Title

Relation of increment thresholds to brightness and luminance.

Journal

Journal of the Optical Society of America, 55(10)

ISSN
0030-3941

Authors

Cornsweet, TN
Teller, DY

Publication Date
1965-10-01

DOI
10.1364/josa.55.001303

for a curved trajectory. This relationship leads to the paradoxical situation that the angular-acceleration stimulus is more sensitive to speed than is angular velocity. It would be expected that the appearance of the environment would change markedly as linear speed is increased, and that there would be acceleratory indications of velocity. The visual appearance of increased velocity on a roadway may be a sharp swoop of objects and road features as they change from a ϕ to a θ direction. A jitter due to acceleratory movements may also be seen in the imperfections of lane markers and road edges. These acceleratory effects have not however been systematically verified.

ACKNOWLEDGMENT

The author wishes to acknowledge the advice and support of Dr. Richard M. Michaels, United States Bureau of Public Roads.

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 55, NUMBER 10 OCTOBER 1965

Relation of Increment Thresholds to Brightness and Luminance*

Tom N. Cornsweet and Davida Y. Teller†
University of California, Berkeley, California 94720

(Received 26 March 1965)

Under ordinary conditions, both the brightness and the increment threshold of an illuminated disk vary directly with its luminance. However, when the disk is surrounded by an annulus more intense than the disk, the brightness of the disk decreases while its luminance remains unchanged.

This set of experiments was performed to determine whether, when brightness is varied independently of luminance, the increment threshold depends upon the luminance or upon the brightness of the disk, or upon both factors. We measured the increment threshold for a flash added to the center of a large illuminated disk when the disk was surrounded by a contiguous annulus whose luminance could be varied. Measurements were also taken of the increment threshold as a function of time after the onset of the annulus. Correcting for light scattered in the eye, we found the increment threshold under all conditions to be independent of the luminance of the annulus (and thus independent of the brightness of the region), and dependent only upon the retinal illuminance of the region to which the test flash was added. It is concluded that brightness and the increment threshold cannot depend upon the same properties of the visual system.

INTRODUCTION

This paper is concerned with two different aspects of the eye's sensitivity to the intensity of a disk of light: the perceived *brightness* of the disk, and the *increment threshold* at the center of the disk. If the disk of light is presented alone on a dark background, both its brightness and the threshold for detection of light added to it depend lawfully on the luminance of the disk.[1] The higher the luminance, the brighter the disk looks; and the higher the luminance, the more light must be added to some area of it to make a detectable change.

However, the brightness of the disk also depends strongly on another physical parameter: the luminance of the area surrounding the disk. If the disk is surrounded by an annulus more intense than the disk, the brightness of the disk is diminished.[2,3] Our question is, how does the presence of the surrounding annulus influence the increment threshold at the center of the disk? Does the increment threshold depend exclusively on the brightness or exclusively on the luminance of the disk, or upon both of these properties? We have found that, under several different and generalizable conditions, the increment threshold depends exclusively upon the retinal illuminance of the test area. It changes lawfully with illuminance and is independent of brightness.

METHOD

General Method

In the present experiments, the observer was presented with a large uniformly illuminated disk of light; the retinal illuminance was varied by neutral-density filtering; the brightness was changed independently of the illuminance by changing the illuminance of the annular surround. A small spot of light of variable illuminance could be added in a brief flash to the center of the disk and the illuminance of that spot necessary in order that the observer detect it was measured under various combinations of illuminance of disk and annulus.

Apparatus

Figure 1 shows the stimulus configuration as it appeared to the observer in monocular Maxwellian view,

---

* Presented in part at the Spring 1964 meeting of the Optical Society of America [J. Opt. Soc. Am. 54, 576A (1964)].

† University of California, Berkeley. This investigation was supported in part by PHS Research Grant No. NBO 3412 from the Institute of Neurological Diseases and Blindness, and in part by a NSF predoctoral fellowship to Davida Y. Teller.

[1] B. H. Crawford, Proc. Roy. Soc. (London) B124, 81 (1937).

[2] H. Wallach, J. Exptl. Psychol. 38, 310 (1948).

[3] E. G. Heinemann, J. Exptl. Psychol. 50, 89 (1955).

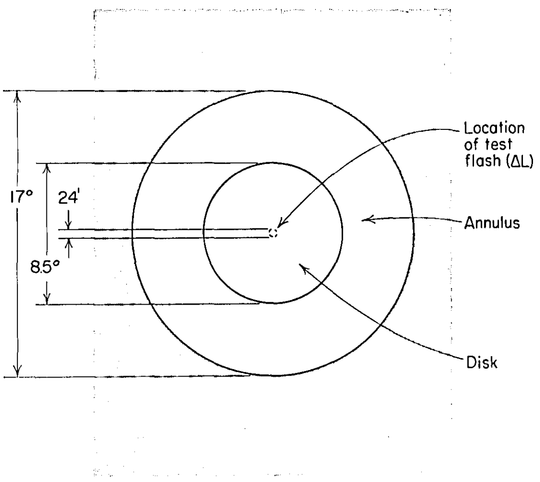

FIG. 1. The stimulus configuration as seen by the observer in monocular Maxwellian view.

and the sizes of the disk, annulus, and test spot. The optical system, a three-channel Maxwellian view, is shown in Fig. 2. Path T forms the test spot, path A illuminates the entire 17° field, and path B adds illuminance to either the inner $8\frac{1}{2}°$ of the field or the outer annular region. The three paths are similar except for their initial segments, and will be described together.

The sources, S_1, S_2, and S_3 are automobile taillight bulbs (G. E. No. 1699), run from a constant-voltage dc supply. Lenses L_1 and L_2 form filament images in the planes of shutters SH_1 and SH_2. Lenses L_3, L_4, and L_5 serve as collimating lenses. Stop ST_1 forms the test spot, while stops ST_2 and ST_3 in combination form the disk and annulus. P_1 and P_2 are beam-splitting pellicles, which serve to combine the light from the three sources. Lenses L_6 and L_7 bring light from all three sources to a focus in the plane of the observer's pupil, and also collimate the light from the planes of the three stops ST_1, ST_2, and ST_3. The superimposed filament images are small enough that changes in the diameter of the natural pupil do not appreciably affect the retinal illuminance. The optics of the eye then image the stops on the observer's retina. The observer's head is held in position by a dental-impression bar.

ST_1 and ST_3 are circular apertures of sizes appropriate to create the 24′ spot and the 17° field, respectively. Two alternative stops can be used at ST_2, depending on the nature of the desired stimulus field. If, as was usually the case, it was desired to make the annulus more intense than the disk, stop X was used (see inset X, Fig. 2) while when the disk was to be the more intense, stop Y was used (see inset Y, Fig. 2). The illuminance of the more intense part of the field was thus determined by the sum of the illuminances contributed by paths A and B. The system was designed in this way to insure perfect contiguity between the disk and annulus; that is, designed so that no dark or bright line would be present at the border between them.

The illuminances in the three paths are controlled in 0.5 log unit steps by filters at F_1, F_2, and F_3; while the illuminance of the test spot can be varied in 0.1 log unit steps by means of filter wheel W. In addition, an opaque stop ST_4 can be silently placed so as to block light in the test spot path T.

The shutters SH_1 and SH_2, are voice-coil-operated vanes, which completely open or close in less than 1.0 millisecond. The duration of the test flash was 8 msec. The sequencing of operations in Experiment II was controlled by an Iconix Corporation electronic preset counter, which triggered specially designed shutter-driver units.

Calibrations

The retinal illuminance of each of the three components of the stimulus configuration was determined in the following way. A piece of milk glass was placed approximately in the position where the observer's retina would be during the experiments, the illuminance on it was calculated from measures of the transmitted light and the transmitting properties of the milk glass. The measures were made with a SEI exposure meter. The retinal illuminances that would result when the observer's eye was in place were then calculated according to the formula

$$T = mL\cdot d^2\cdot 10^3,$$

where T is retinal illuminance in trolands, mL is the luminance of the milk glass surface in millilamberts, and d is the distance from the filament image (plane of observer's pupil) to the milk glass in cm.

The intensity of path T was monitored daily by means of a vacuum phototube and small changes were compensated by adjusting the current through the bulb.

EXPERIMENT I

Procedure

In this experiment, increment thresholds were measured at a number of different combinations of disk and

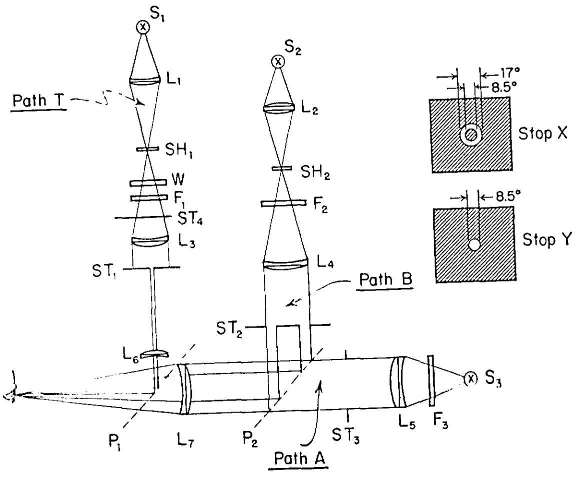

FIG. 2. Schematic diagram of the optical system.

annulus illuminances. The procedure for each single determination (i.e., for one disk-annulus illuminance combination) was as follows. The observer fixated as steadily as possible the center of the illuminated disk-annulus pattern (see Fig. 1) for at least one minute. Then, when he was ready, he pressed a key that opened shutter SH_1 (Fig. 2) for 8 msec. He then waited about 2 sec and pressed the key again, opening the shutter for another 8 msec. On one of these two openings of the shutter, stop ST_4 was positioned to block the light from the test flash, and on the other it was withdrawn from the path to permit the incremental light to reach the eye. The member of the pair on which the light was blocked was determined according to a table of random numbers. The observer, after each pair of shutter openings, was required to choose which shutter opening contained the incremental flash. He was immediately told whether he was right or wrong, and after a period of approximately 10 seconds during which he continued to fixate the center of the pattern, he opened the shutter another pair of times and made another judgment. This procedure was continued for 25 trials.

Between pairs of flashes, the experimenter changed the illuminance of the incremental flash according to the following schedule.[4] If the observer was wrong on trial n, the illuminance of the flash was increased on trial $n+1$. If he was correct on trial n, the illuminance was left unchanged on trial $n+1$, and if he was correct again, the illuminance was decreased on trial $n+2$. The threshold was taken as the median of the last 15 trials. This forced-choice, staircase procedure yields a measure of the increment threshold that is equivalent to the level at which the flash will be detected 75% of the time, and is relatively free from observer and experimenter induced biases.[5,6]

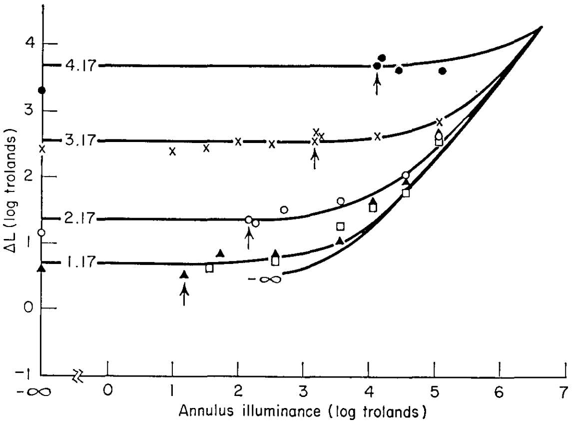

FIG. 3. Results of Experiment I, observer TC. The parameter noted in the break of each curve at the left is the nominal disk illuminance (not corrected for stray light), in log trolands. For the squares, the nominal disk illuminance was zero. The smooth curves are calculated as explained in the text. The arrows indicate the point on each curve for which the disk and annulus have equal illuminances.

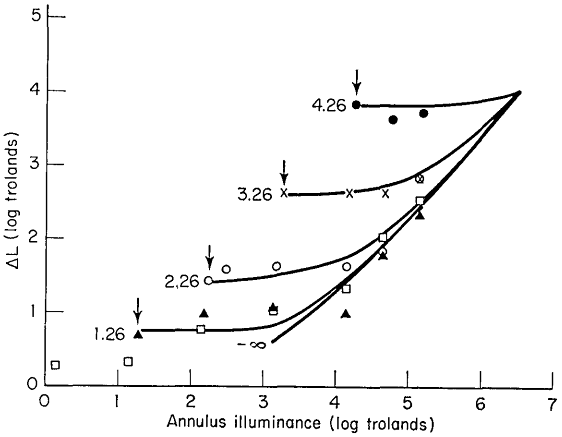

FIG. 4. Results of Experiment I, observer DT. See caption to Fig. 3 for explanation.

On any single run, the threshold was determined for one disk–annulus illuminance combination, and runs were separated by at least ten minutes of rest. In a series of runs, the disk illuminance was held constant, while the annulus illuminance was increased on successive runs from its minimum to its maximum value. Ten minutes of dark adaptation preceded each series of runs.

Results

The results of this experiment, for two observers, are shown in Figs. 3 and 4. For each disk illuminance, the increment threshold at the center of the disk is plotted as a function of the annulus illuminance. (The smooth curves will be explained later.) Note that ΔL is not plotted against the disk illuminance, but rather against the illuminance of the annular surround. The illuminance of the disk (i.e., L) is constant for each set of points (with the qualification to be discussed below). The arrows in Figs. 3 and 4 indicate the point on each curve at which the disk and annulus illuminances were equal, so that the observer saw a uniform field 17° in diameter. Since annulus illuminances less than the disk illuminance produce little if any change in disk brightness,[3] only a few readings were taken to the left of the arrows.

Discussion

If the increment threshold at the center of a uniform disk depends exclusively upon the brightness of the region to which the increment is added, each set of points should drop sharply at annulus illuminances to the right of the arrows, since as Heinemann has shown, the brightness of a disk drops drastically as the illuminance of its surroundings becomes greater than the illuminance of the disk.[3] Our increment-threshold curves do not exhibit such a drop. In fact they turn upward at high annulus illuminances.

If the threshold depends exclusively upon the illuminance of the region to which a flash is added, then it might be expected that each set of points, representing

---

[4] E. G. Heinemann, J. Exptl. Psychol. 61, 389 (1961).
[5] T. N. Cornsweet, Am. J. Psychol. 75, 485 (1962).
[6] T. N. Cornsweet and H. Pinsker, J. Physiol. 176, 294 (1965).

a given value of disk illuminance, should fall along a separate horizontal line. However, that conclusion is not quite correct. The "parameter" that serves to label each set of points is the illuminance at which the disk was set when the annulus was dark. When the annulus is turned on, some of the light from it must scatter to the region where the test spot is to be flashed both because of scatter within the apparatus and because of entoptic stray light. Therefore the actual retinal illuminance on the test region is not exactly the same for each member of a set of points on Figs. 3 and 4.

We have taken, as a reasonable estimate, that the illuminance in the test region contributed by stray light from the annulus is one percent of the illuminance of the annulus. If that is the case, then it is clear that for levels of annulus illuminance below the disk illuminance, scattered light is of little consequence but the scatter becomes important when the annulus is on the order of 100 times the nominal illuminance of the disk, since this would result in an actual illuminance double that of the nominal illuminance.

In Fig. 5 we have plotted increment threshold against disk illuminance for all cases in which disk and annulus were of equal illuminance. The result is an ordinary Weber function. The theoretical curves in Figs. 3 and 4 were then calculated in the following way. For each disk–annulus combination, the actual retinal illuminance of the disk was estimated by adding one percent of the value of the illuminance of the annulus to the illuminance of the disk as measured in the absence of the annulus. The increment threshold for this calculated illuminance of the disk was read from the curve fitted by eye to the points in Fig. 5; this new value was taken as the predicted increment threshold for that particular ring–annulus combination. These values of increment threshold are represented by the smooth curves in Figs. 3 and 4. The fit between the data and the calculated values indicates that under these experimental conditions the increment threshold level depends upon the illuminance of the region to which the increment is added and is independent of the brightness of the region.[7]

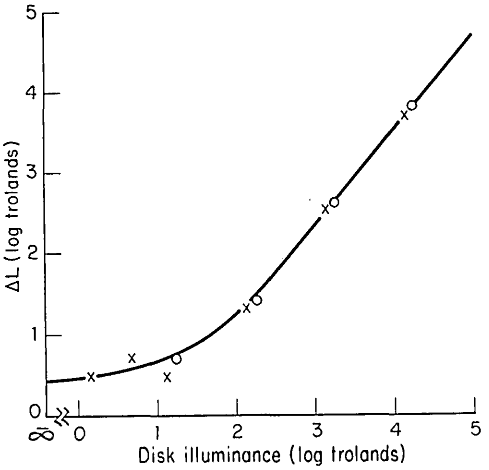

FIG. 5. The Weber function, Experiment I. The X's are for observer TC and the O's observer DT. The curve is fitted by eye.

EXPERIMENT II

The weak aspect of the preceding argument is that our conclusions depend upon a specific assumption about the light scattered from the annulus to the test area. Another set of experiments was therefore performed under stimulus conditions in which the brightness of a disk can be made to change drastically while both disk illuminance and annulus illuminance—and hence stray light—are held constant.

If an observer steadily fixates the center of a large, uniformly illuminated disk until he is adapted to its level—say for one minute—and then suddenly light is added to the outer part of it to form a disk-annulus pattern (see Fig. 6), the central region will abruptly darken. If the illuminance of the *annulus* is very great (e.g., 10^5 trolands) the brightness of the *disk* will undergo the following series of changes. When the annulus is first brightened, the disk looks black, but then, after a period of time, on the order of 5 seconds, that depends upon the illuminances of the annulus and the disk, the disk brightens until its brightness is actually considerably greater than the annulus, and then, finally, the disk darkens again until it appears to have about the same brightness as the annulus. (This phenomenon has

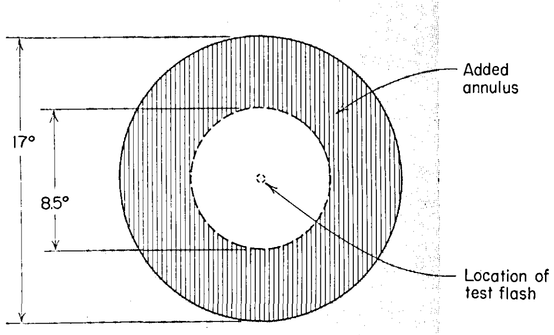

FIG. 6. The stimulus configuration in Experiments II and III.

---

[7] The value of one percent stray-light was a guess. We have been unable to find any data in the literature which would enable us to determine the level accurately. The fit to the data, based on an estimate of one percent, is satisfactory; a similar curve based on an estimate of two percent does not fit as well. It would be possible to find the stray-light value which fits our data best (e.g., using a least squares procedure), but the actual amount of scatter in our experiment depends upon our particular apparatus, and therefore would not be a generally useful datum. For this reason, we do not wish to attribute any particular significance to the value, one percent.

been described and analyzed by one of us.[8]) All of these very strong brightness changes occur while the illuminances in the field, including the scattered light, are constant. Experiment II consisted of measures of the increment threshold during the time that the brightness changes were occuring.

Procedure

The procedure for each experimental run was as follows. The observer positioned himself in the apparatus and steadily fixated a uniformly illuminated disk 17° in diameter for at least one minute. Then, after a warning signal, the outer margin of the disk was abruptly brightened (shutter SH_2, Fig. 2, was opened), and the observer continued to fixate the center of the field. Ten seconds prior to the brightening of the annulus, a small 8-msec test flash was added to the center of the pattern, as shown in Fig. 6; this spot was flashed every 5 sec thereafter until a total of 145 sec had elapsed, making a total of 30 judgments in temporal sequence. At each click of the shutter, the observer indicated whether or not he had seen the incremental flash. After 10 min of dark adaptation, the same procedure was repeated; the illuminance of each of the test flashes was determined as follows. If on run n the observer said he had seen the third flash, then on run $n+1$ the third flash was reduced in intensity by 0.1 log unit; while if he said he had not seen it, on run $n+1$ it was increased in intensity by 0.1 log unit. Thus the threshold for each point in time (relative to the onset of the ring) was measured by a separate staircase. The runs were continued until every one of the 30 staircases had undergone at least five reversals in judgment.[5] This required a total of 15 runs. The threshold for each point in time was taken to be the median intensity of all trials after the third reversal in the relevant staircase.

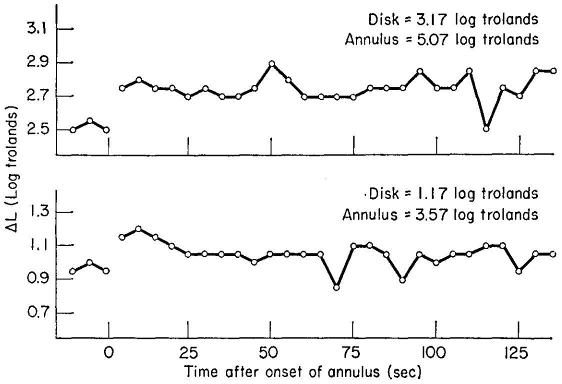

FIG. 7. Results of experiment II, observer TC, for two combinations of disk and annulus illuminances.

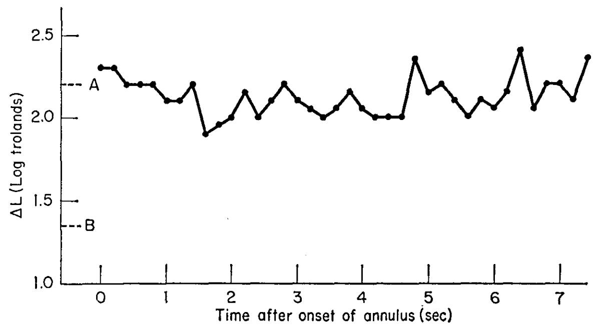

FIG. 8. Results of Experiment III, observer DT. The disk illuminance was 2.26 log trolands and the annulus 5.14 log trolands. The dashed line labeled B is the increment threshold level before the annulus was brightened, and that labeled A is the level predicted on the basis of a 1.0% stray-light level.

Results

The data for two disk–annulus illuminance combinations are shown in Fig. 7. The increment threshold rose immediately, when the annulus was brightened, by an amount corresponding to that to be expected if 1% of the light from the annulus scattered to the disk. Thereafter it remained constant, within the experimental variability, in spite of the fact that the brightness of the disk was undergoing changes equivalent to that produced by illuminance changes of several log units.

EXPERIMENT III

Since the brightness of the disk in Experiment II changed most rapidly during the first few seconds after the onset of the annulus, it seemed advisable to measure the increment threshold during that early period. Therefore, Experiment III was performed. The procedure in this experiment was similar to that in Experiment II except that the flashes occurred every three seconds, and on consecutive runs, the timing of the flashes was staggered so that the flashes occurred at different times relative to the onset of the annulus. In this way, measures were taken every 200 msec after the onset of the annulus. As in Experiment II, a separate staircase was run for each point in time. The results are shown in Fig. 8. Again, although the brightness of the disk was changing the equivalent of several log units, the increment threshold changed very little if at all, except for the initial rise attributable to stray light from the annulus.

GENERAL DISCUSSION

The results show that the increment threshold for a short flash added to the center of a large disk depends upon the illuminance of the disk and is independent of changes in the brightness of the disk caused by changes in annulus illuminance. This conclusion is consistent with the results of some earlier studies. Heinemann[4] published a study of increment thresholds under conditions very similar to those in Experiment I except that

---

[8] T. N. Cornsweet, Psychol. Rev. 69, 257 (1962).

his disk–annulus patterns were much smaller (his disk was 30′ in diameter, his annulus 1° 36′ outside diameter). When his results are replotted in the form of those in Figs. 3 and 4, the curves look very much like our data in Experiment I. His data are fitted well by curves based on the assumption of a 5% stray-light level.

The present results are also consistent with an unpublished study by Burkhardt and Riggs. They measured the threshold for a spot of light added to a disk whose image had been stabilized on the retina. While the disk underwent large changes in brightness because of image stabilization, the increment threshold did not change appreciably.

Pirenne[9] measured the threshold for a flash of light added to an otherwise dark region of the peripheral retina when the test region was surrounded by an illuminated annulus. He found that the presence of the annulus raised the threshold of the test region to about three times the absolute threshold, and stated that this rise was larger than that to be expected on the basis of stray light (although this statement is open to question). He attributed the rise to the action of lateral inhibition. (His experiment also differs from ours in several important ways. Our test flashes were presented to the fovea, our flashes were never presented on a completely dark background, and the inner border of our annulus was much farther away from the test region than was the case in Pirenne's study.)

Under our conditions, the increment threshold depends exclusively upon the luminance of the field. It is well known, however, that, when the state of adaptation of the eye changes, the increment threshold changes while the retinal illuminance is constant. Measurements of this effect, during the early stages of adaptation, have been summarized by Baker.[10] Similarly, Onley and Boynton have shown that when a field of a given luminance is presented to an eye in different states of adaptation both the increment threshold and the brightness vary.[11] Under those conditions, the relationship between brightness and the increment threshold is complex. Evidentally, brightness and the increment threshold each depend on factors related to the state of adaptation of the eye, but the dependencies are different for these two measures.

Some investigators have tried to use relative values of the increment threshold as a measure of relative brightness. For example, Fiorentini *et al.*[12] measured the increment thresholds across a ramp intensity distribution in an attempt to quantify the brightnesses of Mach bands. The results of the present study indicate that the increment threshold cannot be used as a measure of brightness. (Fiorentini *et al.*, in fact, found that the increment threshold rose in the region of the bright band, but it also rose in the region of the dark band.[12])

Implicit in almost all discussions of the physiology of brightness perception is the assumption that the brightness of a region depends upon the strength of activity in the corresponding part of the visual system. For example, regions of abnormally high and low activity in the retina have been postulated to explain the perception of Mach bands.[13] The fact that a disk is darkened by surrounding it with a bright annulus has been explained by postulating that the activity in the entire region of the disk is inhibited by the strong activity in the annulus.[14]

Modern theories of increment threshold also assume at least a partial dependence of the increment threshold on the level of activity in the retinal neurons. For example, Boynton suggests that the transient rise in increment threshold that occurs during the early stages of light adaptation is due to the "on-effect."[15] Rushton's "synaptic summation pool" model of thresholds during dark adaptation is another example.[16]

Our results indicate that increment thresholds and brightness can be varied independently, and therefore cannot both depend directly upon the same properties of the visual system. In our experiment, either the increment threshold at the center of the disk does not depend upon the level of activity there, or the brightness does not; or, of course, perhaps neither one does.

Many phenomena have been demonstrated which suggest that the brightness everywhere in a uniformly illuminated region depends only on the activity at the edges of the region (e.g., see O'Brien[17]). If inhibition becomes weaker as the region sending the inhibition and the region receiving it are more widely separated, then it will be true that the edges of the disk in our experiment will be more strongly inhibited than the center. (Such phenomena have been demonstrated in *Limulus*.[18]) If it is also true that the brightness of the disk depends only upon the activity at its edges, then the brightness of the disk can be reduced by the annulus while the activity in the region of the test flash remains relatively unchanged. Thus our results are compatible with the hypothesis that the increment threshold at the center of a uniformly illuminated disk depends upon the level of activity of the region to which the flash is added, and that the brightness at the center depends only upon activity at the edges of the disk.

---

[9] M. H. Pirenne, Ann. N. Y. Acad. Sci. 74, 377 (1958).

[10] H. Baker, J. Opt. Soc. Am. 53, 98 (1963).

[11] J. Onley and R. M. Boynton, J. Opt. Soc. Am. 52, 934 (1962).

[12] A. Fiorentini, M. Jeanne, and G. Toraldo di Francia, Atti Fond. G. Ronchi 10, 371 (1955).

[13] H. K. Hartline, Rev. Mod. Phys. 31, 515 (1959).

[14] M. H. Pirenne, in *The Eye*, edited by H. Davson (Academic Press Inc., New York, 1962), Vol. 2, p. 171.

[15] R. M. Boynton and G. L. Kandel, J. Opt. Soc. Am. 47, 275 (1957).

[16] W. A. H. Rushton, J. Opt. Soc. Am. 53, 104 (1963).

[17] V. O'Brien, J. Opt. Soc. Am. 48, 112 (1958).

[18] F. Ratliff, in *Sensory Communication*, edited by W. Rosenblith (Technology Press, Cambridge, Massachusetts, 1961).