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U. S. Naval School of Aviation Medicine



U. S. NAVAL AIR STATION
PENSACOLA, FLORIDA

RESEARCH REPORT



PERCEPTION OF CONTOUR:

I. INTRODUCTION

REPORT NO. NM 001 075.01.04

U. S. NAVAL SCHOOL OF AVIATION MEDICINE
NAVAL AIR STATION
PENSACOLA, FLORIDA

JOINT PROJECT REPORT NO. 4

The Kresge Eye Institute under Contract Nonr-586(00)
Office of Naval Research, Project Designation No. NR-142-023
and

U. S. Naval School of Aviation Medicine

The Bureau of Medicine and Surgery
Project No. NM 001 075.01.04

PERCEPTION OF CONTOUR:

I. INTRODUCTION

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17 August 1953

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PERCEPTION OF CONTOUR

I. INTRODUCTION

Vision is frequently taken to be synonymous with visual acuity. In discussing intensity or brightness discrimination and contour discrimination Parsons¹ says, "Only the latter seems worthy of being termed 'vision.' For the essence of vision is the discrimination of contours." To be sure, the measurement of visual acuity consists of the measurement of the ability to discriminate contours or edges but leaves unanswered the more basic question of what an edge is. The object of the present investigation is to ascertain the nature of the retinal stimulus effective in producing the perception of an edge under conditions of photopic, foveal vision.

SUMMARY

Experimental evidence is presented which is interpreted as showing that the higher derivatives of energy with respect to distance on the retina are the main effective stimulus to contour formation and are the feature of the physical world which chiefly carries visual "intelligence." An extensive field of investigation would appear to be available.

METHOD

Ordinarily, the energy distribution in the retinal stimulus is not readily determinable in accurate fashion from a knowledge of the external energy distribution presented to the eye. The chief factors to be considered in evaluating the energy distribution on the retina are listed below:

1. Chromatic aberration.
2. Spherical aberration.
3. Diffraction.
4. Coma.
5. Refractive errors.
6. Astigmatism by oblique incidence.
7. Curvature of field.
8. Distortion.
9. Fixation tremor.

All of these factors with the exception of 3, diffraction, differ from individual to individual. If we confine our attention to relatively small fields of a few degrees in the vicinity of the fovea, factors 4, 7 and 8; coma, curvature of field and distortion become relatively minor effects and factor 6, astigmatism by oblique incidence, is chiefly composed of astigmatism by virtue of the angle K . Assuming an angle K of 2° and a crystalline lens with a power of 16 diopters, in situ, the astigmatism by virtue of the angle K is approximately .02 diopters and, as will appear, is a minor effect. We are left with 1, chromatic aberration; 2, spherical aberration; 3, diffraction; 5, refractive errors and 9, fixation tremor. Assuming a pupil diameter of 4 mm., the approximate diameters of the blur discs attributable to these factors while the eye is viewing a theoretical

TABLE I

Approximate diameter of blur disc expressed in seconds of arc subtended at the nodal point of the eye.	
4 mm. diameter pupil, no filter	
1. Chromatic aberration. ⁵	216"
2. Spherical aberration. ⁶	432"
3. Diffraction.	34"
4. Assumed uncorrected refractive error of .0625 D.	54"
5. Fixation tremor. ⁷	18"
	<hr/> 754"

TABLE II

Approximate diameter of blur disc expressed in seconds of arc subtended at the nodal point of the eye.	
1 mm. diameter pupil, chromatic filter	
1. Chromatic aberration. ⁵	13"
2. Spherical aberration. ⁶	30"
3. Diffraction.	135"
4. Assumed uncorrected refractive error of .0625 D.	13"
5. Fixation tremor. ⁷	18"
	<hr/> 209"

point source are given in Table I. The diameters are expressed in terms of seconds of arc subtended by the blur discs at the assumed nodal point of the eye.

It is observable that the chief causes of blurring are spherical and chromatic aberration. Furthermore, there are large individual differences in the amount and even the sign of so called "spherical" aberration of the eye.^{2,3,4} If, however a theoretical point source of light is presented to the eye through an artificial pupil 1 mm. in diameter, and the effective wave-length range of the source be limited to from 560 to 585 millimicrons, then the calculated diameters of the resulting blur discs become those given in Table II. It will be observed that the chief blurring effect is now attributable to diffraction at the artificial pupil and that the iris of the eye no longer controls the entrance pupil diameter. The effect of individual differences on the remaining four sources of blur has also been greatly reduced. The Airy disc diffraction pattern may, for many practical purposes, be assumed to consist merely of a visually effective portion of the central disc^{8,9} over the surface of which the energy is uniform. If, now, an external stimulus is presented such that derivatives of energy with respect to space in the horizontal dimension have definite values but in the vertical dimension are all substantially zero and if, furthermore, the vertical extent of the distribution be relatively large, then the resulting energy distribution on the retina may be approximately determined between the limits of plus and minus the radius of the visually effective blur disc as projected into the plane of the stimulus.

It should here be observed that the continuous retinal intensity functions obtained by this procedure are not necessarily unlike those obtained by presenting to the eye one or more sharp discontinuous borders as was done for example by Mach in the production of Mach's rings. A sharp distal stimulus of this type will result in the production of a broad, blurred energy distribution on the retina. Unless a very small artificial pupil and narrow band chromatic filter is employed the characteristics of this energy can not be well defined. Ingenious experiments have been conducted to infer the effective radius of the blur disc in the unaided eye from the results of determinations of the energy increment necessary to make lines of various widths distinguishable from their backgrounds. In the experiments here described, however, an aphysiologically small artificial pupil and an aphysiologically narrow wavelength stimulus are employed in conjunction with a continuous energy distribution in the distal stimulus in order to attain a retinal energy distribution which may be computed with substantial accuracy.

The procedure is first to decide what scalar field of energy on the retina is desired. For example, we may require that the third derivative of energy with respect to distance in the horizontal dimension on the retina pass through a maximum and that this maximum have a specific value. We may impose other conditions on the energy at this point and on the rate of change of energy with distance or the energy gradient at this point. The desired scalar field on the retina having been decided upon, an appropriate power series is computed expressing energy, E , as a function of x , distance on the retina in the horizontal dimension. There is then computed that E as a function of x in external space which, when viewed by the eye at a given distance and through a given pupil and filter, will result in the desired energy

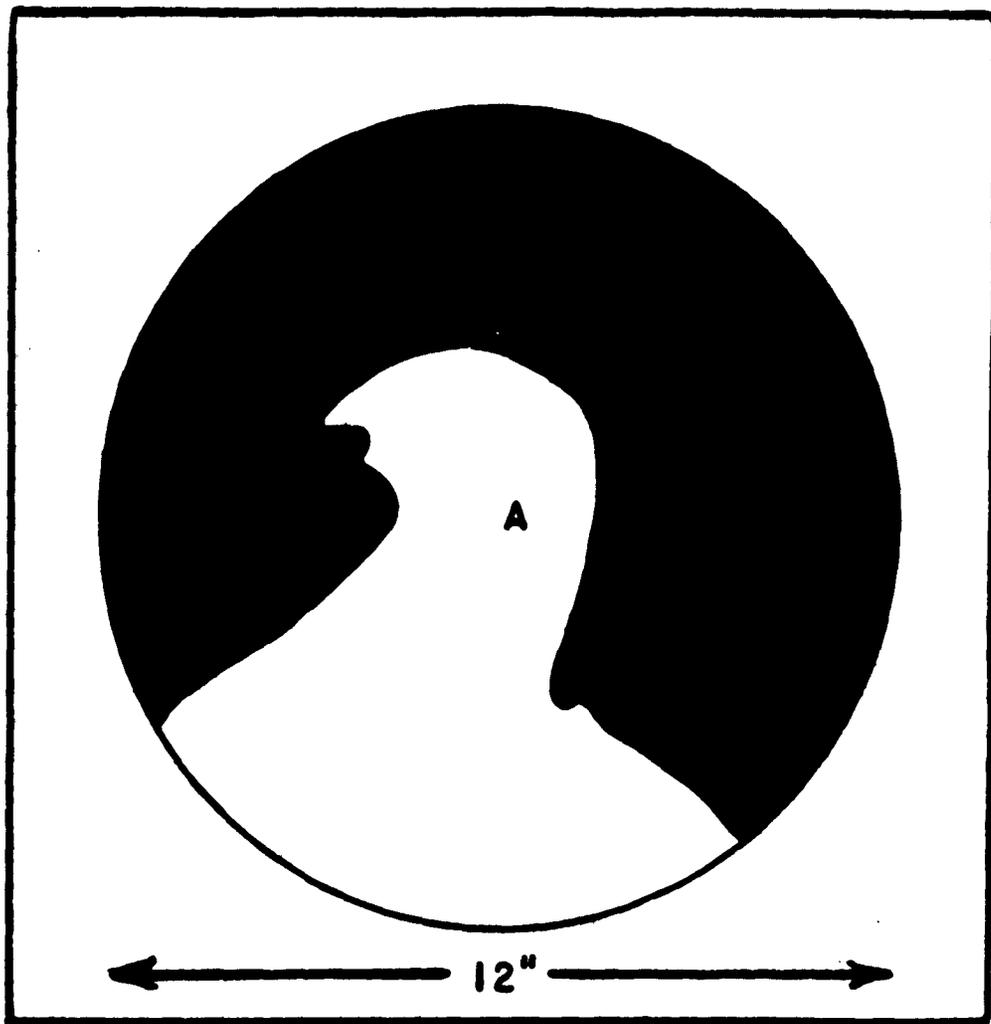


FIGURE 1

distribution being obtained on the retina. That is, a distal stimulus is computed which, under the conditions of observation existing, will result in the desired proximal or retinal stimulus.

APPARATUS

The distal stimulus is provided by mounting any desired, freshly cut white paper disc on a black or gray paper background, for example, as illustrated in Figure 1 and rotating the assembly about an axis passing through the point A and perpendicular to the plane of the paper.

The critical flicker frequency of the fovea is complexly dependent upon the area, intensity and temporal waveform of the stimulus as also upon the surround¹⁰ and varies from point to point on the disc. The angular velocity of the disc was made great enough so that the critical flicker frequency was substantially exceeded for all points on the disc as determined by direct observation. The reflection factor of the white, gray and black papers was measured from time to time with the aid of a Macbeth illuminometer and magnesium carbonate block and by means of a sandwich type barrier-layer photovoltaic cell. As will be noted, the experimental results are not critically affected by slight variations in absolute intensity.

A portion of the rotating disc is illuminated in an otherwise dark room by projecting upon it a rectangular shaped area of light* as also an additional dot of light as shown in Figure 2.

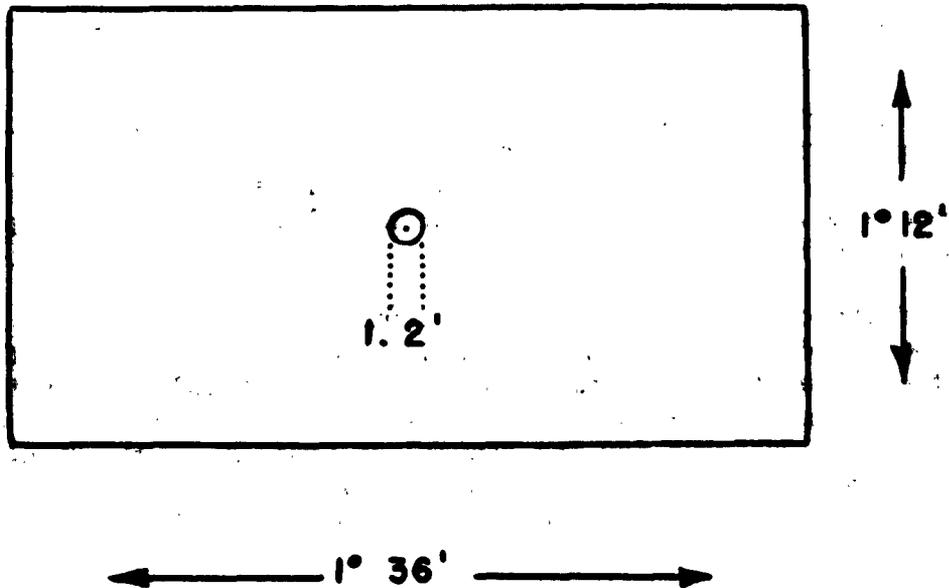


FIGURE 2

*Table III gives values of $E_{\lambda} \bar{y}$ times filter transmission as measured with a Beckman spectrophotometer.

TABLE III

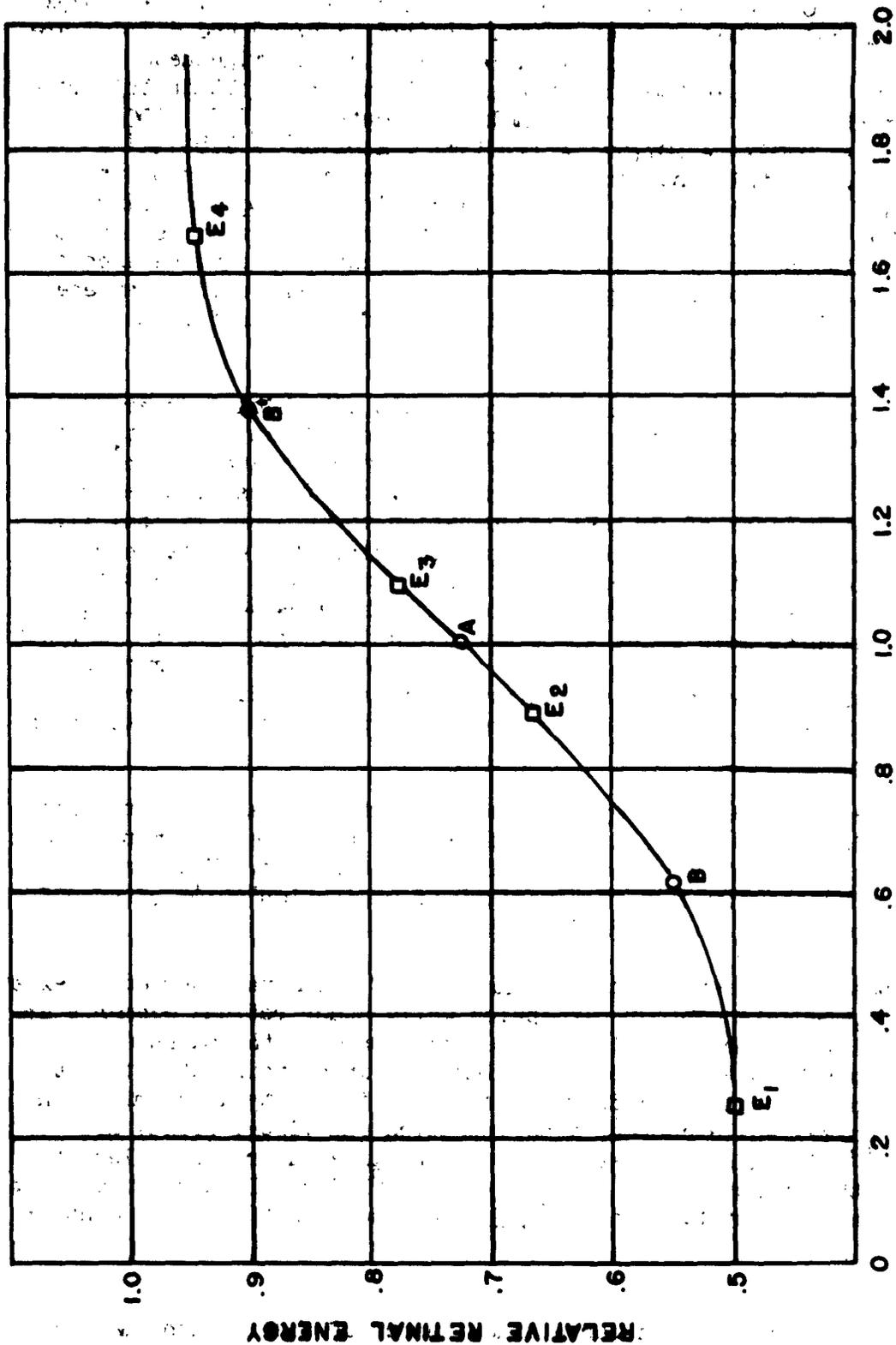
λ	E_{AV} times filter transmission
510 and below	.0
515	.2
520	1.3
525	3.2
530	2.3
535	.4
540	.1
545	.0
550	.0
555	1.0
560	13.0
565	24.1
570	23.2
575	15.7
580	8.2
585	2.5
590	.6
595	.3
600	.1
605	.1
610	.0

The dimensions are given in minutes of arc subtended at the nodal point of the eye. The projecting system and projected pattern are positioned relative to the rotating disc by a pinion and rack gear down mechanism driven by synchro transmission. The energy distribution within the projected pattern is periodically checked with a photocell.

The task of the observer is to set the central fiducial dot over any edge which may be observed on the disc. The small standard deviation of the settings, when the visual task is simple, shows that the total error attributable to manual control and mechanical and electrical backlash is not objectionable. Standard procedures for the control of voltage, lamp ageing, variation in reflection factor of paper, dust, etc. were employed. The total effect is to present a desired time average scalar energy field on the retina.

RESULTS AND DISCUSSION

In Figure 3 on the y axis is plotted units of relative retinal energy. On the x axis is plotted distance on the distal stimulus in inches, each square being .2 inches. The distance of observation was 12 ft. and, therefore, each square corresponds to a retinal distance of about .023 mm., the



DISTAL STIMULUS DISTANCE IN UNITS OF INCHES
RETINAL DISTANCE IN UNITS OF .115 MM.

FIGURE 3

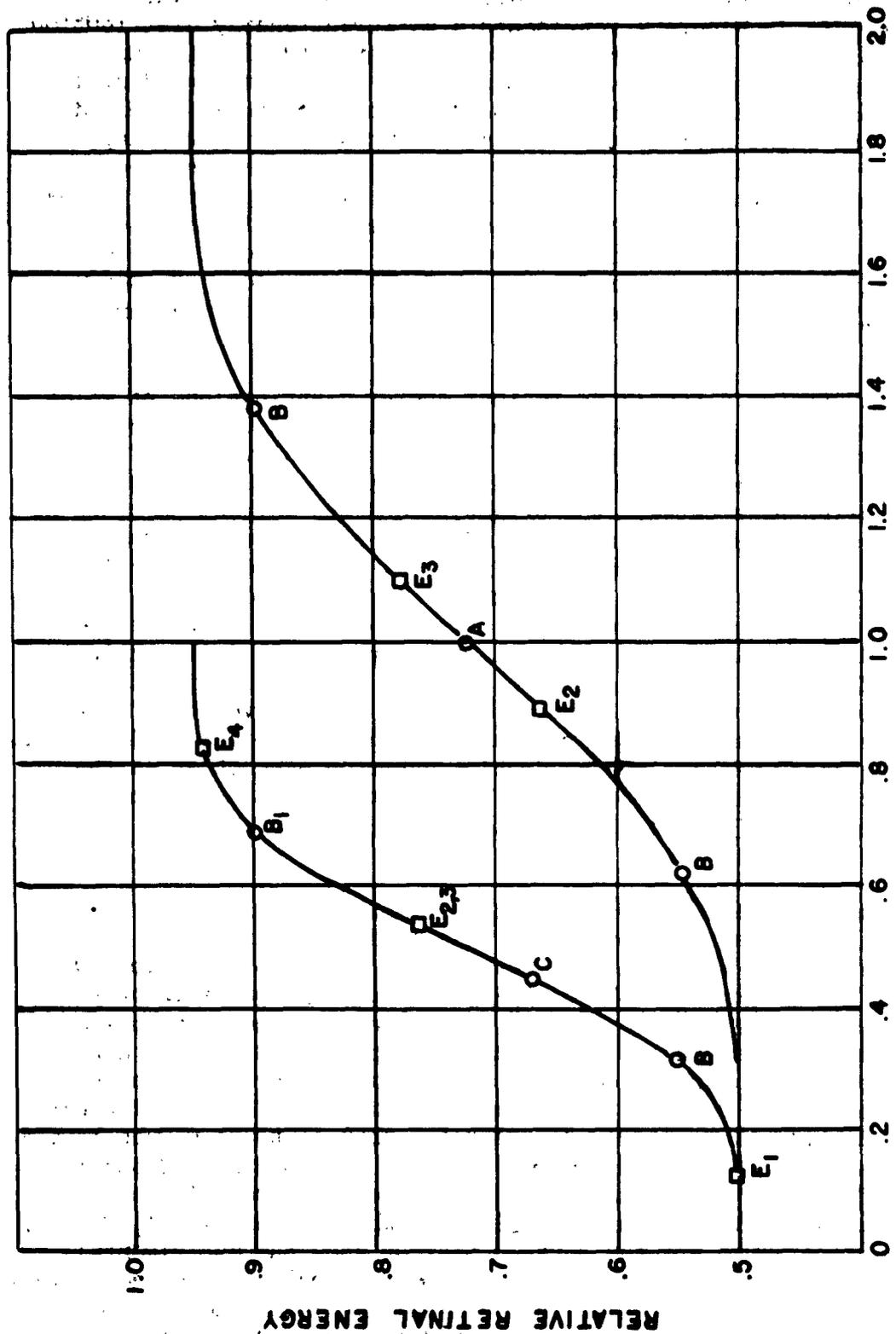
exact figure depending upon the specific schematic or reduced eye used for calculation. A relative retinal energy of 1.0 corresponds to a brightness of 65 millilamberts on the distal stimulus. The function depicted by the solid line is $E = .5000 / 1.7719x^5 - 2.9531x^6 / 1.8984x^7 - .5537x^8 / .0615x^9$. This function was calculated so that dE/dx , d^2E/dx^2 , d^3E/dx^3 and d^4E/dx^4 are zero at both ends of the retinal field while the relative brightness is .5 at the darker end and .95 at the brighter end. In order to obtain this retinal energy distribution, the distal stimulus presented was $E = .5000 / .0001x - .0005x^2 - .0303x^3 / .0775x^4 / 1.7013x^5 - 2.9258x^6 / 1.8945x^7 - .5537x^8 / .0615x^9$. In this instance, because of the small values of the second and higher derivatives, the correction required for optical blur is very slight. The locations of the observed edges or contours or regions of apparent abrupt discontinuity in the field are indicated by squares labeled E_1 , E_2 , E_3 and E_4 . Each observed point is the mean of ten settings apiece by two observers. In general, the standard error of the mean for the data here discussed is less than .02" at the distal stimulus.*

At A, the value of dE/dx is maximal and equals .55 which is over 20 times the value of dE/dx at E_1 where an edge appears. It is apparent that no edge or contour is located where the gradient of retinal illumination^{11,12} is maximal. In the vicinity of E_2 , dE/dx is maximal. dE/dx has been defined as "the ratio of the gradient of retinal illumination to absolute retinal illumination."¹¹ As will appear later in this discussion, the existence of a contour in the vicinity of a region where dE/dx is maximal is a coincidence. Furthermore, this is the only point in Figure 3 where dE/dx is maximal, whilst, there are three more edges to be accounted for. At B and B', d^2E/dx^2 is maximal and it is apparent that no edge occurs at B or B'. It may be noted, however, that the edges E_1 and E_2 are symmetrically distributed as a doublet about B while the edges E_3 and E_4 are symmetrically distributed as a doublet about B'.

If we assume that the human eye possesses on-off retinal elements which are stimulated via either an ocular or head tremor, then these elements would be functioning maximally in the vicinity of A on the retina. However, the rate of change of the excitation or "gradient of excitation"^{11,12} of on-off elements would be maximal at B and B' on the retina.

The hypothesis has been advanced¹³ that on-off elements, assumed to exist in the human eye, mediate contour perception while other retinal elements are involved in the light sense and light difference sense of the human eye. This hypothesis has been supported by showing that in certain patients with amblyopia ex anopsia the light difference sense or intensity discrimination ability can be normal while contour discrimination and visual acuity are reduced ten-fold.¹³ If this hypothesis is correct different retinal elements are involved in the evaluation of E and dE/dx or d^2E/dx^2 . This might make it seem unlikely that a quantity such as dE/dx would be significant for contour

* The standard error of the mean for a fixed number of observations may be taken as a measure of the sharpness or distinctness of the contour. This aspect of the problem will be discussed in a later communication.



DISTAL STIMULUS DISTANCE IN UNITS OF INCHES
RETINAL DISTANCE IN UNITS OF .115 MM.

FIGURE 4

perception. Figure 4 provides experimental evidence on this point.

For convenience, Figure 3 has been partially reproduced in Figure 4. The curve to the left in Figure 4 represents a different energy distribution on the retina produced by presenting a new appropriate distal stimulus. Again, the squares represent observed points. This retinal energy distribution produces only three edges rather than the four previously observed. This is because the right half of the doublet produced by B has overlapped the left half of the doublet produced by B'. The center edge has been marked $E_{2,3}$ to indicate the fusion of the doublet. E_1 and E_4 appear to the left and right of B and B' as in the previous Figure. The circle labeled C indicates the sole point at which $\frac{dE}{dx}$ is maximal. No contour, edge or apparent discontinuity in the Figure occurs at C, thus providing further evidence that $\frac{dE}{dx}$ is not a substantial determining factor in the perception of an edge.

Figure 5 illustrates a family of retinal energy distributions of which the two curves in Figure 4 are members. In each instance a doublet contour or edge appears symmetrically distributed about the maximal values of d^2E/dx^2 , B and B'. The region between E_2 and E_3 appears as a gray strip intermediate in brightness between the brightest and the darkest portions of the Figure. This gray strip appears of uniform brightness despite the fact that in this region dE/dx on the retina is maximal. Abrupt discontinuities appear at E_1 and E_2 where dE/dx is almost zero. As will appear in a subsequent communication, quite different types of retinal energy distribution from those here depicted will also result in the appearance of discontinuities where both dE/dx and d^2E/dx^2 are zero. As the magnitudes of both the second derivative maximal at B and B' are increased and the values of d^4E/dx^4 at B are likewise increased, the separation of the doublet edges is decreased. Nevertheless, the inner members of the doublet approach each other as the separation between B and B' is decreased. This results in a narrowing of the width of gray ring from .310" to .211" to .207" and finally the ring disappears.

As the maximal values of d^2E/dx^2 and the values of d^4E/dx^4 at B and B' are increased in the successive members of this family, reading from right to left, the average doublet separation decreases from .639" to .598" to .392" to .356" to .186" as measured at the distal stimulus. A discussion of the relative importance of d^2E/dx^2 and d^4E/dx^4 in controlling the doublet width is beyond the scope of the present paper (d^3E/dx^3 at B and B' is, of course, always zero). That the E_1 and E_4 edges in this family occur at values of dE/dx equal approximately zero is, of course, fortuitous. The use of other types of energy distribution clearly demonstrates that contours may be formed regardless of the value of dE/dx or $\frac{dE}{dx}$. Indeed, the location of the edges in this family of figures is substantially unaffected by a rotation of the figure about an axis passing perpendicularly through the point $x = 0$, $E = .5$. The small dashed line curve and the squares thereon show the experimental results obtained when the relative energy increment is only .1 instead of .45. The reduction in the values of d^2E/dx^2 and d^4E/dx^4 has increased the doublet separation as compared with the solid line curve at the extreme left but three edges are still produced and, indeed, three edges are still produced with smaller energy increments not conveniently plotted on this figure. Since a relative energy increase from .5 to .6 suffices to produce three edges, a

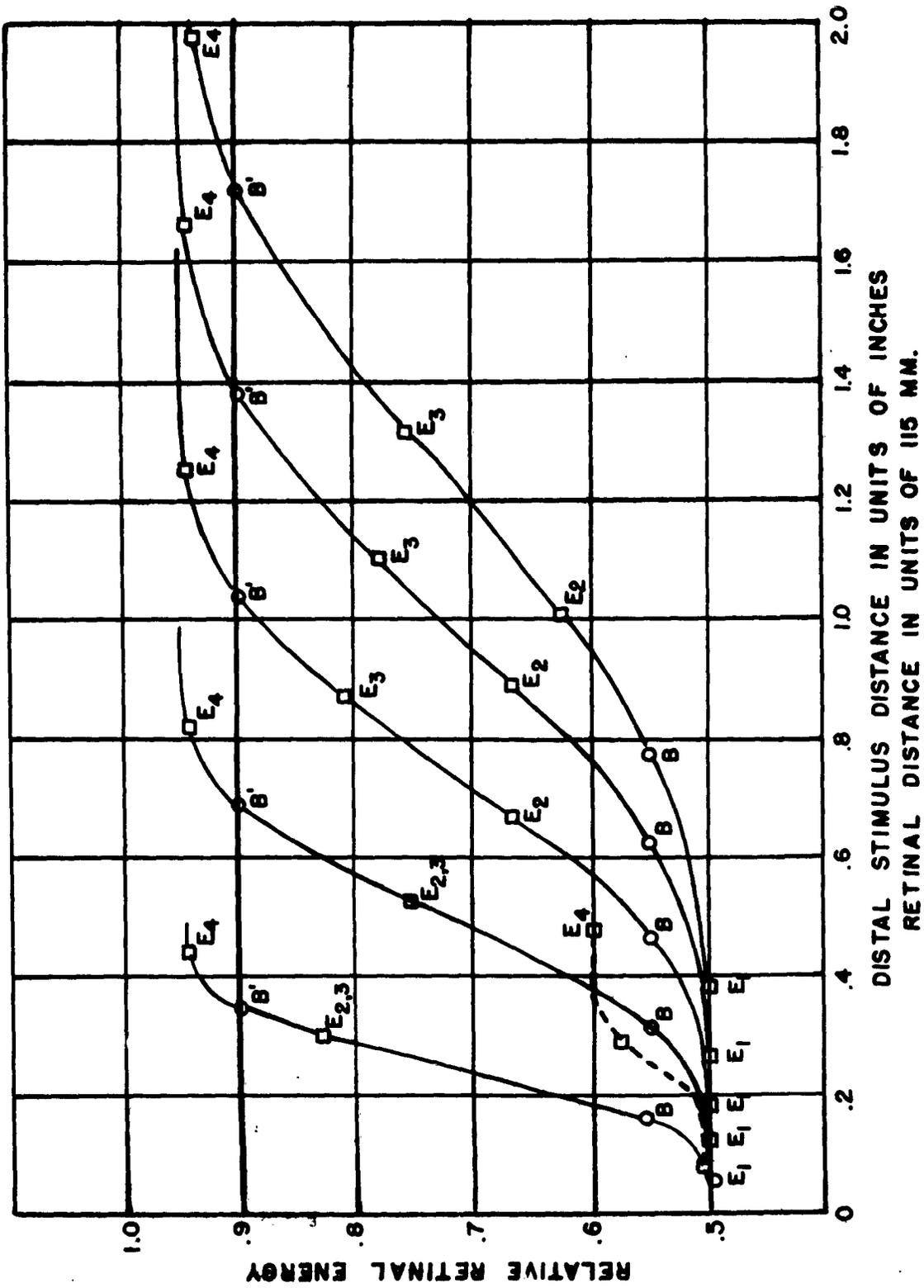


FIGURE 5

relative energy increase from .5 to .95 would suffice to produce some fourteen edges and, indeed, can be caused so to do if the number of B points is increased. This demonstrates that minor increases in E increments, despite huge values of dE/dx , will not produce additional contours.

It remains to describe the subjective appearance of these figures. Where E_1 , E_2 , E_3 and E_4 are all present, the subjective appearance is as follows. All of the figure to the left of E_1 appears as a uniform medium gray, between E_1 and E_2 is a darker gray strip, between E_2 and E_3 is a uniform bright gray strip, between E_3 and E_4 is a uniform white strip whereas from E_4 on to the right is a less bright region. It is apparent from this description that the subjective brightness is far from completely dependent on the energy density incident on the retina and that information received from on-off elements can take precedence over the light difference sense.

A phenomenon which was observed by Mach¹⁴ is probably a special case of Figure 5, but since the figures which Mach employed were of the nature shown in Figure 6, in which all derivatives of the distal stimulus were discontinuous and the nature of the proximal retinal stimulus was unknown, an analysis could not be made and the effect was attributed by Mach to the fact that the "light intensity falls short of the mean intensity of the adjacent parts." As can be seen from Figure 5, the mean intensity of, say, the brightest section may be greater or less than the mean intensity of the adjacent parts depending to a certain extent on the definition of these parts.

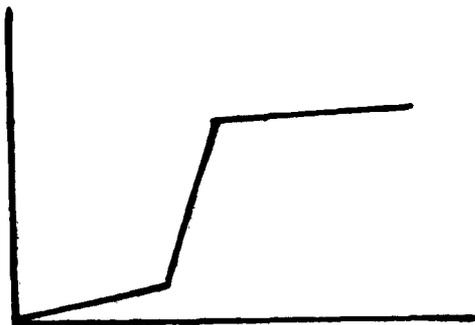


FIGURE 6

This classical view that contour perception is somehow a special case of intensity discrimination can be seen in two investigations of a very practical nature which have been conducted to ascertain the effect on intensity discrimination of making the dividing line between the two sides of a comparison field diffuse. A variable penumbra was employed by Middleton¹⁵ while ground glass discs of various thicknesses were used by Bennett.¹⁶ In both investigations the chief effort was directed toward ascertaining the value of ΔI . The perception of an edge, where it occurred, or the accuracy with which it could be located were not investigated. It is interesting to observe that by controlled manipulation of the proximal stimulus, as in Figure 5, the value of ΔI could have been made zero, or, as it were, negative.

FUTURE DEVELOPMENTS

If further investigation confirms the notion that the higher derivatives of E with respect to retinal distance are the chief effective and only practical stimuli for contour formation, then we have the beginning of an explanation for visual acuity, as Bartley¹⁷ says, "Visual acuity involves the formation of contours; it is scarcely a reality until this occurs." We also have the beginning of an explanation of brightness contrast of which Bartley¹⁸ says, "This has been observed so many times by most of us it is as common as the major facts of gravitation. It simply seems as though it "ought" to occur, but why it does occur has never been explained. Notwithstanding, the phenomenon surely does not fall into the category of those facts of nature which are simply to be taken as axiomatic. The many efforts to explain it show that it hardly has been so taken. But, on the other hand, the phenomenon has been used in consecutive breaths both as a thing to be explained and the explanation."

The values of the various derivatives necessary to produce contours and the interrelations of these values may, of course, be investigated as a function of:

1. Wavelength.
2. Intensity.
3. Temporal duration.
4. Size of field.
5. Length of contour.
6. Location on retina.
7. Anoxemia, fatigue, drugs.
8. Amblyopia ex anopsia, optic nerve defects, retinopathy, etc.

Since not only the location but the sharpness of the contour is a variable and the above factors may be interrelated, it seems likely that no one individual can explore the field.

Preliminary experiments with one stimulus presented to one eye and a different stimulus presented to the other eye suggests that the edge may be the effective stimulus for binocular fixation even with dE/dx differing in algebraic sign to the two eyes and no two corresponding points stimulated by the same E. This should be further examined.

If the significance of the higher derivatives for the formation of contours is as great as it appears to be, then we have found which feature of the physical world chiefly carries visual "intelligence" just as we have found that the upper frequency, although low volume range, chiefly carries auditory "intelligence."

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