless the observer takes thought about other factors, such as his previous exposure to light, including its level and duration, he will have no way of knowing which luminance he is viewing. Since it is difficult to take such factors into account, the man with a camera is usually told to measure the light, or else to base his decision concerning the photographic exposure upon his knowledge of the source of the illumination (e.g., direct sunlight or deep shade). In the jargon of psychophysics, the picture-taker's problem is to commit the "stimulus error," an error that observers should avoid when they try to make valid judgments about the apparent intensity of the sensation itself.[20] In some circumstances it is hard to avoid the stimulus error; in others it is hard to commit it. With visual brightness it is more difficult to judge the stimulus than it is to judge the sensation produced by the stimulus, mainly because the labile operating point of the visual transducer gives the observer little or no clue concerning its location at a given time.

Recovery Functions

When the eye is adapted to higher and higher luminances, the brightness functions change as shown in Fig. 7. An interesting question arises whether an exact reversal takes place during the process of dark adapta-

[19] A. C. Hardy and F. H. Perrin, *The Principles of Optics* (McGraw-Hill Book Company, Inc., New York, 1932).

[20] E. G. Boring, "The Stimulus Error," Am. J. Psychol. **32**, 449–471 (1921).

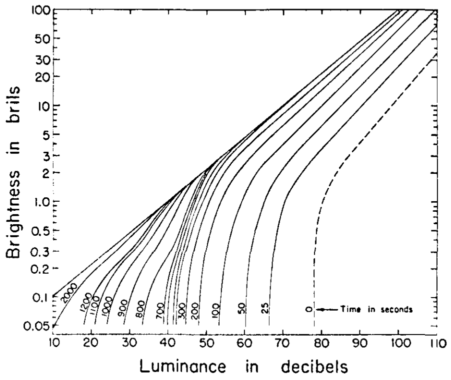


FIG. 11. Showing how the brightness functions change with time after the right eye is exposed for 2 min to an adapting luminance of 106 dB. The brightness seen in the right eye was matched periodically to a brightness seen in the left eye, which was in a dark-adapted state. From the averaged results of three observers the time course of the eye's operating point was plotted for four brightness levels and for threshold. Those curves were used to construct the solid curves in Fig. 11. The dashed curve is a calculated function, the same function shown in Fig. 8.

tion. As a function of time, do the brightness functions change from right to left in Fig. 7 when the adapting luminance is turned off? Otherwise said, can the same operating characteristic be achieved by either of two procedures: adaptation to 50 dB, say, or adaptation to 100 dB followed by a certain period in the dark?

The answer is contained in Fig. 11, which shows a set of brightness functions derived from the measurements of van den Brink.[17] When the adaptation level at time zero is quite high, 106 dB in this case, the two kinds of visual receptors recover at such different rates that the familiar rod–cone break makes its appearance in the curve for dark adaptation. This break corresponds to a warping of the brightness functions in Fig. 11. After about 5 min in the dark, the form of the functions remains rather stationary for another 5 min and then begins a series of rapid changes.

It is plain from Fig. 11 that an eye that is partly recovered from adaptation to a brighter field is not always in the same state as it would be if adapted to a dimmer field. During the first few minutes, however, the recovery functions in Fig. 11 resemble the functions in Fig. 7, which suggests that there may be little difference at photopic levels between an eye partly recovered from a high-level exposure and one adapted to a lower level.

Relation to Other Studies

Since so many important facts about brightness can be deduced from the family of brightness functions in Fig. 7, it is important to inquire further about their agreement with other experimental evidence. Reference has already been made to one such body of evidence, namely, that obtained by Craik.[13]

With the two eyes adapted to various levels, he determined the luminance required to produce equal brightnesses in the two eyes for 1-sec exposures of 45° test fields. The large target size was probably not important, for Craik cites "preliminary results" that indicate a change equivalent only to about 1 dB when the 45° field was reduced to 2°. From our present point of view, the main difficulty with Craik's experiment is the paucity of reported results. The data for only one observer are recorded, and these values show the degree of variability one may expect from a single observer. Nevertheless, the general agreement between Craik's data and the functions in Fig. 7 is reassuring. It would be easy, for example, to pick from our own group an observer or two who would show very close agreement with Craik's observer. This possibility is evident from the horizontal spread of the data in Fig. 5. Individual differences must be expected when observers make interocular comparisons of the brightnesses seen with their two eyes in widely different states of adaptation, because, as Craik points out, the targets then take on slightly different hues, plus other differences in general appearance that hinder the equality judgment.

It is instructive to ask how the family of curves that Craik attempted to delineate would look if they were derived from Fig. 7. Although Craik's interocular matching procedures cannot generate the brightness functions of Fig. 7 (for want of a metric for subjective brightness), the reverse procedure becomes possible. If we know the brightness functions, we can predict the matching functions. Samples of such predicted matching functions are shown in Fig. 12. It is assumed that the right eye is adapted to a level shown by the abscissa; the left eye is adapted to dark or to 70, 80, 90, or 100 dB. The adapting fields are periodically switched off, and a target

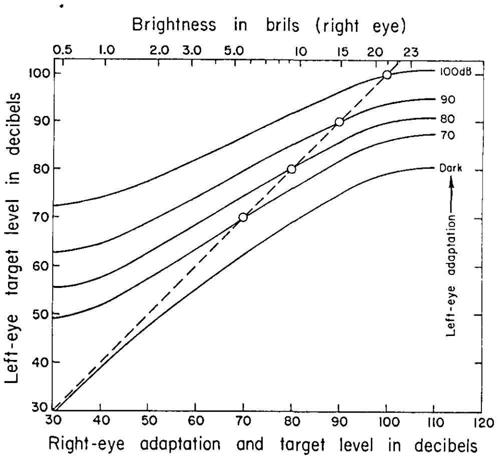


FIG. 12. Curves showing the locus of equal brightness for targets presented briefly to the two eyes when each eye is in a different state of adaptation. The adaptation of the right eye is to a value on the abscissa. This is also the target level presented to the right eye. The adaptation of the left eye is to dark, 70, 80, 90, or 100 dB. The luminance in the left eye is adjusted to match the brightness seen by the right eye. The scale at the top of the graph is the terminal or equilibrium locus from Fig. 7 and shows the brightness seen by the right eye.

level is found in the left eye such that it matches in brightness the target seen by the right eye. The target presented to the right eye has the same luminance as the adapting field for that eye.

In general form, the curves in Fig. 12 resemble those presented by Craik. Figure 12 makes clear, however, several details that were ambiguous in Craik's study. The curve for the dark-adapted left eye has no point of inflection in the range here examined. The inflection in the other curves has two causes: the flattening at the lower ends reflects the effect on the brightness equation of the increase in the threshold L_0, i.e., the steepening at the bottom ends of the curves in Fig. 7. The flattening at the top ends of the curves in Fig. 12 reflects the fact that the terminal or equilibrium brightness shows little or no increase above about 100 dB.

The rather notable agreement between Craik's data and the brightness functions is not wholly matched by the results reported by Pitt,[21] who also undertook interocular brightness comparisons. Unfortunately, Pitt published only a set of smoothed curves, in a form not easy to interpret. From what can be read from these curves, it appears that apparent brightness is somewhat less affected by adaptation than either Craik's data or the curves in Fig. 7 would suggest. For what it is worth, however, it is interesting that a given function in Fig. 7 (e.g., the 100-dB function) lies *between* the general locus determined by Pitt and that determined by Craik.

It has already been noted above that there is generally good agreement between the functions in Fig. 7 and those obtained by Onley.[4] She used three observers and reports results obtained by several procedures.

It should be pointed out that the picture presented in Fig. 7 is sharply at variance with the scheme that Evans adapted from Marshall and Talbot[22] and reproduced twice in his authoritative book on color.[23] One of the questionable aspects of that scheme is its implication that when the eye is light adapted the observer does not experience low levels of subjective brightness. Actually, the range of subjective brightness, the ordinate of the graph, is little if at all affected by adaptation. What is changed is the range of intensities needed to produce the full gamut of subjective levels.

Finally, it is important to note that Figs. 4, 6, and 7 present the effects of adaptation alone, uncomplicated by the kind of simultaneous contrast that results when a surround is placed around a target. Since a surround does more than change the eye's level of adaptation, we do well to distinguish the effects of adaptation from those that result from the simultaneous operation of another stimulus. These simultaneous effects are variously referred to as contrast, glare, masking, induction, inhibition, etc. The distinction between contrast and adaptation has not always been made clear, partly because the two effects are not always easy to separate experimentally. Hopkinson,[24] for example, attributed to adaptation a change in the exponent of the brightness function that probably depends much more on contrast than on adaptation.

[21] F. G. H. Pitt, "The Effect of Adaptation and Contrast on Apparent Brightness," Proc. Phys. Soc. (London) **51**, 817–830 (1939).

[22] W. H. Marshall and S. A. Talbot, "Recent Evidence for Neural Mechanisms in Vision Leading to a General Theory of Sensory Acuity," Biol. Symposia **7**, 117–164 (1942).

[23] R. M. Evans, *Introduction to Color* (John Wiley & Sons, Inc., New York, 1948).

[24] R. G. Hopkinson, "Light Energy and Brightness Sensation," Nature (London) **178**, 1065–1066 (1956).