Brightness exponent as a function of retinal eccentricity in the peripheral visual field: Effects of dark and light adaptation

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Using a method of direct magnitude estimation, the exponent of the brightness power function was determined under dark and light adaptation at luminance levels well above threshold. The exponent was estimated for functions describing the brightness of stimuli presented at the fovea and the following peripheral retinal loci: 10, 20, 30, 40, and 50 deg nasally eccentric to the fovea along the horizontal meridian of the right eye. The exponent for a 1-sec flash was found to be approximately .33 at the fovea and increased slightly with increasing retinal eccentricity. The effect of adaptation on the brightness exponent was not so large when the target luminance was set well above threshold.

Luminance (L) is integrated over time (t) up to a critical duration (t_c) of approximately 100 msec (Bloch's law: $L \times t = \text{constant}$). Beyond t_c , temporal summation ceases and the perceived brightness is determined solely in terms of flash luminance. Furthermore, for prolonged flash durations, brightness in the periphery gradually decreases due to Troxler fading. This relation has been established at threshold luminance as well as at suprathreshold luminance levels in the dark-adapted eye. This implies that perceived brightness is *time-dependent* for flash durations less than t_c , within which Bloch's law holds, and for prolonged flash durations, and *time-independent* for flash durations well above t_c . Flash durations near t_c , however, often yield a nonlinear brightness enhancement known as the Broca-Sulzer effect. The magnitude of this enhancement increases as flash luminance increases. The time locus of the Broca-Sulzer effect (t_c) decreases as a power function of increasing flash luminance at suprathreshold levels (Anglin & Mansfield, 1968). However, t_c increases as eccentricity increases at threshold (Ronchi & Nováková, 1971; Ronchi, 1971).

In foveal-viewing conditions, the exponent of the brightness power function has been found to be close to 1/2 (square-root relation) for flash durations below t_c and 1/3 (cube-root relation) for steady-state flashes (Anglin & Mansfield, 1968; Mansfield, 1973; Osaka, 1975, 1977, 1978; J. C. Stevens & S. S. Stevens, 1963; S. S. Stevens, 1966). It seems appropriate to employ a 1-sec flash duration to study time-

independent brightness function in the fovea and periphery.

Perceived brightness for steady-state stimuli can be estimated by a power function of the form:

$$\psi = k \cdot (L - L_0)^\beta,$$

where ψ , L , L_0 , β , and k indicate perceived brightness, luminance, detection threshold, exponent, and a scaling factor depending on the magnitude of the reference, respectively (Poulton, 1968; J. C. Stevens & S. S. Stevens, 1963; S. S. Stevens & J. C. Stevens, Note 1). At moderate luminance levels well above threshold, the effect of the additive constant L_0 is supposed to be negligible (Marks, 1966, 1968; J. C. Stevens & S. S. Stevens, 1963). It has been found that perceived brightness grows as a power function of luminance in the fovea as well as in the periphery. However, no systematic change of the exponent has been found as retinal locus changes (Lissy, 1976; Marks, 1966, 1968, 1971; Poeppel, 1977; Poeppel & Harvey, 1973). The purpose of the present experiment was to examine the possible influence of retinal locus on the variability in the exponent of the brightness power function for 1-sec flashes under dark and light adaptation.

EXPERIMENT 1: PERIPHERAL BRIGHTNESS EXPONENT UNDER DARK ADAPTATION

Since, in the range between t_c and 1 sec, the Broca-Sulzer effect (Broca & Sulzer, 1902) has been observed at scotopic luminances (White Collins, & Rinalducci, 1976) as well as at photopic target luminance levels in the fovea and in the periphery (Arend, 1973; Baumgardt, 1963; Osaka, 1977; J. C. Stevens

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& Hall, 1966), only flashes above 1 sec in duration can be considered to be steady-state flashes.

In foveal viewing under dark adaptation, the exponent of the brightness power function has been found to be approximately .33 (Mansfield, 1973; J. C. Stevens & S. S. Stevens, 1963; S. S. Stevens, 1966). Mansfield (1973) obtained an exponent of $.33 \pm .01$ for a .72-deg target and $.34 \pm .02$ for a 2-deg target in the fovea, and $.32 \pm .03$ for a 2-deg target 20 deg in the periphery. Mansfield (1973) and Marks (1966, 1971) have suggested that the exponent of the brightness function is relatively independent of retinal locus, in the near periphery, under dark-adapted conditions. Theoretically, this implies that luminance changes should not significantly affect the shapes of constant brightness contours across this retinal region.

In this experiment, the brightness exponent was measured using an extended range (4 log units) of luminances well above threshold, at retinal positions extending into the far periphery under conditions of dark adaptation.

Method

Observers. Sixteen graduate students who had normal or corrected vision served as observers. All observers had had extensive experience in magnitude estimation experiments.

Apparatus. A Sylvania Glow Modulator tube (Type R1131C with 30-mA current drive), with rise and fall times of less than 10 μ sec, was mounted on a perimeter as a light source. The light was collimated, passed through neutral density filters and a circular aperture, and projected onto the diffusing surface of the pe-

Figure 1. Perceived brightness as a function of log relative luminance under dark adaptation. Each arrow indicates a luminance of 2.8 cd/m^2 . Each data point represents a geometric mean based on 32 brightness estimates across 16 observers. The parameter is retinal locus. Lines were fitted by the method of least squares.

Figure 2. Brightness exponent as a function of retinal eccentricity under dark (open squares) and light (open circles) adaptation. The dotted line drawn horizontally shows standard brightness exponent under dark adaptation.

rimeter forming a circular target subtending a visual angle of 2.02 deg. Using a square pulse generator (Nihon Kohden, Type MSE-3), the duration of the target was fixed at 1 sec and six retinal loci along the horizontal meridian of the right eye were investigated: fovea, 10, 20, 30, 40, and 50 deg nasally eccentric to the fovea. The luminance of the target was changed over a 4 log-unit range by means of Kodak Wratten No. 96 neutral density filters: .028, .28, 2.8, 28.0, and 280.0 cd/m^2 . The luminance was calibrated with a Sanso photometer (Model 12A). The fixation field consisted of a diamond-shaped array of four just-visible dots (650-nm light-emitting diodes with a half bandwidth of 100 nm).

Procedure. The observer's head was supported on a chinrest which set his right eye at a 32-cm viewing distance. After 15 min of dark adaptation, five stimuli were presented in random order at each of the six retinal loci. The observers judged each stimulus twice ($5 \times 6 \times 2$ trials) using the method of direct magnitude estimation. The standard target, or modulus, was a foveally presented stimulus of 2.8 cd/m^2 , the brightness of which was assigned the reference value of "10"; it was presented every 10 trials. The observers were asked to assign a number to the test-flash target as an estimate of its perceived brightness in proportion to the perceived brightness of the reference target. The intertrial interval was about 15 sec. The data from all of the observers were pooled and averaged.

Results and Discussion

As Figure 1 shows, perceived brightness increased as a power function of relative luminance for each of the six retinal loci. The positive slope in Figure 1 corresponds to the exponent of the power function. The brightness exponent as a function of retinal locus under dark adaptation is shown in Figure 2. In general, the results indicate that the exponent increased slightly, but significantly ($p < .05$), as the retinal locus was shifted from the fovea to 50 deg in the periphery. The ratio of the largest exponent to the smallest was about 1.2 under dark adaptation. These

results are not in complete agreement with those of other studies (Mansfield, 1973; Marks, 1966, 1971). Although the data of Marks (1971) also showed a gradual increase in the exponent with increasing eccentricity, that is, .31 (fovea), .34 (12 deg), and .37 (20 deg), this trend was not statistically significant (Marks, Note 2).

EXPERIMENT 2: PERIPHERAL BRIGHTNESS EXPONENT UNDER LIGHT ADAPTATION

In Experiment 1, the brightness exponent was shown to depend slightly on retinal locus under dark adaptation. Would the same relation be obtained under light adaptation? Drum (1976) showed an "unmistakable increase" (p. 1404) in the exponent as a function of increasing retinal eccentricity on the temporal retina, with the eye light-adapted to 15 mL. This suggests that target luminance changes should significantly affect the shapes of constant brightness contours across the retina (Drum, 1976).

However, several studies (Lissy, 1976; Mansfield, 1973; Marks, 1966, 1968, 1971; Poeppel & Harvey, 1973) concluded that the exponent does not change systematically with eccentricity under both adapting conditions. The discrepancy may be due, in part, to possible influences of different background adapting levels. As suggested by Drum (Note 3), it is quite important to eliminate rod input, because the brightness component due to rod activity becomes relatively less important at higher luminance levels and could effectively decrease the exponent of the brightness power function. Experiment 2 was performed to examine the influence of light adaptation on the brightness exponent under conditions in which the rod response to the target was eliminated.

Method

Observers. Fourteen graduate students who had normal or corrected vision served as observers. Some of the observers had participated in Experiment 1. All observers had had extensive experience in magnitude estimation experiments.

Apparatus. The apparatus was the same as that used in Experiment 1, with the following differences. Four target luminance levels were used, 2.8, 28.0, 280.0, and 2,800.0 cd/m^2 , with a background luminance of .52 cd/m^2 . The 28.0- cd/m^2 foveally presented target was called "10" as the reference.

Procedure. The procedure used was the same as that used in Experiment 1, except that the observer was light adapted for 10 min to the .52 cd/m^2 background prior to the presentation of the stimuli ($4 \times 6 \times 2$ trials). The background was spatially continuous, and the test flash was an increment superimposed on the background.

Results and Discussion

The results are shown in Figure 3. As indicated there, perceived brightness again grew as a power

Figure 3. Perceived brightness as a function of log relative luminance under light adaptation to .52 cd/m^2 . Each arrow indicates a luminance of 28.0 cd/m^2 . Each data point represents a geometric mean based on 28 brightness estimates across 14 observers. The parameter is retinal locus. Lines were fitted by the method of least squares.

function of relative luminance. The exponent, as a function of retinal eccentricity, is also shown in Figure 2 (indicated by open circles). As in Experiment 1, the brightness exponent was found to depend on retinal locus. The value of the exponent ranged from .31 to .36. The exponent tended to decrease slightly (from 0 deg to 20 deg) and to increase as eccentricity increased ($p < .05$). The ratio of the largest exponent to the smallest was about 1.16 under light adaptation. The exponent reported by Drum (1976) showed a remarkable increase² as retinal eccentricity increased under the 15-mL light-adapting condition, which was considerably greater than the increase found in the present experiment. Using a 1.1-deg target presented at near-threshold luminances, Drum (1976) found the brightness exponents of .33³ in the fovea and .36 (2 deg), .43 (5 deg), .45 (20 deg), and .67 (30 deg) in the periphery. Similarly, using a 10-min target, he found exponents of .33 in the fovea, and .38 (2 deg), .37 (5 deg), .48 (20 deg), and .70 (30 deg) in the periphery. As retinal eccentricity increased up to 30 deg, the exponent doubled from .33 in the fovea to .67 at 30 deg. It seems somewhat puzzling to find such large exponents, although Drum (1976) has suggested that he may have obtained large peripheral exponents because "the luminance range ... are too narrow and too close to threshold to provide accurate estimates of the slope (exponent)" (Drum, 1976, p. 1404). The target luminance for his 1-deg target condition was also below the background luminance. It has been shown that

the exponent is larger near threshold and, furthermore, that, where the luminance ranges are small, the resulting exponents are likely to be too large, and vice versa (Marks & J. C. Stevens, 1968; Poulton, 1968). Recently, Zihl, Lissy, and Pöppel (in press) obtained two brightness power functions with different exponents under photopic-level adaptation: They found that the exponent increased with increasing retinal eccentricity for the luminance range from 1 to 10 mL, whereas the exponent remained nearly constant for the range from 10 to 100 mL. This finding of dependence of the exponent on retinal locus at lower luminance range also suggests the range effect.

Jameson (1965) and Marks (1966, 1971) showed how perceived brightness depends on the retinal locus of stimulation in the dark-adapted eye. They found that perceived brightness produced by a target of constant luminance was greater in the periphery than in the fovea when low levels of target luminance were used. This implies that the ratio of peripheral-to-foveal brightness was relatively large at lower target luminances near threshold and the ratio was small at target luminance well above threshold in the dark-adapted eye. In the light-adapted eye,⁴ however, Marks (1968) found that the brightness aroused by a target of constant luminance was maximal at the fovea and decreased as a function of increasing retinal eccentricity, and that the ratio of peripheral-to-foveal brightness was practically independent of the level of target luminance (Marks, 1968). Perceived brightness, as a function of retinal locus for both adapting conditions in the present experiment, is shown in Figure 4. Figure 4 clearly shows that perceived brightness was minimal at the fovea under dark adaptation but maximal at the fovea under

light adaptation. These results are generally in good agreement with the Jameson (1965) and Marks (1966, 1968, 1971) data. As shown in Figure 4, the most obvious difference is that sensitivity is greatest at about 10 to 20 deg from the fovea when the lower luminance target was used.

Although there exist several differences in the experimental conditions employed in these studies (such as luminance ranges, adapting luminance, target size, naso-temporal locus difference, and so forth), it is interesting to find such large differences in the measured brightness exponent (Drum, 1976, vs. Marks, 1968, 1971, and the present data). Drum (1976) employed 47.7-cd/m² background luminance, whereas the present experiment employed a .52-cd/m² luminance level, which was about 2 log units lower than the Drum level: It is likely that the weak intrusion of rod activity could affect the size of the exponent in the periphery. Furthermore, locus of stimulation may affect the exponent: Marks (1966) and Osaka (1975, 1977, and the present experiment) tested the nasal retina, and Marks (1968, 1971) and Drum (1976) tested the temporal retina. The retinal surface is not symmetrical, and vision at a given nasal retinal eccentricity is usually most comparable to that at a somewhat smaller temporal eccentricity.

Marks (1968) reported that the exponent decreased with increasing adapting luminance (changed from .2 to 200 cd/m² in steps of 1 log unit) and was constant within a given adapting-luminance condition (although, at three of the four adaptation levels, the exponent did increase slightly as eccentricity increased from 5 to 60 deg, these differences were small, ranging from about 8% to 17%; Marks, Note 2). But Marks did not discuss the implications since each

Figure 4. Perceived brightness as a function of retinal eccentricity under dark and light adaptation. Open circles with cross indicate the modulus luminance. The parameter is luminance level.

adaptation condition was investigated in a separate experimental session and the data for different adaptation levels were not tied together. The differences in exponent could represent differences in what Stevens called "regression." However, Drum (1976) showed that the exponent significantly increased with increasing eccentricity at approximately the same adapting luminance. This discrepancy can be explained partly in terms of some differences in methodology, especially with regard to the procedure employed in each study. Drum (1976) employed a simultaneous matching procedure, whereas the present study employed a direct magnitude estimation procedure.

In conclusion, the data from Experiment 1 and 2 indicate that the brightness exponent of the power function fitted to a luminance range well above threshold increases slightly as eccentricity increases under both dark- and light-adaptation conditions.

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NOTES

1. The lowest target luminance level (2.8 cd/m²) was set about .7 log units above the background luminance so that the effect of L_0 on the photopic power function would be negligible.
2. Drum found a statistically significant increase in the exponent as a function of retinal eccentricity at the 5% level (Note 3).
3. To compute relative slopes (exponents), Drum (1976) adjusted the foveal data on the relative brightness axis to make the resulting function a straight line with a .33 slope.
4. Marks (1968) measured brightness under four levels of *prior* light adaptation between .2 and 200.0 cd/m².

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