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A METHOD OF CONTROLLING STIMULATION FOR THE STUDY OF SPACE PERCEPTION: THE OPTICAL TUNNEL [1]

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The apparatus to be described is designed for the study of the stimulus conditions which yield tridimensional visual perceptions. The methods of psychophysics can probably be extended to the investigation of space as well as color if devices can be built for the control and systematic variation of these stimulus conditions. Devices have been constructed in the past for the control and systematic variation of luminous intensity and wavelength; we now need devices for the control and systematic variation of luminous *pattern*.

The stimulus for visual perception is focusable light, that is, light which is capable of forming a pair of images in the two eyes. In an environment of clear air (which transmits light) and solid surfaces (which reflect light) these images will constitute a sort of dual projection of the solid portion of the environment.

The retinas are adapted to register this dual projection. The receptor system is sensitive not only to the pattern of each image but also to the difference between the patterns (their disparity) and to the change of both patterns in time (their motion). Each pattern is composed of *transitions*, or differences in luminous energy, and we know that the eye functions by accommodation so as to make these transitions as abrupt as possible, that is, to maximize what is called the "sharpness" or "definition" of the image. In the focused image, the abrupt transitions will generally correspond to the edges or margins of objective surfaces. Gradual or slow transitions, if present, will generally correspond to such physical conditions as the penumbras of cast shadows or to the shading on curved surfaces in the environment.

Within the gross areas of relative light and dark in the image there will usually be found finer areas. There may exist *alternating* transitions of

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luminous energy along both meridians of the image, or "optical texture."[2] The optical texture of the image is generally a projection of the physical texture of the reflecting surface, that is, the pattern of one corresponds geometrically to the pattern of the other. When the density of the transitions along one meridian exceeds the density along the other, this "one-way compression" of the texture (**2**, p. 173) generally corresponds to the *slant* of the surface to the line of sight. A continuous increase in the density of such transitions along one dimension of a two-dimensional image corresponds to the *recession* of the surface, for example, a floor or ceiling. The density of the texture surrounding a given point in this image corresponds to the *distance* of the corresponding point in the surface. Such facts of optical geometry help to resolve the paradox of how a retinal image in two dimensions can yield information about a space of three dimensions.

The *density variables* of the monocular image are associated with physical distance by virtue of the geometry of perspective, which is concerned with a projection to one center at one instant. The visual stimulus, however, is ordinarily a projection to two centers, and moreover each center of projection ordinarily changes with time. The image in one eye differs from that in the other, and each image is altered whenever the observer changes his position. Hence we must also look for variables in the visual stimulus which depend on the geometry of *parallax* or, more generally, the geometry of *projective transformations*. If the visual stimulus is a dual, moving projection, the density variables in the array will be supplemented by variables of disparity and deformation. Along with degrees of density along a meridian, the array will manifest degrees of displacement of one image relative to the other, and degrees of displacement in each image relative to what it was before. A reasonable hypothesis is that the latter can be analyzed as gradients of the array and considered stimulus variables for visual experience.[3] The angle of inclination of a textured surface to the line of sight, for instance, is ordinarily specified by three concomitant gradients in the stimulus array: the rate of change of density, disparity, and motion of the texture elements.

A Method of Presenting Spatial Stimulation

In order to discover whether these gradients actually serve as stimuli for impressions of a spatial world, a means must be found of experimentally producing and controlling them. For this purpose a device has been constructed which delivers to each eye a sheaf of light rays whose cross section is a set of concentric rings of alternating high and low intensity ("white" and "black"). It consists physically of a series of

[2] The senior writer has suggested elsewhere (**2**, Chap. 5) that the elements of an optical texture might be defined as "spots" with "gaps" between them, or as "cycles" of intensity each composed of a spot and a gap. This definition, apart from its mathematical vagueness, now seems to be an error. The element of optical texture is best defined as an abrupt change in luminous intensity, either an increase or a decrease. These changes themselves, not the areas they segregate, seem to be what is of first importance in the retinal image. They can be analyzed mathematically for slope and rate of change of slope. The retinal image, in short, is not composed of objects but of transitions. The "rays," in terms of which we analyze the optical stimulus, should be conceived as points of change, not as entities.

[3] Introspectively, these two modes of optical stimulation are manifested as the illusory double images of objects in the binocular field and the illusory apparent motion of objects in the field. These impressions can be called sensations and the apparent displacements can be called clues or cues for assumptions or inferences about the distances of the objects, but this line of theorizing is obviously roundabout.

circular holes in alternately black and white diffusing surfaces hanging behind one another, perpendicular to the line of sight. The surfaces are sheets of plastic uniformly illuminated from below. A longitudinal section of the resulting sheaf of light rays is diagramed in Fig. 1. The solid lines represent reflecting surfaces and the broken lines represent divisions between lighter and darker ray sheaves, that is, abrupt increases and decreases in luminous intensity. The end of this pseudo tunnel consists of a white or black sheet, not shown, which fills the center of the stimulus array.

Only the stimulus for one stationary eye is represented in Fig. 1, and the eye is centered with the tunnel. The cross section of its ray sheaf is shown in Fig. 2A. The stimulus for

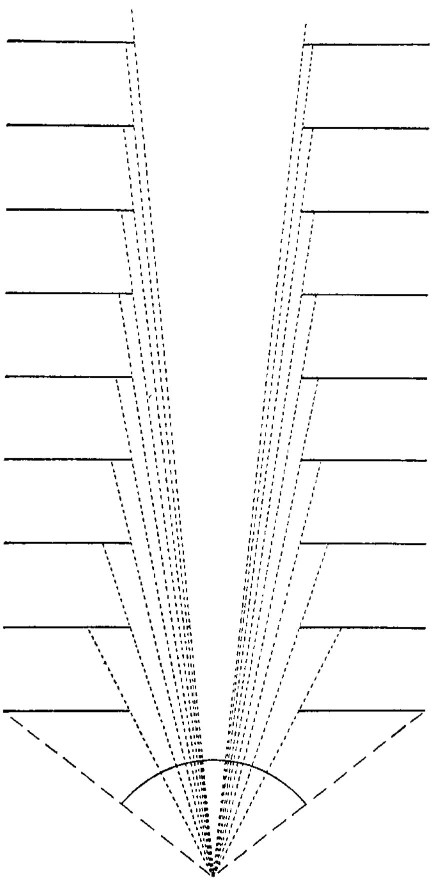

FIG. 1. Longitudinal section of an optical pseudo tunnel. Nine elements or transitions are shown as projected to a single centered eye. The increase in density of transitions from periphery to center of the array is evident on the angular cross section.

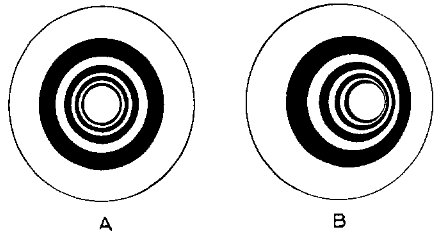

FIG. 2. Perspective cross sections of the optical tunnel of Fig. 1. Transitions are shown as white to black or the reverse. The picture on the right (B) represents a projection to a point to the right of the centered eye.

another eye (or for another position of the same eye) must be represented by an off-center projection. The cross section of such a ray sheaf is shown in Fig. 2B from a point to the *right* of center. In the latter picture it may be noted that the peripheral-to-central rate of increase of density is shallower on the left and correspondingly steeper on the right, but is unaltered downward or upward. It may also be noted that the over-all density of this optical texture is very coarse.

The series of apertures shown in Fig. 1 is one of a variety of arrangements which can be made. The size of the first aperture and its distance from the eye determine the *angular extent* of the stimulus array, that is, the amount of the field of view filled by it. The length of the pseudo tunnel determines to what extent the rings fill up the array toward its center, that is, the *maximum* density of the texture, a density which can increase up to a theoretical vanishing point as the tunnel lengthens. The number of sheets placed in a tunnel determines the *mean* density of the array, that is, the total number of texture elements in it. In other words, the physical spacing of the apertures determines the optical variables of the stimulus. The artificial visual environment produced is "flexible," in that it can be altered by E in the systematic way necessary for psychophysical experiments.

A peripheral-to-central increase of density is represented by the arrangement of Fig. 1 and 2. A constant density of texture or zero gradient can, however, be arranged. This corresponds to a surface of zero optical slant, i.e., a flat frontal surface. The arrangement is shown in Fig. 3. It should be noted, however, that the ray sheaf represented is single and stationary, and that if the rays are projected to *two* points or to a *moving* point, a peripheral-to-central gradient of disparity or of relative motion would appear in the array which would be inconsistent with the zero gradient of density. The two parallax gradients would thus be discrepant with

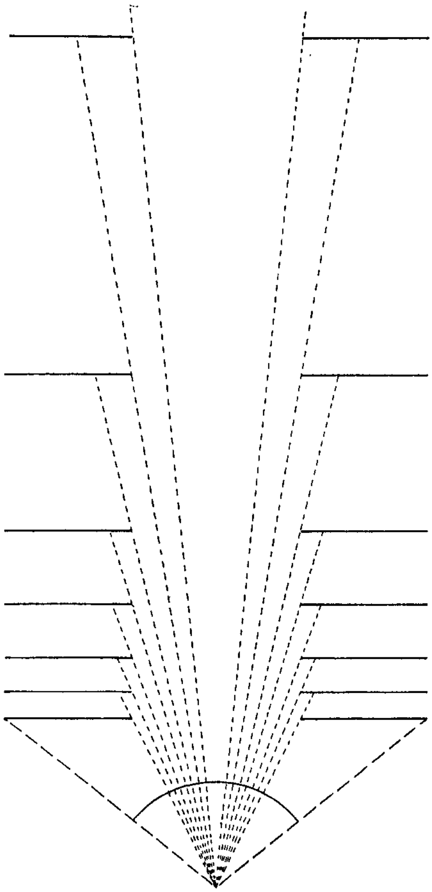

FIG. 3. Arrangement of a pseudo tunnel which provides a constant density of transitions from periphery to center.

the perspective gradient, and the result for perception could be observed.

If the apertures of the tunnel are of constant size, variations of the stimulus are produced by the spacing of the sheets. It is possible, however, to cut a series of holes of decreasing (or increasing) size. Variations of the stimulus then depend on *both* the size of the holes and the spacing of the sheets. A given projection to a stationary point can, geometrically speaking, arise from an infinite set of tridimensional arrangements and, accordingly, there is an infinite set of possible combinations of serial size and serial spacing which will yield a given pattern of concentric rings. Figure 4 illustrates a tunnel which is one such projective equivalent to the "normal" tunnel shown in Fig. 1.

It is important to realize that, although the gradients of texture density in these projective equivalents are identical, the gradients of disparity and of relative motion are not. The latter are not as steep in Fig. 4 as they are in Fig. 1. Consequently it might be predicted that the percepts induced by these two tunnels would be the same with monocular vision and a motionless head, but different with either binocular vision or a mobile head or both.

The specifications for an optical tunnel.—The aim is to construct a synthetic perception of tridimensional space by arranging the differences of intensity in a stimulus array. Great care must therefore be taken to eliminate all variables in the light entering the eyes except the intended alternations of dark and light rings. To this end, the reflecting sheets must be thin and their surface must be matte and very smooth. Vinylite plastic has been employed. When a clean black or white sheet of this material is observed monocularly through a viewing tube, accommodation fails and the impression of a dark or light "film" at the end of the tube results. The surfaces, therefore, are diffusing reflectors which yield no visible texture when seen at a sufficient distance.

The holes cut in these surfaces must have sharp edges in order to produce an optically sharp margin and the cut must therefore be beveled on the invisible side. The plastic sheets used were .03 in. thick, which is thin enough to permit exact cutting but thick enough for rigidity. Material which warps, such as cardboard, cannot be used. The use of metal

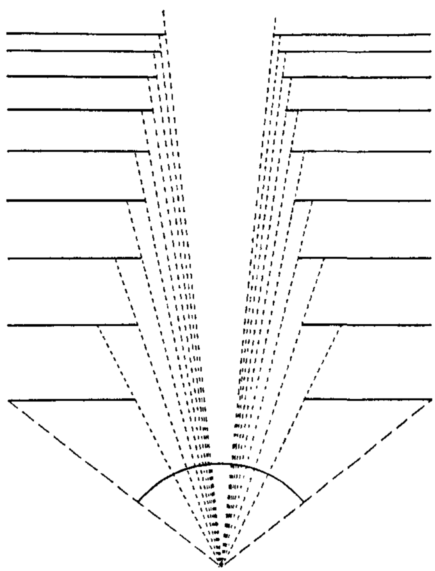

FIG. 4. Arrangement of an optical tunnel which is equivalent of that of Fig. 1 for the fixed single-point projection shown.

instead of plastic, it now appears, would probably be desirable. Circular holes are easier to cut than square holes.

The surfaces and holes in the existing tunnel are of rather large dimensions in order to minimize the effect of imperfectly smooth surfaces or imperfectly sharp edges. Exploratory work with a tunnel of small dimensions revealed this effect. The holes are 12.6 in. in diameter and the sheets are 36 × 42-in. rectangles. The maximum length of the existing tunnel is 21 ft. along one wall of a room. There is enough space for a 15-ft. comparison tunnel at right angles to the standard tunnel along the adjacent wall. The plastic sheets had to be large relative to the holes in order to make possible a long tunnel composed of only a few texture units, that is, relatively coarse concentric rings. Relatively fine concentric rings in a tunnel of equal length can always be obtained by hanging a large number of sheets behind one another. Fifty or more sheets can be set up within 21 ft.

The top of each sheet is sandwiched between two strips of aluminum angle whose ends rest on a pair of steel tracks 21 ft. long. These tracks, running the length of the tunnel, are supported at a height of 5.5 ft. from the floor, level, and parallel. The centers of the holes are thus at eye level for a seated *O*. The sheets can be spaced by sliding them along the tracks, or by adding to or subtracting from their number. The end of the tunnel can be set at any point short of 21 ft. by hanging a plain sheet at that point.

Uniform illumination of the alternating black and white surfaces which reflect alternating intensities of light had to be arranged if the different intensities were to depend wholly on the different reflectance values. The method adopted was to set a series of fluorescent lamps end to end underneath the plastic sheets, each tube overlapping the next slightly, so as to provide each surface with an equal amount of illumination. Reduced illumination was obtained by covering the lamps with one or more layers of paper.

The viewing position of *O* may be either free, or fixed by a headrest or biting-board. The headrest can be equipped with occluders which will permit either binocular or monocular vision. The whole device is screened from the view of *O* at all times so as to prevent any expectation of the kind of scene to be viewed. When ready to observe, *O* faces a rectangular sliding panel which can be raised and then lowered. The plane of this window is at 40 cm. from the eyes. At any convenient distance beyond it, the first of the series of apertures can be set.

The two-mirror setup for constructing an optical tunnel.—If a pair of mirrors of identical shape are set up facing one another in parallel planes, and a small hole is made in the silvering of one mirror to which an eye can be applied, a "normal" optical tunnel (Fig. 1) can be constructed of small bulk and at little cost. Such a tunnel is of indefinitely great length, i.e., it recedes to a vanishing point. Its elements have as much depth as the distance between the two mirrors and its over-all density can be varied by altering this distance. The edges of the two mirrors repeat themselves as successive reflections down what appears to be an endless corridor. The optical geometry is such as to produce the sheaf of rays in Fig. 1. The perception of distance is compelling. A sort of dark spot appears in the space of this corridor, which is the image of the viewing hole. A pair of holes or a slit can be made for binocular viewing, but these will be correspondingly imaged.

The size and spacing of the tunnel elements cannot be independently varied in this arrangement. It is doubtful if the elements can be made to consist of simple transitions of luminous intensity as can those of the aperture tunnel, but this is not certain. The walls will consist not only of the mirror edges but also of anything lateral to these edges. It is possible to fit a sort of translucent diffusing collar around the edges of the mirrors (circular or square) and to illuminate the tunnel through it. Textures can be imposed on this surface. Preliminary work suggests the necessity of using front-surface mirrors.

No formal experiments have yet been performed with this device. It is described here so that other *E*s may work with it if they choose.

Results

Does a Pseudo Tunnel Yield the Perception of a Phenomenally Real Tunnel?

The first question to be asked about the aperture tunnel is whether it can produce the experience of a solid objective environment. Can the light be so manipulated as to yield the perception of a continuous substantial surface receding from *O* in the form of a cylinder or tube?

Preliminary experiments suggested that when the stimulus array consisted of only a few margins from periphery to center, they looked like edges and the rings between the margins looked frontal to the line of sight; the tunnel was seen for approximately what it was. When, however, the array consisted of *many* margins, they no longer looked like holes and the rings appeared to be black-and-white stripes on the interior of a cylinder. It is possible, then, that a surface is seen when the jumps of luminous intensity in the array (Fig. 2) are sufficiently dense.

In order to verify this hypothesis, three arrangements of the apertures were set up in succession so as to give three degrees of density in the stimulus: a 7-element tunnel, a 13-element tunnel, and a 19-element tunnel. In the first there were 7 sheets 90 cm. apart, in the second 13 sheets 45 cm. apart, and in the third 19 sheets 30 cm. apart. The total length of the tunnel was about 6 m. for all three arrangements, and the physical distance from the first aperture behind the square window to the last aperture in front of a solid sheet was always 540 cm. These three arrangements were shown to three groups of naive *O*s. They were simply asked what they saw. The sheets were adequately illuminated (about .1 ft.-candle), both eyes were used, and the headrest permitted some sideways movement of the head. The stimulation, in short, was not impoverished or reduced to a single fixed sheaf of rays; it was a dual fluid sheaf of rays.

The reports desired were not introspective descriptions but statements of what *O* perceived as "there." The instructions, accordingly, were as follows:

"When I lift the panel in front of you there will be something there that I would like you to describe to me. Tell me as much about it as you can, in as much detail as possible. I will first give you a very brief look, about 5 sec., and later, a much longer look. Note such things as color, shape, dimensions, etc. You may compare it to something you may have seen before if you like. I will ask you a few questions after you have reported. (Subsequent questions, using whatever noun *O* used in his report, were as follows.)

"(1) Would a ball, given a little push, roll from one end of the . . . to the other? (2) How far is it from you to the end of the . . .? (3) Is this . . . the same diameter all the way through, or does it narrow, or get wider at the other end? (4) What is the diameter of this end? Of the far end? (5) (If stripes or bands are mentioned) How are they arranged? How wide are they? Do they all look the same width, or do they get wider or narrower at the far end? (6) Where is the light coming from? (7) What does this look as though it were made of? How would you go about making it?"

Each *O*, in complete ignorance of the experimental setup, was led into a sort of booth in the experimental room, the window was opened for 5 sec., he peered into it, and his first report was recorded. All *O*s used nouns like "tube," "cylinder," "tunnel," "sewer pipe," or something equivalent, but whether the percept was that of a *solid continuous* surface had to be determined from the description and from the answers to questions (especially No. 1 and 7 above). On the basis of these records it was found that all percepts could be put into one of three categories: (*a*) a continuous solid cylinder, (*b*) solid cylindrical segments with space or air between the segments, and (*c*) apertures or holes in frontal surfaces. The second category consisted of a compromise between the first and third, that is, a percept in which one ring (usually the black) looked like a surface but the next (usually the white) looked like a gap. It may be noted that the third category is "correct" but this is irrelevant to the experiment.

The results are given in Table 1, in the form of percentages of the group of *O*s getting each type of percept. It can be noted that as the number of intensity jumps in the stimulus array increases, the impression of solidity or continuity of surface also increases. With as few as 19 elements the percept of a "real" surface is induced in 95% of the *O*s.

The results when *O*s were permitted to look into the pseudo tunnel for as long as they liked are given in Table 2. The instructions were probably such as to put *O*s on the lookout for

TABLE 1

Solidity of Tunnel as a Function of Density of Texture with Short Exposure

O's Report	7-Card Tunnel ($N=21$)	13-Card Tunnel ($N=20$)	19-Card Tunnel ($N=21$)
Solid cylinder	33%	70%	95%
Solid segments with air between	19%	10%	0%
Series of apertures	48%	20%	5%
Total	100%	100%	100%

TABLE 2

Solidity of Tunnel as a Function of Density of Texture with Prolonged Exposure

O's Report	7-Card Tunnel ($N=21$)	13-Card Tunnel ($N=20$)	19-Card Tunnel ($N=21$)
Solid cylinder	33%	45%	62%
Solid segments with air between	33%	10%	19%
Series of apertures	33%	45%	14%
Total	100%	100%	95%*

* The additional 5% is accounted for by one *O* who saw *part* of the tunnel as segments and the *remainder* as apertures.

an "illusion." The variety of objects seen by them became much greater, and the descriptions were equally various. The percepts could be classified in the same way as before, however, chiefly on the basis of Question 1. There was either a continuous solid surface on which a ball would roll, or there was no such surface, or there were places where a ball would drop out. With prolonged observation the frequency of reports of a solid cylinder decreased for the denser tunnels, but the trend of the results was the same as before.

The reason for the increased tendency to see edges and apertures with long exposure may be that stimuli for the perception of edges had not been wholly eliminated from the stimulus array and could be detected by some *O*s. Minute high lights reflected from the physical edges would be such stimuli. This possibility will be considered later.

It is notable that no *O* in this experiment ever saw as solid the space between the square window in front of his eyes and the circular hole in the first plastic sheet. This peripheral portion of the array was always perceived correctly as an air space. The edges of this window, of sawn wallboard, were perceptible as such. Between the first and second circular apertures, however, there was very frequently the clear perception of a black (or white) surface, as if a sort of stovepipe had been fitted to the hole in the surface. Only at this junction would an imaginary ball rolling toward *O* drop out. If this first ring was seen as solid, the entire tunnel appeared so. This perception was often wholly compelling, even for *O*s who knew the physical setup.

The solidity of the pseudo tunnel under the best conditions was also indicated by the reports of what it seemed to be "made of." Paper, cardboard, plastic, or metal were suggested, and the surface was said to be painted or to consist of sections joined together.

It is concluded that the pseudo tunnel will produce the optical stimulation for the perception of a solid surface in three dimensions. The critical factor for solidity seems to be density or frequency of the abrupt transitions between light and dark in the sheaf of light rays. As few as 19 jumps of intensity from periphery to center of the array will yield a surface perception. A subsequent arrangement where the elements were increased to 36 yielded the perception of a solid tunnel in all *O*s tested.

Perception of distance and size in the optical tunnel.—All subjects in the foregoing experiment perceived a three-dimensional scene. No one ever reported seeing a flat surface or a picture. The so-called cues of perspective, binocular disparity, and motion parallax were present and can be specified as gradients in the stimulus array. But the so-called cue of "known size" was absent. The scene was not identifiable as any well-known entity, even when it appeared most thing-like. It might be supposed that the unfamiliarity of this

TABLE 3

Apparent Length and Size of the Phenomenal Tunnel

(Actual diameter = 12.6 in.; Actual length = 17.7 ft.)

Dimension	7-Card Tunnel		13-Card Tunnel		19-Card Tunnel	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Length (ft.)	10.2	3.3	10.5	5.2	13.9	6.8
Near diameter (in.)	13.3	2.7	14.1	5.4	15.4	4.0
Far diameter (in.)	11.7	3.5	12.4	6.4	12.0	5.0

artificial space would make its size and its depth difficult to judge, and would make it as likely that the walls should appear to converge as that they should appear to be parallel. The *O* had no "information," apart from the light entering his eyes, as to whether the scene was a cone or a cylinder. Peripheral to the tunnel, there was visible, of course, a square window on a wallboard surface, part of a headrest, and *O*'s own nose, which is a familiar object in any normal field of view.

All *O*s were required to estimate in feet or inches the length of the tunnel, its near diameter, and its far diameter. They were also asked to say whether its sides were parallel. The mean estimates are given in Table 3 for the reports after prolonged inspection. The length was in general underestimated, but less so with the arrangement which gave the greatest solidity. Considering that these are absolute judgments by unpracticed *O*s, they are not far off. The diameters are also not far off, although apparent size seems to increase somewhat with solidity. Two-thirds of the *O*s reported that the sides were parallel, but one-third said they got closer together as they receded. The decrease in mean far diameter as compared with mean near diameter reflects this difference of opinion.

These results are exploratory, but it can safely be concluded that a phenomenal tunnel which approximates to solidity is seen in approximately its true scale. Both size and distance are perceived with some degree of accuracy and there is constancy of size with increasing distance.

Does the Phenomenal Tunnel Disappear When the Steps in Luminous Intensity are Eliminated?

The array of light reflected into the eyes from the optical tunnel consists theoretically of steps of intensity determined by the difference in reflectance between the two kinds of plastic, each being equally illuminated. A test can be made of the extent to which this theoretical condition is fulfilled. If surfaces of the *same* reflectance are substituted for alternating surfaces of different reflectance, the steps of intensity should disappear. The stimulus should then be homogeneous and the surface reflecting it should become invisible. The experiment predicts that an arrangement of physical surfaces in good illumination can be made to vanish.

The substitution of either all-black or all-white surfaces for the alternating ones provides a kind of control for the proper arrangement of an optical tunnel. If the microstructure of the surfaces is too coarse, if the illumination falling on each successive surface is not the same, or if the cut edges of the apertures are thick enough to yield even hairlines of reflected light or shadow, then the light entering the eyes will *not* be homogeneous. Brightness contrasts will appear in the field, differential accommodation and convergence of the eyes will occur, and something like the edges and surfaces of an ordinary visual world will ensue. If, however, the array of light entering the eyes *is* homogeneous, or sufficiently so, none of these conditions will apply and the resulting impression will be a void, film, or fog (4).

The experiment was set up first with all-black surfaces and later with all-white surfaces, of 8 and 10 elements, respectively. The experiment showed the imperfections in previous setups. A considerable amount of trial and error was required to eliminate them. The presence of reflections or shadows from the cut edges of the sheets seemed to be the greatest cause of inhomogeneous stimulation. An arrangement was finally achieved with white sheets in which the holes had been cut with a "ring and circle shear" (a machine designed for sheet-metal work). For this setup the beveled edges could be made invisible on the upper semicircle of each aperture and almost invisible on the lower semicircle. Illumination was wholly from below, and there is reason to believe that a balanced illumination from above would have made even these disappear. A sufficient approximation to invisibility was obtained to warrant the conclusion that *when differences in luminous intensity within the stimulus array are made to approach zero, the objective or surface-like qualities of the percept tend to vanish.*

During the early stages of this experiment, the all-black or all-white tunnel appeared relatively insubstantial. It looked filmy, glassy, or transparent, and the interior seemed full of what was variously called smoke, haze, mist, or fog. This was a "dark" fog in one setup and a "light" fog in the other. With further adjustments and modifications the fog became thicker and the walls became less definite. When contrast between the surfaces had been nearly eliminated, it is fair to say that the tunnel as an object had practically disappeared beyond the first aperture. A few shadowy circles sometimes appeared within the first aperture, and a fleeting cylindrical impression then resulted, but the main impression was that of a film or fog.

In order to verify these observations, 10 *O*s were asked to describe what they saw when the observation window was raised, with both monocular and binocular vision. All had knowledge of the actual setup, and all had some training in visual observation. Words like filmy, translucent, soft, milky, hazy, or misty were generally applied to the luminous circular area. Sometimes this looked flat or two-dimensional, sometimes it looked deep, like "3-dimensional light," and for two *O*s it looked like a homogeneous convex sphere or disk which later became concave. Faint rings or circles were sometimes (but not always) apparent, and an impression of depth usually accompanied this. Something tunnel-like was often seen, but the reports were variable as between *O*s and from one moment to the next. There was little difference between the reports with monocular and binocular vision except for a somewhat greater tendency to depth in the latter case. The conclusion above seems justified.

The fact that a set of substantial objects can be made invisible by manipulating reflectance and illumination is not important in itself, however interesting it might be to a professional magician. An even more interesting question is why objects are usually *visible.* What the psychologist needs to know is the general relation between stimulation and perception. The deeper implication of this experiment is that visual objectivity has a basis in stimulation. The previous experiment indicated that this basis may be found in the density of abrupt transitions in the stimulus. The fact that both experiments can be thought of as setting up an illusion or a misperception with respect to the physical sources of the stimulation is incidental, and can have misleading implications. The arrangements were not objects of perception, but were *E*'s devices for systematic variation of the stimulus.

The implication of these first two experiments, then, would be missed by calling them illusions or emphasizing that *O*s were deceived or misled. The construction of visual illusions for their own sake, however interesting, does not constitute systematic research. The optical pseudo tunnel is comparable to some of the striking illusions of space devised by Ames (**5**), but its purpose and implications are different. It enables *E* to produce synthetic perceptions of space so as to test hypotheses about the natural perception of space.

Fixed Monocular Vision as Ambiguous Stimulation

The experiments so far described permitted *O* binocular vision and head movement when looking into the pseudo tunnel. The stimulus consisted of a dual ray sheaf and was "fluid" instead of fixed. The question which arises is what happens to perception when the stimulus variables are restricted to those of a single ray sheaf to a fixed point such as is represented in Fig. 1.

A sheaf of rays to a fixed point may have for its reflecting source any surface which reflects that particular sheaf to that point. All such possible surfaces are related to one another by geometrical transformation. They are members of a mathematical *family* of objects. The fixed single ray sheaf, then, may be called *ambiguous* with respect to the different objects of the family. Applying this rule to a tunnel-shaped surface, it says that the fixed projection illustrated in Fig. 1 might be reflected from the interior of a regular striped cylinder, or from a longer tube whose walls diverge as they recede (like a megaphone), or from a shorter one whose walls converge as they recede (like a cone such as Fig. 4), or from a plane surface frontal to the eye (like the picture in Fig. 2A), or finally from the *exterior* of a short conical surface protruding toward the eye. The cylinder with parallel sides, the "tunnel," is only one of an infinite set of possible surfaces corresponding to the fixed monocular stimulus. Considered as an object in the world it is perhaps more "probable" than the others, but it is not specified in the projection. It is true that if the stripes of the regular cylinder are *equally* spaced, the stripes of all the other possible surfaces will have to be *unequally* spaced. The equal spacing of texture is a highly probable property of environmental surfaces, and this makes the even-textured regular tunnel still more highly probable. Nevertheless, it is not specified in the projection.

A fixed single-point projection does not specify any particular member of its family of transformations, but it does specify the family. In our example a family of cone-like surfaces is required whereas a family of pyramid-like surfaces is excluded. One member of the family is the "picture" of a regular cylinder, but the "picture" corresponding to Fig. 3 is *not* a member. The ambiguity is only partial.

If, however, instead of the "frozen" projection of Fig. 1, we consider a dual projection to two points or a fluid projection to a moving point, the member of the family of surfaces becomes geometrically determined and the ambiguity disappears. The "information" is supplied by the difference between different projections to different points in space. Consider for instance the noncongruence or disparity shown in the two parts of Fig. 2. This difference is unique. It is obtainable only from an evenly striped cylinder, not from a concave and unevenly striped cone, not from perspective rings on a plane surface, and not from a convex unevenly striped cone. The disparity or deformation of the two projections, whether simultaneous or successive, is in correspondence with the depth of the object from which they issue.

A psychological hypothesis is now possible. If we assume that human *O*s can respond to such disparities, it might be predicted that, whereas the ambiguous stimulus may yield a variable percept, a dual or fluid projection will yield an invariable percept. In other words, with the use of two eyes, or with normal head movement, or both, the tridimensional shape of an object should become compellingly visible where it was not so previously.

There is reason to believe that a fixed single-point projection can induce variable perceptions. A photograph is a physical record of a fixed single-point projection, and it is possible to assert both that one perceives depth in a photograph and that one perceives it as flat—assertions which seem to be contradictory. The monocular view of an ordinary room from one position, such as a peephole, is a fixed single-point projection; accordingly a physical room may be constructed which is radically distorted from the ordinary room (if the proper transformation of rectangles into trapezoids is made) and yet appear ordinary through the peephole. But this perception may change to that of a distorted room if only *O*'s attitude or expectation is altered (**5**). Anyone who holds his head still and closes one eye gets a fixed single-point projection; one can then usually observe that the scene before him loses some degree or quality of its depth, and many psychologists have described this experience as a flat patchwork of color "sensations." However, most *O*s have great difficulty in seeing it as literally flat and the impression fluctuates. Among the controversies aroused by the theory of depthless sensations, one fact is clear: the kind of perception obtained with fixed single-point projection depends on the attitude of *O*. The optical pseudo tunnel provides a good opportunity to study perception under these conditions.

The Zero Gradient of Texture Density

Consider the pseudo tunnel shown in Fig. 3. As a fixed monocular stimulus it has a zero gradient of density of optical texture. It should therefore specify a family of objects the most probable of which is a flat frontal surface with a texture of evenly spaced rings. Tridimensional members of the family are possible but they have to be surfaces with *uneven* textures. A regular tunnel with even texture is excluded. The question is whether it will be *seen* as a flat frontal surface or, rather, how invariably it will be so seen. The senior writer has implied in earlier publications that a gradient of texture density is by itself a stimulus for the phenomenal slant of a surface (**2**, Chap. 6) but the present hypothesis is that it is by itself only an *ambiguous* stimulus.

In order to answer this question, two experiments were performed with an optical tunnel of the type shown in Fig. 3, that is, with accelerated spacing of apertures so as to provide optical rings of equal visual angle. In the first experiment 8 sheets were used and in the second 20. In the second, moreover, the nearest aperture was placed farther from the eye (176 cm.) so that the stimulus array was both smaller and denser. In both arrangements the farthest aperture was more than 6 m. from the eye. In the first arrangement the density was insufficient to yield a high degree of surface quality, but in the second it was. Observations were made with one eye occluded and with the head fixed by a biting-board. Naive *O*s were given 5-sec. exposures under these instructions: "Look carefully at what is behind the window. It is nothing complicated or surprising. I will ask you to describe it later, that is, to tell me how you would go about making something like it. Remember to keep your head motionless."

The 17 *O*s of the first experiment gave reports which were then classified. But they did not fall into categories indicating clearly either a bidimensional or a tridimensional perception. Most of the reports (59%) were of something ambiguous, or of a thing which fluctuated between flat and deep. Of the remainder, about half fell into each category.

The 20 *O*s of the second experiment had much stronger impressions of a surface, and it was easier to classify the reports with respect to the flatness of the percept. The reports included answers to questions about the continuity of the surface (if one was seen) and about the amount of depth (if any was reported). For 25% of the *O*s the surface seen was perfectly flat and for 75% it had some depth. Examples of the latter were a "striped vase," a "funnel," or a "Mexican straw hat" (convex at the center and concave at the periphery). The depth perceived was always shallow and in no case did it even approach the actual depth of the tunnel, which was over 18 ft. The mean estimate of the depth of the object seen, omitting the flat cases, was 6.4 in. That the surface appeared continuous is indicated by the fact that only one *O* reported seeing anything like edges.

The conclusion must be that a peripheral-to-central gradient of texture density (in this case zero) does not by itself compel a perception of corresponding slant (in this case flat). This suggests that gradients of density in general are not in isolation determining stimuli for impressions of slant, as the geometrical considerations would predict. The psychophysical correspondence is not perfect. Nevertheless, as will appear later, they appear to determine *something* in the perceptual process. Perhaps it is a relationship between apparent slant and apparent spacing of texture elements. It would seem that the senior author has overstated the case in the past for the definiteness of fixed monocular depth perception.

The fact that a bidimensional percept can be the outcome of monocular stimulation from an 18-ft. tridimensional source implies strongly that the supposed cue of accommodation is not very significant for depth perception at these distances.

The Effect of Adding a Positive Parallactic Gradient to the Zero Density Gradient

If fixed monocular stimulation is not compelling for depth, how about fluid binocular stimulation, either or both? In the latter of the two experiments described above,. all *O*s were given another 5 sec. presentation using both eyes and a third presentation using both eyes without the biting-board. The instructions were the same and the 20 reports were treated as before but they all fell into a new category. The surface seen had extended depth approaching the actual depth of the setup. Estimates were made in terms of feet, not inches, and the mean estimate was 5.8 ft. for binocular fixed vision and 6.2 ft. for binocular vision with head movement. The difference is not significant. So great was the contrast between the thing seen on first presentation and the thing seen on later presentations that a few *O*s expressed the suspicion that *E* had "done something" to the apparatus. In effect the object became a tunnel instead of something shallow or flat when parallactic stimulation was added. According to the reports of trained *O*s, as distinguished from naive *O*s generally employed in these experiments, either binocular or movement parallax would convert the object into a tunnel, and both together were not noticeably more effective than either alone.

The trained *O*s could mostly describe an unusual feature of the tunnel surface under these conditions: that its stripes or markings were not evenly spaced. They seemed to become wider as the surface receded.

The conclusion must be that when a positive gradient of disparity or deformation is added to a zero gradient of density, from periphery to center of the stimulus array, the qualities of slant and recession appear in the perception. They determine these qualities despite the gradient of density, which seems to be wholly ineffective in this situation. There is some evidence that they do so only at the cost of deforming the phenomenal texture of the surface, i.e., making its elements unequally spaced.

The Effect of Adding a Negative Parallactic Gradient to the Zero Density Gradient by Means of a Pseudoscope

A check on the results of the last experiment can be obtained by introducing an "artificial" gradient of disparity to the stimulus instead of the "natural" gradient produced by using two eyes. If this peripheral-to-central gradient is reversed in direction, it would have to be predicted that the qualities of slant and recession would be reversed in the percept and, accordingly, the interior surface of a tunnel would be converted into the exterior surface of a truncated cone. Just such a reversal of the gradient can be produced by a pseudoscope (1, Ch. 7).

The effect of a pseudoscope can best be understood by turning to Fig. 2 and considering the horizontal disparities of the component margins in the two pictures. If each were separately inverted (rotated 180°), the effect would be that obtained with a lenticular pseudoscope, which is a pair of inverting lens systems. It may be noted that the disparities will then have been reversed in direction, which is to say that the gradient of disparity has been reversed. Precisely the same reversal will be produced by overturning each picture right for left out of the plane of the paper. This effect is obtained with a prism pseudoscope, which is a pair of totally reflecting prisms. These pictures, it should be remembered, represent the perspective of a "normal" optical tunnel with equally spaced apertures.

An ordinary scene like a room when observed through a lenticular pseudoscope looks upside down, and when observed through a prism pseudoscope looks reversed from right to left. Anomalies of depth may appear but the surfaces of the room do not appear to have been turned inside out. A better scene for pseudoscope viewing is a symmetrical object like a tunnel, which keeps the same bidimensional form when inverted or reversed. The ideal object for the purpose is probably the special optical tunnel used in the foregoing experiments which has the perspective of a flat surface.

A lens pseudoscope was mounted in front of the tunnel with its tubes parallel to and equidistant from the tunnel axis. As a control for the main experiment a small group of naive *O*s, in complete ignorance of the setup, were asked to apply an eye to one tube of the instrument and to report "what was there." The reports were comparable to those of the first experiment with monocular vision; the object seen was a surface of concentric rings, either flat or with shallow depth, the depth being for some *O*s concave, for others convex. The substitution of a lens system for free viewing had little effect on visible depth. Another group of 18 naive *O*s were asked to apply *both* eyes to the instrument and report. All without exception saw a striped convex truncated cone, or the equivalent, protruding from a background (presumably the nearest plastic sheet). The impression was immediate for nearly all *O*s, and the phenomenal object was stable. The prediction about reversed gradients of disparity and the slant of a surface is therefore confirmed.

Observers with knowledge of the setup see the same thing as *O*s without knowledge. Observations with a prism pseudoscope give the same result. The convex phenomenal surface seen in this situation, as compared with the concave phenomenal surface seen with binocular vision of the tunnel, is nearer, smaller, and tapered instead of cylindrical. Its apparent distance, size, and shape are probably such as would be expected for a projective transformation of the interior surface of a cylinder into the exterior surface of a truncated cone—as if the cylinder had been pulled inside out within the defining sheaf of light rays.

When a pseudoscope is used with a "normal" optical tunnel (Fig. 1 and 2) instead of the special tunnel with the zero gradient of density, the outcome is not the same as above. In this situation a gradient of texture density is in full opposition to the gradient of disparity. Many but not all *O*s can see the protruding truncated cone, nearer and smaller than the receding cylinder, but the percept is unstable and gives way at times to the cylinder or to some compromise between them. When the cone is seen, it has a very odd distribution of stripes, extremely small and close together at the front but very large and far apart at the rear. This is further evidence to show that *when a gradient of disparity wins out over a conflicting gradient of texture density it does so at the cost of giving the phenomenal texture an uneven scatter or unequal spacing, that is, deforming it.*

When the cone is not seen but gives way to the cylinder or to a compromise, there are indications that *O* has lost his binocular fusion and is getting double imagery. The diplopia can usually be observed under these conditions. This suggests the hypothesis that *when a gradient of texture density wins out over a conflicting gradient of disparity it does so at the cost of producing double images.*

The implications of these results for ordinary visual perception.—The last three experiments have been stimulus situations where the gradient of density was isolated from or discrepant with the gradients of disparity and motion. In ordinary stimulus situations they are concomitant, not discrepant. In the everyday environment the reflecting elements of surfaces tend to be evenly spaced, both eyes are open, and the head moves. The implication is that the limited ambiguity of fixed monocular vision is removed when binocular or motion parallax is operative.

Summary

A method is described for inducing and controlling a perception of *surface* and *space*. Conclusions are: (*a*) There is evidence that surface quality depends on the density of transitions in the optical stimulus. When the transitions are absent, surface quality disappears. (*b*) There is evidence that the gradient of texture density in isolation need not always determine the qualities of slant and recession. It is ambiguous, but only with respect to the members of a family of surfaces. (*c*) There is evidence that the gradients of textural disparity and motion can determine the qualities of slant and recession. Presumably when the gradients are concomitant, ambiguity is removed.

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