Journal of
Experimental Psychology

VOL. 45, No. 4 APRIL, 1953

THE KINETIC DEPTH EFFECT

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The problem of how three-dimensional form is perceived in spite of the fact that pertinent stimulation consists only in two-dimensional retinal images has been only partly solved. Much is known about the impressive effectiveness of binocular disparity. However, the excellent perception of three-dimensional form in monocular vision has remained essentially unexplained.

It has been proposed that some patterns of stimulation on the retina give rise to three-dimensional experiences, because visual processes differ in the spontaneous organization that results from certain properties of the retinal pattern. Rules of organization are supposed to exist according to which most retinal projections of three-dimensional forms happen to produce three-dimensional percepts and most retinal images of flat forms lead to flat forms in experience also. This view has been held mainly by gestalt psychologists.

Another approach to this problem maintains that the projected stimulus patterns are interpreted on the basis of previous experience, either visual or kinesthetic. However, such empiricistic assumptions do not explain much, unless it is made clear how those previous experiences come about whose influence is supposed to account for the current perception. Kinesthetic form perception itself presents far more complex problems than does three-dimensionality in vision, and recourse to kinesthesis appears at present quite futile. Retinal disparity can of course account for that previous visual experience insofar as *S*s with binocular vision are concerned. Whether in the absence of binocular vision, e.g., in congenitally monocular *S*s, head movement parallex can fully play the role of binocular parallex appears doubtful. It seems that all we have left to account for an original experience of three-dimensional form in monocular *S*s is the assumption that certain patterns of retinal stimulation will naturally produce experience of solid form. However, once it is assumed that perception of three-dimensional form can follow directly from retinal stimulation because of spontaneous organization of visual processes alone, there is no point in postulating an influence of past experience.

Unfortunately it appears that no one has succeeded in formulating rules of

[1] Most of the work reported in this and the following paper was done while the senior author was holder of a John Simon Guggenheim Memorial fellowship.

spontaneous organization adequate to predict which pattern of retinal stimulation will lead to perceived flat figures and which one will produce three-dimensional forms. We have made a vain attempt of our own and have become convinced that the three-dimensional forms perceived in perspective drawings, photographs, etc. are indeed a matter of previous experience.[2] In this situation the search for a visual process which can account for an original perception of three-dimensional form in monocular vision becomes imperative. Such a process will be described in this paper.

When one moves about, the retinal image of solid objects lying to the side of one's path not only expands but also distorts, because the objects are seen successively from different directions. More specifically, a retinal image distorts under these conditions as if the corresponding object were rotated through a certain angle in front of the eye of a stationary observer.

This fact suggests a simple technique for the investigation of the perceptual results of these distortions. An object is placed between a punctiform light source and a translucent screen and is rotated or turned back and forth. Its shadow is observed from the other side of the screen. The shadow-casting object is placed as close to the screen as possible, whereas the distance between the light source and the object is made large. Owing to this arrangement isometric projection is closely approximated. The shadows of a great number of three-dimensional forms, solid or wire-edged, will be perceived as three-dimensional under these circumstances. The shadows of some forms will look three-dimensional *only* in such a moving presentation; that is, in none of the positions through which such a form passes during rotation will it cast a stationary shadow which looks three-dimensional. With such forms one can study this effect in isolation. It will be referred to by the term "kinetic depth effect." It is important because it answers our problem: It appears that the kinetic depth effect can cause a genuine perception of three-dimensional form in a monocular *S* whenever he moves and keeps looking at an object which does not lie directly in his path.

[2] Evidence supporting this point of view will be reported in a subsequent paper.

Similar set-ups have been used before by Miles (3) and Metzger (2). Miles presented to *S*s the shadow of a two-bladed fan wheel in rotation, the shaft of which was parallel to the screen on which the shadow was formed. His *S*s reported a large number of different motion patterns, most of them involving depth, but no attempt was made to find out whether the object that was seen in motion was a good representation of the fan wheel whose shadow was presented. Metzger also was not primarily concerned with the perception of three-dimensional form which such a set-up can yield. In fact, he investigated with great thoroughness the effects of a very special kind of arrangement which is not favorable to the emergence of stable three-dimensional forms. He had arrangements of vertical rods rotate about a vertical axis and showed their shadows in a low oblong aperture which hid the ends of the rod shadows from view. As in Miles's experiment the motion patterns seen by a given *S* during an extended period of inspection were very changeable. Moreover, naive *S*s mostly differ among each other as to whether the first movement process which they perceive is in three dimensions or takes place in a plane. Suggestion has a strong influence, in the course of longer observation as well as initially. We shall see below that the patterns of line shadows which Metzger presented to his *S*s do not contain the condition essential for the kinetic depth effect.

The depth observed in Lissajous figures (1, 4) is the result of complex effects and will be discussed in a later paper.

Experiments to Define Conditions of Kinetic Depth Perception

Experiment 1: Rotation of solids.—One of the figures which we presented to many *S*s was a solid block in the

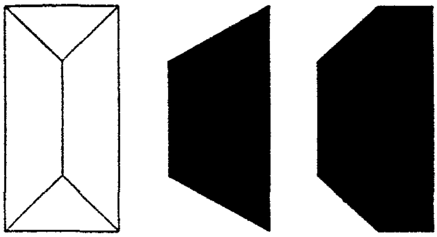

FIG. 1. Solid form (A) used in Exp. 1, and two samples (B, C) of its shadows

shape of a roof with sloping gables, as shown in Fig. 1A. This was rotated continually about its longest axis. Figures 1B and 1C show two of the forms of the shadow during rotation. When any one of the three figures is shown stationary to a naive *S*, it is described as a two-dimensional figure. When the solid is slowly rotated so that the shadow undergoes continuous deformation, *S* sees a three-dimensional solid in rotation. The direction of the seen rotation may or may not coincide with that of the object behind the screen, and this is in agreement with the conditions of stimulation which give no clue of the object's real direction of rotation. Which one of the two directions of rotation is seen seems entirely a matter of chance, and with prolonged observation *S* usually experiences a number of spontaneous reversals of the direction of rotation. Occasionally an *S* sees for long periods reversals after each rotation of 180°.

In experiments like this the impression of three-dimensional form is so natural that many *S*s who are not psychologists are not astonished by their observations. They correctly assume that behind the screen is just such an object as they see. Only after reversals of the direction of rotation have occurred do they begin to wonder.

Where the kinetic depth effect takes place, a rigid three-dimensional form in rotation is seen instead of the distorted two-dimensional figure given on the shadow screen. The distorting two-dimensional shape may occasionally be *seen* after prolonged exposure of the same kinetic presentation, or when one looks from a sharply oblique direction at the screen. The *S*'s experience of a continuously flowing form seems to him abnormal or unusual although this is exactly what is given on the retina.

The essential difference between this two-dimensional experience and the three-dimensional form which is usually seen seems to be that the latter is unchanging and rigid instead of ever changing and flowing. The changes in the shape of the retinal image are accounted for by a perceived rotation of the three-dimensional object, whereas in the two-dimensional process the seen movement distorts the form itself. As far as we can see, the distortions of the perceived two-dimensional form agree closely with the changes of the retinal image. But the perceived three-dimensional form is not determined merely by what is presented on the retina at a given moment. A single one of the projections of the shadow-casting object which make up the changing shapes of the shadow does not look three-dimensional. Only the sequence of changing shapes gives rise to the seen three-dimensional form. In other words, a single projection causes a three-dimensional form to be seen only because it was preceded by a number of other projections. By itself, it simply does not convey enough data about the three-dimensional form which it represents. The seen three-dimensional form is richer in structure than any single projection and it is built up in a temporally extended process. The individual retinal image determines only which aspect of the turning three-dimensional form appears to be given at the moment. Thus, perceptual experience far surpasses what one should expect of a process determined by momentary stimulation and seems to a higher degree a product of the immediate past than of stimulation occurring at a given moment.

Experiment 2: Partial rotation of wire figures.—Experiments of the kind just reported differ in two ways from the realistic situations in which the kinetic depth effect occurs. In the first place, a shadow-casting object is put through a complete rotation and produces a pattern of distortion on the screen which corresponds to that obtained when under natural viewing conditions an *S* moves completely around an object, which is hardly ever done. In the second place, in the shadow of a solid object an edge of the three-dimensional form is visible only

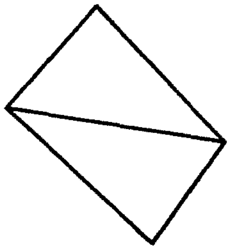

FIG. 2. The wire "parallelogram" used in Exp. 2

for a comparatively short period, namely as long as it forms a contour of the shadow, whereas in the realistic situation it usually can also be seen when it passes across the front of the figure. We therefore performed quantitative experiments with wire figures which of course show all edges continuously, and had them turn back and forth through an angle of only 42°.

Figures 2 and 3 each show projections of two of the wire figures used. The figure represented in Fig. 2 can best be described as a parallelogram containing one diagonal, which was bent along this diagonal so that the planes of the upper and the lower half formed an angle of 110° with each other. The other figure (Fig. 3A) consisted of a piece of wire twice bent to form part of what might be described as a triangular helix. Figure 3B shows a view from the top. These figures were turned back and forth through an angle of 42° at a rate of one cycle per 1.5 sec. and their deforming shadows were shown to individual *S*s one at a time for as many periods of 10 sec. as were necessary to obtain a clear report. After each 10-sec. exposure, *S* was asked for a report.

In the case of the parallelogram (Fig. 2) all of 50 *S*s sooner or later during the exposure periods reported

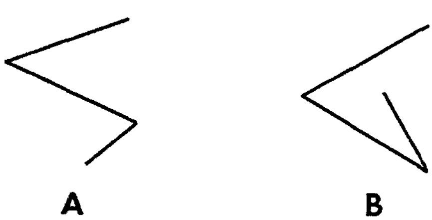

FIG. 3. The wire "helix" used in Exp. 2 (A) and its appearance from the top (B)

seeing a three-dimensional figure turning back and forth apparently very much like the wire figure behind the screen, except that it sometimes appeared to *S* in its inverted form. In the case of the "helix" 48 of the same 50 *S*s reported a three-dimensional form like the wire figure and 2 *S*s saw a flat zigzag line which distorted before their eyes, a process which corresponds to the changing pattern of stimulation. Evidence that the three-dimensional forms which were perceived were due to the kinetic depth effect and that none of the projections represented in the deforming shadow by itself would have been seen as three-dimensional was obtained in the following way. To a new group of 22 *S*s five such projections of each figure were presented individually in random order. They were the projections of the two extreme positions at which the figures stopped and started to turn the other way and of three intervening positions chosen to be at about 10° of rotation apart. None of these stationary projections looked three-dimensional to any one of the 22 *S*s. Positions intermediate between the ones presented resembled them so closely that it seems impossible that they would lead to a radically different perceived form.

Often the turning wire figures were seen three-dimensionally immediately upon presentation. Of 16 *S*s for whom time records were taken 11 reported the "parallelogram" in the correct three-dimensional shape after the first 10-sec. exposure period. In the case of the "helix" only 4 of 16 *S*s reported its shape correctly after the first exposure. The reason for this difference is yet to be investigated.

Once it has occurred, the three-dimensional impression is so strong that one cannot voluntarily see the two-dimensional figure which is given on the screen. It has been mentioned that the perceived three-dimensional figure may resemble the inverted form of the wire figure rather than that figure itself. This is to be expected, inasmuch as a three-dimensional figure and its inverted form have identical projections, such that a given projection is always a representation of both, a figure and its inverted form. The added fact that with prolonged observation of the distorting shadow the perceived three-dimensional figure may spontaneously invert in Necker cubelike fashion is also a consequence.

Experiment 3: Rotation of a truncated cylinder.—A systematic investigation of the kinetic depth effect resulting from rotation of a solid was attempted in the following manner.

A cylinder which is rotated about its axis casts a shadow which does not change in any way, but any cut that is taken off the cylinder and which is not at right angles to its axis produces a characteristic deformation of its shadow. A large number of wooden cylinders, about as high as wide, were made and cuts were varied systematically. The solid forms which were produced in this fashion were shown in complete rotation to *S*s who had no previous experience with our studies.

The results can be summarized in the following way: (*a*) Shadows whose only deformation consists in an expansion and contraction in one dimension will look flat; a dark figure is seen which periodically becomes wider and narrower. An example is the shadow of a rectangular block which is rotated about an axis parallel to a set of edges. (*b*) Shadows which display contour lines that change their direction and their length will appear as turning solid forms. The roof-shaped figure described above (Exp. 1) is an example; the shadow contour produced by an edge of a gable tilts and changes its length simultaneously (compare Fig. 1B and 1C). (*c*) Curved contours which are deformed without displaying a form feature which identifies a specific point along the curve are seen as distorting, often even if for some reason the shadow is seen as a three-dimensional form. This peculiarity is in disagreement with our description of the kinetic depth effect and has delayed our work for years. It is now clear that the perceived distortions of deforming curved contours are not related to the kinetic depth effect at all. They will be dealt with in a later paper.

Experiment 4: Rotation of straight rods.—When it became clearly recognized that shadows which display contour lines that change their direction and length will appear as turning solid forms, we checked whether this would also apply to single lines. Will a detached line which changes its direction on the screen and its length at the same time display a kinetic depth effect, i.e., will it appear to tilt into depth in such a way as to account for its shortening? The following experiments show that this is the case.

When a rod is fastened to the end of a vertical shaft at an angle of, say, 45° and is rotated about this shaft, the shadow which it produces tips from side to side. From a tilt of 45° toward the left, the shadow rights itself and goes through the vertical into a tilt of 45° toward the right and back through the same positions. At the same time it shortens and lengthens periodically. Its end points move on horizontal lines across the screen. This process is invariably seen as a motion in three dimensions, as nearly as one can tell exactly like the real movement of the rod behind the screen, a rotation describing a conical surface about a vertical axis.

This set-up lends itself to a variation which is interesting because the three-dimensional motion which is perceived is a different one from that which the rod behind the screen undergoes. The shaft on which the rod turns is tilted toward or away from the screen by 15° or 20°. This changes the pattern of expansion and contraction of the rod shadow completely; its end points now move on elliptic paths on the screen. Only rarely does the rod motion seem to describe a circular cone like the real movement of the rod behind the screen. In most cases a movement is seen in which the movement component of tilting toward or away from *S* is much smaller than the lateral movement component such that the surface described is that of an elliptic cone. Whereas the real rod goes in one rotation from a tilt toward *S* into a tilt away from him, the perceived motion of the rod is restricted either to a changing forward tilt or to a changing tilt away from *S*. Either one of these two different movements can of course be perceived because, like a three-dimensional figure and its inverted form, they would if they were objectively given produce the same projection.

It seems that what distinguishes in these experiments perceived movement from the two-dimensional process which is given on the screen and therefore on the retina is the fact that the perceived rod is seen with a constant length. Tilting into depth is seen instead of shortening. Inasmuch as the rod as a whole must anyway be seen to move, this tilting motion is only a modification of a necessary process and not an added change, which is what a perceived stretching and shrinking would amount to. Thus, a tendency to see one motion instead of the two simultaneous movements of the two-dimensional process (a tipping from side to side, and a stretching and shrinking) may be held responsible for the depth effect. Another possibility would be a selective principle according to which a line of constant length is seen rather than a changing one. No decision between these two possibilities can be made on the basis of our present results.

Experiment 5: Rotation of T *and* Δ *figures.*—It is important to realize that a shadow line must undergo both a displacement and a lengthening or shortening in order to produce a kinetic depth effect. Both these changes must be given together. A change in length alone is not sufficient to produce a reliable kinetic depth effect. This is shown in the following experiment.

A piece of 1/16-in. wire 4 in. long was fastened at right angles to a vertical shaft of the same diameter so that the two formed a figure of T shape. When this form was turned back and forth about the vertical shaft through an angle of 42°, the shadow of the horizontal wire formed a line of 105-mm. length which periodically contracted to a length of 75 mm. and expanded again. We presented it with a rate of one period per 1.5 sec. for 10 sec. to 24 *S*s.

Eighteen of 24 *S*s saw a line in the plane of the screen expanding and contracting and only 6 *S*s perceived the line turning in the third dimension. Had the horizontal wire been in an oblique position with respect to the axis of rotation so that its shadow had shown a displacement in addition to the change in length, the kinetic depth effect would have been obtained with the majority of the *S*s, as the experiment with the oblique rod would predict.

Because of its importance we had the experiment with the T figure repeated by another *E* and obtained the same result: Of 40 *S*s, 30 saw the horizontal line expand and contract in the plane of the screen and 10 saw it turn.

These results must be compared with those of a different wire figure which does produce a kinetic depth effect under identical conditions. Comparable data come from a shadow presentation of an equilateral triangle. Its sides consisted of wires 5 in. in length, and one of them was tilted by 15° against the horizontal. When this figure was turned back and forth, the shadow of one of its sides changed from a slope of 45° to one of 57° and thus presented conditions favorable to the kinetic depth effect. Of 20 *S*s who observed the triangle for 10 sec. 17 reported a turning in depth and only 3 expansion and contraction. (With such a plane figure the kinetic depth effect consists, of course, in the perception of a plane figure that turns into depth.) This score is to be compared with that for the **T** figure where only one-third of the *S*s saw a turning. The difference is reliable at the .001 level of confidence.

Still, the 6 and 10 *S*s who saw the **T** figure turning in depth need be accounted for, if our claim is correct that they are not the outcome of a genuine kinetic depth effect. Here the following result is significant. When the **T** figure was presented *following* the presentation of the triangle, 15 out of the 17 *S*s who saw the triangle turn saw the **T** figure turn also. (Three *S*s who saw the triangle expand and contract reported the same for the **T** figure.) In other words, when a figure that *S*s saw turning preceded the presentation of the **T** figure, a large majority of *S*s saw it turning also. This shows a strong influence of a previous perception on the manner in which the **T** figure is seen, for only one-third of the *S*s saw the **T** figure turning when it was given as a first presentation. This difference is significant at the .05 level of confidence. We suggest that in the case of these latter *S*s some such influence of a previous experience, though a more remote one, has been at work also.

We are inclined to conclude that a line which changes in length but is not displaced at the same time does not give rise to the kinetic depth effect. This agrees well with the already reported finding that a solid shadow which expands and contracts only in one dimension will not show the kinetic depth effect either.

The Accuracy of Kinetic Depth Perception

When we described the kinetic depth effect in complex figures, we stated that the change in the retinal image is accounted for in perception by a rotation of a three-dimensional form. This implies, of course, that a *real* form which is like the perceived one would in rotation produce a sequence of retinal images very similar to that actually given, or, in other words, that the perceived form resembles closely the shadow-casting object. That this is the case has been confirmed by many *S*s to whom the shadow-casting object was directly shown immediately following the kinetic presentation.

For more stringent confirmation several methods were used: In the case of the "helix" (Fig. 3), *S*s were asked to bend a piece of wire into the shape of the figure which they saw turning on the screen. Only *S*s who reported seeing a three-dimensional form turning back and forth were given this test. Of 29 *S*s, 13 made good reproductions, 12 fair ones, and only 4 *S*s made poor reproductions. Eleven of the 12 *S*s whose reproductions were fair were later asked to make another reproduction while they looked *directly* at the turning wire figure. Of these only 7 were able to make good reproductions and 4 made only fair ones under these conditions. Altogether there were 8 *S*s who could make only fair reproductions when they viewed the figure directly.

In the case of the parallelogram (Fig. 2), the accuracy of perception by virtue of the kinetic depth effect was checked by showing *S* four similar wire figures and asking him to pick out the one that matched best the form he saw turning on the screen. As mentioned earlier, the bend in the shadow-casting figure amounted to an angle of 110° between the planes of the two triangles which made up this figure. This angle is, of course, characteristic of its three-dimensional form. If this angle were 180°, the wire figure would be plane. In our four models the bend amounted to angles of 95°, 110°, 125°, and 140°, respectively. The one with the 110° angle was an exact copy of the shadow-casting figure; the other three models had the same height as the standard and were made to produce projections on the frontal plane which were identical with the projection of the standard. The four models were inserted in a wooden block and handed to *S*. The choices of 30 *Ss* who had previously reported seeing the three-dimensional figure were 8, 17, 4, and 1 for the 95°, 110°, 125°, and 140° figure, respectively. Only one *S* found it impossible to make a choice. It is unfortunate that we did not include one more model with a still sharper angle, but even so the data give a rough idea of the accuracy of the perception of three-dimensional form which is based on the kinetic depth effect.[3]

Experiment 6: Rotation of luminous rod.—Another attempt to obtain a measure of the accuracy with which depth perception functions by virtue of the kinetic depth effect was made employing a straight line which rotated in an oblique plane. When a line is turned in a frontal-parallel plane about its midpoint, the end points of its retinal projection move on a circle. However, when it rotates in an oblique plane, its retinal image changes in length as it turns, and its endpoints move on an elliptic path. Therefore, when in the dark a luminous line is rotated in a frontal-parallel plane about its midpoint and is exposed from behind an elliptic aperture, its retinal projection will be the same as that of a line which turns in an oblique plane, for the aperture causes the line to be visible with the same changes in length. If the motion of the line that rotates in an oblique plane can be correctly perceived with the help of the kinetic depth effect alone, then the line rotating behind an elliptic aperture should also appear to rotate in an oblique plane, because the two lines produce identical stimulation so far as the kinetic depth effect is concerned. Other cues for depth perception as, for instance, retinal disparity, would give rise to experienced rotation in an oblique plane only in the first case. Thus when the rotating line behind the aperture is presented to a naive *S* and he perceives it turning in a properly oblique plane, one can be sure that this is due to the kinetic depth effect. By this procedure, as by the use of the shadow screen, the effect can be studied in isolation; other cues for depth perception would tend only to prevent the line from turning in an oblique plane.

A ½-in. lucite rod, approximately 23 in. long, served as light source for the luminous line. Its ends were flat and finely ground to admit a maximum of light. They were inserted in metal caps which contained hidden flashlight bulbs and also served as mountings. The light from these bulbs made the lucite rod appear to glow evenly over its whole length. The rod was inserted in a U-shaped sheet-metal trough of proper length and attached by the mountings. A bushing was fastened to the back of the trough at its midpoint and attached to the horizontal slow shaft of a reduction gear motor, so that the lucite rod could be turned in a vertical plane. The trough and rod were covered by a long strip of cardboard into which was cut an aperture 22 in. long and ⅛ in. wide. Through this aperture part of the rod's surface was visible. In front of this apparatus was a frame to which cardboards with different elliptic apertures could be attached parallel to the plane of rotation of the rod. Three different elliptic apertures were used. They were 40 cm. long and 35 cm. wide, 39.5 cm. long and 28.9 cm. wide, and 40 cm. long and 20.6 cm. wide, respectively. They produced projections of the turning luminous rod identical with the projections produced by a luminous line that turns in a plane forming an angle of 29°, 46°, and 59°, respectively, with the plane of the aperture. They were attached with the large axis of the elliptic opening in vertical position.

The *S* was seated in front of this apparatus at a distance of 9 ft. He had before him a small table covered with a light gray cardboard. A metal rod was joined at right angles to a shaft which was fastened vertically to the table, so that the rod could be swung around in a plane parallel to the table top about an inch above it. A degree scale was marked out on the cardboard by which the position of the rod could be read. With the help of the rod, *S* could indicate the position of the plane in which the luminous line

[3] It should be noted that a turning by 42° produces only a moderate distortion of the shadow. Its width which is most strongly affected suffers a reduction of only 27%.

seemed to turn. A darkroom amber bulb illuminated this arrangement in such a way that *S* could see the rod but not the scale markings and that the remainder of the room was completely dark. After each setting of the rod *E* asked *S* to close his eyes and then read the scale with a flashlight.

During testing *E* asked *S* to look at the luminous line before him and close one eye, and that eye was covered. The luminous line which, when presented in the appropriate elliptic aperture, produced the projection of a 46° tilt was set into clockwise rotation at a rate of one revolution in 10 sec. When *S* reported that it turned in an oblique plane, he was asked to turn the measuring rod before him into a position parallel with that of the luminous line in rotation. This was repeated with the 59° and the 29° apertures, and thereafter the three apertures were used twice more in random order for the purpose of practice. Neither in this practice period nor later during the experimental trials was *S* told whether his settings were correct or not correct. No time limit was set on the presentation of the revolving line and *S* made his setting when he felt ready. After a rest period of 3 or 4 min. the experimental series began. It consisted of nine presentations, that is, each one of the three apertures was presented three times in random order.

The means and *SD*'s of the 15 means of the three measurements for each of the three degrees of tilt were 14.9 (*SD* = 6.6), 44.0 (*SD* = 3.4), and 59.8 (*SD* = 4.4) for the 29°, 46°, and 59° tilt, respectively. There was *no* overlap between the means of the settings by individual *S*s from one tilt to another, and there was *no* overlap between the individual settings which a given *S* made for the three tilts.

Where projections of tilts of 46° and of 59° were presented, the averages for all *S*s came close to the expected values. However, in the case of the 29° tilt, the average of 14.9 deviates significantly from this value; only one individual setting out of 45 is as high as, or exceeds 29°.

Why this is so is not clear. However, it should be pointed out that the change in length which a line turning with a 29° tilt undergoes amounts only to 12.5% and one of 14.9° tilt (the value of the average) only to 3.4%. In other words, a tilt of 14.9° produces a change in length that is very likely below the limen. Yet, that does not necessarily mean that those *S*s who gave settings of 15° or lower did not receive effective stimulation for a tilt. Whereas the small angles of tilt (due to the negligible change of the cosine function in this range of values) probably do not lead to a change in length sufficient to produce a kinetic depth effect, settings of such low values do not indicate that no tilt was perceived when these settings were made. In experience, a tilt of 15° is of distinct significance, and objectively conditions of stimulation of 29° were given.

It would have been important to find out whether these results can be improved by making the luminous line wider. To make it wider would have the advantage that the contraction of the line would be given by a change in its proportions, that is, in figural terms, rather than by a change in its absolute length. Improved results would indicate that change in proportions is effective in producing the kinetic depth effect. Unfortunately, this variation could not be done with the present set-up, because a wider line would have shown up the intersections with the elliptic aperture by their changing obliqueness. A more expensive manner of presentation would be needed.

Other Factors in Kinetic Depth Perception

Experiment 7: The effect of angle constancy.—Such a variation of the experiment might have contributed to the solution of the following problem. It has been reported that shadows of solid blocks will produce the kinetic depth effect only if they have contours which are displaced and change their length simultaneously. Should we assume then that the presence of such contours solely accounts for the kinetic depth effect in complex forms, imparting their depth to the whole figure, or do complex forms produce such an effect in their own right? Just as we have considered the possibility that a line is seen to move into the third dimension to account for the given change of its retinal image while it is perceived with constant length, we might assume a tendency to see in

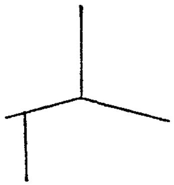

FIG. 4. The figure used in Exp. 7

general rigid, unchanging forms instead of the given distorting shapes. For the present this question must remain unanswered.

However, a question which can be considered a part of the question just raised was actually put to a test. Most shadows of turning figures do not only display contours which are displaced and change their length; their angles also change. Is there a separate tendency for angles to remain constant which produces kinetic depth effects?

To answer this question we used a figure which consisted of three rods all meeting in one point under angles of 110° and forming a wire-edged representation of an obtuse corner (Fig. 4). When this figure was turned back and forth through an angle of 42° and its shadow was shown to 56 *S*s who before had seen its stationary shadow as two-dimensional, 53 *S*s reported seeing a rigid obtuse corner. In this presentation two of the three dark lines forming the shadow were not only displaced but also underwent considerable changes in length.

Entirely different results were obtained when the length of the shadow lines was made indefinite. To achieve this, the shadow screen was covered with a cardboard with a circular aperture where the shadow of the corner figure fell on the screen. The size of the aperture was so chosen that the ends of the shadow lines were always hidden from *S*. Thus, only movement of the corner point, angular displacements of each of the three lines, and changes of the angles which they formed with each other were visible. As the corner point shifted sideways, one of the lines seemed to move farther under the aperture edge and another one seemed to pull out from under it, and the length of all three of them seemed indefinite.

All 22 *S*s employed in this experiment reported seeing a flat figure which distorted. Had the kinetic depth effect occurred, the *S*s would have seen instead a rigid three-dimensional form with constant angles. However, no such effect was observed where changes in the length of the lines which constituted the figure were not given, because that length was indefinite. We may conclude that a displacement of lines which is linked only with a change of angles does not give rise to the kinetic depth effect; displacement of lines and change in their length is needed. The question remains unanswered whether length must be understood only in absolute terms, or whether change in proportion has an effect of its own.

Experiment 8: Variation of distances between objects.—Not only are the retinal images of solid objects deformed when one moves about, the same is true to various degrees of the projection of the whole environment. That the objects which make up the environment are seen arranged in three-dimensional space and with unchanging distances between each other may also result from a kinetic depth effect. Just as some of the contours of solid objects produce appropriately changing retinal projections when the objects are seen from different angles, the projections of many of the intervals between objects change their length and their direction when one moves about. That this has the effect of producing visual depth can be demonstrated with the shadows of an arrangement of several objects on a rotating platform.

We used spheres supported by thin vertical rods because the shadow of a sphere in rotation does not change its shape and will therefore not produce a kinetic depth effect of its own. Four spheres of 1 3/16-in. diameter were arranged at the corners of a square concentric with the platform. The four rods were all of different height so that all the intervals between the shadows of the spheres were periodically oblique when the platform turned, and changed length and direction simultaneously. The lower part of the screen was covered so that the shadow of the turntable itself was hidden. The arrangement was turned at a rate of one revolution in 5 sec. and was exposed to individual *S*s for 20 sec.

Under these circumstances all 30 *S*s who took part reported the spheres to move in three dimensions. Twenty-four *S*s saw the spheres in a rigid spatial arrangement which turned about its center just like the actual arrangement behind the screen. The others saw them move in open single file in snakelike fashion into depth. In this latter motion only the shorter intervals between spheres are rigidly maintained, and each sphere changes direction of rotation with each excursion; but there can be no doubt that this is an incomplete form of a kinetic depth effect. It should be mentioned that 15 of the 30 *S*s had no other experience with these shadow experiments except for another experiment with the spheres which will be reported below. It is apparent that the kinetic depth effect will readily yield a perception of a rigid spatial arrangement of unconnected objects.

Experiment 9: Variation of distances between objects.—The arrangement of Exp. 8 offers still another opportunity to check on our finding that a line must change both in length and in direction in order to produce a kinetic depth effect. From our experiments with solid blocks and with the T figure we concluded that a shadow which merely expands and contracts in one dimension will not give rise to the effect. Here we set out to show that the same is true for intervals between objects; we modified the experiment with the spheres to correspond to these experiments.

All the rods were given the same height so that the spheres were aligned on a horizontal line and the intervals between the shadows changed in length only. This arrangement was shown to the same 30 *S*s and under exactly the same conditions that prevailed in Exp. 8, but was presented prior to it. The fact that the T figure proved so susceptible to the influence of previous perceptions made this sequence advisable. The experiment with the luminous rod which has been reported at length was done with the same *S*s in between the two experiments with spheres.

As in the case of the T figure, only a minority of the *S*s now saw movement in three dimensions, namely 10 out of 30. The difference between this result and that of Exp. 8 is reliable at the .03 level of confidence. Of the 15 naive *S*s, 12 saw the shadows move back and forth in the plane of the screen, 1 *S* reported movement in three dimensions, and 2 saw in the beginning of the observation period the plane and later the three-dimensional version. For the other group of 15 *S*s who had observed the shadows of some wire figures before, the numbers were: 8 flat, 2 three-dimensional, and 5 first flat and later three-dimensional. When these results are compared with those of the previous experiment where imaginary lines connecting sphere shadows changed both in length and in direction, it becomes again apparent that these are essential conditions for the kinetic depth effect and that a mere expanding and contracting of retinal distances is insufficient.

This is the reason for our view that Metzger's work (2) is not directly concerned with the kinetic depth effect. He exposed shadows of arrangements of vertical rods whose changing patterns presented *Ss* with rectangular intervals which changed in width only. No other deformations were visible, because no marks were distinguishable along the shadow lines, and the latter ended only at the edges of the aperture in which they were given. As with the aligned spheres, no reliable depth effects are produced spontaneously in naive *Ss* with such an arrangement. Whether Metzger's work contributes to an understanding of the kinetic depth effect remains to be seen when more of the nature of the effect is known.

Experiment 10: Effect of set.—In our experiments, the kinetic depth effect results in two perceptual characteristics: (*a*) a turning in the depth dimension and (*b*) three-dimensionality of form. However, when the effect is observed under realistic conditions, namely when by moving about one obtains a changing retinal projection for a stationary solid object, no turning is perceived. The reason for this is that the object remains in unaltered relation to its environment with respect to which *S* perceives himself moving. Thus, only three-dimensionality and rigidity of form, seen instead of the deforming two-dimensional pattern which is given on the retina, are here the overt manifestations of the kinetic depth effect.

The fact that under realistic conditions the object remains in unaltered relation to its environment needs some consideration, because this is not so in our experiments. There the deforming shadow of the object denotes a turning while the environment, that is, the screen on which the shadow is shown, remains stationary. Under realistic conditions, on the other hand, both the object and its environment are given retinally with deformations which denote a turning in relation to *S*. The kinetic depth effect transforms the deforming retinal projection of the environment into a three-dimensional structure, and once this has happened, the perception of the object as a three-dimensional form is probably facilitated. That such a facilitation is likely to take place is indicated by experimental results which show a strong influence of preceding exposures on the readiness with which the kinetic depth effect occurs.

The following results may serve as an example. When the "helix" (Fig. 3) was shown following the presentation of one or two figures which readily show the kinetic depth effect, all of 18 *Ss* saw it as three-dimensional during the first 10-sec. exposure. This is to be compared with results in Exp. 2 according to which only 4 out of 16 naive *Ss* gave a clear report of three-dimensional form for this figure after the first 10-sec. exposure.

The question of how this influence is exerted must remain open. It is conceivable that it consists merely in a set to see a turning in the depth dimension. However that may be, the influence is a strong one.

If such an influence is effective between succeeding exposures of different figures as shown, it should be expected to work also within a given visual field. Under realistic conditions, once the environment of a given object is perceived as a rigid spatial structure which changes its orientation with respect to the moving *S*, such an influence should facilitate a kinetic depth effect for the object. There are several reasons why the environment should easily be seen in this fashion. To mention only one: the environment will usually contain familiar features which would cause the facilitating influence of previous experience with similar situations to operate. Thus we have good reason to believe that the kinetic depth effect takes place more readily under realistic conditions than it does in our shadow-screen experiments.

Summary

When a three-dimensional form, solid or wire-edged, is turned behind a translucent screen and its shadow on the screen is observed, the shadow will appear as a rule as a three-dimensional rigid object which turns, quite similar to the physical object behind the screen. This happens notwithstanding the fact that *S* actually looks at a plane figure which is being deformed.

One condition seems to be essential for the occurrence of this effect: the shadow must display contours or lines which change their length and their direction simultaneously. If this condition is not fulfilled, a plane distorting figure like the one on the screen is perceived unless an influence of previous perception operates.

This effect is believed to operate widely under ordinary circumstances. When one moves about, objects near one's path are successively seen from different angles, and this change in orientation of the object to *S* is the same as occurs when the object is turned by an equivalent angle. Thus, the object's retinal projection undergoes the same deformations as do shadows in our experiments, and the same perceptual processes should result.

(Received August 11, 1952)

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