Complexities of Perceived Brightness

Apparent brightness may increase, decrease, or remain constant as illumination is increased.

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It is quite generally recognized that if the amount of light falling on a given surface is doubled, and the intensity of the retinal light image is thereby doubled, the apparent brightness may be perceived to increase by an amount that is quite different from the twofold increase in stimulus luminance. The precise relation between perceived brightness and stimulus luminance has been extensively investigated by the various experimental procedures used to develop psychological scales of sensory attributes, and on the basis of such studies, perceived brightness has come to be described as a visual attribute that increases with the logarithm or with some power (less than 1.0) of the stimulus luminance (*1*). This psychophysical relation is of concern to psychophysicists, photometrists, colorimetrists, illuminating engineers, and scientists interested specifically in sensory mechanisms.

Others, especially psychologists, who are primarily concerned with the visual perception of real objects emphasize a different aspect of the problem of apparent brightness. They point to the relative constancy of apparent brightness of visually perceived objects that is found in spite of tremendous changes in the intensity of retinal (proximal) stimulation: White snow continues to look bright and black coal continues to look dark even through a range of illumination so great that the coal in the high illumination may actually reflect more light to the eye than does the snow at the low extreme of illumination. Consequently we find a second group of investigations concerned not with the precise manner in which brightness increases with luminance but, rather, with the degree to which perceived brightness remains independent of stimulus luminance—that is, with the problem of brightness constancy (*2*).

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Brightness Constancy

In experimental analyses of brightness constancy, brightness matches are usually made between a single test object viewed under various conditions of illumination and surround and a separate, continuously variable comparison, or matching, stimulus that is seen in a constant surround. Independent controls for test and surround stimulation may be provided, as in the classical experiments of Hess and Pretori (*3*) and those of Wallach (*4*), or test and surround may be varied together by a single control for the over-all level of field illumination. The results usually fall somewhere between two extremes: If a so-called "reduction screen" is used for viewing the test stimulus, so that only the focal area to be matched is visible in otherwise dark surroundings, apparent brightness increases with increase in illumination, and matching luminance is directly proportional to luminance of the test stimulus ("stimulus matches"); if, on the other hand, the reduction screen is removed and the total scene is made visible, brightness matches to the same focal area may then remain constant, or nearly so, in spite of increases in illumination of the over-all scene—that is, matching luminance remains constant and independent of test-stimulus luminance. This tendency away from stimulus matches and toward brightness constancy is sometimes described as a perceptual regression from the proximal stimulus toward the real object (*5*). Some investigators explain it by saying that perceived brightness is a judgment that is influenced both by the intensity of light stimulation reflected from the surface of the object to the retina and by a "correction factor" that takes into account the over-all level of illumination incident on the various objects in the visual field. This "correction factor" or "allowance for the illumination" presumably compensates for the changes in stimulus intensity, and the perception thus remains constant (*6*).

Another proposal that has been made to account for the tendency toward brightness constancy is the suggestion that perceived brightness is not a matter of interpretation, but a direct response controlled by the ratios of the various luminances in the total visual field rather than by the luminance of any given focal area (*4*). Since the reflectances (or transmittances) of all objects in the field remain constant, their luminance ratios relative to one another are also invariant as over-all scene illumination is increased, and consequently, in this view, the perceived brightnesses of the various objects in the field remain constant and independent of level of illumination.

A careful study of the earlier data suggests that neither the "interpretation" hypothesis nor the "constant-ratio" hypothesis can adequately explain the variety of brightness phenomena observed, and the experiments discussed below will make clear why this is so.

Table 1. Luminance matches to individual areas of the test pattern for three levels of over-all illumination. Mean luminance data and variability for three subjects.

Focal area of test pattern	Log photometric luminance (mlam) of focal area	Mean log luminance (mlam) of matching field
Center	0.18	1.47 ± 0.10
	0.47	1.61 ± 0.20
	1.28	1.78 ± 0.10
Right	0.08	1.37 ± 0.08
	0.37	1.44 ± 0.14
	1.18	1.61 ± 0.14
Upper	$\bar{1}.78$	1.08 ± 0.14
	0.07	1.18 ± 0.17
	0.88	1.37 ± 0.17
Left	$\bar{1}.15$	0.54 ± 0.10
	$\bar{1}.44$	0.45 ± 0.20
	0.26	0.55 ± 0.10
Lower	$\bar{2}.74$	0.25 ± 0.17
	$\bar{1}.04$	0.22 ± 0.20
	$\bar{1}.85$	$\bar{1}.78$ ± 0.33

Matching Apparent Luminances

In our experiments (*7*), a pattern of squares of different luminances (see Fig. 1) comprised the visual scene, and each square differed from its neighbor and from the background by a constant ratio. The maximal ratio of focal-area luminances within the test pattern was 27:1 for the brightest (center) to the darkest (lower) of the square areas. The test pattern was projected on a screen 110 centimeters from the subject's eyes. The limiting boundaries of the rectangular illuminated test field subtended visual angles of 11°50′ by 10°20′, and each side of the individual squares of the test pattern subtended a visual angle of 3°. The over-all level of illumination of this scene was varied in three steps through a range of 1.1 log units.

With the total pattern visible, the subject matched the apparent brightness of each square area within the pattern at each of the three levels of illumination. He made these matches by successive inspection, by looking first at the designated focal area of the test pattern on the screen located to his right and then at the matching field contained within a shielded cubicle directly in front of him. The matching field was an illuminated rectangle (1°45′ by 2°24′) of continuously variable luminance, located about 41 centimeters from his eyes and centered in an illuminated surround (tungsten illumination, 60 mlam) that subtended an angle of about 145° at the eyes. Matches to the individual focal areas were made in random sequence, and the over-all level of scene illumination was also randomized. Results were obtained for three subjects, each of whom repeated all matches in a second experimental session.

Results

The averaged results for the luminance matches for both sessions and for all subjects are presented in Table 1 and in Figs. 2 through 6. The means are geometric averages—that is, averages of the logarithm of the luminance values. Each of the figures contains the mean data (open circles) for a single focal area of the test pattern and shows the relation between the calibrated luminance of that area of the test pattern (plotted as the abscissa) and its apparent luminance as measured by the matching luminance (plotted as the ordinate). Each figure also shows the alternative relations to be expected if (i) apparent brightness were constant and independent of increase in luminance (the law of brightness constancy), or (ii) apparent brightness increased according to some invariant law with the luminance of the retinal image in the focal area (the law of retinal stimulus). Figures 2, 3, and 4, for the center, right, and upper squares, respectively, show that for these three areas apparent brightness increases with increase in stimulus luminance but the matching luminance increases at a rate that falls between the rates predicted by the stimulus law and the constancy law. On the other hand, the mean data for the left square, shown in Fig. 5, closely approximate the function predicted by the law of brightness constancy. Finally, for the lower (and the darkest) test area, Fig. 6 shows that the apparent-luminance matches fall below the luminances predicted by the stimulus law and the brightness constancy law. Here we have the paradoxical result that apparent brightness *decreases* as stimulus luminance is *increased*. Conservative skeptics who find the result of Fig. 6 difficult to accept are asked only to observe, say, a bottle of india ink or a standard telephone set under dim illumination and then note the increased blackness when the overhead lights are switched on.

The results contained in Figs. 2 through 6 make it clear that no single generalization concerning brightness constancy is applicable to all of the objects of different reflectances in any single visual scene or stimulus configuration. With a general increase in illumination, light objects may increase in apparent brightness, intermediate objects may remain constant in brightness, and dark objects may become still darker in appearance.

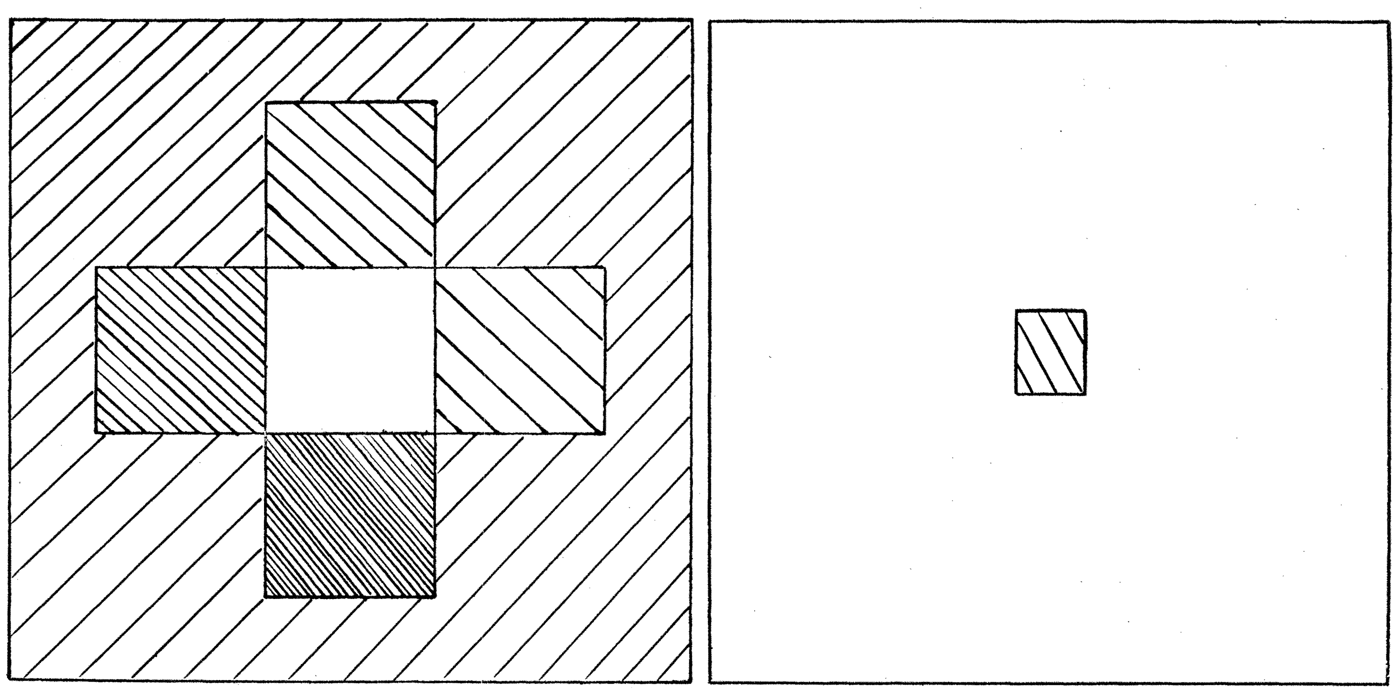


Fig. 1. Outline of test pattern (left) and matching field (right). Striations of test pattern are used in the figure only to illustrate density differences of different individual areas.

Findings versus Hypotheses

How do such results square with the explanations of brightness perception referred to above? If the experimentally determined luminance matches depart from the law of simple stimulus proportionality because the subject is applying a "correction" for level of illumination, then the data of Figs. 2–4 imply that he is systematically under-correcting, and consequently perceiving some increase in brightness with the general increase in illumination. The data of Fig. 5, however, imply, on such an analysis, that the subject's "correction" is nearly perfect: the apparent brightness shows almost perfect constancy as the level of illumination is increased. But if we use Fig. 6 as an index, the subject is presumably applying an overcorrection for illumination, since this area of the test pattern appears increasingly *darker* as the level of illumination is *increased*. When we remember that the subject is viewing a single test pattern, it hardly seems likely that he is applying a different correction for illumination to each of the different areas of the pattern. The concept obviously loses any usefulness it might have had as an explanatory principle once we recognize that the "illumination correction" would have to be multivalued for a single scene.

We run into similar difficulties with the hypothesis that invariant luminance ratios yield constant perceived brightnesses. The luminances of the various areas within the test pattern used in our experiments maintain invariant ratios with respect to one another as the illumination of the whole field is varied, and yet only one of the five areas remains constant in perceived brightness.

Thus, the two most frequently cited explanations for brightness constancy phenomena fail in this situation: Both

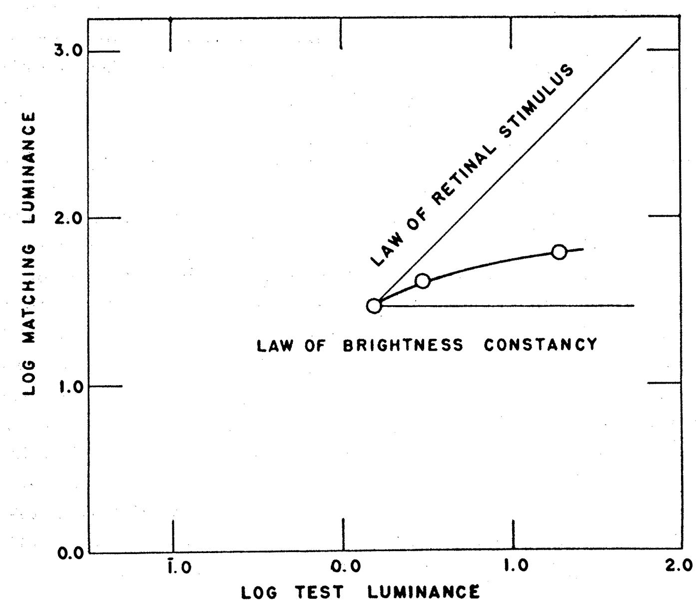


Fig. 2. Relation between photometric test luminance and matching luminance for center square of test pattern.

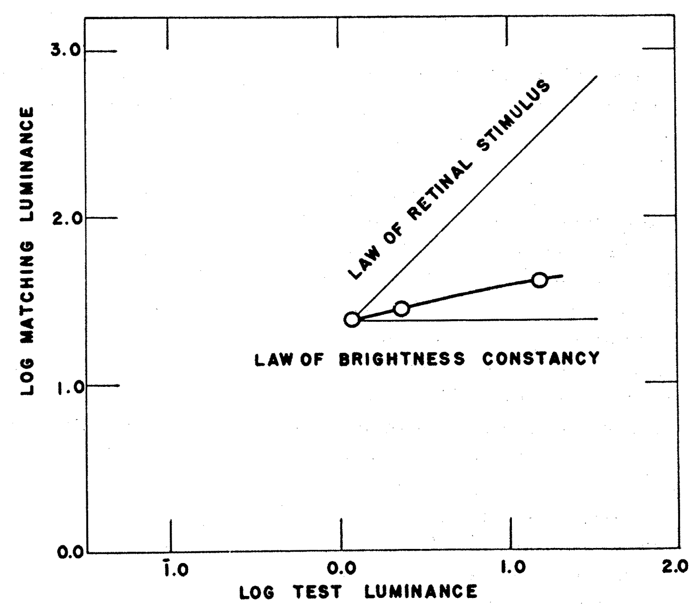


Fig. 3. Relation between photometric test luminance and matching luminance for right square of test pattern.

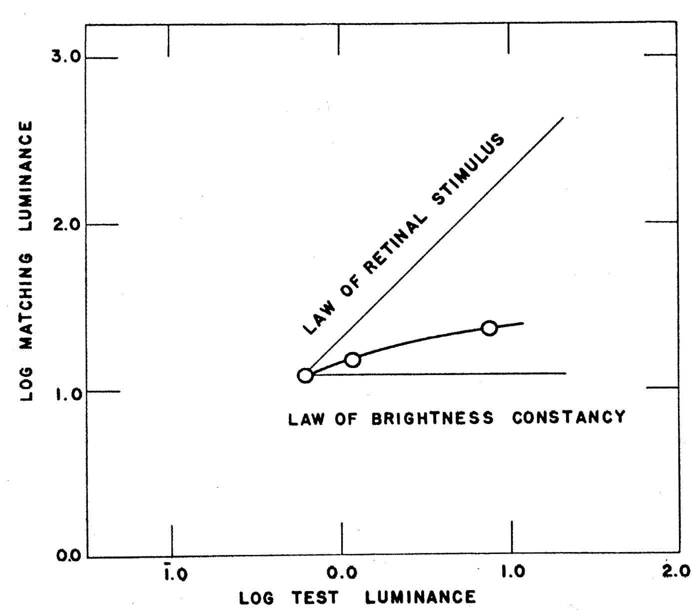


Fig. 4. Relation between photometric test luminance and matching luminance for upper square of test pattern.

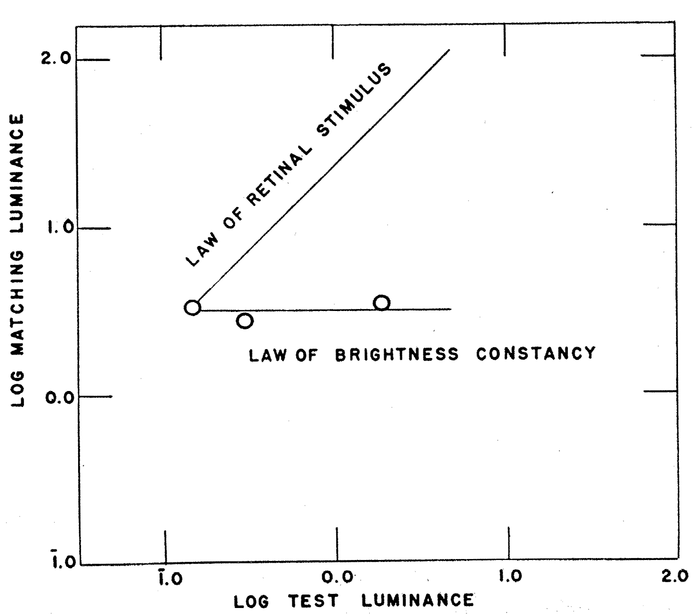


Fig. 5. Relation between photometric test luminance and matching luminance for left square of test pattern.

of these explanations require that all areas of the test pattern behave in the same way, and hence they do not account for the observed result that each individual area of the total scene shows its own characteristic and different dependence on stimulus luminance.

An important consequence of these characteristic variations can be seen from the combined data as plotted in Fig. 7. Here the graph shows the relation between the stimulus luminance and the apparent (matching) luminance for all five focal areas of the test pattern at each of the three levels of general illumination. Although the calibrated photometric gradient of this stimulus pattern is identical for all three levels, the *apparent* luminance gradient increases with increase in the level of over-all illumination. This effect is obvious from the figure if one simply compares the extent labeled R_1 (the range of apparent luminance for the lowest level) with that labeled R_3 (the corresponding range when the over-all level has been increased by 1.1 log units). The photometric range of stimulus luminance is constant at all three levels of illumination: log L_{max} minus log L_{min} equals 1.44. For the apparent luminance matches, however, log L_{max} minus log L_{min} at the lowest level of illumination is less than the photometric range and equal to 1.22; at the intermediate level it is equal to 1.39; and at the highest level of illumination the apparent range exceeds the photometric range and log L_{max} minus log L_{min} equals 2.00.

Table 2. Relation between luminance and magnitude of perceived brightness of matching field with constant, uniform luminance of the surround. Mean results for three subjects.

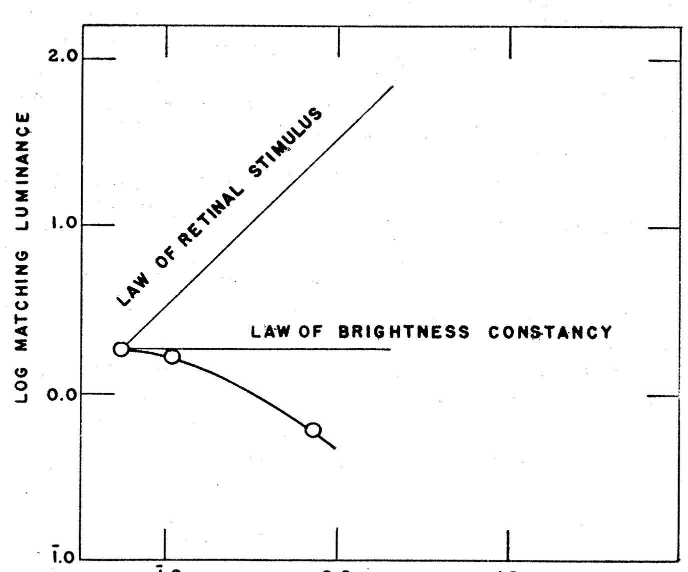
Log luminance (mlam)	Mean log brightness magnitude
$\bar{1}.07$	$\bar{2}.6332$
$\bar{1}.51$	$\bar{2}.8554$
$\bar{1}.94$	$\bar{1}.1662$
0.30	$\bar{1}.8554$
0.70	0.5366
1.09	1.2796
1.51	1.7835
1.89	2.0538
2.11	2.1844

Could these results simply be an artifact of the experimental conditions? Our yardstick for apparent luminance of the various areas of the test pattern is the matching luminance of the comparison field, and this field is itself seen in its own bright surround. We know that the relation between units of stimulus luminance and units of perceived brightness is not usually a simple one of direct proportionality. We also know that this relation is itself dependent upon the particular visual circumstances under which it is determined—that is, level of bright-adaptation, nature of surround illumination, and so forth (*8, 9*). Since our concern here is with apparent brightness per se, it becomes critical to determine directly the perceived brightnesses of the matching stimuli that were used to specify the apparent luminances of the various areas of the test pattern in these experiments.

Perceived Brightness and Luminance of Stimulus Field

Consequently, the relation between perceived brightness and the luminance of the matching stimulus field was determined, for the same three individuals who made the apparent luminance matches, by a method of subjective magnitude estimation. In this psychological scaling procedure, the apparent brightness of the illuminated surround (60 mlam), which remained constant, was assigned an arbitrary brightness magnitude value of 100. With this value for the surround as a standard of comparison, the subjects were required to assign estimates of numerical magnitude to the apparent brightness of the stimulus matching field as the luminance of this field was varied in a series of nine steps through a luminance range of three log units.

The geometric means ($n = 12$) of the magnitude estimates for the three individuals are given in Table 2, and the functional relation is plotted in logarithmic units in Fig. 8. The curve has been fitted by inspection to the plotted points representing the mean data obtained by the scaling procedure. The slope of the function is quite steep throughout most of the range, becoming less steep at the high levels where the stimulus luminance exceeds that of the surround, and also leveling off at the very low luminance levels at which an appearance of "maximal blackness" is approached.



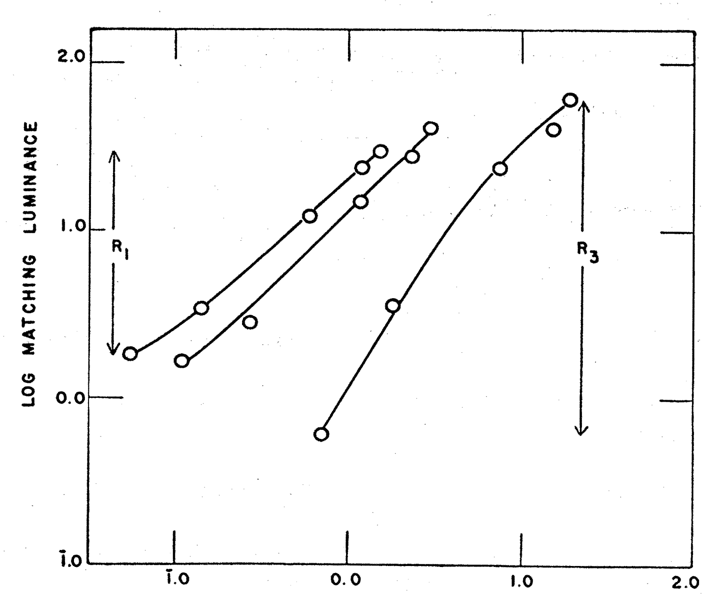
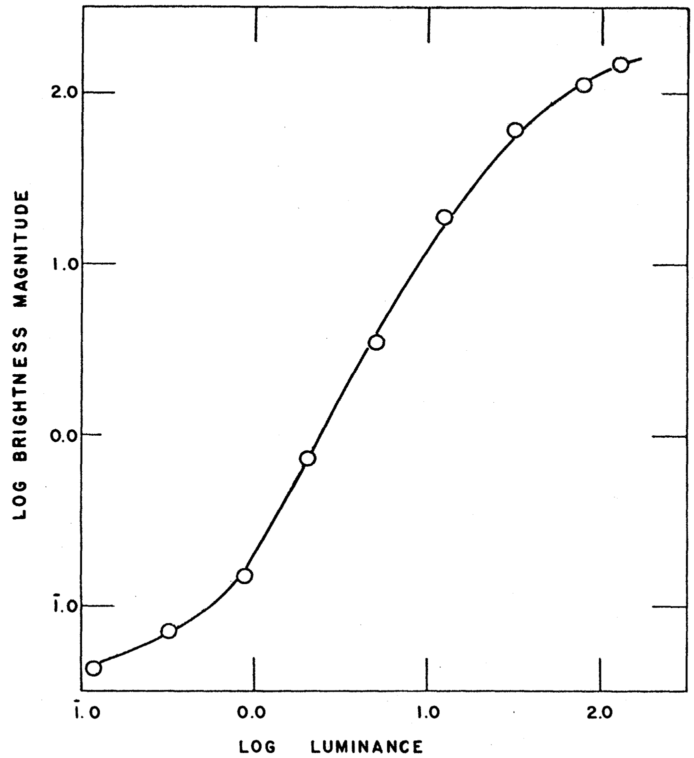


Fig. 6 (left). Relation between photometric test luminance and matching luminance for lower square of test pattern. Fig. 7 (right). Relation between photometric luminance gradient of test pattern and apparent (matching) luminance gradient for three levels of general illumination.



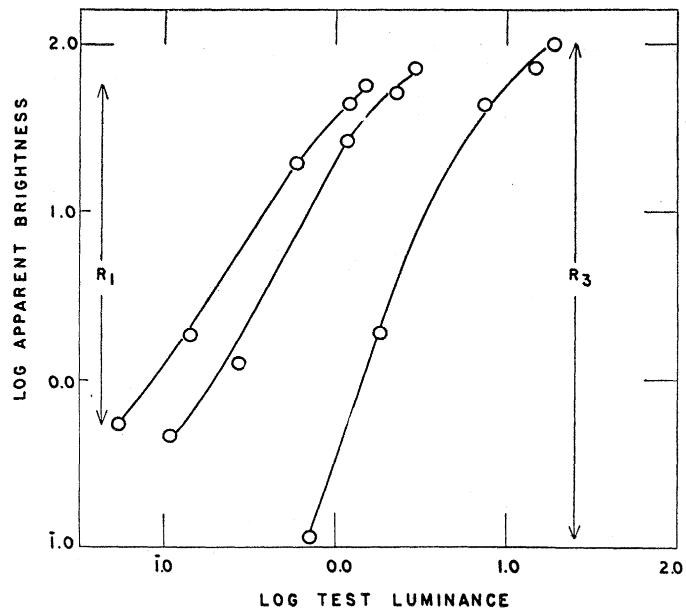


Fig. 8 (left). Relation between luminance of matching field and estimations of perceived brightness magnitude. Fig. 9 (right). Relation between photometric luminance gradient of test pattern and apparent brightness gradient for three levels of general illumination.

With the subjective magnitude function of Fig. 8, we now have the means at hand for "calibrating" in units of apparent brightness the luminance units of the matching experiments, and Fig. 9, based on this conversion, shows the relation between the apparent brightness gradient of the scene and the photometric luminance. Correlative with Fig. 7, the extent labeled R_1 represents the range of apparent brightness from the darkest to the brightest area of the test pattern for the lowest level of over-all illumination, and R_3, the corresponding range for the highest of the three illumination levels. The expansion in range of perceived brightness is obvious, and it occurs because of a dependence on luminance that is opposite in sign for the different areas of the test pattern: Whereas the brightest area gets brighter as luminance is increased, with the same increase in illumination, the darkest area in the configuration becomes progressively blacker.

Implications

The data expressed in brightness units confirm the conclusion already drawn from the data on luminance matches. We cannot accept the suggestion that there is a simple equivalence between fixed ratios of stimulus luminance and fixed ratios of apparent brightness, with brightness constancy resulting when the stimulus ratios are invariant. The data of Fig. 9 are in direct conflict with such a hypothesis.

The results have some interesting implications for the alternative "interpretation" or "correction factor" hypothesis, which requires that an observer be able to take into account the level of illumination. The data of Fig. 9 make it clear that even in the absence of "secondary cues," such as penumbras, highlight flecks, and so on, there is indeed a perceptual basis for differentiating between high and low illumination levels in terms of the difference in brightness gradients at the different levels (*10*). But to assume that the gradient discrimination could serve as a correction factor for illumination level and yield a result of perceived brightness constancy would be both circular and absurd, since the difference in brightness gradients at the different levels is itself based upon departures from brightness constancy in both the brightening and darkening directions.

It is difficult, furthermore, to see how the different brightness ranges could be accounted for in terms of Helson's (*11*) quantitative formulation of adaptation-level theory, which states, in essence, that the zero of organic functions shifts with changing conditions, thereby preserving invariant relations between the stimulus field and the organism. Presumably, in the experiments reported here, the adaptation luminance was approximately equal to the luminance of the focal area for which complete brightness constancy was most closely approximated for the three levels of over-all illumination. Relative to this adaptation luminance for constant perceived brightness, however, the photometric luminances of the remaining areas of the test pattern and of the background remain in constant ratio with respect both to the adaptation level and to each other. Unless one resorts either to ad hoc manipulation of the constants in Helson's quantitative adaptation-level formulation or to a systematic exploration of what he calls the residual terms of his general formula, we do not see how consideration of "adaptation level" alone can account for the fact that *both* the lighter and darker focal areas depart from the adaptation level in apparent brightness by different amounts at the different levels of illumination.

The opponent-colors formulation that we ourselves have been exploring in comparable experiments concerned with the *chromatic* aspects of perceived color (*9, 12*) assumes that the perceptual response in any focal area will be a function of a number of variables: (i) the focal stimulation per se; (ii) the momentary sensitivity of the responding mechanism; and (iii) the ongoing physiological activities in the focal area that are not directly determined by the focal stimulation. These ongoing activities include spontaneous events, which would presumably be of significance at near-threshold stimulus levels, and usually also include induced activities that depend on immediately preceding stimulation of the focal area, or on induced activities dependent on simultaneous stimulation of the nonfocal, surround areas, or on both. The latter two factors are clearly involved in the ordinary brightness contrast and constancy situations, of which the experiments discussed here are an example. The general nature of induced effects has been shown to be one of antagonism and proportionality. Illumination of an area surrounding a focal area induces blackness in the focal area, and in proportion to the magnitude of the surround excitation. The relative effectiveness of a constant blackness increment (or brightness decrement) in a focal area is small where the direct response to the focal stimulus is large, and the induction increment becomes progressively more significant as the direct focal response decreases in magnitude. This concept of opponent spatial interaction at the physiological response level accounts for the perception of increasing blackness with increasing illumination of the surround—a phenomenon that cannot be accounted for in terms of adaptation or sensitivity changes alone. The physiological, opponent induction concept derives from both Hering (*13*) and Mach (*14*). The perceptual effects of such induced response activities have long been obvious in unusual phenomena such as Mach rings, as well as in the commonplace observation that dark objects definitely become "blacker" as the room illumination is increased from an initially "dim" level; and quantitative results of the sort reported here for a relatively complex stimulus pattern are actually predictable from the classical experiments with simple infield-surround field configurations of the sort first reported by Hess and Pretori (*3*) and from the shadowed illumination experiments of Helson (*15*). Direct evidence for the physiological basis of opponent induction processes is more recent, and is beautifully demonstrated in the work of Hartline and Ratliff (*16*) on the electrophysiological responses recorded from the eye of *Limulus*. The systematic, physiologically based, visual response relations involved in contrast and constancy situations need to be more fully explored and understood before we shall be able to deal with the nonspecific "judgmental" and "interpretive" processes that also influence our perceptions of real objects in the natural environment.

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Science in the News

The Last Days: Ike's Final Budget; Reports to Kennedy on Space and Disarmament; Wiesner's Appointment

The last Eisenhower budget, presented to Congress this week, is a liberal budget by the standards of 1953, or by Senator Goldwater's standards today, but a conservative one by the standards set during the campaign by both Kennedy and Nixon.

The budget calls for moderate increases in almost all categories of scientific research, and an aid to education program to assist both colleges and public schools in financing bond issues (as opposed to the more expensive grant programs talked about by Kennedy and Nixon during the campaign). The student loan program under the National Defense Education Act would not be increased, "pending further information as to the rate of applications."

In all, the budget recommends about $1 billion for support of education and $9.4 billion for support of research and development, mostly by the Defense Department. Both figures represent modest increases over last year's recommendations.

Even without a change in Administration, it is difficult to translate these recommendations into precise estimates of how much will be spent. Congress revises the budget, normally cutting more than it adds, and the Administration, although it is bound by the cuts, does not have to spend all the additional money voted. The result is that actual spending is usually less than the budget predicts.

This year the Eisenhower budget will serve primarily as a gauge to suggest how great a difference there is between Eisenhower's and Kennedy's views of what the federal government should do. Kennedy's revisions of the budget should begin to appear soon after his inauguration, and everyone assumes that the revisions will be uniformly upward, particularly in the areas of science and education.

Eisenhower, in closing his budget message, took special pride in pointing out that under his Administration the