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MOTION PARALLAX AS A DETERMINANT OF PERCEIVED DEPTH[1]

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Motion parallax is the optical change of the visual field of an observer which results from a change of his viewing position. It is often defined as the set of "apparent motions" of stationary objects which arise during locomotion. Psychologists assert that it is a "cue" for perceiving the depth of the objects, but the optical fact of motion parallax must be distinguished from its capacity to induce perceptions. It has not been experimentally demonstrated that motions in the field of view will actually yield corresponding judgments of depth. This is a purely psychological problem. The optics of motion parallax, on the other hand, is a problem for geometry and ecology.

Recently, the suggestion has been made that a continuous gradient of motions in the field of view will induce the perception of slant-depth (J. J. Gibson, Olum, & Rosenblatt, 1955) inasmuch as the perception of depth is intimately connected with the perception of surfaces (J. J. Gibson, 1950). This statement also needs experimental test. The purpose of the present study is to investigate what kinds of motion in the light entering an eye do in fact consistently arouse certain judgments of depth, and what do not.

The experiments must be carried out with artificial motions in a field of view rather than those obtained in a natural environment if we wish to study the effect of motion parallax in isolation from other cues or stimuli for depth. The variables of size, density, linear perspective, differential blur, and binocular parallax should be eliminated or so reduced as to be ineffective in the array of light entering *O*'s eye. A method of achieving this result has been devised, and a suitable control employed.

The experimental method should also preclude actual movement or locomotion of *O*. If the cue of motion parallax is so defined as to require *active* head movement or locomotion, proprioceptive and vestibular stimulation is also present. This definition is unjustified, since passive locomotion in trains and airplanes should be admitted as circumstances when motion parallax occurs. Certain patterns of motion in the field of view of *O* do induce impressions of being moved through space if we accept as evidence the illusions of locomotion obtained in viewing a panoramic motion picture, or in a training device for simulating aerial flight.

Perception of absolute distance and of relative depth.—The apparent displacements of the sensations of objects are said to be cues for perceptions of their depth. What kind of depth? The question arises whether their distances from the perceiver can be judged or whether they will only appear to be separated in the third dimension. Helmholtz, in his description of motion parallax, asserted both hypotheses. On one page he described the appearance of objects "gliding past us" as we walk through

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the countryside, and asserted that "evidently under these circumstances the apparent angular velocities of objects in the field of view will be inversely proportional to their real distances away; and consequently safe conclusions can be drawn as to the real distance of the body from its apparent angular velocity" (Helmholtz, 1925, p. 295). On the next page he described the appearance of an indistinguishable tangle of foliage and branches in a thick woods as a man stands motionless, but noted that "the moment he begins to move forward, everything disentangles itself and immediately he gets an apperception of the material contents of the woods and their relations to each other in space, just as if he were looking at a good stereoscopic view of it" (Helmholtz, 1925 p. 296).

In the first quotation Helmholtz says that angular velocity is a cue for the perception of absolute distance. In the second, he suggests that a difference in angular velocity is a cue for the perception of separation in depth, or of relative distance only. These two hypotheses are by no means the same, and they should be considered separately and tested separately. We will be concerned here primarily with the second.

Two-velocity motion parallax and flow-velocity motion parallax.—Although motion parallax has been said to apply to the whole array of objects in an environment and a large array of apparent motions in the field, the experiments performed have in the past been confined to two objects and two velocities in a restricted field of view.

Bourdon (1902) reported experiments in which *O* looked with one eye at a pair of luminous spots in a dark corridor. The sources were at different distances but the spots were of the same angular size. When the head was fixed with a biting-board, *O* "could not judge at all accurately" which light was the nearer, but with the slightest movement of the head from side to side "it was easy to judge" the relative depth of the two. But the absolute distance of neither light was detectable.

Tschermak-Seysenegg (1939) improved on this arrangement with what he called a "parallactoscope," by analogy with the stereoscope. He defined motion parallax as arising from movement either of a group of visible objects on the one hand, or the position of *O*'s eye on the other, emphasizing the relativity of the situation. But, he studied only the detection of depth of two objects with voluntary head movement. His apparatus was a modification of the familiar two-pins setup used to obtain the threshold for binocular depth perception. It permitted *O* to move one eye from side to side, with a sliding headrest, so as to obtain *successive* impressions equivalent to the *simultaneous* impressions obtained with both eyes open. The average error of equating the distance of the vertical wires was small under these conditions, although not as small as the error with both eyes open. When only one eye with a fixed head was used, the error was very large.

Graham, Baker, Hecht, and Lloyd (1948; see also Graham, 1951) obtained the threshold for separation in depth of two needles pointing toward one another, as seen on a uniform field through a window. The needles moved from side to side on a common carriage. They appeared to be aligned at the center of their motion cycle and offset at the extremes of the cycle unless the adjustable needle had been set into the same frontal plane as the fixed needle. Graham thus eliminated for the first time in this type of experiment the additional sensory information produced by voluntary head movement.

More exactly, what Graham obtained was the just noticeable difference between two angular velocities in a field of view, under probably optimal conditions. The threshold was extremely low—about 30 sec. of arc per second of time. It is notable that the reports of what *O*s perceived, however, were not unanimous. Some saw the separation in depth as such; others perceived either the difference in velocity of the two needles or noticed the change of alignment or offset of the needles. Although the latter impressions may be cues for the former, the experiment was not concerned with the effectiveness of such cues for producing depth impressions.

Somewhat later, a case of motion parallax different from the two-velocity case was defined mathematically by Gibson, Olum, and Rosenblatt (1955). This is the array of angular velocities of the optical elements projected from a surface to a moving station point. There is a flow of velocities rather than a pair of velocities in such an array, and the phenomenon was named motion perspective to distinguish it from motion parallax as it had been studied up to that time.

For the study of the perceptions induced by flow-velocity in a field of view, including gradients of velocity, skew motions, and transformations, a different sort of apparatus is required from that previously employed. The two-velocity experimenters used a pair of real objects at real distances to produce the optical motions. More freedom is achieved by using a projection screen or some other optical means to produce them. The experiments to be described used shadows on a translucent screen. Accommodation is thereby controlled.

Several exploratory experiments have been published on flowing motion. They are of various types, and they have been produced in various ways. J. J. Gibson and Carel (1952) attempted to induce the perception of a receding surface in a darkroom with a bank of luminous points which carried a gradient of velocities. This stimulus failed to arouse the perception of a surface, however, and the depth judgments were ambiguous. O. W. Smith and P. C. Smith (1957) investigated the perception of convexity or curvature of a textured surface with various combinations of depth cues, including the flow-velocity type of motion parallax. Although motion in the field contributed to the judgment of convexity, in no case did motion cause a surface otherwise judged as flat to be judged as curved. Hochberg and O. W. Smith (1955) studied the perception of depth induced by the centrifugal flow of luminous pattern elements in the dark, the expansion phenomenon. J. J. Gibson and E. J. Gibson (1957) investigated the perception of the rigid rotation of an apparent surface elicited by the continuous perspective transformation of regular and irregular patterns or forms.

These experiments differed in the structure of the optic array used to "carry" the motion in question, and they also differed in the degree to which perceptions of space were aroused. They led to the choice of the kind of random texture employed in the present experiments, which is intended to yield the experience of a plane surface.

What is now needed is an experimental comparison of the judgments obtained with *two* velocities in a field of view and those obtained with *many* velocities in a field of view. Although no clear line can be drawn between them, the two-velocity type of motion parallax applies to the problem of perceiving a group of objects in otherwise empty space, while the flow-velocity type of motion parallax applies to the perceiving of a background surface such as a wall (or substratum). These are not the same problem for perception even though it may be difficult to distinguish sharply between their respective kinds of stimulation.

Optical geometry of motion parallax.—The environmental situation which leads to an array of different motions in a visual field should be defined more carefully. This is the optical geometry of motion parallax, as distinguished from the visual appearance of motion parallax. Graham (1951, pp. 878 ff.) has given the geometry of certain special cases of this situation. J. J. Gibson et al. (1955) have analysed the case of an extended surface such as the ground. What will be discussed here is the case of an environment of discrete objects.

When light rays from permanent objects of an environment converge to a point, they constitute what may be called an optic array, and the elements of this array constitute a pattern. An eye or a camera at the station point can register this pattern of luminous elements. If the point moves, the pattern is altered in a way which depends on both the displacement of the point and the layout of the objects. How the eye responds to this alteration of pattern is our problem.

The first question is how to specify mathematically the change of pattern in a way that is relevant for vision. By choosing a coordinate system for the array, one can specify the absolute position of each element and the displacement of each element per unit of time, that is, its absolute angular velocity. It would then be true in a certain sense, as Helmholtz (1925, p. 295) said, that "the apparent angular velocities of objects in the field of view will be inversely proportional to their real distances away." But more exactly, it would be true only if the linear velocity of the station point were constant (J. J. Gibson et al., 1955). A given angular velocity is a cue for distance, or permits a "safe conclusion" about distance, only if the speed and direction of one's locomotion is known.

The trouble with positions and angular velocities of elements in a field is the difficulty of understanding how an eye can register them. As the Gestalt theorists have emphasized, what the eye seems to pick up is the mutual separation of elements, their pattern, rather than their position or directions. And, accordingly, it is easier to suppose that the eye responds to changes of separation, or change of pattern, rather than to absolute displacements or velocities. Helmholtz might better have asserted that a difference between the angular velocities of two elements in the field will be directly related to the difference in distance between the corresponding objects in space. Such relative velocities involve a transformation of pattern, and this may be what the eye is primarily sensitive to. It is not immediately evident what the best method is for specifying the information about objects in an array of light projected to an eye.

But one fact should be clear. Only if there is an eye at the point of projection and only if it is sensitive to the motions in the optic array, relative or absolute, does a psychological question arise. Will the possessor of the eye see merely the change of pattern of the array? Or will he see moving objects in the field of view? Or will he see stationary objects at different distances? In order to show that motion parallax is effective for the perception of depth it must be demonstrated experimentally that differential motions in an array of light to an eye will yield differential judgments of depth. And the array should be such that when the motion is eliminated the judgments of depth will cease, for only then will motion parallax have been isolated from other cues for depth.

Experiment I: Motion Parallax With Two Velocities

Problem and Method

The two-velocity experiments were repeated with (*a*) two spots in a field to carry the motions, and (*b*) two superimposed textures filling the field to carry them. In both cases the velocity *difference* was taken to be the essential cue for possible judgments of depth, not the absolute velocities. In this experiment, reports were obtained for a large velocity difference, a small velocity difference, and no velocity difference, that is, a motionless field. The last was a control.

Apparatus and stimuli.—The light entering *O*'s eye came from the translucent screen of a point source shadow-projector (J. J. Gibson, 1957; J. J. Gibson & E. J. Gibson, 1957). He saw only a luminous rectangular field in which dark circles or textures could be made to appear and to move. These were actually the shadows of opaque substances attached to a transparent mount behind the screen. This was a large sheet of glass or plastic whose edges were never visible. Differential translatory velocity of the shadows was produced with two mounts, one behind the other, which could be made to move parallel to the screen on a common carriage. The array of light to the eye was simply the reverse of the array projected to the screen, since the eye and the point source were symmetrically located equidistant from the screen (Fig. 1). The window was 32.2 $\times$ 36 cm. at a distance of 126 cm. from the eye, subtending an array 14.5° high and 16.2° wide. The window was viewed through an aperture by a seated *O*.

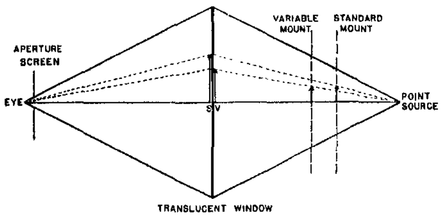

FIG. 1. The shadow projector viewed from above. In a unit of time, the shadow of a spot at the center of the standard mount sweeps through a certain angle and that of a corresponding spot on the variable mount sweeps through a lesser angle, as shown. The two mounts roll on the same carriage. If they are close together, there is no difference in angular velocity, but as the variable mount is positioned farther from the point source and closer to the screen, the angular velocity of its shadow decreases. With this apparatus, it can decrease to about one half of the angular velocity of the standard. By trigonometry, the ratio of the lesser (V) to the greater (S) angular velocity is equal to the inverse of the ratio of the distances of their respective mounts from the point source. In the diagram above, it is about 0.7.

The carriage which bore the two mounts rolled silently on tracks and could be pulled from side to side through an excursion of 45 cm. It was operated by hand to produce a motion cycle in about 8 sec. A small shutter close to the point source enabled *E* to eliminate the shadow between trials, leaving the screen illuminated by diffuse light.

The two adjacent spots in the field were produced by attaching small paper circles to each mount, at different elevations so that their shadows did not pass through one another as they moved across the field. The faster spot was above the slower spot. The diameter of both was 5.2°, one paper circle being compensated in size to match the shadow of the other.

The superimposed random textures were produced by a technique of sprinkling talcum powder over the surfaces of the two transparent mounts. This yields an optical texture with indefinite contours and indefinite elements. When the two were superimposed but motionless, they constituted a single texture with no cue for superposition, and gave the appearance of a single surface, something like that of a cloud. This apparent surface filled the whole window and appeared at an indefinite distance from *O*.

As noted, the two angular velocities as such were not uniform, decreasing to zero at either end of a motion cycle, and changing direction alternately. Minor variations in velocity also occurred as a consequence of moving the carriage by hand. The independent variable of this experiment was the difference in velocity between the two shadows. It was expressed as the ratio of the slower (the variable) velocity to that of the faster (the standard) velocity, or V/S.

Procedure.—Each *O* was seated at the apparatus, asked to apply his preferred eye to the aperture, and instructed simply to "describe what he saw in the window." He was first presented with a motionless field for as long as he needed to make a report, which was recorded. He was then presented with continuous cycles of motion at the maximum velocity difference (V/S = .51) until his report was completed. Finally he was given the minimum velocity-difference (V/S = .97). The *E* made no comment at any time, since wholly spontaneous reports were desired. The order of presentation was intended to minimize the effect of suggestion on the perceiving of depth.

A group of 26 *O*s went through this procedure with the spot field and another group of 46 with the textured field. Formal judgments and answers to questions were obtained afterwards from some *O*s, which will be described when relevant. They were requested in the terms used spontaneously by the *O*.

Results

The words used by the *O*s to describe what they saw varied widely, and the effect to identify things was reminiscent of descriptions of cognitive inference (Vernon, 1957). But the reports could later be classified easily with respect to depth or distance. The motionless textured field was unanimously reported to be a single surface without any difference in depth. The motionless spots, however, were reported at different distances by 4 of the 26 *O*s. The spots, therefore, did not wholly satisfy the requirement that impressions of depth be absent in the absence of motion, although the combined textures did.

A large velocity difference (.51) for the textured field always gave a perception of two surfaces separated in depth, as evidenced by the reports of all 46 *O*s. For the spot field, the reports were not unanimous, but 22 out of 26 *O*s did describe a difference in depth of the two objects.

The small velocity difference (.97) was evidently close to the threshold. None of the *O*s reported two separated surfaces for the textured field, and only 7 out of 26 reported different distances for the spots.

The direction of the difference in depth reported was not unanimous for either the spots or the textures. Insofar as two-velocity parallax is a reliable and effective indicator of relative depth, the faster velocity should correspond to the nearer object or surface. But 7 out of 26 *O*s saw the slower spot as the nearer object instead of the reverse, and 10 out of 46 *O*s saw the slower texture as the nearer surface. Some degree of ambiguity as to the depth-difference is also indicated by the fact that 7 *O*s reported spontaneous reversals of the front-back relationship between the two surfaces at one time or another.

The amount of separation in depth between the two objects or the two surfaces was estimated on formal request by a sample of these *O*s, after the main procedure. The estimates were highly variable. For the spots they ranged from zero to 5 ft. For the textures they ranged from 2 in. to 3 ft. Some *O*s were unwilling to judge, saying, "It depends on what it is," or "It could be infinity." Evidently the impression of how far apart these entities were was indefinite, as also was the impression of how far away they were.

Figure 2 represents an ideal theoretical possibility of what the *O*s might have seen in this experiment, but it cannot be asserted that this is what they did see. The reports indicated that they perceived two things of some kind in some kind of space behind the screen, but neither the direction nor the amount of their separation in the third dimension was definite.

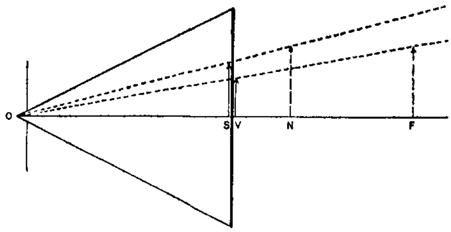

FIG. 2. The two angular velocities of Fig. 1, with a pair of virtual objects at different distances moving in apparent space. The two apparent objects (or surfaces) are shown as if seen behind the translucent window. The nearer (N) is shown close to the window; the farther (F) is shown at the distance it would have to be if the two were taken to be in rigid translation (if the two vectors were equal). In the diagram ON/OF = V/S, by trigonometry. That is, the distances are such that the optical velocities are inversely proportional to them. (Note that N corresponds to S, and F to V.) But this relation depends entirely on the assumption of rigidity. The absolute distances of N and F may vary, but the ratio of ON/OF will remain constant on that assumption. If rigidity is *not* assumed, however, there is no rationale for predicting any relation of distance or depth or even which object will be seen in front of the other.

Discussion

The significant result of this two-velocity experiment is not so much the effect of motion on depth perception as its effect in separating one surface into two. With the textures, all *O*s saw a single frontal surface when there was no differential motion, and all *O*s saw two frontal surfaces when there was a sufficient degree of differential motion. This separation is not what is ordinarily meant by depth, since it was not always clear which surface appeared in front and which behind.

The phenomenon is similar to the

"disentanglement" of foliage and branches which Helmholtz noted when he began to move in the thick woods. But this is not the same as his "apperception of depth." The separation is probably related to Wertheimer's (1923) demonstration that a group of spots interspersed among others will be unified by what he called their "common fate" if they moved together. Other conditions for the seeing of one thing in front of another, for transparency and superposition, have been discussed by Koffka (1935). Although the phenomenon may not seem relevant for some kinds of space perception it is certainly relevant for object perception.

How can this result be explained? Instead of appealing to a process of organization, or a law of "common fate," one might look for its basis in the geometry of the optical stimulus. Geometry distinguishes between (*a*) perspective transformation of forms, (*b*) topological transformations of forms, and (*c*) *disruptions*. These correspond roughly with the distinctions in physics between rigid motions of bodies, elastic motions of bodies, and the motions of breaking, tearing, or splitting. In this experiment, the motion of one set of textural elements relative to the other was a disruption, geometrically speaking. When sufficiently different velocities were imposed on them, the *adjacent order of elements* in the textures was destroyed. More exactly, there was a permutation of this order. It was a particular sort of permutation, to be sure, for each of two sets of elements retained an adjacent order, but the disruption of order as between these sets broke the original continuity. And this produced the perception of different surfaces with separation between. The detection by the eye of continuity or solidity as compared with discontinuity, disruption, or separation, is probably a fundamental kind of perception. The continuity of a single surface in two dimensions may be given by a static optical texture. But the continuity of a solid object in three dimensions probably depends on the kind of optical motion presented to the eye. Perhaps it was this lack of solid continuity or rigid connectedness between the nearer and farther surface in our experiment which prevented the ideal possibility represented in Fig. 2 from having been realized.

The earlier investigators of motion parallax were willing to assume that an eye was sensitive to the stimulus of motion, but they did not seem to realize that differential motion necessarily entails a *change of pattern*. In our experiment there were motions of the elements relative to the window but there were also motions of one set of elements relative to the other. For example, when both sets of elements were moving to the left, relative to the window, and one moved faster than the other, the slower was moving to the right, relative to the faster. Spontaneous reports of this appearance were given by several *O*s. Why should not a differential velocity be perceived just as directly as the two component velocities? When two moving elements are far apart in the field, one might suppose the slower and the faster velocity might have to be compared in order to detect a difference between them. But when the elements are adjacent in the field the difference is given by the change of pattern. Permutation of order is one type of change of pattern. In order to study the sensitivity of the eye to *form*, to *change* of form, and to the *forms* of change of form, a taxonomy of these variables is desirable.

Experiment II: Motion Parallax with a Flow of Velocities

Problem and Method

If a two-velocity field does not arouse consistent perceptions of depth, will a flow-velocity field do so? In order to make this comparison, the apparatus already described was modified so as to present to the eye a texture in which the horizontal velocities of the elements varied from slow to fast from the top to the bottom of the field, that is, a gradient. As before, the field could also be motionless.

Apparatus.—The shadows on the screen were produced by spattering paint on a transparent sheet interposed between the point source and the screen. This mount was slanted toward the screen at an angle of 45° (Fig. 3). By the principle of mirror reversal, the gradient at the eye should yield an apparent slant *away* from the screen.

If this texture had been composed of elements regularly spaced in a grid or pattern, then the gradients of size and spacing would have been effective in producing the impression of a slanted surface even when the texture was motionless, as previous research has demonstrated (J. J. Gibson, 1955). But as it was, the brightness-transitions which composed the texture were not sharp, the elements had indefinite sizes and shapes, and the static gradients, if present, were not effective in producing a perception of slant. This texture was nevertheless sufficient to produce the perception of a continuous surface.

As before, *O* looked through an aperture which prevented his seeing either the edges of the window or any other part of the apparatus. The field was 82° wide by 52° high. The eye and the point source were each 75 cm. from the window.

Procedure.—All *O*s were naive. Each was told that when he applied his eye to the aperture he would see a gray field of view, and was asked to report what he saw. They were divided into two groups, one of which was presented with the moving texture without ever seeing it static (Group I), and the other with the moving texture after having seen it static (Group II). Their spontaneous descriptions were recorded and later classified. Questions were asked only after these reports, and in the same terminology used by *O*.

Results

Nineteen out of 21 *O*s (Group I) reported a rigid moving plane surface of some kind slanting away from them at the top of the field. The inclination of the surface was estimated without difficulty, and they judged it to be receding upward. Of the 2 remaining *O*s, one's report was uninterpretable, and the other's was of a surface perpendicular to his line of sight.

With the static texture, 25 *O*s out of 28 (Group II) reported something which could be classed as surface-like, but which was in no case slanted backward into space. Of the remaining 3 *O*s, 2 saw a surface whose lower part was perpendicular but whose upper part was slanted back, and one saw the surface slanting back into space. When these 28 *O*s were later presented with the moving field, 26 saw it unambiguously to be a receding rigid surface at a fixed inclination. Of the remaining two, one saw it perpendicular to the line of sight; the other's report was uninterpretable.

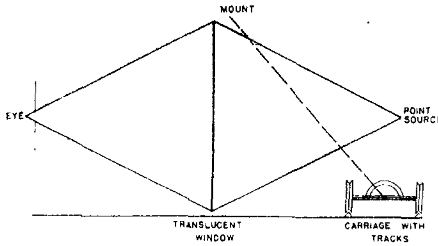

FIG. 3. The shadow projector giving a gradient of angular velocities, viewed from the side. The carriage and mount move back and forth parallel to the translucent window. The angular velocity is greatest at the bottom of the window, where the mount is closest to the point source, and least at the top, where the mount is farthest from the point source. At an inclination of 45°, this yielded a ratio of the minimum to the maximum velocity of 3 to 1. The apparent surface should appear to slant backward at the top.

Estimates of the slant of the apparent moving surface were obtained from each *O* in terms of degrees of inclination backward from the frontal plane. For Group I, the 19 judgments varied from 20° to 60° with a median of 40°. For Group II, the 26 judgments varied from 12½° to 55° with a median at 37½°. The theoretical value based on the gradient of velocities alone would be 45°. The medians show a constant error of underestimation. The surface never appeared to be at 90°, that is, it never looked like a ground on which *O* might be standing.

Estimates were requested of *how*

far away the apparent moving surface seemed to be from *O*, but these judgments, in contrast to those of slant, could not as easily be made. For the total of 49 *O*s, they varied from 3 in. to 5 miles. Some of these *O*s reported that it was possible to see themselves moving with respect to the surface instead of the surface moving with respect to them.

Discussion

These results indicate that motion parallax with a continuous gradient of velocities does induce consistent judgments of slant. This is the property of receding in depth in a certain direction. It is combined with the experience of a continuous rigid surface. The second experiment was like the first in most respects except that continuity of differential motion was introduced. To put it another way, permutation of textural elements was absent, but a skew of the pattern of elements was present. Judgments of distance in this experiment were highly variable and were made with reluctance, as they were in the first experiment.

There is evidently more than one kind of "depth" and more than one kind of motion parallax. The two experimental situations so far described were sufficient for judgments by naive *O*s of two kinds of spatial perception, (*a*) the phenomenon of separation in the third dimension and (*b*) the phenomenon of recession in the third dimension. Neither situation, however, was sufficient for absolute judgments of distance. This may be connected with the fact that no perception of a level ground was induced.

Experiment III: Correspondence Between Velocity-Pairs and Judgments of Depth Under Various Instructions

Problem and Method

In Exp. I, a difference in optical velocity did not induce the perception of a difference in visual distance with any great consistency. An explanation of this result has been suggested in terms of the absence of continuity between the two velocities. Another possible explanation however, in the spirit of Helmholtz, would be that the expected perception did not occur because *O* did not interpret the two motions as a difference in distance, or had not learned to perceive differential velocity as a difference in distance. On this theory, the suggestion that there was always an element of depth between the objects, with instructions about the limits of this separation, would be expected to alter the perceptions and lead to consistent judgments of depth. This prediction was tested in Exp. III, using the textures and spots of Exp. I.

Naive *O*s were given one of three degrees of suggestion or verbal information about depth, and were asked to reproduce on an adjustable but unmarked scale 1 m. in length the separation between the nearer and the farther apparent surface. The degree of velocity difference, the V/S ratio, was systematically varied so that judgments could be correlated with it.

Procedure.—All *O*s, as previously described, initially made spontaneous observations to the request "Describe what you see," in response to the motionless stimulus, the greatest velocity difference (V/S = .51), and the least velocity difference (V/S = .97). The apparatus was that of Exp. I. Each *O* then made 20 judgments of amount of separation for both the textures and the spots. The variable transparent mount was so set as to produce 10 velocity ratios of .51, .54, .57, .61, .65, .70, .76, .83, .90, and .97. Each ratio was presented twice, in random order, in the texture series and the spot series. Half the *O*s began with one series and half with the other. An *O* was assigned to one of three groups, and then instructed as follows:

Group I (*Least information*): The *O* was shown the sliding scale beside his chair and was told that it could be used to indicate the distance between the nearer and farther of the two (surfaces, spots). If *O* had used other terms instead of "nearer" and "farther," these terms were employed. He was then told that he would be shown a number of different settings of the apparatus, and that each time he would be asked to make a judgment (degree of separation, distance between, etc.). No other information was given. The *O* was encouraged to report as he went along but no comments were made on his performance. There were 16 *O*s.

Group II (*Maximum and minimum*): After the adjustable scale had been demon-

TABLE 1

MEDIANS AND RANGES OF CORRELATIONS BETWEEN VELOCITY RATIOS AND JUDGMENTS OF DEPTH

Measure	Stimuli	Group I ($N=16$)	Group II ($N=17$)	Group III ($N=20$)
Median r	Surfaces	+.72	+.67	+.83
	Spots	+.57	+.51	+.84
Range	Surfaces	−.23 to +.95	+.34 to +.85	−.18 to +.96
	Spots	−.52 to +.94	−.14 to +.85	−.45 to +.99
Number r's significant at $<.05$	Surfaces	12/16	15/17	19/20
	Spots	14/16	8/17	19/20

strated, these *O*s were given another demonstration of the greatest and the least velocity-difference and were told which one was the maximum and which the minimum. The procedure thereafter was the same as for Group I. There were 17 *O*s.

Group III (*Most information*): After the preliminaries described, these *O*s were told: "These are shadows of two (surfaces, objects) which are actually at different distances from you. One is farther away from you than the other. This is what they look like at their maximum separation, which is 18 in. (The *O* was shown 18 in. on the adjustable scale.) This is what they look like at their minimum separation, which is ½ in. (The *O* was shown ½ in. on the scale.) Each time I will ask you to estimate how far apart the (surfaces, objects) making the shadows are." The procedure was thereafter the same as for the other groups. There were 20 *O*s.

When each *O* had finished his judgments, he was questioned by *E* as to how he had made them unless he had already made this clear. The questions were: How did you make your judgments? Did you go by appearance of depth, or did you try to use some other cue? If some other cue, what was it? Did you ever see the front and back (surfaces, spots) change places or fluctuate? Did the two (surfaces, spots) ever appear to be connected, like parts of a rigid object?

Results

For each *O* a rank order correlation was run between his 20 judgments of separation and the corresponding velocity-ratios. Table 1 summarizes the median coefficients for the three kinds of instruction and for the two kinds of apparent objects, surfaces and spots. They range from .51 to .84. Eighty-seven of the 106 correlations were significant at the 5% level ($r > .44$). The data thus demonstrate some correlation between amount of differential velocity and degree of depth judged. The spread of the *individual* correlations was very great, however, ranging from −.52 to +.99.

Group III, which was given the most information, had higher correlations (medians of .83 and .84) than the other two groups. If individual correlations are considered, 19 out of 20 were significant for both the surfaces and the spots. The correlations of Groups I and II do not differ from one another. The demonstrating of the maximum and minimum stimulus presentations at the ends of the scale did not, therefore, improve the ordering of the estimates. But telling *O* that he was seeing shadows of two things separated by a given amount of space did so.

When the instructions were given, they seemed to make *O* begin searching at once, and quite deliberately, for cues which he could put into some order. Only a minority of the *O*s reported that they had depended on any "appearance of depth" in making their estimates. Considering all *O*s, 70% reported that they had used the "relative motion," or the "difference in speed," or "how far one passes the other" as the basis for judgment. Evidently, most of them saw motions of some kind of entities but did not clearly see the amount of space separating them.

The appearance of a connection between the two surfaces or spots "like parts of a rigid object" was almost never reported in answer to the question. The appearance of exchanging place or fluctuating in depth was reported by 17 out of 53 *O*s.

Because the more specific instructions raised the correlations, two *O*s (both psychologists and familiar with the apparatus and the problem) were run on consecutive days with reinforcement, to see how high the correlations might go and how stable they might become. The spots were not used in this experiment. The first 20 trials on each day were run without comment. But on the next 10 trials *O* was corrected after each judgment. The *E* did so by marking off on the scale the actual distance which separated the standard and variable mounts behind the translucent screen. This procedure of 20 uncorrected and 10 corrected trials was repeated for 9 days with one *O* and 7 days with the other.

The correlations improved rapidly from coefficients of .20 and .30 to ones of .90 or more. The introduction of new and unfamiliar textures had little effect on the correlation. Neither did the requiring of one *O* to use a verbal rating scale of 1 to 10 instead of the adjustable sliding scale.

These *O*s definitely took a problem-solving approach to the task and checked their methods of judging against the corrections given by *E*. One estimated the ratio of the two velocities and tried to express this numerically each time. The other said, after a few days, that the task had become similar to memorizing paried associates; he was trying to link up ordered "cues" with particular scale positions. The training did not have the effect of producing or enhancing an immediate appearance of depth.

Discussion

After verbal suggestion, information, or training concerning separation in depth, a correlation was present between the degree of velocity-difference and the degree of separation judged. It was raised by information and corrected training. But the reports indicated that the *O*s generally saw motions rather than depths, and that the appearance of depth was not induced by information or training. They were led to look for and use cues for the required judgments of depth, but not to report that they perceived it. They could interpret a velocity-difference as a depth-difference if given instructions, and they could improve the consistency of their estimates if given reinforcement. They could learn to perceive in one sense of the term, but they did not learn to see a differential velocity as a difference in depth.

This result does not support the theory of "unconscious inference" or point to any process for the conversion of bidimensional impressions into perceptions. It should be remembered, of course, that in these experiments motion has been isolated from other determinants of perception. This does not occur in everyday life. Motion usually comes in conjunction with size, shape, density, and disparity. But it might be supposed that the fact of this conjunction over years of past experience would have given an associative cue value to the motions in our experiment. In that case the velocity-pairs should have produced spontaneous judgments at once. Since they did not, this particular theory of cue learning is not supported by our results.

SUMMARY

The common assertion that motion parallax is a cue for depth perception is vague. The optics of differential velocities of the elements in a field of view were examined and two cases were distinguished: that of *two* velocities in the field and that of a *gradient* of velocities in the filed. The two-velocity case yielded consistent perceptions of the separation of one surface into two. The flow-gradient case (motion perspective) yielded consistent perceptions of slant, or rate of recession in depth. In neither case were there consistent judgments of distance from *O*. Still another case, that of two different velocities of

two different spots in an otherwise empty field, did not yield consistent space perceptions of any kind. Evidently Helmholtz was wrong about an "immediate apperception" of the distances of bodies or the depth between them solely from an impression of the velocities of spots in the field of view. The only consistent or "immediate" impressions obtained were those of separation in depth (in response to a permutation of adjacent order of texture), and recession in depth (in response to a transformation of the texture).

These were spontaneous perceptions in the sense that no other information was given *O* than that carried in the optical stimulation. When he was given verbal information about depth in the two-velocity situation he was able to correlate a judgment of depth with an impression of motion. But the correlations were not perfect, and a minority of *O*s "saw" the depth. One might conclude from these facts that there are two kinds of optical stimulation for experiences of space: a kind which requires additional information to yield consistent judgments, and another kind which does not require it—which is compelling or coercive. The facts also suggest that there are two kinds of experience of space: "empty" depth, as exemplified by one surface in front of another, and "filled" depth, as exemplified by the slant or recession of a surface. The depth of a surface is perceived more consistently than is the depth of the space between surfaces, in our situation.

As regards the perception of absolute distances, this probably depends on the perception of a terrain or ground surface, the conditions for which were not reproduced in the present experiments. For the investigation of this problem, a very large field of view is required.

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