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OPTICAL MOTIONS AND TRANSFORMATIONS AS STIMULI FOR VISUAL PERCEPTION [1]

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How do we see the motions of objects in the world around us? The way to go about answering this question is to note the kinds of physical motion that occur in the human environment and then to examine the kinds and variables of optical stimulation that correspondingly occur. The isolation and control of these variables with suitable optical apparatus will make possible an experimental psychophysics of kinetic impressions. The desirability of such a psychophysical approach has been pointed out in an earlier paper (4) and the following proposals modify or make explicit a number of suggestions there made.

Distinction Between Physical Motions and Optical Motions

Ever since Isaac Newton supposed that the motions of things revealed the forces behind them and thereby the causes of all events, physics has been concerned with the observation of motions. The beauty of the idea for physics is that it applies to *all* things: stars and planets; stones, machines, and animals; particles and atoms. Of these motions, however, only a certain class is the concern of perceptual psychology. The things whose motion is visible are substances which, in the first place, differentially reflect or emit light and, in the second place, are not either too far away or too small. The motion of the wind is invisible because gaseous substances transmit light instead of reflecting it. The motion of the heavenly bodies is invisible because their angular change of position is too small per unit of time. And the motion of microscopic bodies is invisible because their boundaries reflect an optical texture too small for the eye to resolve. But the environment of man contains an enormous variety of surfaces which do project focusable light to his eye, and these are the bodies the psychologist must be interested in. For when they fall, rise, turn, roll, bend, flow, twist, writhe, stretch, or break, an eye can register this event and the animal possessing the eye can respond to it.

We may observe that physical motions can be classified as *rigid* or *nonrigid,* the former being characteristic of crystalline substances and the latter of elastic or fluid substances. Rigid physical motions are exemplified in mechanics; they are analyzable into components of translation and rotation on or around any of three axes, and they have been studied since the time of Newton. Nonrigid physical motions are exemplified in biology since the growth and also the reactive movements of living animals are generally of this sort (10).

The motions of the physical environment might also be classified as *connected* or *nonconnected.* In the former the parts of the moving substance remain adjacent, even if not rigid, whereas in the latter they do not and are not even considered parts of the "same"

[1] This essay is part of an address entitled *Stimulation and Perception* delivered by the author in September 1955 at San Francisco as retiring president of the Division of Experimental Psychology, APA. The film which accompanied it, and serves to illustrate this paper (5), was produced with the support of the Office of Naval Research under Contract NONR 401(14) with Cornell University, which is concerned with research on the perception of motion and space.

substance. Instead they are treated as separate motions of different objects. The separations and fusions, attractions and repulsions, or collisions of things, animals, and people are all of this sort.

Physical motions are given to an eye only in the form of optical motions. An optical motion is an event in the *optic array,* that is, in the light reflected from an illuminated environment to an eye or, rather, to any position in the air where an eye might be placed (7). An eye is an organ for exploring an optic array. The solid sector of this array which an eye takes in is the basis of patterned vision; neither objects nor their motions could affect the eye except by means of it. External motion can be seen only if some differentiated part of the array is displaced relative to the rest of it, or to some other part, or if parts move relative to one another. There has to be some change of its pattern, considered as a projection to a point.

An optical motion, then, is a projection in two dimensions of a physical motion in three dimensions. The projection may be taken either as on the surface of a sphere centered at the eye or as on a plane in front of the eye. When locomotor movements of the observer are to be considered, the former is preferable (8), but when, as here, they are not involved, the plane projection is better. The one can be converted into the other if necessary. Our question is, What kinds of optical motion occur which might serve as stimuli for perception?

KINDS AND VARIABLES OF OPTICAL MOTION

How can optical motions be described or specified? The question has to do with the motions of a texture or pattern in a two-dimensional array. Tentatively, there seem to be two general possibilities. First, one could divide the pattern into convenient elements, describe the positions of all the elements by pairs of coordinate values, and finally describe the motions of all the elements by the successive pairs of values. Or one could describe the motions of the elements by direction and speed at successive moments of time. This procedure is analytical. Second, a non-analytical method of specifying optical motions is possible. One could simply take the pattern as given, and then use the operation defining a *perspective transformation* in geometry to describe a family of changes of pattern. This method does not exhaust all the varieties of optical motion, as will be evident, but it has advantages for an experimenter who needs to produce an artificial optical array.

Continuous perspective transformations. In geometry, any form or pattern on one plane which is a projection of a form or pattern lying on some other plane is called a *perspective transformation.* These forms are static. When the point of projection (the focus of the sheaf of lines which connect the pair of forms, point for point) is near the two planes, we speak of a *central* or *polar* projection; when this point of projection is at a very great distance from the planes, we speak of a *parallel* projection. (It may be useful to recall that the "plans" and "elevations" of an architect are cases of parallel projection, but that his drawing for the client's eyes is a case of polar projection. This latter is the case we are chiefly concerned with.) When the two planes are parallel, the difference between the projected form and the given form is one of size only; it is called a *similarity* transformation. When the two planes are not parallel, the difference between the forms is that to which common meaning applies the term "perspective," or sometimes the term "foreshortening." In geometry, both the difference of size and that of shape are classed as perspective transformations.

We can now speak of motion. When the angle or the distance of the first plane relative to the second plane is altered, the projected form is correspondingly altered. The fact is that the relation between any earlier and any later projected form is *also* a perspective transformation. The relation holds between any two of its stages in times. Hence, the motion in question may be described as a continuous series of perspective transformations. It is a relation between a temporal series or family of static forms, not merely between two forms. Any such moving transformation can be analyzed by six parameters corresponding to the six components of the possible movements of the first plane—that is, three of translation and three of rotation.

Families of continuous perspective transformations. It can now be observed that all optical motions resulting from the rigid physical motions of the flat face of an external object are continuous families of perspective transformations, as defined above. These are optical motions as taken on a plane in front of the eye. The six parameters of optical motion can be visualized as (*a*) vertical translation of the pattern in the plane, (*b*) horizontal translation of the pattern, (*c*) enlargement or reduction of the pattern, (*d*) horizontal foreshortening of the pattern, (*e*) vertical foreshortening of the pattern, and (*f*) rotation of the pattern in the plane.

These parameters of transformation are for the case of a *polar* projection. As the focus of projection is taken at an increasing distance from the two planes, one approaches the case of a *parallel* projection. For the latter case, three of the six parameters have been altered in character, namely (*c*), (*d*), and (*e*) above, while (*a*), (*b*), and (*f*) remain unaltered. Enlargement or reduction of the pattern has vanished; horizontal foreshortening becomes a mere horizontal flattening; and vertical foreshortening becomes vertical flattening.

These "pure types" of optical motion can be observed on a motion picture screen (5). An irregular or regular contour shape or an irregular or regular group of spots can be made to undergo continuous perspective transformations, and the observer can note the various types of motion in the plane of the screen. One can note, for example, that in types (*d*) and (*e*) a square is transformed into a trapezium with polar projection, but is transformed into a flattened rectangle with parallel projection. The interesting fact, however, is that for types (*c*), (*d*), and (*e*) with polar projection it is *very difficult to notice* the motion in the plane. Instead, one sees a sort of "virtual" object or surface which (*c*) moves toward or away from the screen, (*d*) rotates on its vertical axis, or (*e*) rotates on its horizontal axis. One sees, in other words, rigid motion in depth. The suggestion is that the parameters of transformation are stimuli for the phenomenal parameters of the motion in space of one face of an object.

The rotations in depth are similar in some respects to the kinetic depth effect obtained by Wallach (14). Such effects have been observed for Lissajous figures (3), and long ago for the silhouette of a rotating windmill against the horizon (1, p. 270). All these apparent rotations are said to be characterized by ambiguity as to the direction of rotation, and by spontaneous reversals in the direction of rotation. The apparent rotations shown in the film, however, are *not* characterized by ambiguity or reversals of direction when the transformations are those obtained with polar projection, but only when the transformations are those obtained with parallel projection.

A psychophysical experiment has been performed on the degree of perceived semirotation in depth as a function of the transformation sequence (6).

APPARATUS FOR PRODUCING CONTINUOUS PERSPECTIVE TRANSFORMATIONS IN THE OPTIC ARRAY

The method used to display the geometrical transformations on a motion picture screen was not by "animation" of film; the procedure, rather, was to photograph the window of a device which might be called a shadow transformer. Details of its construction are given in the report of the experiment (6). It will here be described only as it suggests possibilities for a psychophysics of motion perception. It consists of a translucent screen with a point source of light on one side and an observer symmetrically on the other side. In the square luminous window, dark shapes, patterns, or textures can be made to appear. They are shadows, not objects, so that only two grades of intensity exist, surface texture and binocular disparity are eliminated, and accommodation and convergence are controlled for this sector of the optic array to the eye. The variables of form and transformation are thus isolated for study.

In the diverging ray sheaf from the point source to the translucent window a mount can be placed, a pane of transparent material large enough so that it can be moved without its edges being projected on the screen. Forms, patterns, or textures cut from gummed paper or masking tape can be attached to this mount, or it can be traced with ink or even sprinkled with talcum powder, so that shadows of many varieties are projected on the screen. The mount can be rotated on any of three axes, or translated in any of three dimensions. Hence, considering the mount and the screen as two geometrical planes, changes in the position of the mount will yield all possible perspective transformations of the shadow relative to the shadow caster, and likewise all parameters of continuous perspective transformation of the shadow itself. Previous shadow-casting devices, most recently Wallach's (14), have not been constructed for this systematic purpose. They have also not utilized polar projection. For purposes of comparison, the present apparatus can also be illuminated by a projector

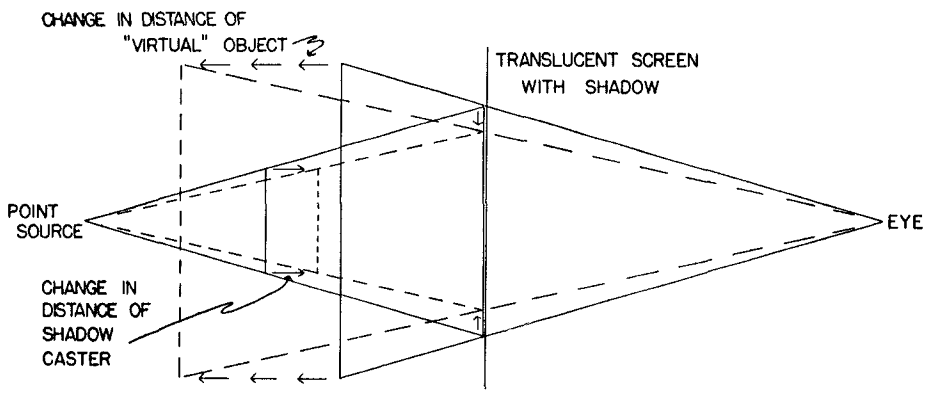

FIG. 1. The shadow transformer.

beam at 80 ft. instead of a point source at 5 ft.; the former yields an approximately parallel projection. The use of a transparent mount obviates the necessity of any visible support for the shadow caster, or of having the shadow it casts extend below the bottom of the window.

The optical geometry of the apparatus is given in Fig. 1 for a size transformation. It may be noted that the converging ray sheaf to the eye is the geometrical opposite of the diverging ray sheaf. The relation of the shadow to its "virtual object" (by analogy with the "virtual image" in a mirror) is simply the reverse of the relation of the shadow to the shadow caster. This reversal does not affect the transformations in any other way. It is true that the motions perceived are opposite to those of the shadow caster, but this does not present a paradox if one remembers that vision depends on the optic array, not on the way an optic array can be artificially produced.

Internal Depth of Transparent Objects and Collections of Objects

So far, consideration has been limited to continuous transformations of textures corresponding to the opaque face of an object. What about the optical motions corresponding to the physical motions of transparent objects, or things with different parts in depth, or rigid collections of things like a forest of trees or a tangle of wire? The phenomenon termed "stereokinesis" (11, Ch. 13 and references) and the kinetic depth effect of Wallach (14) involve an impression of *internal depth*. The "virtual object" of these experiments is often a collection of posts or a figure of bent wire.

The complex optical motions of these experiments can be analyzed by considering different parameter values of the same perspective transformation corresponding to the different planes of depth of the object. This suggestion becomes clearer with a concrete example. If, with the shadow transformer, one casts a shadow on the screen through several parallel sheets of glass, each of which has been sprinkled with talcum powder, the composite shadow looks something like the Milky Way in the night sky. When the sandwich of mounts is *moved*, however, the perception separates into clear planes of depth, each layer of nebulous material standing in front of its neighbor. The effect is shown in the film (5).

The internal depth of the virtual object produced by the moving shadow of a bent wire, or by an arrangement of vertical sticks on a horizontal turntable, has been frequently studied. The writer suspects that it will yield to the kind of analysis proposed. The depth is similar to binocular stereoscopic depth; a unifying hypothesis would be that the simultaneous disparity of binocular images is only a special geometrical case of the successive disparities of a continuous image. Both rest on the geometry of parallax, that is, the projection of a collection of objects in space to a point in space, and this has led Tschermak to include both under the term "parallactoscopy" (13). Both are transformations in the most general sense of the term, and perhaps both sorts of disparity should be treated as transformations.

The impression of surfaces meeting at a corner. With the apparatus described, one can also produce the impression of *more* than one flat face of an object moving in depth. If two transparent mounts are joined to make an angle, and if both are given some opaque texture of any kind, the combined shadow looks like a plane surface so long as the combined mounts are kept stationary. When they are moved, however, the shadow becomes two faces or surfaces making a corner. The relative slant of one surface to the other can be judged with some accuracy.

WHAT IS THE STIMULATING EFFECT OF NONPERSPECTIVE TRANSFORMATIONS IN THE OPTIC ARRAY?

If the rigid mechanical motions of the physical environment are represented by one kind of geometrical transformations in the pattern of light, are the nonrigid biological motions of the environment represented by a *different* kind of geometrical transformations in the pattern of light? The difference is suggested when the geometer describes topology as "rubber sheet geometry." This is concerned with changes of bidimensional form *other* than the changes heretofore described. Considering an organism in silhouette, its reactive movements cannot be compounded of the six pure types of optical motion considered above. Neither can its growth be described as magnification. Medawar, a biologist following D'Arcy Thompson, seems to have demonstrated that the change of shape of the human figure from infancy to adulthood, disregarding the change of size, is a specific continuous transformation which can only be suggested in words. A "tapered stretch" describes it approximately (10, pp. 177 ff.). The change is monotonic, i.e., it keeps the same trend. Geometrically, there are different *forms* of change of bidimensional form. Conceivably, the visual mechanism is sensitive to these forms of change.

The shadow transformer can be adapted to display nonperspective transformations if an elastic or flexible sheet is used for the transparent mount which carries the shadow-casting form or texture, and if this is stretched or bent in some way. Preliminary observations suggest that the resulting perception of motion is correspondingly elastic instead of rigid. There are technical difficulties in controlling such optical motions. But if apparatus can be built for systematically producing them, it will be open to the perceptual psychologist to study such phenomena as animate, expressive, and physiognomic movements in the manner of psychophysics.

DISJUNCTIVE OR SEPARATE OPTICAL MOTIONS

The converting of a single form on a plane into *two* forms is something which goes beyond the continuous transformations heretofore considered. There is, instead, a discontinuity in both the temporal and the spatial series. The geometer is tempted to describe it by saying that there is a breaking or tearing of the surface, thus falling back on a physical analogy.

If certain parts of a connected optical pattern undergo one kind of transformation while other parts undergo another kind, it might be predicted that the perceived surface will become two perceived surfaces, each composed of the parts carrying the same transformation. This is obvious when one set of parts moves in one direction and the other in a different direction, and the fact was recognized in Wertheimer's law of "common fate" as a determiner of sensory organization (11, Ch. 13). It should equally be true, however, when one set of parts carries a slant transformation or a size transformation different from that of the other; the texture will break into two textures each moving in its own tridimensional way. Some of these possibilities have been investigated by using a "sandwich" of mounts in the apparatus, and the film illustrates a few of these possible dual disjunctive motions. Perceptual separation does result. Evidently when the parts of an optical texture undergo *joint motion* this does not have to be understood as a set of motions with the same velocity in the same direction.

It is also possible to note what happens when *all* the parts of a connected optical pattern move, each in a different direction: the pattern becomes many smaller objects, like a swarm of ants. This result also suggests that what connected the elements of the pattern in the first place was their nonmotion relative to one another; in the optic array, after all, stability is only a special case of transformation. Research on the problem of how elementary motions might be *organized* into a single unitary motion has been performed by Johannson (9), Duncker (2), and Metzger (11).

The varieties and dimensions of optical motion in which the parts are *not* connected in adjacent order are of formidable complexity. It is not even clear how to go about classifying them. Disjunctive optical motions are, however, the stimuli by virtue of which we see occurrences, happenings, and actions in the world around us. There is certainly order and lawfulness in them, for Michotte has studied the impressions of causality induced by higher order variables of nothing more objective than the motions of separate spots (12). These abstract variables are clearly discriminable by observers, for the impressions can be made to come or go as the experimenter varies certain spatiotemporal conditions.

CONCLUSIONS

If the optical geometry here expounded is correct, there is a possible basis in optical stimulation for the ability to distinguish between and among rigid, elastic, and multiple moving things. The basis lies in different mathematical modes of transformation and motion. The implication is that we see both the constant and the changing properties of things in this way. We see them not because we have formed associations between the optical elements, not even because the brain has organized the optical elements, but because the retinal mosaic is sensitive to transformations as such. These are stimuli for perception.

Is it really plausible, one might ask, to call anything as apparently abstruse as a continuous series of transformations a *stimulus?* A bit of evidence may here be convincing. A puff of air to the cornea of the eye is a stimulus for the blink reflex in the pure and original sense of the term. The fact is that when an observer with the apparatus described is near the screen, a rapid expansion of the shadow until it fills the screen will also produce a blink reflex. The latter event ought to be considered as much a stimulus as the former.

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