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Abstract of the Problem

This problem was designed to test Mach's (32, 33) old contention, that the retina responds to marked changes in the second differential of luminous intensity as well as to changes in the first differential of luminous intensity. His thesis was that contours will be seen at these marked changes in the second differential of luminous intensity. We were concerned with testing the following hypotheses: (1) If the formation of contour is a function of a change in the rate of change of luminous intensity, then a boundary should occur through the points of inflection on a symetrical figure bounded by the requisite curves; (2) Reversal of figure and ground should have no effect on this boundary; and (3) A boundary will not be generated along curves that do not possess a point of inflection.

A series of three experiments were run. The figures used in the first experiment were four pointed stars bounded by sigmoid, convex, concave and linear curves. These were presented to the subjects on a color mixer under varying speeds of rotation. The results were that a contour was not established through the points of inflection.

A second experiment was run using a figure reported by Fry (13) which generated a contour at a point not obvious from the inspection of the figure. Also, some other figures with various indentation along the curves were used. The Fry effect was reproduced and a contour occurred through the slight indentation only when the figure was white, it did not occur when the figure was black.

However, in the case of the marked indentations (a series of 90° angles along the curve) a contour was formed at each angle and the reversal of figure and ground had no apparent effect.

The third experiment was run using figures that possessed two points of inflection along the curves instead of one. The result was that no contour was formed at either series of points of inflection.

We can conclude that a change in the rate of change of luminous intensity will generate a contour only under limited circumstances: when the change is markedly abrubt and when certain figure-ground conditions are met. Mach assumed this was demonstrable over the whole retina but this was not the case here. The event may occur over the fovea alone and these experiments should be followed up with vision limited to the homogeneous foveal region before one can or cannot say that the retinal cells respond in a differential way according to the mathematical concept of a change in the rate of change of a gradient of luminous intensity.

Introduction and Review of the Literature

The Physiological Basis of Visual Acuity

This has been determined chiefly by investigating the size of the minimum visual angle, and the effect of various stimulating conditions upon this minimum visual angle. One of the most important of these variables is the intensity of illumination. However, the order of magnitude of the measure depends to a large extent upon the characteristics of the visual target used. The main purpose of those who have made these measures has been to determine the nature of the physiological processes underlying visual acuity. The old idea that the basis of resolution was the separation of two stimulated cones by one unstimulated cone has been shown to be inapplicable, and measures a good deal finer than the width of a single cone have been presented. Senders (38) has reviewed the literature on the physiological basis of visual acuity and concludes that visual acuity varies in a systematic way with an increase in the intensity of the stimulus illumination, and that this must be accounted for by any complete theory of visual acuity. Senders says that two points of view characterize visual acuity theory today. The first is a theory of visual acuity based on peripheral processes of which Hecht has been the principle recent proponent. This type of theory is essentially a static one: the retinal image is conceived of as a (usually stationary) distribution of intensities. Some receptors are stimulated and others are not, because the brightness gradient at boundaries is sufficient to cause differential stimulation in some cases and not in others. This concept of visual acuity as a form of brightness discrimination accomplished chiefly at a retinal

level underlies most thinking on the subject today. Of the second type are theories which consider events in the retina, optic tract, and brain. The only authors who elaborate such a theory today are Marshall and Talbot (27). They have attempted to take into account all possible static and dynamic, retinal, and neural processes which might influence the mechanism of visual acuity. Senders says that this theory is new and is by the authors own admission inconclusive and is not entirely documented by experimental evidence, but that it represents a new type of thinking about an old problem and should bear fruit in future research. (That it has will be pointed out below, p. 27.)

The experimental evidence in support of the first type of theory is as follows. (24) At the lowest light intensities (0.0000603 milli Lamberts) the eye can see a line whose thickness subtends a visual angle of about 10', while at the highest intensity the eye can resolve a line subtending 0.008' which is very near 0.5" of visual arc. This is a range of about 1-1200, and is 10-25 times the ordinary range found with test objects like a broken circle, a hook, or even a grating. These have a range of 1-60 or 20'-30' to 0.51' of visual arc. These results are not confined to the human eye for Ehrenhardt (1937) measured a lizard for the relation between illumination and visual acuity and found a range of 1-25, the lowest intensity at 30' and the highest at 1.3' of visual arc. He found similar results for the bee also. Hecht and Mintz (24) attempted to compute the size of a band of cones that 0.5" of visual angle will stimulate and cause the blur gradient (Zoethout (42) says that the focus of a

luminous point is never a point-image on the retina. The refractive mechanism of the eye makes this impossible, resulting in circles of diffusion, or blur circles, which are always present; these occur even with the sharpest focusing. Bartley (1), says the transition from illumination in the image to darkness outside of it is not abrupt, but gradual.) which tends to increase irradiation as it increases. They computed this to be 8μ which they claim is about 5 cones wide. From this they postulate the difference in resolution threshold between the central row of cones and its neighbors would be about 5% and point out that this is a course intensity difference to be a limiting factor in visual acuity. They believe that a fine line is perceived at the small angles they found because its blurred shadow reduces the light on one extended row of cones to a level which is just functionally less than the light on the row of cones to either side of it. They think that the line appears sharp because it produces a recognizable shadow on one row of cones only. They conclude that a sharp line is seen simply because the illumination of only the center row of cones is sufficiently different from the rest. However, Bartley (1) says that; "This explanation does not seem to cover the situation with low illuminations when the minimal resolvable angle is 10' of arc, a spatial value 1200 times as great as the one we have just dealt with, and again we may have to resort to some neural process to account for contour".

In 1911, Cobb (9) studied the effect of illumination by a side light on visual acuity. He used two systems of parallel lines on 1/8" milk glass disks rotated in opposite directions in an

Ives frame. (This is a collar with vernier adjustments which allow the two milk glass disks to be varied by minute amounts. Thus any amount of angular displacement can be read at a glance.) The side light was mounted on a Wundt perimeter with the test object placed in front. His general findings were that visual acuity was diminished due to the side light for which he postulated three possible causes: (1) The image of the side light source itself on the retina which may reduce the general retinal sensibility by induction, (2) That portion of the scattered light from the same source which superimposes itself upon the image of the test-object and so reduces the contrast in the latter, (3) The scattered light falling upon the remainder of the retina, and especially that contiguous and near to the image of the test-object, influences the state of the portion of the retina upon which that image falls by induction.

Prolonged stay in feeble light caused no noteworthy change in visual acuity, but the brighter the light from a bright source entering the eye, the more the visibility of an object is reduced, the brighter the source; the lower the brightness of the object of vision, the smaller the visual angle subtended by the two sources (test-object and side light). Under conditions initiating the worst practical conditions for reading (the light 10° from the visual axis, equal illumination of the eye and the test-object, in this case printed characters on white paper) the reduction in visual acuity is negligible at any intensity of illuminations. The retinal image of the light source in itself is a negligible factor in the depression of vision, at least at angles of 15° and

ever, since conditions being equal, it is indifferent whether the image falls on the blind or sensitive portions of the retina.

The depression of vision is due to light which, by reason of reflection or diffusion, partly from imperfect transmission of the eye media, is scattered over the retina upon and near the image of the object of vision. Cobb concludes that; "Visual acuity behaves in general, but not wholly, the same with (a) illumination of the eye from a source and (b) a haze of light thrown over the rod free central retina (subtending 2 in the visual field) with proportional variations in the light flux in the two cases". (p. 99)

Fisher (12), investigating monocular foveal acuity reached similar conclusions. He tested monocular acuity in the 2 foveal area as measured by an Ives grating at retinal illuminations of 0.193, 10.07 and 318 photons. A 2 mm artificial pupil was used before the tested eye and a field of low contrast brightness was placed before the unused eye. Annular surrounds, whose inner margins formed the boundary of the test object, were used. There were five sizes of surrounds with radial widths of 2.5, 5, 7.5, 12.5 and 20 degrees of visual angle. These were illuminated separately from the test object and were used at relative illuminations of 0.0566, 0.193, 10.07, 318 and 8560 photons. The method of limits was applied only from below. The subjects were dark adapted and one minute of light adaptation to the conditions about to be used, preceeded the readings. Each test object illumination was predetermined with each surround's illumination, except that the lowest of each was not used with the highest of

the other. His findings are as follows: (1) When the surrounds were brighter than the test-objects visual acuity progressively decreased with increasing size of surrounds, (2) When the surrounds were dimmer than the test-object visual acuity progressively increased with increasing size of surrounds, and (3) When the surrounds and test-objects were of equal brightness, increasing the size of the surrounds had no consistent effect on acuity. He concludes that the explanation of none of these results can be made on the basis of neural interaction in the retina because of the spatial limits of such effects. The decreasing acuity occurring when the surrounds are brighter than the test-objects was explained on the basis of scattered light, but in interpretating the improving acuity found when the surrounds are dimmer than the test objects recourse must be made to an hypothesis which involves interaction on the physiological level.

Dietrich (10) compared the efficiency of the right half with the left half of each retina and the two right halves of the retina with the two left halves in brightness discrimination by the method of average error and a special photometer. He found the nasal half of each retina was consistently as efficient as, or more so than the other half of the retina. When both eyes were used there appeared to be no tendency for the left halves or the right halves to be more efficient. The right halves or the left halves of the retina together are no more efficient than the right or left half of either retina singly.

Berry (4) investigated visual acuity of vernier, real depth and stereoscopic tasks under similar conditions. The test ob-

jects, two black, cylindrical rods one above the other in the median vertical plane, were viewed through apertures such that contours other than those of the rods were minimized. The subjects under the vernier condition were required to judge whether the bottom rod was to the right or left of the upper one; in the second condition (real depth) the response was back or front. The third condition (stereoscopic depth), in which two sets of vernier displacement was presented to one eye and the opposite to the other, also required a back or front judgment. The method of constant stimuli was used. Each rod subtended 107" in width and 1 27' 7" in height of visual angle and were presented over a range of 3.6" to 891" of visual arc. He concluded that for vertical separations of more than 135" between the test objects vernier and real or stereoscopic depth acuity have a simple relation, and that depth acuity is slightly less than twice as good as vernier. For the smaller vertical separations the relation is more complex, and vernier acuity is superior to both types of depth acuity. Real depth acuity and stereoscopic acuity obtained by presenting ecual and opposite vernier displacements to each eye by means of right angle prisms are qualitatively the same.

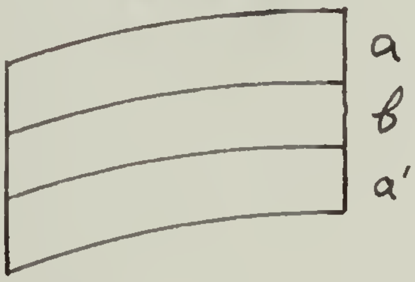
Fry (16) investigated the relation of the configuration of a brightness contrast border to its visibility using the following conditions: (1) long straight borders, (2) circular borders, (3) segmented borders, and (4) wavy borders. The subject fixated an image projected inside four dots on an opaque glass in a lantern slide projector. He found that the width of a rectangle

does not affect the threshold until the width is reduced to a size comparable to the diameter of a blur circle of a point source. The effect is a reduction in contrast (at fovea only). By using disks with wavy borders he demonstrated that the higher the curvature the higher becomes the threshold.

If the pitch of a right angle saw-tooth border or a wavy border is fine enough, the border appears as a straight edge at the threshold level. This indicated to Fry that the contrast border mechanisms of the eye and brain are better adapted for a long straight border than for a saw-tooth or wavy border.

In another experiment, Fry (14) investigated the effect of a second flash of light on the retina on activity aroused by a prior flash of light. He used three arcs each one quarter of an inch wide and one and one-fourth inches long which were adjacent to each other and which could be illuminated independently.

Figure 3.



He showed that the activity aroused by a flash of light may be depressed by applying a second flash immediately afterwards to adjacent areas of the retina. His findings, in general, were: (1) The effect of varying the interval between the two flashes was found to have an increasingly depressive effect as intensity was increased up to 150σ. Beyond 150σ, b appears separate in time from a and a' and he assumed that the depressive affect must

begin to decrease and gradually disappear, (2) When intensity and duration of the flashes was varied it was found that a decrease in duration corresponded to a decrease in intensity, (3) Varying the distance apart of the stimulated areas shows that the depressive effect gradually dies out as the distance increases, and (4) Varying the wave length composition of the light had no affect.

Luckiesh and Moss (31) think a cortical integrational process is responsible for the perception of liminal visual stimuli. Since details of objects are seldom, if ever, recognized as a result of the stimulation of a single retinal receptor, they believe the visual sensory process involves some kind of interaction of various individual neural stimuli. For convenience they assume that the cerebral mechanism of this integrational process is the occipital cortex. The purpose of their study was to present qualitative data pertaining to the characteristics or efficiency of this cortical integrational process as the number of retinal elements involved in seeing a colorless object of a simple geometrical pattern is varied with corresponding changes in the intensity of stimulation by luminous energy.

The test-objects consisted of two parallel black bars upon a white background separated by the width of the bars. The contrast between the bars and the background could be readily changed. The test-object was rotated at a speed above that at which the elements of the pattern are discernable and the time allowed for recognizing the object was controlled by stopping the rotation for brief and accurately measurable intervals. The

rotation of the test-object was to provide a confusion pattern which preceeded and followed the brief presentation of the stationary critical stimulus. The subjects were required to report the position of the bars of the test-object as they appeared during the brief presentation in the stationary phase, involving a visual task of resolution of the details by foveal vision. The conditions of threshold vision were approached by successively reducing the contrast between the test-object and the background.

The background, for convenience, was considered indefinite in extent and the energy of the stimulus as expressed in terms of the energy per unit area subtracted from the visual field by the darker elements of the test-object. The energy in this case they termed as negative, representing the amount subtracted when a unit area of the test-object elements replaces an equal area of the white field. They say a conspicuous characteristic of the negative energy curve for a brightness level of 204 Lamberts is that the energy is a minimum when the size of the test-object subtends a angle of approximately 1.5' of visual angle. They found an increase in negative energy required for the visibility of objects less than 1.5' and say that is due largely to the blurring of the retinal image as a result of diffraction and chromatic and spherical abberation. They conclude, in addition, that the small number of cones included in the image of a small object and their irregular spacing may seriously distort the pattern of the test-object. These factors become insignificant in the case of much larger objects.

In the experimental procedure, the area and the intensity

of the stimuli were varied over wide ranges in such a manner that the test-object was always at threshold. Thus, it was possible to vary both the number of functional retinal elements and their relation to stimulus intensity without altering the state of retinal adaptation. They feel this assumption of the retinal adaptation appears to be justifiable notwithstanding the variations of brightness in the test-object. At one extreme of size the bars of the test-object are small and black in comparison with the indefinitely large area of the surround. At the other extreme of size, the contrast is low, that is, the brightness difference between the test-object and background is unimportant and eventually indistinguishable. A comparison of the time required for signigicant changes to occur in retinal adaptation and the duration of the fixational pauses provides additional proof of the constancy of the retinal adaptation for the various photometric characteristics of the test-object.

The conclusions they draw about energy is that although the difference is not the same for all sizes of test-objects, it is nearly so in view of the wide range in number of retinal elements involved in the images of the different objects. Actually the energy difference increases less than three fold for a ten fold increase in the width of the elements of the test-object, or for a one hundred fold increase in area. Such a variation indicates to them; (1) that the integrational process for objects of a simple pattern is a highly efficient one, and (2) that the efficiency of the process decreases somewhat with an increase in the size of the retinal image of the test-object. In general, it

may be assumed that the integrational process, as the area of the retinal image is increased, is less efficient at the higher brightness level.

Another factor effecting visual acuity and contour processes is the vascularity of the eye itself. It is known that thrombosis of the retinal artery, with resultant hemorrhages in the retina results in loss of vision. Josephson (26) in his study with subjects having normal eyes did not find it possible to materially alter vision except by the "make" and "break" (The restructuring of ions when the current is first applied and again as it is removed.) of the current applied to the cornea, due to the rich vascularity of the eye. However, he found it possible in many cases to check vision and create a sensation of "blackness" by pressing upon the carotid arteries. In cases in which the vision and the vascularity of the eye were materially altered by disease, gross changes in vision associated with parallel changes in the size of vessels of the eye-grounds have been demonstrated. They were induced by galvanization -- negative galvanic current causing dilation of the vessels with marked improvement in vision, and positive galvanic current causing constriction of the vessels with diminished vision. He found it possible to improve vision (abnormal cases) or to reduce it almost to the point of blindness, by means of galvanic stimulation. He felt that this offered proof of the qualitative dependence of the sensation of vision upon the vascularity of the eye. A number of cases were reported with rapidly failing vision, who by means of galvanic stimulation

were restored to a useful level of sight and maintained there for long periods of time by this therapy.

Since test-objects with contours have been used to test visual acuity we can assume that the mechanism for contour processes is essentially the same, as the operation used to investigate each process is one of examining the differential visual threshold, however, other factors influence the perception of contour. That field-forces also have an effect is well known and have to be taken into consideration in any discussion of contour processes.

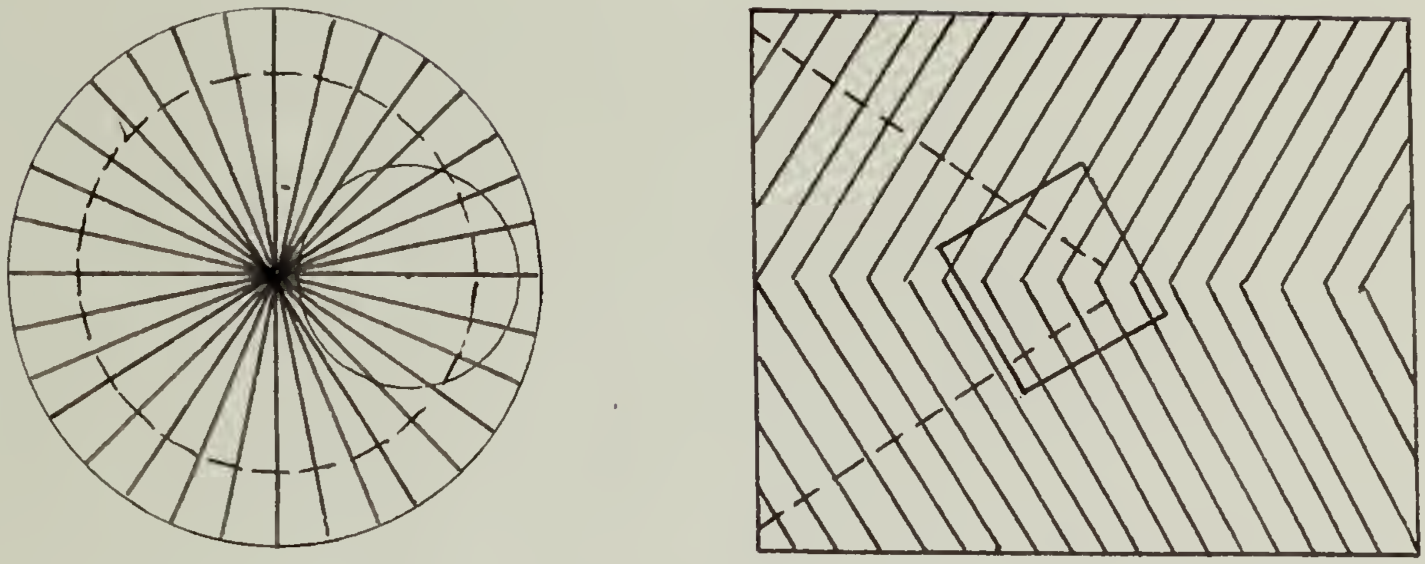
<u>The Relationship of Field-forces to Contour Processes</u>

Brown and Voth (7) claim that three limiting conditions for the field are possible: (a) when the combined restraining forces (Σ R) are greater than the combined cohesive forces (Σ C), (b) when the combined forces of the two kinds are equal, and (c) when the combined restraining forces are less than the combined cohesive field-forces. Thus, Brown and Voth say the first condition describes chaos, and such phenomena as autokinetic movement occur; the second describes stability; and in the third predictable movement occurs.

Orbison (35) reported an experiment designed to test this concept of field-forces. He says that; "In order to treat geometrical figures as vector-fields of cohesive field-forces, it is necessary to suppose certain relations between the field-forces and the properties of the object's stimulus pattern. If two objects are brought into the visual field, they will immediately be acted upon by cohesive and restraining field-forces whose magnitudes are functions of the physical properties of the object's stimulus pattern". (p.33) To illustrate this see fig. 2-A. The positions of cohesive equilibrium are dashed lines in the form of circles within the larger circle and having its center. If another circle, whose diameter is less than the radius of the larger circle, is introduced into this field so that it lies between the center and periphery it will appear to be bulged out in the direction of the periphery of the larger circle and squeezed in on the side of the center. However, when the center of the smaller circle coincides with the center of the larger circle,

no distortion of its circumference is apparent. As a further illustration see fig. 2-B.

Figure 2.



A B

Dashed lines to the sides of the angle show the positions of cohesive equilibrium. When the light intensity of the figure was decreased relative to the field, the subjects reported a greater distortion than when the figure and the field were of the same intensity.

Orbison contends that the results show that shape is determined by the total situation, and also, that where the total situation is ordered into a vector-field, it is possible to predict the shape which an object will have in a given total situation. Thus, he feels that the vector-field concept has been demonstrated to apply to stable configurations as well as to motion phenomena and that the results further confirm the hypothesis that the optic cortex functions as a vector-field (after Brown and Voth, 7). Orbison concludes that the empirical determinations of the relationship between the field-forces and the physical

variables used offers the possibility of a methodical treatment of the values of visual space.

Bartley (1) takes a similar position, concluding that contour has meant two things: "Edge, boundary or gradient, and also shape." Both, to him imply coordinate activity in the neural mechanism of a nature that is not predicted by a random conduction of nerve impulses through a system of synaptic connections viewed as an aggregate of independently characterized junctures. To him the only coordinating influence now recognized as containing adequate potentialities is a field.

If the contour is vague and broad as when one part of the field shades off gradually into the other, the shape of either is indefinite. For these reasons, Rubin (reported in Woodworth, 41) called contour formative of shape, as "shape producing".

Contour as Shape Producing

Woodworth (41) says; "When, as is so commonly the case, the field is divided by the contour into figure and ground, the contour shapes the figure only, the ground remaining shapeless. The tendency of contour is to exert its effect upon the enclosed figure, that is, upon what may be called the concave side of contour. It exerts its forming influence inward rather than outward". (p.635)

Koffka (28) says; "Briefly, then we propose as a tentative hypothesis that the contour bounds a figure rather than segregating itself as a line from the rest of the surfaces, because this is the better, the more stable organization". (p. 152)

Gibson (22) points out that form has many meanings; that shape, figure structure, pattern, order, arrangement, configuration, plan, outline, contours are similar terms without distinct meanings. A definition of what is perceived is necessary before the problem of how men and animals perceive form can be solved. He criticized past experiments on the ground that they used lines to represent forms when they are really only abstract concepts of forms. A criticism directed against lines to represent solid forms is that lines have two edges while the form have only one. He proposes that there are three general meanings of the term form (dealing only with those associated with or derived from physical objects): (1) the substantial shape of an object in three dimensions, (2) the projection of the object on a flat surface (by light from the object, or by drawing, or through the operation of geometrical construction) and (3) the abstract geometrical form composed of imaginary lines, planes, or families

or families of them".

Outline-form stands for something to the observer. To demonstrate this he presented ten subjects with simple outlines on cards, for example, an arrow, an oval, a trapezoid, etc. and says that; "At no time did any observer describe anything like black deposits or marks or traces on a white surface. All the terms and phrases used fell into three other classes: lines and angles, geometrical figures, and solid objects with physical surfaces". He concludes that the primary task of the psychologist "is to isolate the invariant properties in visual stimulation which are in psychophysical correspondence with constant phenomenal objects". According to his proposed definitions only solid forms and surface forms are realities. All other are representations which the perceiver takes to stand for realities. These necessitate a special theory of picture perception. "Geometrical forms, both plane and solid, are abstractions which cannot even be represented, strictly speaking, but can only be specified by symbols." If his definitions are accepted, the concept, form - in - general as held by the Gestalt theorists will vanish. To explain visual Gestalten, he says; "we have studied only the disembodied varieties of form -- i.e., ghost shapes -- which are ambiguous representations or equivocal symbols, and which consequently yield fluid, variable, or inconsistent percepts".

To arrive at an understanding of form he says; "At least three separate levels of theory will be required: first, a theory of how we perceive the surfaces of objects -- a theory

of slant-shape, or in older words, of shape - constancy; second, a theory of how we perceive representations, picture, and diagrams; and third, a theory of how we apprehend symbols. Development of these three theories will cause the category "form - perception", in psychology to evaporate as well as the efforts to show what happens in the brain when one perceives form - in - general.

It is now apparent that we must go beyond the retina to account for the sensation of vision. For example, an explanation of after-images makes such a demand.

<u>The Relationship of Figural After-Effects to Contour Processes</u>

When after-images are present, Bartley (1) says; "changes in latency with test-objects in the central field of vision are dependent not upon the effect of spatial summation but upon the fact that the edges or contours fall successively on sense-cells of changing character as area is increased, and that the edges become further and further separated". (p. 254) This indicates that the latency of the after-image depends upon the contour-building processes as a critical factor.

Gibson (19) reported an experiment in which the subjects wore prisms which displaced the visual world 15° to the right. Straight lines observed and felt simultaneously were reported as curved. On removal of the prisms, the visual world appeared curved in the opposite direction. The adaptation and the negative after-image are of the same magnitude, the inference being that for the perceptual process a decrease in curvature -- left, is equivalent to an increase in curvature to the right. Curvature adaptation and after-effect occurs for kinesthetic as well as for visual perception. The evidence seems to indicate that the negative after-effect of curvature is fairly closely limited to the specific area of the visual field occupied previously by the stimulus line. If a number of curved lines in a group are fixated, adaptation and after-effect can be correspondingly induced in a number of directions simultaneously in different parts of the visual field. Also the negative after-effect of curvature shows itself in the corresponding area of the other eye when only one has undergone stimulation: the effect is less, however, in

the unused than in the stimulated eye. Gibson draws the conclusion that, "the process involved in curvature adaptation; whatever its nature may be, must take place not in the sense organ but at or subsequent to an early stage of the central process". He continues that the fact of curvature adaptation and after-effect has some relation to the question of whether or not we can derive an explanation for form perception from the concept of local signs. He hypothesizes that every retinal point has a specific spatial value which differentiates it from all other points. The experience of form, a line, for example, would be due to the building up of a unique pattern of local signs in the course of experience, which in the end comes to mean a line. According to this hypothesis, a change in particular pattern of local signs corresponding to a particular line could be effected only by experience -- since experience is the only agent by which the pattern has been made to cohere. However, from the standpoint of this theory, nothing, under the conditions of the experiment, could have happened during the period which could be expected to alter the local signs. however, even though the local sign hypothesis is not in itself adequate to explain the facts presented; there is justification for assuming that perception of lines depends upon a configuration in a single homogeneous field of stresses in the cerebral cortex (Köhler and Wallach view, 29) the configuration being wholly determined by the tendency of the forces within the conducting system to reach an equilibrium, and therefore in part unpredictable from stimulus conditions which aroused it.

Edridge-Green (11) reports that if an eight inch square of black cardboard is placed on a wall of colored paper and fixated with one eye (held as immovable as possible) from a distance of six feet under normal daylight, portions of the colors of the wallpaper will appear to detach themselves from the wallpaper and move with a slow spiral motion into the black area until the whole black area has completely disappeared and the surface being covered with a mixture of colors similar to those on the wallpaper. One can even make a color disappear. For example, place a piece of red paper 1½" square on a piece of yellow-green cardboard and the yellow-green surface will invade the red until only the yellow-green surface is seen. He said if the reader fails to observe this phenomena, to reduce the light in the room and it should occur as it has for everyone he has had try it. However, the present writer tried the effect of a black circle of very high contrast to a tan wallpaper and had the circle disappear except for a portion of the border that appeared to have a greatly enhanced brightness, like viewing an eclipse of the sun. He found that when the eye was fixated a diameter of the circle away that a very brilliant pale yellow after-image, the same size as the circle, occurred. This was so intense that details in the pattern of the wallpaper could be seen which were not visible on the wallpaper outside this area.

Bartley (2) says the mechanism which underlies brightness enhancement is the same one that underlies cortical "driving". Driving is a form of effect of visual stimulation upon the cortical alpha rhythm, a component of the well-known electroenceph-

alogram (EEG). Peripheral stimulation will evoke an observable change in the electrical record obtained from the cortex (termed the specific response). This response has two pronounced components, the first consists of one or more alpha waves attributable to the elements responsible for the alpha rhythm. Thus one component of this specific response consists of one or more alpha waves, in a continuous cortical record which up to that time was nearly devoid of such waves. Where alpha waves are already present, this aspect of the response may consist in an alpha wave out of phase with those present, or a shift in the time of onset of the succeeding train of alpha waves or it may combine with the alpha activity already present, resulting in a reduction in amplitude or a complexifying of the record. Where peripheral stimulation succeeds in establishing its own train of alpha waves, it is said to 'drive' the cortex. However, this occurs only under limited conditions. These include the factors governing the activity-rest cycle of the elements in the circuits which produce the alpha waves. The period of this alpha cycle was found to be the measure of the frequency at which any single parallel circuit from the periphery to the center could be activated. Rapidly repeated stimuli to be effective, must reorganize cortical activity. This involves the alternation of response principle. Pulses delivered at rates higher than the alpha rhythm succeed in producing the small responses. Other circuits must be available if any response is to occur when successive stimuli follow each other too closely. Where trains of such stimuli succeed in driving the cortex, successive pulses must activate alternate circuits in

turn. Since there is a limit in the number of circuits in the pathway, individual pulses will be able to activate only a fraction of the total, rather than the total, as would be the case when the timing is delayed long enough to allow all units to recover between each stimulation. These results were worked out by neurophysiological techniques, for light pulses to the retina as well as electrical stimulation to the stub of the optic nerve in experimental animals. It was, Bartley said, "no surprise that perceptual results as manifested in brightness enhancement, tallied in principle with what was found in neurological experiments, although a number of comparative aspects of the matter have yet to be investigated, such as the conditions which produce the various sizes of cortical response. As no driving occurs with very weak stimulation, it is expected that weak intermittent visual stimulation will fail to produce brightness enhancement".

Köhler and Wallach (29) postulate non-neural electrical field processes in the visual cortex. These processes "satiate" the medium in the immediate neighborhood of the cortical representation of a figure inspected over a prolonged period, thus modifying the medium for a subsequent test figure. They believe that some region of the central nervous system must be conceived of as a quasi-homogeneous volume of tissue through which electrical currents can flow. Their assumption is that a "standing" (potential) energy is available in such a volume of quasi-homogeneous tissues. The arrival of the pattern of impulses representing the figure serves to disrupt the balance and sets up a flow of direct current. This takes the shortest path, which lies about the contours of

the inspection figure, and in doing so gradually increases the resistance of the tissues through which it flows. This results in a gradient of satiation (increasing resistances) about the contour of the inspection figure, which persists even after the test figure is removed. The flow of current representing a subsequent test-figure will necessarily detour about heavily satiated regions of the medium, giving rise to size and displacement phenomena and, although not as clear, brightness and distance effects.

For an example of this displacement fixate Figure 3-A at x, 13" from the eye, for forty seconds. Now, when two small white squares (Figure 3-B) are substituted the left hand test square will appear smaller than the right hand one, and will also appear displaced away from the cross, its borders appearing paler and it may also seem farther away in three-dimensional space.

Figure 3.

A B

Osgood and Heyer (37) have offered a reinterpretation of figural after-effects in the light of Marshall and Talbot's theory of vision. It is known that corresponding retinal points for the two eyes project to the same cortical area. But the continuous movement of the eyes (physiological nystagmus) further enlarges the neural region excited by a fine line or contour. The nature

of the eye muscular system makes perfect fixation impossible, for between 10-100 times a second there are tremors falling within 2' of arc (4 cones wide), about 5 times per second fluctuation occur within 4' (8 cones), and about once per second there are movements as gross as 30' (60 cones). It is this movement of the ocular system that makes possible the resolution of fine contours and continuous vision at all in an adapting, fatigable system. Under normal conditions the retinal image is a shifting pattern of intensity gradients. This replaces the classical geometrical concept with a statistical one which is the Marshall and Talbot hypothesis, "that a projection of a fine line, or contour will be a Gaussian distribution of connections symetrical about its axis".

Marshall and Talbot (27) state that it is known that a fine "hair", 1/60 of a cone in width can be seen, if it is 150 cones long, projected on a bright, uniform background. The reason for this they believe is that; "The neural image plays continuously over the projection area at every synaptic level, building gradients and peaks of activation at every edge and line. Multiplication of the path both increases the reciprocal overlap and refines the mosaic in proportion to the sharper gradients and peaks produced, as sand forms sharper peaks than bricks -- a fine line oscillates over 4 - 5 rows of receptors producing a center of gravity through the action of partially shifted overlapping connections".

Osgood and Heyer postulate that the on-off fibers carry the load. "The more often the intensity change representing the line or contour passes over and 'on-off' receptor (that is, the nearer

its locus of response to the imitial gradient) the more frequently will it deliver bursts of impulses." However, since these bursts of impulses are somewhat prolonged in time, fibers situated near such changing gradients will be in continuous, or nearly so, activity at rates determined by their location. Following the intensity-frequency principle, the magnitude of the reaction in 'on-off' receptors will vary directly with the amount and rate of intensity change. From this they conclude that the amount of excitation per unit time in such mechanisms will also vary directly with the sharpness of the intensity gradient which constitutes the line or contour. The implication is that, within certain lines dependent on irradiation locally the retina and diffusely within the globe of the eye, contour resolution, figural after-effects and related phenomena will vary with the sharpness of the intensity contrast between figure and ground.

Lashley, Chow and Semmes (30) in a recent evaluation of Köhler's "field theory" present facts from the anatomy of cortical folding, distribution of body fluids (low resistance to current), and pathology (large tumors and ablations may be present with apparently normal vision) which, in themselves, argue strongly against this theory. However, a direct experimental test was desired, so they placed gold strips on the visual cortex of several monkeys and embedded several gold pins in the striate cortex of some other monkeys on the assumption that, if an electrical field was present due to the stimulation from some simple visual pattern, then "insertion of a number of conductors through the cortex should produce permanent local regions of de-

polarization and establish dominant cortical currents which would distort, or prevent the formation of, continuous figure-currents by peripheral excitation". Prior to operation, the monkeys had been trained on four problems of visual discrimination. An immediate postoperative (within 24 hours) test for discrimination habit retention was given and no significant change in errors was found. In addition, eye movements, orientation, distance perception, extent of the visual field and object recognition showed no evidence of being any different from normal animals.

They admit possible defects in the experiment in that "the metallic conductors in contact with the tissue would become polarized, with resultant decrease in conductivity". The pia, the tough, dense membrane over the cortex, may block conduction to the metallic strips, however, field theory assumes that the currents can be picked up from the scalp and therefore readily traverse both the pia and skull. They conclude that the obsence of demonstrable visual disturbances is evidence against the theory.

There is also evidence (23, 8) that the learning process alters the perception of contours.

The Effect of Learning on Contour Processes

Hebb (23) says that; "The congenitally blind patient after operation at first sees any figure as an amorphous mass, but may be able with effort to count its corner; the perception is then alternately of the whole and of its parts. As the figure becomes a distinctive whole, there is still the same fluctuation of the figure-ground relationship -- attention directed now to the whole, now to its parts". (p. 99) He also reports Riesen's (1947) observations that chimpanzees reared in darkness were unable to discriminate the white-clad attendant from the rest of the environment even after 40-50 hours visual experience and strong motivation due to hunger and the desire to cling to the attendant. In further tests, a dozen trials with a strong electric shock failed to create any avoidance whatever in a large, distinctive stimulus object although normal animals (of the same age) learned a violent avoidance response after one trial with the painful object.

Bruce and Low (8) report a study on testing central acuity which has significance for perception as a learned response. They tested 113 naval pre-flight cadets and 30 medical students. Both groups were retested after eight weeks during which the cadets had extensive practice on the identification and recognition of airplanes and surface craft over both brief and long exposures. At the retest the cadets demonstrated a significant increase in their ability to perceive the test-object (landolt broken circles) which the medical students did not show. Next, 116 cadets were tested for peripheral visual acuity and retested after a similar

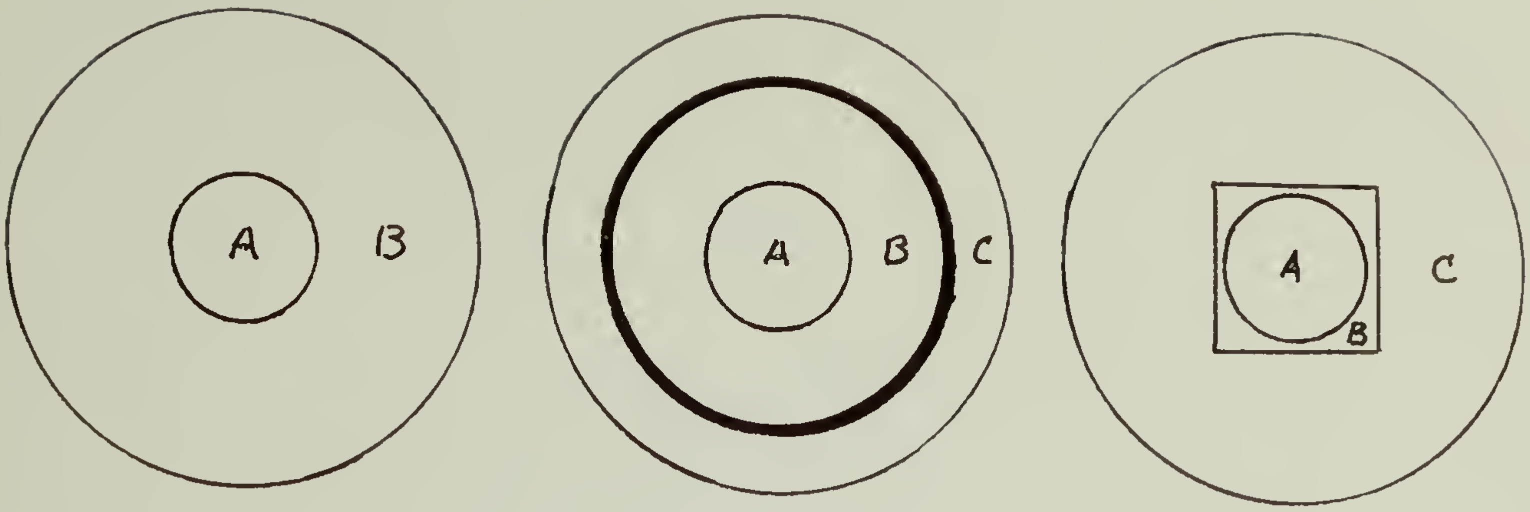
training period. In this case no significant increase in ability was found. The coefficients of correlation for various positions on the periphery of the retina tested revealed no indication that any one position could predict the test score of the peripheral test. They conclude that the development of visual acuity is an example of a perceptual motor skill, amenable to the learning process rooted in the effector processes basic to an organism in the process of adjusting to the environment.

It is now apparent that the perception of contours are effected by many factors, with this in mind we can view the contour experiments.

The Contour Experiments

It is known that the apparent size of an object considerably decreases when it is observed through a pin-hole, and the apparent distance between the object and the observer becomes correspondingly greater. Maier (34) in attempting to determine the factors involved in the illusion studied brightness of the object, illumination of the room, knowledge of the room, the size of the pin-hole, the size of the object, and the dispersion of light. A variable primary light was matched by a comparison light while viewed through a series of pin-holes. The results showed that the smaller the pin-hole the greater was the illusion. Maier concluded that the decrease in brightness and the elimination of the environment through the pin-hole are small factors in the result; but that the "illusion" is largely due to a reduced retinal image on account of a combination of near accomodation with the pin-hole between the object's visual angle. However, the above effect is limited to the fovea and where the image falls on a larger less homogeneous portion of the retina, interaction at this level does not appear adequate to account for contours. For example, Blackowski (1, 1913) used a small black disk, A, on a larger white annulus, B, and showed that the differential brightness threshold between the disk, A, and the Annulus, B, decreases as the width of the annulus, B, increases. (See figure 4-A.) This increase in area, he supposed, is responsible through a summation process. But contrary to this idea, Bartley (1) says it is the outer border of the annulus which affects the threshold, through its influence on the forma-

Figure 4.



A B C

tion of the border between the test-object and the annulus which must emerge before there is a perceived brightness difference between the two surfaces under comparison. As a check on the influence of area, Fry and Bartley (15) placed a black ring on Blackowski's figure. (Figure 4-B) The width of the black band and the outside diameter of C (annulus) were kept constant so that the total area (B and C) remained constant and the only factor varied was the distance of the black ring from A. They found a decrease in the threshold also and offered the explanation that the border at the outer edge of B interferes with the establishing of the border at the edge of A, and that the amount of interference decreases as the border at the edge of B gets more and more remote from the edge of A. This, they feel, demonstrates a fundamental property of a border, that of preventing activity from spreading across the retina. This action of the border process on the threshold disappears after the borders have been separated by about 4° of visual angle.

Dittmer (1) demonstrated this border phenomena in another experiment. He used a square surround around the test-object (small disk) and a larger annulus around the square. (Figure 4-C) He found that when the annulus differs in brightness from the square the resulting border interferes with the formation of a border around the test-object. It is the gradient between the two surrounds that causes the interference and it does not matter which surround is brighter or if the test field itself is. This effect has been further demonstrated with additional figures by Fry and Bartley (1, pp. 232-234.)

Wilcox, in Bartley (1), tested visual acuity with two parallel bars on which intensity was varied. He unexpectedly found that as the intensity was raised the bars expanded, contracted, and then expanded again. From this he assumed that variations in subjective width are the basis for visual acuity. Hence the discrepancy between the physical and apparent widths then furnish a measure of the shift in apparent contour. Irradiation has been postulated as an explanation but Bartley proposes that if irradiation were absent the bars would have to be separated a certain distance before they would be seen as separate. If the bars so separated are subjectively widened (irradiation) they will not actually appear separate.

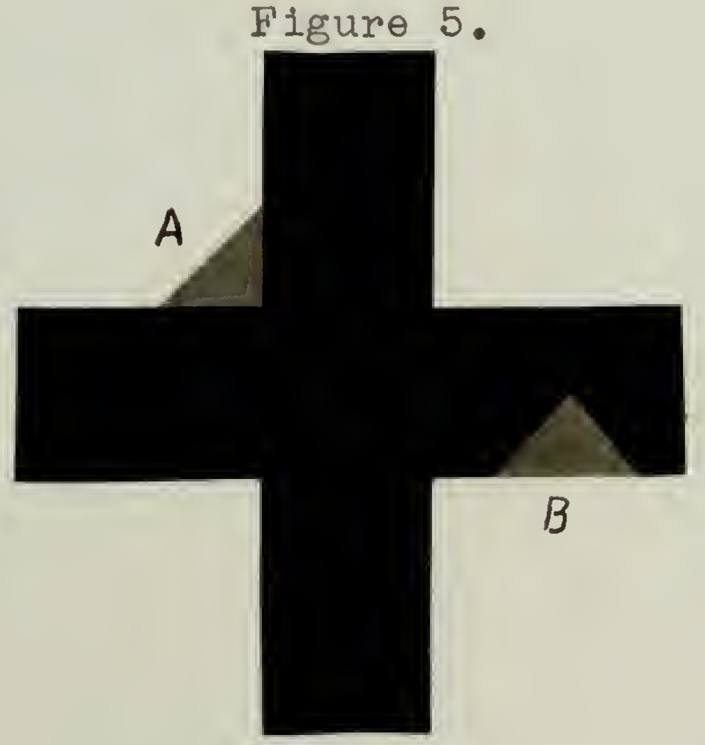
Fry and Cobb, in Bartley (1), experimented with bars of various widths and found that broad and narrow bars do not act alike: visual acuity first rapidly rises, but for the narrow bars falls again very slowly. For wide bars, it continues to ascend slowly after the first rapid rise. To account for this they use the Fry

and Bartley principle that a threshold border is demonstrably interfered with by the existence of another border in the vicinity. Thus bar width itself becomes a critical factor in determining the minimum perceptable interspace between them.

Binocular effects are apparent in that border contrast alters the brilliance of an object seen binocularly. For example, if two squares are equated for brightness, then if intensity is held constant for one eye and varied for the other from 0 to 1 candle per square foot (c/ft^2), the brightness of the variable intensity first decreases to a certain point and then increases again and finally reaches a brilliance much greater than the original. Bartley says this is due to the fact that summation is not the only process involved and concludes that; "Fechner's paradox then is not a question of the presence or absence of summation but rather a demonstration of one of the roles played by contour processes".

Fry and Robertson (16) in a discussion of retinal interaction reported Benary's finding that if two gray triangles,(Fig.5)

Figure 5.



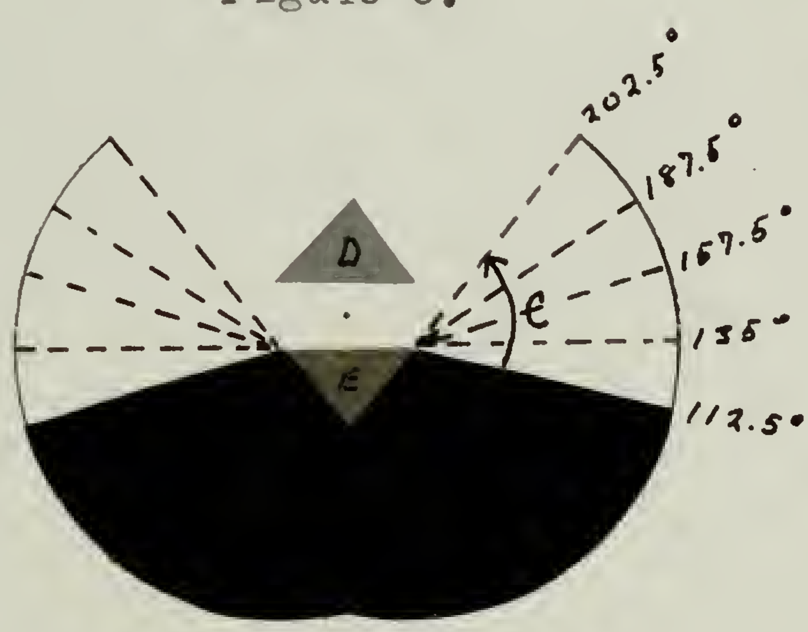
which are photometrically and geometrically equal, are placed on the figure of a black cross on a white surround composed of equal cross-bars so that two sides of one triangle fit into one of the intersections of the cross arms and the base of the other triangle (B) rests on the lower side of the cross arm opposite to the first triangle (A), triangle B will appear more brilliant than A. The parts of the triangle bounded by black and white are identical in both cases, but white is more predominant in the region of B than A, and, according to the current theories of simultaneous contrast, the latter should be more brilliant. Ordinarily the cross shaped black area including triangle B is seen as figure and the surrounding white area, including triangle A, is seen as ground. Benary asserted that the perceptual inclusion of triangle B as part of the figure helps to account for the difference in brilliance between the two triangles. He definitely rejected the possibility that differences in the stimulus conditions of the two triangles might affect physiological processes at a peripheral level in such a way as to produce the effects actually obtained. Mikesell and Bentley (16) considered the possibility whether "mutual excitatory influences of neighboring retinal areas" could account for the facts, but they were unable to determine the crucial stimulus factors affecting interaction.

There is one difference in the stimulus conditions of the two triangles not dealt with by the previous authors, which might affect interaction in a special way. Each of the triangles is joined by a black and white field. The two legs face the black field and the hypotenuse the white field, but the lines dividing

the white field from the black are constructed with the legs of triangle A and the hypotenuse of B. Fry and Robertson (16) felt that this factor affects brilliance and that this effect is ample to account for Benary's phenomena so they constructed the following experiment.

A series of patterns was designed in which the angle (C), formed when a radius is rotated from the opposite ends of the inverted triangle E, varied from 112.5° - 202.5°. The legs of the right triangles (D and E) were 3/8", the gap between the two triangles (then bases facing each other) was 1/4", and the radius of the black sectors 1" long. (See figure 6.) The distance from

Figure 6.



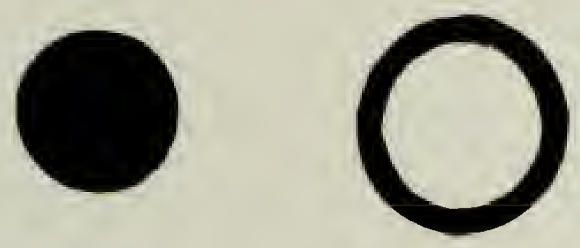
the eye was 12". A point was fixated midway between the two triangles. The brightness of the field was set at 1.68 c/ft and that of the triangle E at 0.79 c/ft. That of triangel D was gradually adjusted until the two triangles were seen to be equal in brilliance. The brightness of D is a relative measure of the brilliance of E. The fact that the triangle E is seen as more brilliant when angle C is 135° than when 180° accords with Benary's

findings that triangle B is seen more brilliant than triangle A. Their results did not furnish clear evidence that the figure-ground relationship as alleged by previous investigators affected hue and brilliance. They conclude that the effects presented as evidence of this relationship may be attributed in some cases to motor adjustment of the eyes and in other cases to factors which were neglected in the stimulus conditions. They continue that; "In certain cases of color assimilation and filling in of after-images we have found subjective changes in color which were not correlated with changes in the stimulus conditions because these were kept constant, but they were correlated with changes in perceptual configuration. These changes in color, however, have not been proved to result from the changes in configuration."

Helson and Fehrer, in Bartley (1), in a study where objects presented tachistoscopically were first seen as dim patches of light before any definite form was recognized, found that as the interval of exposure was lengthened definite form emerged showing that contour is also a function of time.

Werner (39) in his classical studies on contour, presented tachistoscopically a black disk 15 mm in diameter followed by a ring 20 mm in diameter whose inner border was the same as for the disk. (See Figure 7.) He found that if there is a sufficiently

Figure 7.



rapid rate of succession, (120σ - 240σ pause) the black disk will disappear. When the sequence is reversed only the disk was seen. The explanation offered is that when the disk is presented first but is followed very soon by the ring, the border of the disk has not had time to form and the ring develops as a ring without the disk ever having been seen. If the inner border of the ring has had time to develop before the presentation of the disk, this event, by changing the illumination within the ring, inhibits the condition for its continuance, especially under the depressive influence of the outer contour of the ring. If figure and ground (black and white) are reversed the basic phenomena does not change. In the optimum time limit only the white ring can be seen, the white disk having completely disappeared. Angular and irregular figures yield the same results although latency varies slightly. If the black disk is succeeded by a half ring instead of the full ring, the following is usually observed. In the optimum interval that part of the disk which fits into the half ring will be absorbed. On the other hand, the semi-disk which has not fitted into the ring will appear increasingly dark from the inside out towards its unframed edge.

In another study (40) where the disk was presented strobo-stereoscopically to one eye and the ring to the other the disk disappears. If the order of succession is reversed so that the ring appears as the first member of the pair, the disk does not disappear within the limits of time in the experiments mentioned above. Reversal of figure and ground had no effect here either. He reported the disappearance of the disk when succeeded by the

ring can be observed whether both figures are seen binocularly, or, one figure is presented to the right and the other to the left eye. This suggests that higher centers are involved for the observer's attitude played an important role -- enhancing or reducing the effect intentionally. The explanation offered is that; (1) Every visual object, even when it is presented simultaneously in all its parts, it built up by a psychophysical process which, as a process, has a certain temporal duration, and (2) Such a construction comes into existance normally because of a psychophysical difference in relation to the surrounding field; the figure is conceived from the point of the strongest psychophysical difference -- contour. Because of this, when some optical object is disturbed in such a way that as a result of certain conditioning factors, contour cannot be formed, then this optical stimulus becomes psychophysically ineffective. Thus the process of forming the contour of a disk will be used in building up the ring. A separate and specific perception of the contour of the disk is absent. Since this factor of greatest tension (contour) is lacking, the total picture of the black disk is also lacking. However, when the ring is presented first, it is already in the first stage of development which permits the contour of the disk to be established as a separate figuration and the whole disk will be seen.

Beck (3) theorizing in a different manner stated that; "For the case of vision, deviations from three assumptions predict that a subject can manipulate area-brightness sequences number wise". The assumptions are: (1) any change in stimulation that

is just psychologically effective must produce a constant change in muscular activity, (2) in the sequence of transformations (optical, photochemical, neural, etc.) from stimulus to response no transformation alters the preceeding transformations, (3) unknown transformations operate collectively linearly. He says that with these assumptions psychologists can contribute to the mathematical theory for vision in that the threshold response is treated as a set of product functions operating on the essential variables of the threshold visual stimulus, Just how such phenomena as after-images would be treated was not explained.

Booth (5) would incorporate the principle of relativity into visual theory. He said that vision is dependent on a combination of time, velocity and distance; omit one and vision disappears. We estimate distance by the length of time required to move, at a certain velocity, from one of its extremes to the other. Booth(5) uses the example that if three persons, one myopic, one hyperopic, and one normal, all look at one thing, the three retinal images are different in size. Since the judgment of distance depends upon the size of the retinal image, the estimates of these three observers must vary. He concludes that agreement is learned by experience. The value of these two theories needs to be established by emperical means.

Fry (13) commenting on Meyer's (1922) suggestion that border contrast compensates for the ill defined border of the retinal image and thus "subserves the important biological function of sharply outlining seen object", says that to prove this hypothesis it is necessary to demonstrate that a graded stimulus can

yield a visual image with a distinct border because border-contrast, as ordinarily conceived, is held to be contrast at the border and does not involve the actual creation of a border where none exists in the physical stimulus.

A glance at figure E' in appendix II will show that if the disk is rotating above flicker, the distribution of physical intensity along the diameter would be graded from the widest part of the figure out to the tips. This should appear as a blurred white patch in the center of the disk with a zone of fusion out to the periphery. Instead there appears a sharply bounded, uniform, white disk, surrounded by a halo similar to the halo of an after-image. This indicates that border contrast may involve creating border where no border exists in the physical stimulus.

Fry says that according to Hering; "The physiological processes underlying border-contrast are retinal processes involving the interaction of retinal areas," i.e., "a process of assimilation set up by a stimulus in one part of the retina bringing about a process of dissimilation of the same apparatus in neighboring parts of the same retina". Then he states the Rollet and MacDougall view that the interaction takes place between the retino-cerebral elements, that contrast is due "to the inhibitory action of a given cortical visual process upon the visual processes in neighboring regions". They supposed that such inhibition is due to drainage of neural energy from the less active into the more active regions. MacDougall supposed that the more intensely stimulated cerebro-retinal elements drain away to themselves (by their central connections) the energy from the less

intensely stimulated. Fry says that "both enhancement and inhibition involve perhaps the interaction of the retino-cerebral elements, but as to the nature of this interaction we have, it seems, no means of investigation". He concludes that border-contrast confirms Meyer's hypothesis that border-contrast may compensate for the ill defined border of the retinal image which is the result of the inevitable irradiation of light.

As long ago as 1865, Ernst Mach (32, 33) offered a mathematical explanation for the phenomena of contour along with experimental evidence which he felt verified his theoretical contentions. We were concerned with retesting this old concept which is being used in visual theorizing today (21, 41). Mach (32) said:

"It may seem surprising that in addition to intensity, the second differential quotient of intensity, but not the first di/dx, di/dy, seems to influence the sensations of brightness. We scarcely notice a regular and continuous rise in the intensity of illumination of a surface, -- for instance, in the direction x, -- and special devices are necessary to convince one that there is a rise. Call the horizontal direction x, and the distance as regards depth of a point on the illuminated surface r; the di/dx and d^2r/dx^2 are parallel. This expression, which of course is only to be understood symbolically, means that we have the representation of a cylindrical surface with vertical generatrix and plane horizontal directrix $r=f(x)$, of which the second differential quotients d^2r/dx^2 (curvature) are parallel to the first -- the rise in intensity of illumination." (pp.219-220.)

When we let $y = f(x)$ be the equation of a plane curve we can read at a glance the course of the values of dy/dx on the curve, for they are determined by its slope (m); and the eyes give us, likewise, qualitative information concerning the values of d^2y/dx^2 for they are characterized by the curvature. When the second derivative is zero and the acceleration of a point along the curve is positive on one side of this zero point and negative on the other, a point of inflection is present, the point where the curve crosses its tangent. Mach (32) pointed out that the question naturally arises why we cannot arrive at an immediate conclusion concerning the values d^3y/dx^3, d^4y/dx^4 etc., and said that the answer is that what we see are not the differential coefficients, which are an intellectual affair, but, only the direction of the curve elements, and the declination of the direction of one curve elements from that of another. To demonstrate the effect of the second derivative, Mach used a rectangular figure, similar to figure 8. The brightness gradient is from A to B. When several

Figure 8.

of these rectangles were mounted in succession on a cylinder and rotated, a bright line was formed at α and a dark line at β. The points which correspond to the indentations α are not physically brighter than the neighboring points. Mach's explanation

is that their light intensity exceeds the mean light intensity of the immediately adjacent points while on the other hand, the light intensity at β falls short of the mean intensity of the adjacent parts. He claims to have demonstrated this with other figures; the phenomena being known as the "Mach rings". Woodworth (41) in discussing Mach's point of view says a part of the field is prominent in proportion as its brightness differs from the mean brightness of the immediately surrounding field. A contour is thus a relatively abrupt change of gradient in either brightness or color and belongs in the same class as marginal contrast. He holds that contrast enhances contour and makes the outlines of objects more distinct than they are in the retinal image itself. Woodworth maintains that not only peripheral factors like contrast but central factors as well, enhance and complete contour. This is illustrated by a circular band with a dot in the center. (See figure 9.) If these are cut in half

Figure 9.

vertically and separated by approximately the length of the radius of the band, the subject tends to see a line form across the ends of the bands and where the dot was cut in half. Woodworth says this is often called a "tied image" and is a central addition to the retinal image.

According to Gibson (21) the principle seems to be that a

visual margin or border is given in experience by either a step in the level of luminous intensity (a steep microgradient -- after Bartley) or by a step in the second differential of luminous intensity (a change in the rate of change). These two seem to be equivalent as types of ordinal stimulation. The retina responds to an abrupt change of change as readily as it responds to abrupt change. Abruptness seems to be the critical condition. Gibson says that perhaps the function of the retina has been misconceived in developing the theory that it responds to light rays and their directions. It seems to respond to gradients and their differentials instead. He continues that, "the retina is probably to be conceived as an organ of the body which is sensitive to grades of light, not points of light."

Fry (17) hypothesizes that much of brightness contrast borders depend upon interaction between retino-cortical pathways. It is assumed that at any level in one of the pathways from the retina to the brain, the frequency of impulses is the variable which is the counterpart of brightness in the introspective world and the counterpart of retinal illuminance in the physical world. One can edentify a given pathway as associated with a given region of the retina and speak of a distribution of frequencies in the retino-cortical pathways in the same sense as a distribution of illuminance on the retina. Two different types of mechanisms of interaction must be involved; (1) Inhibition -- which reduces the frequency of impulses transmitted through the retina both at the point in question and in adjacent regions, the effect waning as the distance increases., (2) Frequency-equalizing mechanism

which makes adjacent pathways respond at about the same frequency (but not necessary in synchronization) so as to wash out minor differences in brightness across the field of view. At brightness contrast borders, the mechanism either washes out the impression of the border entirely, or tends to make the fields on both sides of the border uniform up to the border. The first mechanism is assumed at a very low level (only receptor and bipolar cells). At a higher level the frequency equalization mechanism involving interaction at synapses imposes further modifications upon the impulse frequencies in the retino-cortical pathways. (This would be duplicated at each synapse at which interaction can occur.)

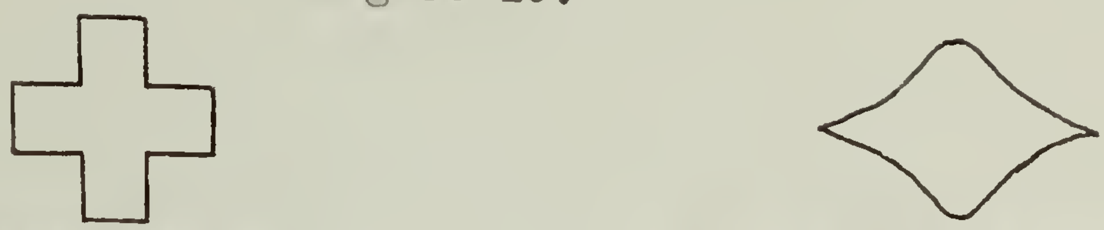
The evidence accumulated in recent years supports an electrical mechanism of inhibition, where the electrical potentials between the retina and the back surface of the eye generated by the response of the retina to light exert an inhibitory influence upon the response of the ganglion cells at the point of the retina in question and in adjacent regions also. However, the bipolar response which precedes may be the one primarily affected. Granit, in Fry (17), has recently shown that the frequency of the ganglion cell response recorded with a micro-electrode can be enhanced or inhibited by causing a galvanic current to flow through the eyeball.

Fry says that although the Mach rings are usually demonstrated with rotating disks, they can also be demonstrated with stationary test-objects.

When figure 10-A is placed in the aperture of a projection

lantern and projected upon an opal glass on one end of a box and viewed through an artificial pupil (2mm.) at the other end of the box, it is possible to produce a distribution of intensity at various points along the horizontal diameter of the retinal image of the test-object such as illustrated in figure 11.

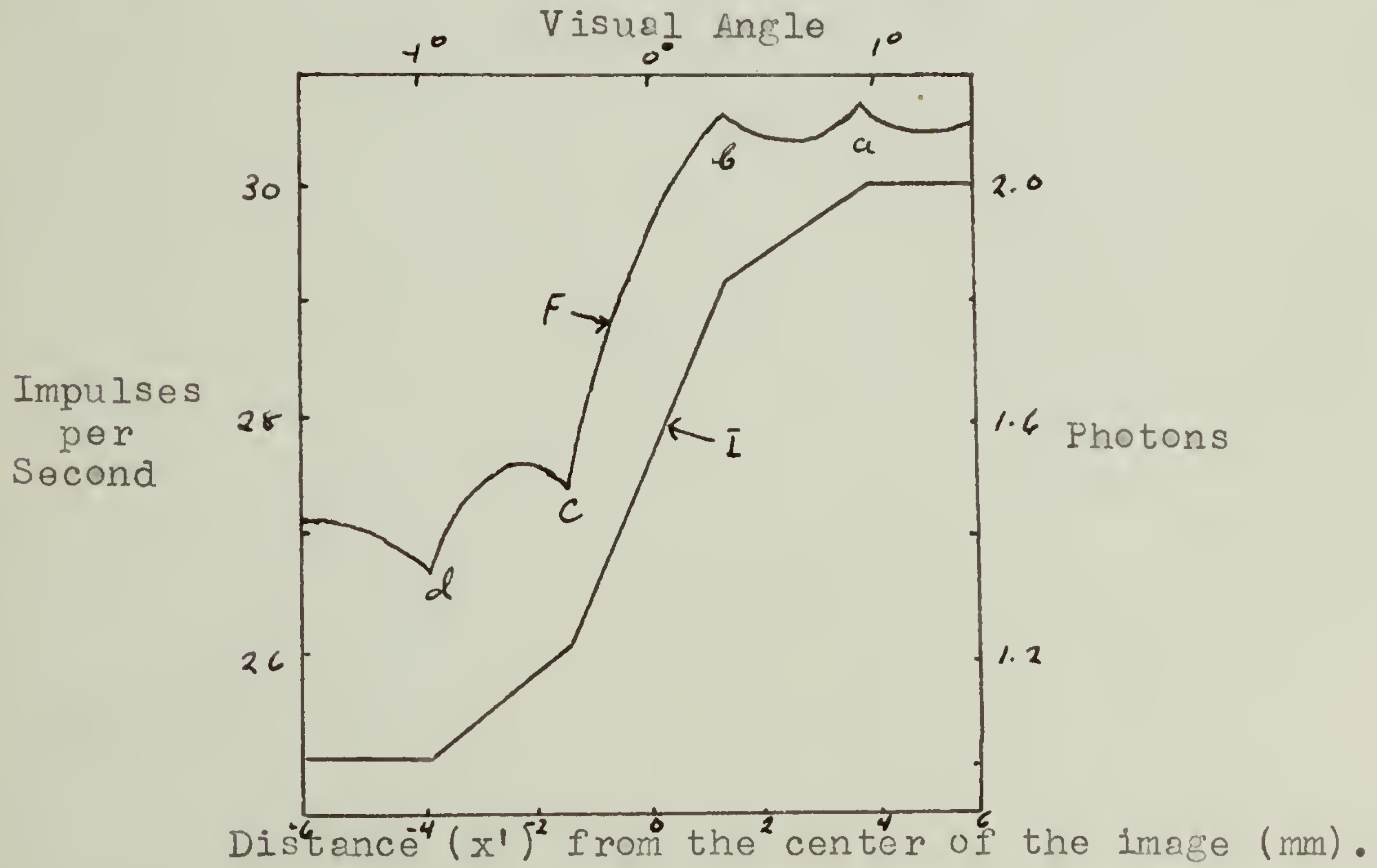
Figure 10.



A. Mach Bands B. Ogive Gradient

Fry says the striking thing about the appearance of this type of stimulus pattern is that bright Mach bands are seen at (a) and (b) and dark ones at (c) and (d).

Figure 11.

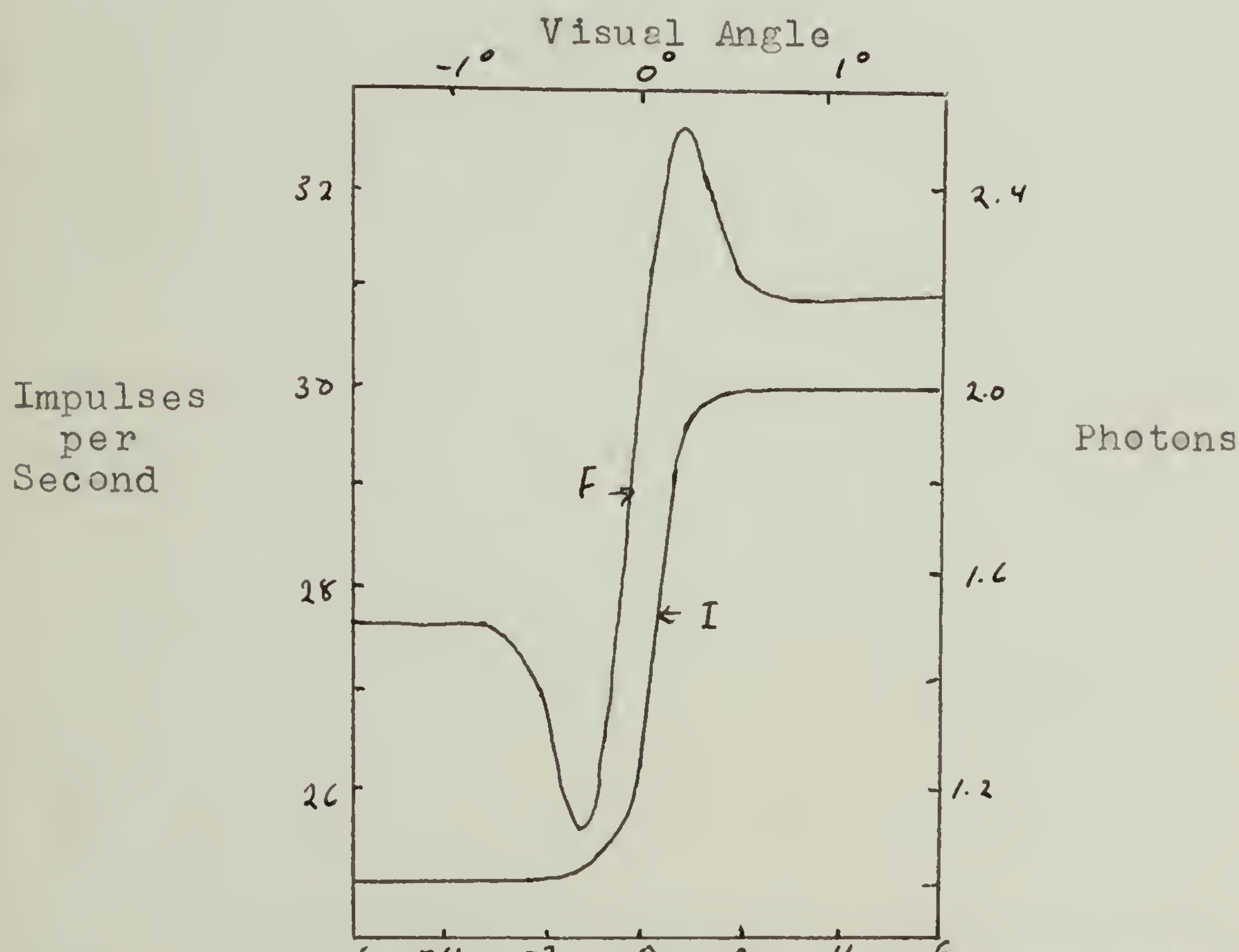


The bright and dark Mach bands can be accounted for by the peaks and depressions in the frequency distribution.

A further consequence of the hypothesis is that the inhibi-

tion mechanism in the retina accentuates the "contrast" at a brightness contrast border. Fry says that "no matter how sharp the transition across a brightness contrast border may be, the distribution of illuminance on the retina is graded because of the abberrations of the eye and other factors such as the rapid, fine oscillations of the eye which add to the blurredness. This condition of blurredness can be accentuated by starting out with a blurred border in the stimulus pattern presented to the eye. By substituting figure 10-B in place of figure 10-A, a shadow with a blurred edge can be produced which gives an ogive distribution of retinal illumination (I) as shown in figure 12.

Figure 12.



Distance (x') from the center of the image (mm).

If the degree of blurredness is small, the subject sees a sharp contrast border separating the two halves of the test-object, and each half appears to be uniformly bright up to the border.

Although the mechanism of inhibition sharpens the contrast, it is necessary in addition to postulate a frequency equalizing mechanism, which smoothes out the frequency differences on each side of the border, and which determines at what point the border will be located.

When the blurredness is increased, (by varying the amount of light with crossed polaroids in the path of the beam) the sharp border breaks down and the distribution is perceived as graded. At one stage the observer can see broad bright and dark bands corresponding to the peak (a) and the depression (b) in the frequency distribution.

In summary then, Fry concludes that stimulation at any given point of the retina sets up an electrical field in which the potential difference between the front and back of the retina gradually decreases as the distance from the point of stimulation increases. The potentials produced at any given point due to the stimulation of a number of surrounding points are additive. The potential at any given point reduces the frequency of impulses transmitted through the retina at that point, resulting in a modification of the distribution of frequencies in the retino-cortical pathways. The frequency-equalizing mechanism operates at a higher level in the retino-cortical pathways to equalize the frequencies in adjacent pathways except at contrast borders; at such borders the mechanism tends to smooth out the frequencies on the two sides of the border.

The impetus to the present problem was given by a recent lecture the writer heard, in which the professor pointed out that

if a figure similar to (A) in appendix I was rotated, the observer would see two bands of different gray rather than a gradient. The contour, which separated these two bands, occurred at the points of inflection on the curves bounding the figure, while this figure was in rotation. As no immediate explanation was found for this phenomena the writer decided to make an experimental test to see if this contour was limited to said points of inflection or was merely an artifact. We may now consider the experimental investigation.

The Experimental Investigation

The Problem

The purpose of this experiment is to see if the perception of contour varies in a systematic way in relation to the gradient generated by the stimulus. More specifically, to test the following hypotheses: (1) If the formation of contour is a function of a change in the rate of change (the second differential of luminous intensity) as Mach (33) contends, then a boundary should occur through the points of inflection on a symmetrical figure bounded by the requisite curves; (2) Reversal of figure and ground should have no effect on this boundary; (3) A boundary will not be generated along curves that do not possess a point of inflection. During the course of experimentation it became apparent that three experiments were required to adequately test the above assumptions. They are reported in the order performed.

Experiment I

Apparatus: A color mixer, vibrator tachometer, plastic ruler, one 200 Watt and two 100 Watt lamps, photometer, dark room, and the stimulus figures described and illustrated in appendix I. A dark room was used to maintain a constant luminous intensity. Due to the small size of the room the subject could sit only four feet from the mixer, however, a pre-test showed that the perception of the disk did not change a few feet either side of the distance used (four feet). The line of regard was approximately normal to the surface of the disk. The luminous intensity level of the room was raised to a level well above threshold for cones -- a 200 Watt overhead lamp was used. This cast

shadows on the disk so two side lamps (100 Watt each) were introduced, two feet in front and one foot to each side of the mixer to produce a shadow free surface. The stimulus disk was always presented in motion, either just below critical fusion frequency (c.f.f.) or at a high rate of rotation. The experimenter stood in front of the mixer while changing disks, preventing the subject from gaining a view of the figure which might bias the report of his perception of it. To further safeguard against biased results, the order of presentation for the eight figures was randomized, both for the order of figure presentation and rotation frequency (one half of the trials began at a low rate and increased to maximum speed, for the other half the order was reversed). This was accomplished by representing on a card each condition, 16 in all, for figure presentation and rotation frequency. These were shaken in a box and drawn until 80 trials were assigned. This provided 10 trials for each figure. The critical figures A and A' appeared 20 times throughout the series, thus, to sustain hypothesis 1, a contour must be seen at the points of inflection each time for 20 trials. The order of presentation is shown in table 1.

Subjects: Three young male adults (undergraduates of the University of Massachusetts) with "normal" vision. An inquiry was made as to whether they required glasses or not, to which they replied in the negative.

Procedure: The subject was seated and given the following instructions:

"You are to view the disk on the color mixer and describe

Table 1.

The order of presentation for the stimulus figures.

	1	2	3	4	5	6	7	8	9	10
1.	D'i*	A'i	Ai	Cd	Ad	C'd	Bd	Dd	Bi	A'd
2.	Dd	B'd	Ci	D'i	Cd	B'i	Ai	A'i	D'i	Ad
3.	Cd	Di	A'd	Bi	B'i	Bd	Dd	C'd	D'd	C'i
4.	Ci	B'd	Dd	Bd	C'd	B'd	Ad	C'i	A'i	D'i
5.	B'i	Ai	Bi	Cd	A'd	Ci	C'd	Di	Bi	Dd
6.	B'i	D'd	A'i	C'd	Ad	D'i	Bd	A'd	B'd	Cd
7.	C'i	Di	Ai	Ci	A'd	B'd	C'i	Bi	Ci	A'i
8.	Dd	D'd	Ai	D'd	Di	Ad	C'i	D'd	B'i	Bd

* The prime sign indicates the reversal of figure and ground, the figure being white in this case, with a black ground. The small (i) indicates increasing rate of rotation and the small (d) a decreasing rate of rotation.

what you see. Next, you are to report any changes that take place as I vary the speed of rotation. Fixate only on the disk and keep your body posture as constant as possible."

The disks were presented according to the order established in table 1. The subjects were given a short break after each 10 trials due to the intense summer heat plus the heat generated by 400 Watts of luminous energy confined to a small dark room.

Results: The percentage of the trials where a contour was reported is indicated in table 2. The mean distance from the center of the disk of reported contours is indicated in table 3.

Each subject reported a center circle of black or white; for A and A' respectively, whose diameter varied over a range of 3 9/16" to 3 11/16". This was generated by the four points that form the bases of the tips of the figure. Each point lies 1 12/16" from the center of the disk. They also reported that this circle appeared to expand or contract slightly as the rate of rotation was increased or decreased. The point of greatest brightness appeared at this boundary, with the central area being slightly less white or black as the case may be. Beyond this circle appeared another circle less well defined in nearly every case when the figure was black. However, only the first subject reported a second contour for (B). Subjects two and three reported indeterminate results in that a contour was reported for only a part of the ten trials. A second contour was reported in every case for C and D. When figure and ground were reversed, with the figure white, the results were indeterminate, with a steady gradient reported for every case with figures A', B', C', and D'. In-

Table 2.

The percentage of trials where a contour was reported excluding the center circle formed by the points at the base of the tips of the figure.

	A	A'	B	B'	C	C'	D	D'
Subject 1	100%	20%	100%	0%	100%	0%	100%	30%
Subject 2	100%	10%	80%	10%	100%	0%	100%	10%
Subject 3	100%	30%	70%	20%	100%	0%	100%	30%

Table 3.

The mean distance of reported contours from the center of the disk not including the center circle generated by the points forming the base of the figure.

	A	A'	B	B'	C	C'	D	D'
Subject 1	$1\frac{15}{16}$"	∞*	$1\frac{14}{16}$"	$\rightarrow$**	$1\frac{15}{16}$"	$\rightarrow$	$1\frac{14}{16}$"	∞
Subject 2	$1\frac{15}{16}$"	∞	∞	∞	$1\frac{15}{16}$"	$\rightarrow$	$1\frac{13}{16}$"	∞
Subject 3	2"	∞	∞	∞	2"	∞	$1\frac{13}{16}$"	∞

* The indeterminate sign indicates that a contour was reported for only a fraction of the trials, a gradient being reported for the remainder of the trials.

** The arrow indicates that a continuous gradient was reported for each trial..

creasing or decreasing the speed of r.p.m. had little affect on this contour. An attempt was made to measure the rotation rate with a tachometer but the friction drag was so great that the mixer was nearly stalled. However, when the reading was approximated before the mixer slowed it was evident that the rotation rate was not a critical factor above c.f.f., the subjects reporting the contour over a wide range of rotation frequencies.

The luminous intensity was measured with a photometer, both at the target and at the subject's eye. This was found to range from a constant 30 foot-candles at the subject's eye to an average of 180-foot-candles at the target for the black figures and 210 for the white figures.

Another result which was noted was the appearance of color when the black figure disks were rotating over a range slightly below and slightly above c.f.f. Each subject reported this as a bright bluish-green band which ran around the border of the center circle like a small flame radiating from this border.

Experiment II

Apparatus: The apparatus was the same as for Experiment I except that the tachometer was omitted and only one 100 watt lamp was used to supply luminous energy. The stimulus figures as illustrated in appendix II were used.

Subject: Two young adult males (undergraduates of the University of Massachusetts) with "normal" vision. The same inquiry as to whether the subjects required glasses or not was made as in Experiment I.

Procedure: The subjects were seated, one at a time, about four

feet from the color mixer. The same instructions as for Experiment I were used. Each figure was presented for 10 trials with an ascending and descending order for rotation rate. (This was to determine if the report for ten successive trials with a figure which possessed points of inflections would correspond to the results for each figure in the randomized order of Experiment I.)

The luminous intensity was varied by having the subject move one of the 100 Watt lamps in front of the disk until the disk was at its best definition for him. A short break was given as before with each series of 10 trials to reduce fatigue.

Results: The amount of luminous intensity did not appear to be a critical factor, for as long as some light reached the target the affects of the different disks could be observed. (This intensity level was below the level of the photometer used to measure it.)

Both subjects reported what appeared to be another contour in the gradient of gray out from the white circle in figure E'. This was reported to occur over a range of 1 5/16" - 1 12/16" from the center of the disk. When the figure (E) was black, this contour did not appear. When figure F was presented, both subjects reported a gray band formed 1/8" wide, 1 13/16 - 1 14/16" from the center. The first subject also reported a second contour for F' which was not reported by the second subject. Another result noted was that a contour was formed at the change of direction on figure G' but not on G where the figure is black. This occurred at a reported 2 9/16" from the center which coincides with the distance of the indentation from the center. Figures H and H' are reported as five bands of gray of varying brightness.

The reversal of figure and ground had no apparent effect, the bands being reported at the same distance for either case. The mean distances from the center of the disk of contours reported are indicated in table 4.

The lack of consistent results for figures possessing points of inflection in Experiments I and II made a third experiment necessary.

Experiment III

Apparatus: The same apparatus as for Experiment II was used except the stimulus figures shown in appendix III. These figures are unique with respect to all prior figures, in that the tips of each figure possess two points of inflection along each boundary. The reason for this is that if Mach rings are caused by changes in the second differential of luminous intensity then a contour should occur at two successively marked changes in the second differential.

Subject: One experienced observer (Dr. Feldman of the Psychology Department of the University of Massachusetts.) was used, who was familiar with observation of color mixers.

Procedure: The subject was seated at approximately four feet from the color mixer, as was the case with the subjects in the previous experiments. The initial line of regard was approximately normal to the surface of the disk. Figure I was set in motion on the mixer while screened from the subject's view. This was presented to the subject and he was instructed to report what he saw as were the subjects in the previous experiments. The rate of rotation was varied up and down several times, while the subject varied the luminous intensity by moving the lamp and changing his line of regard. Figure I

Table 4.

The mean distance from the center of boundaries generated by figures E, E', F, F', G, G', H and H'.

Subject 1.

	E	E'	F	F'	G	G'	H	H'
1st. contour	1 13/16"*	2"	1 12/16"*	1 13/16"*	1 12/16"*	1 12/16"*	1 10/16"*	1 10/16"*
2nd. "		2 6/16"	1 14/16"*	2 13/16"	1 14/16"	2 8/16"*	1 12/16"*	1 12/16"*
3rd. "							2 1/16"*	2 1/16"*
4th. "							2 5/16"*	2 5/16"*
5th. "							2 12/16"*	2 12/16"*

Subject 2.

	E	E'	F	F'	G	G'	H	H'
1st. contour	1 15/16"*	1 14/16"*	1 13/16"*	2"*	1 12/16"*	1 13/16"*	1 10/16"*	1 10/16"*
2nd. "		2 5/16"	1 15/16"*		2 2/16"	2 2/16"*	1 12/16"*	1 12/16"*
3rd. "							2 1/16"*	2 1/16"*
4th. "							2 5/16"*	2 5/16"*
5th. "							2 12/16"*	2 12/16"*

* Indicates a reading that was constant throughout the ten trials.

was removed, screened from the subject's view while not in motion, and figure J was set in motion on the mixer. The revolution of the disk and the luminous intensity was varied as before. This procedure was repeated for figures I' and J'.

Results: In no case, were contours other than the circle generated by the points which comprise the base of the figure, reported. The subject was then shown the stimulus figures and it was ascertained that he was not aware that two points of inflection were present along the boundary of the tips of the figures.

Discussion and Conclusions

When one inspects the curves bounding the figures in Appendix I, he will note that the acceleration of each is different. The acceleration of A and A' first decreases (tracing a point from the base of the figure to the tip) until it is momentarily at rest (at the point of inflection) and then increases out to the tip of the figure. The rate of change along the curves of B and B' is a constant because the function is linear and no change in acceleration is present. The acceleration for C and C' is increasingly negative and for D and D' it is increasingly positive. The significance of the results reported for this investigation is that the rate of acceleration along the curve had little effect on the contour reported. By referring to table 3, one will note that where a contour is reported, it is at nearly the same place for each figure. To occur at the points of inflection this contour would have to lie 2 9/16" from the center of the disk. Thus the results from experiment I for the figures possessing points of inflection embedded in a randomized order of presentation do not support hypothesis (1). If the formation of contour is a function of a change in the rate of change (the second differential of luminous intensity) as Mach (33) contends, then a contour should occur at the points of inflection on a symetrical figure bounded by the requisite curves. The results from experiment II where the figures were presented for ten consecutive trials do not possess a contour at the points of inflection in experiment III make it necessary to reject the first hypothesis.

The reversal of figure and ground had a marked effect except

with figures H and H' (appendix II). When the figure was black, only a black circle in the center of the disk was seen with very little gray surrounding it. However, when the figure was white, a white circle was seen surrounded by an increasing gradient of gray out to the periphery of the disk. With figure G', the white figure, a contour was formed at the indentation of the tips of the figure; when the figure was black (G) this did not appear. This contour and the ones formed through the midpoints of the horizontal elements of figures H and H' are the only ones that lend any support to Mach's claim of a contour at abrupt changes in curves. However, the reversal of figure and ground has a very marked effect that has to be accounted for. Only with figures H and H' was the effect essentially the same after a reversal of figure and ground. The contours were formed at the midpoint of the horizontal elements in the figure. These were constant for the ten trials and for the reversal of figure and ground. Thus, the second hypothesis (Reversal of figure and ground should have no effect on the contour.) will have to be limited to these two cases. An explanation may be that there is a more abrupt change in stimulation due to the sharp, right angle corners. Another factor which may cause the contour nearest the the periphery (one inch) to be seen is that the figure is one-half an inch wide clear out to the periphery where in the other cases the figure runs out to a point. This may cause a marked break in the stimulation. Whereas the tips of the other figures are so small in area as the periphery is approached that they do not have a reaction time latency long enough to reach threshold

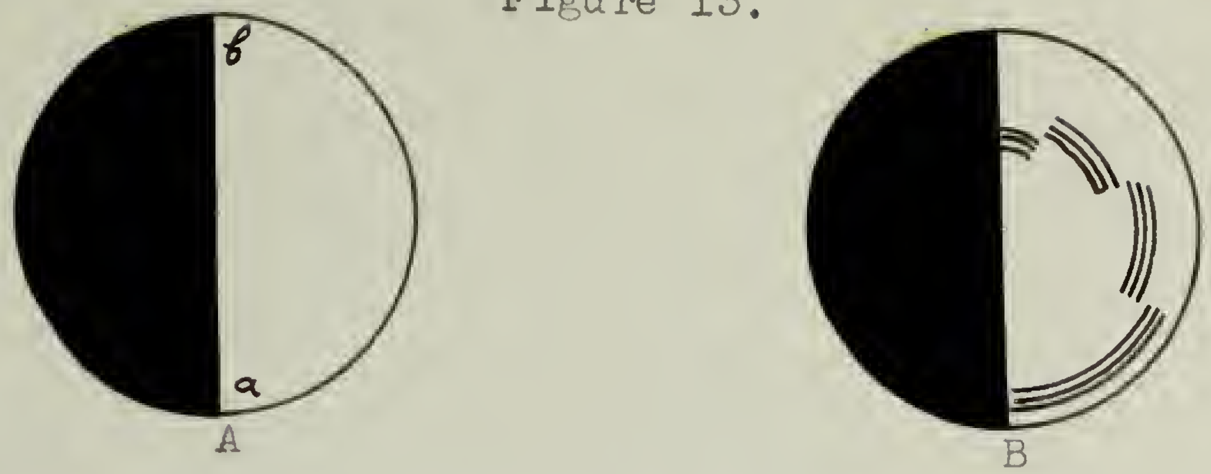
and be perceived.

The results with the Fry (13) figure (E') alone is enough to void the third hypothesis (A boundary will not be generated along curves that do not possess a point of inflection.) Here the circle is generated by the points which form the base of the figure as in the previous cases, however, the curve falls off in a smooth arc to the center of the disk. An abrupt change is not present yet a well defined contour is perceived. A well defined contour is perceived at high rotation rates at the indentations on G' but not on G.

There is a possible source of error which could effect the results -- the disk in some cases might not be centered, this could cause the points forming the base of the figure to appear as a band and would also throw the points of inflection out of line. Also in these experiments an artificial pupil was not used on the assumption that if the marked changes in the intensity gradient produced contours, these should be apparent to the whole retina. Fry (17) used a 2mm artificial pupil in his experiment explaining the Mach rings. This restricted the changes in intensity to a homogeneous region of the retina (fovea). In the present experiment, the intensity of illumination is dispersed over inhomogeneous regions of the retina as well. This would greatly reduce the frequency of impulses, changes in which Fry contends indicate where Mach bands will be seen.

That the frequency of impulses is a factor in apparent from the fact that Fechner's colors were seen on the disks with black figures. These are usually demonstrated by two other disks (42).

Figure 13.



When disk A is rotated clockwise under the illumination of a very bright light, the following phenomena occurs; at (a) a sensation of red is perceived, at (b) a sensation of blue. This is more strikingly illustrated by rotating Benham's disk (figure 13B). When this disk is in rotation (4 - 5 times per second) in a counterclockwise direction, the inner segments take on a reddish-yellow coloration and the outer segments appear blue. When the direction of rotation is reversed, the colors are reversed, with blue in towards the center. The explanation, Zoethout (42) says, lies in the latencies of the cones to stimulation by the primary wave bands which make up white light (red, green and blue). As the white section of the disk advances on the unstimulated portion of the retina (occupied previously by the black portion of the disk), the time of stimulation by this white arc corresponds to the latency period of the red receptors, i.e., it is of just sufficient duration to cause the red receptors to fire and cause a sensation of redness. This is followed by green, which when mixed with red produces yellow. Then finally the blue sensation is felt as the effect of stimulation begins to die out. In the present experiment the affect of blue-green occurred only for a short interval above c.f.f. Above this interval, white was per-

ceived. The gray band formed when the figure was black was then due to enough black being present under the tips to interrupt the effect of stimulation by the white ground. As the area of black under the tips decreased, then the effect of stimulation by the white area became great enough to inhibit the lack of stimulation by the black, causing the affect of white only to be perceived. This would account for the contours being formed in figure H. Enough black must have been present out to the periphery of the disk to interrupt stimulation due to the white area and thus cause a sensation of grayness.

It is concluded from this experiment that: (1) Contours were not formed at the points of inflection along the tips of the stimulus figures even though this is a marked change in luminous intensity gradient -- where the acceleration of this gradient is momentarily zero, while changing from negative to positive acceleration. (2) The reversal of figure and ground results in a shift in stimulation from a strong intermittant one at the outside of the disk, to a steady stimulation by the white area in the center of the figure, surrounded by a relatively weak intermittant stimulation due to the white tips of the figure. This would cause a very marked change in the frequencies of impulses in the retino-cortical pathways which Fry says are the basis for the Mach rings. Here Bartley's concept of cortical driving would make a good test of the impulse frequency theory. The alpha rhythm should be altered when the Mach bands are present. (3) One cannot generalize from these results where an artificial pupil was omitted to cases where only a homogeneous retinal field is

stimulated by use of an artificial pupil. Here contour may occur at the points of inflection while not in the former case due to retinal interaction in an area which includes an inhomogeneous region of sense cells.

Summary

The literature relating to various factors affecting contour processes was reviewed. This experiment was designed to test the concept that contours are due to changes in the second differential of luminous intensity. Contours were not demonstrated at points of inflection, which are marked changes in the second differential of luminous intensity where acceleration is momentarily zero and changes from negative to positive. An explanation was offered on the basis of intensity of intermittent stimulation.

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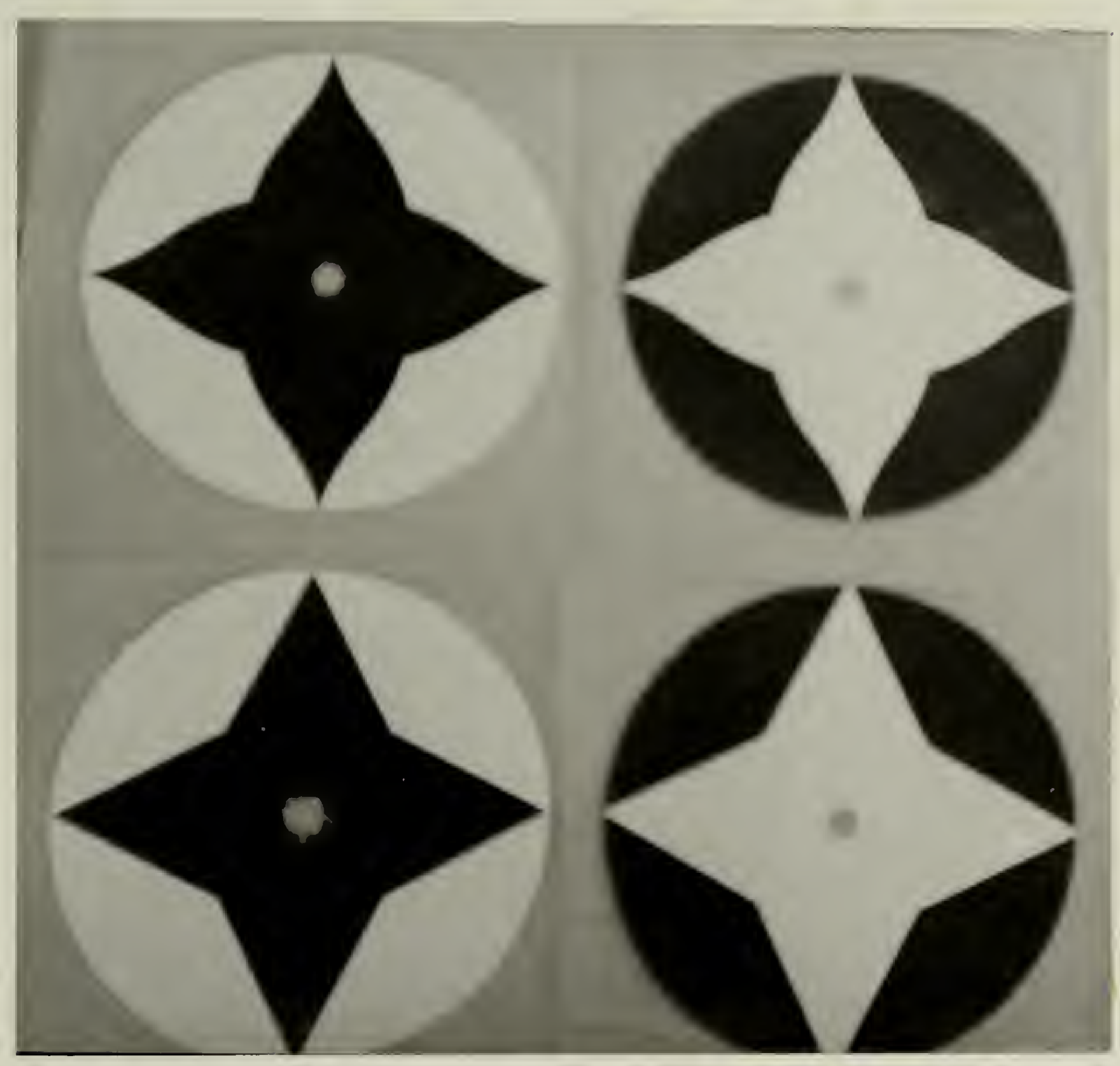
Appendix I.

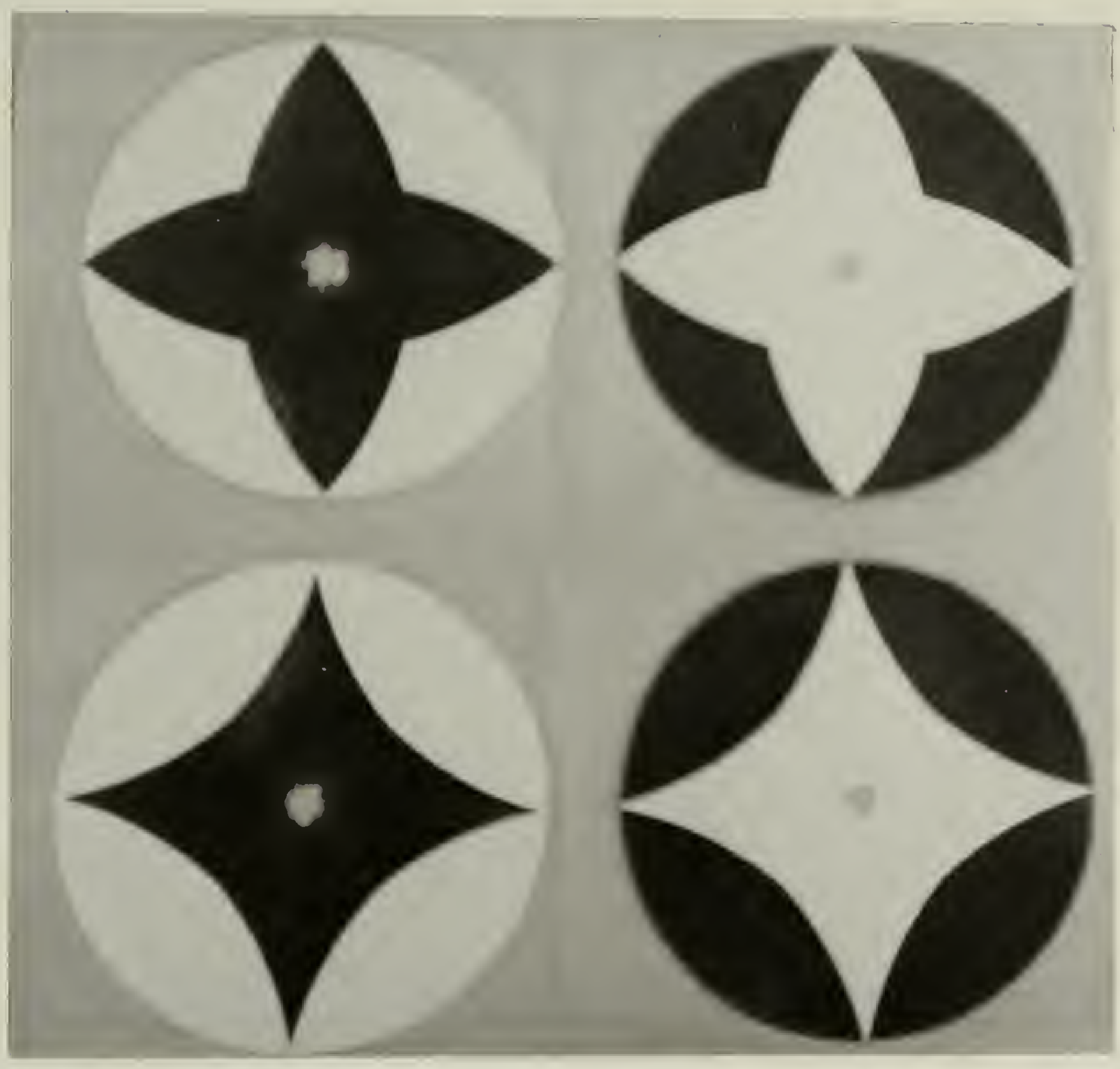
A word about the construction of the figures is necessary here. The original plan was to equate each figure for area and one half the area of the ground, while keeping the radii constant for all. This would stimulate the same area of the retina each time. Thus the variation in the curves bounding each figure would be the only variable. It soon became apparent that this was a next to impossible task, so on the suggestion of Prof. Wagner (Mathematics Department) the figures were laid out with a compass, using the same radii and the same points for the base of the figure. Only figures A, A', B, B' are equal in area and equal to one half of the ground. Figures C,C' are slightly larger, and figures D, D' are slightly smaller than the first two figures. When arcs of a circle are used in the construction, the point of inflection can easily be set at the midpoint of curved sides of the figure. These arcs have the same radius as the circle and are laid out by bisecting a line drawn from each corner of the base to the apex of the tips. Arcs can then be laid out from these points to provide centers for the arcs which bound the figure. For figures C, C' and D, D' the radius of the curve is twice the radius of the circle.

A A'



B B'

C C′



D D′

Appendix II.

Figures E, E', F, F', and G, G' were modified from those in Appendix I in the following manner. For figures E and E' two of the tips were omitted and the curves drawn in towards the center in the shape of a cusp. This was to reproduce Fry's (13) figure as closely as possible. The four points which formed the base of the tips in the previous figures are retained here as the widest parts of the figure. In figures F and F' two tips were omitted also and arcs cut away in the form of half circles. The abrupt points here correspond to the base of the figures in Appendix I. In figures G and G' and indentation was cut which fell 1 3/16" from the periphery. This figure is the same as figure (B, B') otherwise. Figures H and H' were constructed with abrupt 90 changes to see what effect this would have.

E E'

F F'

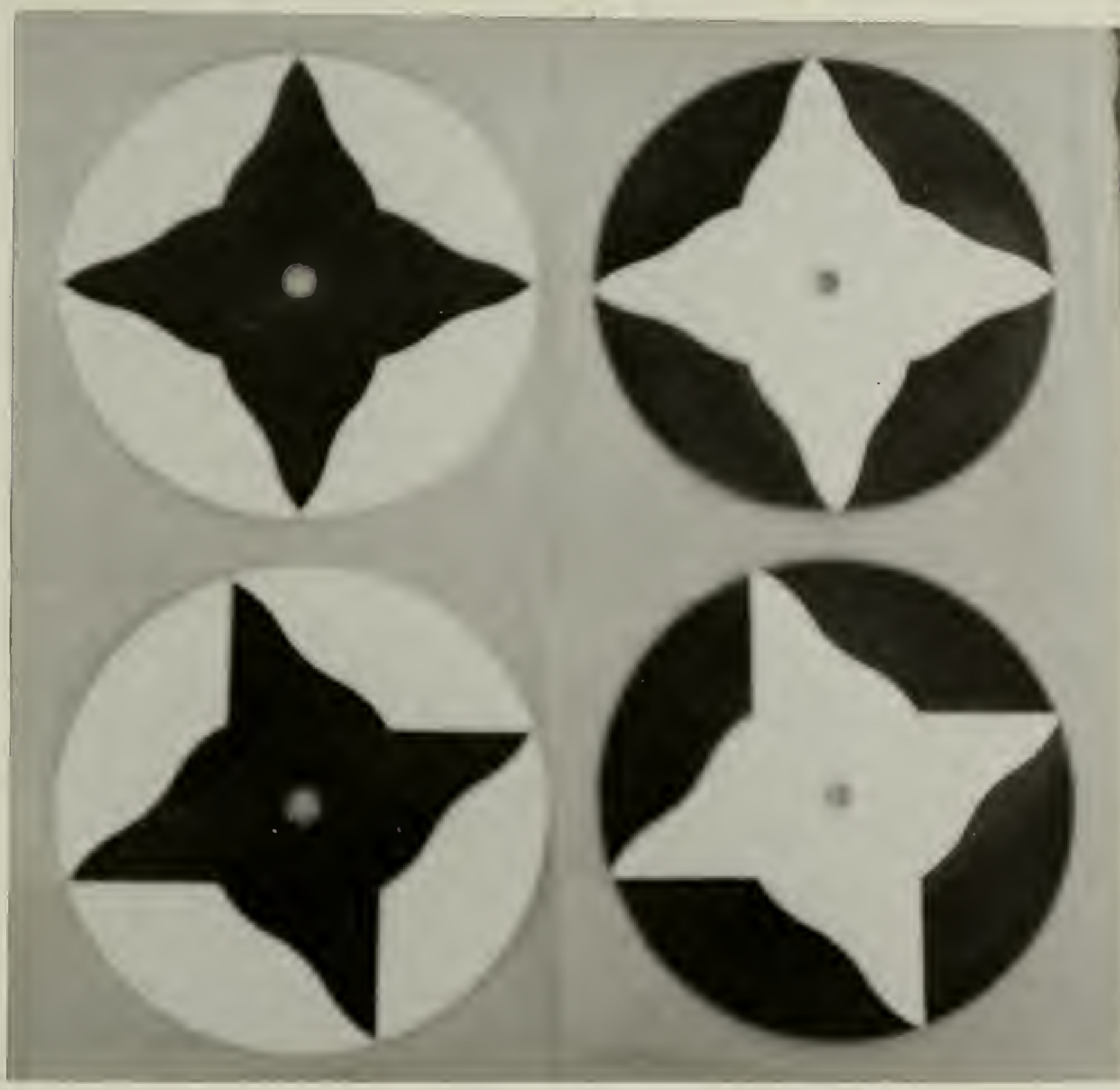
G G′

H H′

Appendix III.

Figures I, I'; J, J' have the same base as the previous figures, however, they were constructed to possess two points of inflection. In figures J and J' only one side of the tip is bounded by the curve with the double inflection. The other side was left straight to see if this would counteract in any way the effect of the curve with the double inflection..

I   I′



J   J′

Approved by: Robert S. Feldman

Claude C. Neet

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