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FIGURE COHERENCE IN THE KINETIC DEPTH EFFECT

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When an observer views the two-dimensional (2-D) projection, e.g., shadow, of a moving three-dimensional (3-D) object, he usually perceives the shadow pattern as a form with depth. This has been called the Kinetic Depth Effect (KDE). Wallach and O'Connell (1953) concluded that an essential condition for the occurrence of the KDE seemed to be contours or lines that change their direction and their length simultaneously. Wallach, O'Connell, and Neisser (1953) showed that experience with an unfamiliar figure undergoing the KDE led to later perception of depth in the stationary shadow of the object. Gibson and Gibson (1957) studied the apparent slant of a 2-D surface formed by a set of regular or irregular forms. They obtained accurate judgments of slant when these forms underwent the continuous perspective transformations associated with plane rotation. Their experiments could be considered instances of the KDE but the Gibsons emphasize the importance of perspective for the perception of rigid motion, while perspective was apparently not an important determinant in the studies of Wallach et al.

In the KDE the relative motion of the various parts of a 3-D figure provides information not only about depth but also about the shape of the figure. The visual system in some way transforms the relative motions of the shadow's elements into the perception of a single rigid object, and this process appears to be a major factor in our normal perception of three-dimensional objects in the world around us. Johansson (1958) states the case as follows: "Mathematical relationships in the continuously changing energy distribution on the retina may be substituted for the classical static retinal picture, as the source of information from the external world. The substitution is viewed as an application of Gibson's gradient theory" (p. 3). It follows that a set of isolated dots or unconnected lines undergoing the appropriate changes can be perceived as a coherent rigid figure. White and Mueser (1960) studied the accuracy of the perception of arrangements of elements in a KDE setting. They found that all of their figures were perceived as rigid configurations in 3-D, but that reproducing the exact spatial relationships among the elements was a difficult task.

This paper reports a series of experiments designed to isolate the effect of relative movement from all other cues to depth and coherence. The experiments explore some of the conditions under which the KDE imparts perceived rigidity (coherence[2]) to elementary patterns of dots and lines. The *O*s viewed the changing 2-D projection associated with a rotating rigid 3-D configuration of dots or straight lines, and judged the apparent rigidity and coherence of the configurations, i.e., the extent to which the elements appeared to maintain their relative positions in the configuration. Independent variables were the num-

[1] Operated with support from the United States Army, Navy, and Air Force.

[2] Rigidity and coherence are treated as synonyms in this paper.

ber of elements in the configuration, the amount of constraint on the placement of elements, the type of rotation, the type of figure, and the speed of rotation.

General Procedure

The stimuli were 16-mm. motion pictures showing the 2-D projections of rotating 3-D figures and were made by an animation technique. Each frame of the film showed the figure's 2-D projection from a certain 3-D orientation. Successive frames showed projections from a succession of different orientations that corresponded with a particular rotation of the figure. A succession of 250 frames formed the film strip for a figure. Projected at a rate of 20 frames per sec., the strip gave a 12.5-sec. movie of a rotating figure. The films were produced frame-by-frame, by an automatic camera that photographed a display generated on a cathode-ray tube by a digital computer. (The M.I.T. Lincoln Laboratory's Memory Test Computer, which has since been dismantled, was used to generate the stimuli in Exp. I, II, and III. The Laboratory's I. B. M. 704 computer was used for Exp. IV, V, and VI.) The computer was programed to display the 2-D perspective projections of a set of isolated dots or straight lines whose 3-D coordinates were stored in the computer. After making the display, the computer actuated the camera, advancing the film by one frame. The computer then calculated new 3-D coordinates for all the points or lines according to specified rotation formulas and repeated the cycle, displaying the 2-D projection, advancing the film, and rotating the figure, until the specified number of frames had been photographed. The particular series of pictures to be made on any computer run was controlled by the initial parameters, which included the initial coordinates of the dots or lines, the type of rotation, and the parameters of the rotation formulas. The computer program, in FORTRAN language, is available from the author. It is appropriate for the IBM Type 704 and 709 computers with an on-line CRT display.

The regular figures that we used were symmetric about the origin, with the origin being the centroid of the figure. The random figures were samples from a population for which the origin was the centroid, on the average. Two types of rotation were used: spinning about a fixed axis through the origin, and tumbling about the origin. In the spinning rotation, the figures revolved about a fixed axis as the earth revolves about its polar axis. The axis itself was not shown—it was merely used to specify the direction of movement. (The fixed axis is the locus of points that do not move.) In addition to specifying the axis, the programer specified the angular velocity of the spin about the axis. Except in Exp. IV, where speed was varied, the speed was always 64°/sec for all figures. In the tumbling rotation, the origin of the 3-D coordinate system was the only point that remained fixed. From any one frame to the next the tumbling rotation amounted to a spin about an axis, but throughout the film strip, the orientation of the axis changed continuously. To tumble the figure about a fixed point (the origin of the coordinate system) the programer used Euler's formulas (Snyder & Sisam, 1941, p. 42) to specify the rates of change of three angles, representing components of rotation about each of the three coordinate axes in turn. The speed of the tumbling rotation, as measured by the spin about the moving axis, was not constant. Also the movement of the axis did not have a constant velocity. Nevertheless the average angular velocity could be controlled; it was equated to the constant velocity of the spinning rotations.

The 2-D projections included perspective, which was computed in terms of the ratio of nominal figure diameter to nominal viewing distance. In all our experiments this ratio was about $\frac{1}{10}$, which is so small that the stimuli would have been nearly the same had we used a parallel 2-D projection rather than a perspective projection. The *O* sat 9 ft. from the projected display, on which the figure diameter was about 1 ft., making the visual angle $6\frac{1}{2}°$. On the projected display, dots and lines were white on a dark ground. All dots had the same brightness and size, as did all lines.

Each configuration was displayed, rotating, for about 12.5 sec. The *O* was informed truthfully that he was actually viewing the 2-D projection of a rigid 3-D configuration, but he was instructed to rate the configuration as it appeared to him, rather than as he knew it to be. The *O* was told to use a 5-point subjective scale of rigidity or coherence, on which he was to give a rating of 1 if all the elements maintained their relative positions in the configuration throughout the exposure, and a rating of 5 if elements appeared to be moving independently. Intermediate ratings were to be given according to the proportion of coherent elements, and the relative amount of time that coherence was perceived. The

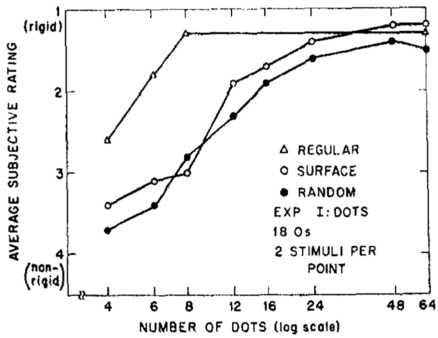

FIG. 1. Average ratings of rigidity in Exp. I, for three types of dot configurations. (In this and subsequent figures, the chance variability cannot easily be portrayed, because of the large individual differences. To assess the differences between any two figures, a difference in mean ratings of about $\frac{1}{2}$ rating step is roughly equivalent to a significant preponderance of ratings of one figure over another. When comparing points each based on two figures, the equivalent mean difference is about $\frac{1}{3}$ rating step.)

*O*s had no difficulty making the ratings after five practice trials. All *O*s were members of the laboratory staff, and were familiar with psychophysical experiments. Each *O* was tested individually, and made his responses orally.

EXP. I: CONSTRAINT AND NUMBER OF DOTS

Procedure

The first experiment used configurations of dots under three conditions of constraint. In the *random* condition, the 3-D coordinates of the dots were chosen so as to keep the dots within a 3-D cubical confine, i.e., each coordinate was chosen at random from the interval $-c \leq x \leq c$, where 2c is the length of one side of the confine. In the *surface* condition, dots were placed on the surface of a hypothetical cube or double pyramid (the latter has six vertices, $[0, 0, \pm c]$, $[0, \pm c, 0]$ and $[\pm c, 0, 0]$). In the case of the cube this was accomplished by setting one coordinate to $\pm c$, and choosing the other two at random. A similar method was used for the double pyramid. Each surface had the same number of dots as far as possible. For both surface and random conditions, eight values of n, the number of dots, were used: 4, 6, 8, 12, 16, 24, 48, and 64. In the *regular* condition, dots were placed at the vertices of a regular tetrahedron ($n = 4$), a regular double pyramid ($n = 6$) a cube ($n = 8$), and in a $4 \times 4 \times 4$ regular cubical array ($n = 64$). The tumbling rotation was used.

Eighteen *O*s were used. Two stimulus films were made for each of the 20 conditions (the regular conditions were repeated, but new random samples were drawn for the random and surface conditions). The 40 film strips were arranged at random in two blocks of 20 and spliced into a single film. Nine *O*s viewed the film projected in the forward direction, the others saw the film projected in reverse—they not only received the reverse order of stimuli, but also saw the stimuli moving in the reverse direction.

In this and subsequent experiments, the data will be reported in terms of the average ratings of coherence, pooling *O*s and stimuli within conditions. An attempt was made to scale the stimuli by the method of successive intervals. The results were in very close agreement with the simple averages of ratings, except for stimuli that most *O*s rated "1". For these, the scale values were very erratic, being violently affected by two or three ratings other than "1." Because of this instability, the scaling results will not be reported.

Results

The average ratings of coherence are shown in Fig. 1. Clearly, the regular configurations were judged to be more coherent than the surface and random configurations, for small n, while for 64 dots, all conditions yield the same high degree of perceived coherence. There is also a small but consistent difference between surface and random configurations, leading to the conclusion that the amount of constraint or regularity affects perceived coherence. The strong effect of the number of elements, n, is also clear from Fig. 1; the more elements, the more coherent a configuration appears.

An analysis of variance was made for the data from the random and surface constraints. The *O*s were divided into two groups, according to the order of presentation of stimuli,

TABLE 1

ANALYSIS OF VARIANCE OF RATINGS OF COHERENCE IN EXP. I

Source	*MS*	*df*	Error Term	Error *df*	*P*	Variance Components
Number of dots (*n*)	6.4046	7	.3100[a]	12.2	.001	.7618
Groups (G)	2.9714	1	.1954	7	.01	.0868
Constraint (C)	.7855	1	.1415[b]	23	.05	.0201
NC	.0640	7	.1753	16	—	—
NG	.1954	7	.0607	16	.05	.0336
CG	.0123	1	.0607	16	—	—
NCG	.0955	7	.0607	16	—	—
NC(S)[c]	.1753	16	.0607	16	.05	.0573
NCG(S)	.0607	16	—			.0607

Note.—Procedures and notation follow Green and Tukey (1960).
[a] NG + NC(S) − NCG(S).
[b] NC(S) and NC pooled.
[c] Stimuli nested in NC.

giving an analysis of 2 constraints, 8 numbers of elements, 2 groups, and 2 stimuli nested in the combination of number of constraint. The analysis, shown in Table 1, indicated that both *n* and Groups have strong effects. The Group effect includes individual differences as well as presentation differences, and we suppose that the former predominates. The effect of constraint is barely significant at the .05 level. The significant *n* × Group interaction reflects the fact that the group differences, which in this analysis are surrogates of individual differences, are more apparent in the low values of *n*. For large *n*, most of the responses are "1." The analysis shows a large effect for *n*, and a strong effect of Group. The significant mean square for stimuli within *n* × Constraint indicates a small effect of particular stimuli.

EXP. II: LINES AND ROTATIONS

Procedure

The configurations in Exp. II were random line segments, the endpoints being specified in the same way as the dots in the random condition of Exp. I. The lines were either unconnected and independent, or connected, one to the next and the last to the first, to form a single closed 3-D curve. No 3-D curve lay in a plane—all had three dimensions. Two rotations were used: spinning about a vertical axis and tumbling. Five values of *n*, the number of lines, were used: 4, 6, 8, 12, and 16. Thus there were 20 conditions: 2 rotations × 2 types of figures × 5 values of *n*. Two stimulus movies were prepared for each condition, and were arranged in random order within each of two blocks of 20. Unfortunately the stimuli for the condition of 16 unconnected spinning lines were faulty and could not be replaced. Sixteen *O*s were used; most had served in Exp. I.

Results

The average ratings are shown in Fig. 2, averaged over *O*s and stimuli within conditions. Clearly the connected figures are seen as more coherent than the unconnected, and the spinning figures are seen as more

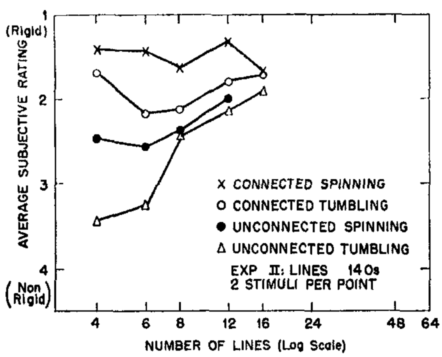

FIG. 2. Average ratings of rigidity for straight line figures in Exp. II.

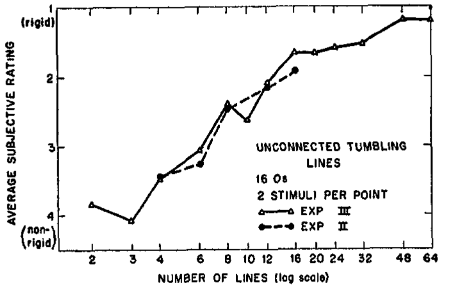

FIG. 3. Average ratings of rigidity for unconnected tumbling figures in Exp. III.

coherent than the tumbling. The statistical significance of these effects is established by a sign test. The effect of *n* is negligible for the connected lines, minor for the connected spinning figures, and important only for the unconnected tumbling figures.

The favorable effect of the spinning rotations is interesting. Rotation about a vertical axis is the most common kind of transformation seen when one walks about in the world. It is the type of rotation used exclusively by Wallach and O'Connell (1953). It is also a simpler rotation than tumbling, since every element moves at a constant angular velocity, and each element moves in a single plane, perpendicular to the axis of rotation. The questions of simplicity and familiarity are studied further in Exp. V and VI below.

The favorable effect of connected lines may be related to reversals. Since perspective is virtually absent from the stimuli, and since there are no brightness or size cues, depth is imparted solely by the KDE, so there is front-back ambiguity. In many cases, lack of coherence occurs because some, but not all, of the elements have reversed for *O*. With the unconnected lines, any one line can reverse independently of any other, but when the lines are connected, a reversal must involve at least two lines. Thus there is slightly more constraint on reversal in the connected figures, and this may account in part for the difference between the two types of figures. If the connected lines are interpreted as being more constrained than the unconnected, then the results of Exp. II are consistent with the effect of constraint found in Exp. I.

EXP. III: NUMBER OF UNCONNECTED LINES

Procedure

The third experiment extended the range of *n* in Exp. II for the unconnected tumbling figures, and also checked on the reliability of ratings. The stimuli for Exp. III were those from the unconnected tumbling condition of Exp. II, plus similar stimuli for additional values of *n* to cover the range of *n* from 2 to 64. In all there were two stimuli at each of 13 values of *n*, arranged at random in two blocks of 13 stimuli. The 16 *O*s used in Exp. II also served as *O*s in this experiment.

Results

The average ratings of coherence are shown in Fig. 3, together with the comparable curve from Fig. 2. It is clear that the ratings are adequately reliable, since the curves are about the same. Further, the effect of *n* for these figures is regular. Roughly, the average rating is linearly related to log *n*, at least up to 24 lines. Beyond 24, the average ratings decrease very little. The curve is very similar to the curve for the random dot figures in Fig. 1.

EXP. IV: SPEED OF ROTATION

Procedure

The fourth experiment was designed to study the effect of speed of rotation on judgment of coherence. Very slow and very fast speeds were expected to reduce the effectiveness of the KDE. Five speeds were used: 16, 32, 64, 128, and 256° per sec. The middle value, 64°/sec, was the speed used in all previous experiments. Five types of figures were used: 4, 16, or 64 random dots; 4 or 16 random unconnected lines. Only the tumbling type of rotation was used. Two versions of each speed × figure combination were prepared, yielding 50 stimuli. Each of 14 *O*s, most of whom had served in the previous experiments, saw the 50 stimuli in the same random order.

Results

The results are shown in Fig. 4. Clearly there is very little effect of speed over the range in our experiment. There is a hint of slightly less coherence at the slowest speed, but the other four speeds, covering an eightfold range, show no differential effects on coherence.

The range of speeds covered in this experiment nearly spans the range of possible speeds in our experimental procedure. Another factor of two faster would give so much change from one frame to the next (25°) that apparent movement would probably be destroyed. Another factor of two slower would result in a total excursion of only about 100° in the viewing time for each figure; no point in the figure could move much more than half way across the display, so that to get meaningful judgments of coherence, the viewing time would have to be increased. White and Mueser (1960) found a similar effect of speed on accuracy of perception in their KDE setting. They obtained differences among speeds of 2, 8, and 32 rpm in a spinning rotation, which correspond with 12°/sec, 48°/sec, and 192°/sec. They found reduced accuracy with a slower speed of 1 rpm (6°/sec), but they used an exposure time of 30 sec., and their results suggest that a longer viewing time would have allowed greater accuracy. Slow speed by itself may not detract from the KDE.

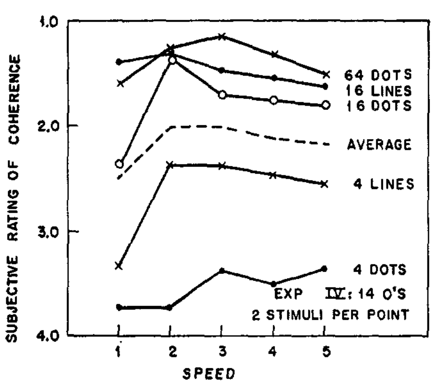

FIG. 4. Average ratings of rigidity for figures tumbling at five speeds in Exp. IV.

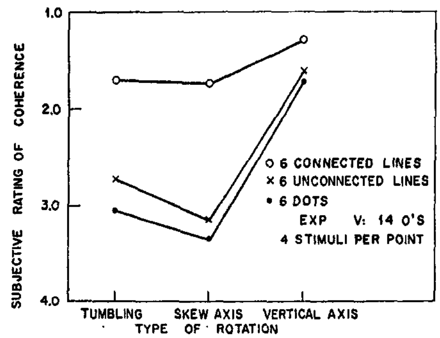

FIG. 5. Average ratings of rigidity for figures under three types of rotation in Exp. V.

EXP. V: SKEW SPINS

Procedure

A large difference was obtained in Exp. II between tumbling and vertically spinning. Experiment V was intended as a demonstration that spinning about a nonvertical axis would yield coherence judgments that were somewhere between those obtained with a vertical spin and with tumbling. The notion was that the judgments of coherence were related to the complexity of the rotation.

Three types of rotation were used: tumbling, spinning about a vertical axis, and spinning about a skew axis that was at an angle with all three coordinate axes. Two different skew axes were used. The cosines of the angles made by one skew axis with the horizontal axis in the display plane, the vertical axis, and the axis perpendicular to the display plane, were in the ratios 1:2:3, respectively. The other skew axis had cosines in the ratios 1:1:1. Three types of figures were used: six random dots, six unconnected random lines, and six connected random lines. Four versions of each figure type were made for the vertically spinning and the tumbling rotations, and two versions of each were made for each skew axis, yielding 36 stimuli. The 14 *O*s who had served in Exp. 4 were enlisted for Exp. 5.

Results

The results are shown in Fig. 5. Since the results for the two skew

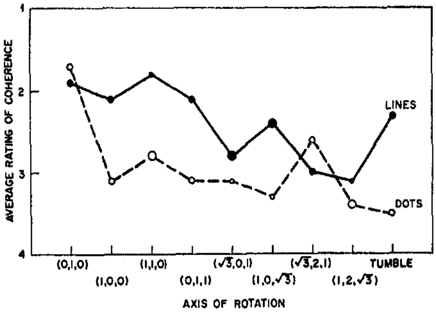

FIG. 6. Average ratings of coherence for various rotations in Exp. VI. (Small points represent 16 *O*s rating one stimulus; medium points, 16 *O*s rating 2 stimuli; large points, 16 *O*s rating 3 stimuli.)

axes did not differ more than differences between stimuli for a given axis, the results for the two skew axes were averaged. The results for the skew axes are in no sense intermediate between tumbling and vertically spinning. If anything, tumbling is intermediate. Clearly the effect of axis of rotation is more complicated than we had supposed. Another experiment was designed to study a variety of axes of rotation, in an attempt to resolve the complication presented by Exp. V.

EXP. VI: AXIS OF ROTATION [3]

Procedure

Nine patterns of rotation were used: the tumbling rotation and eight different fixed axes with the spinning rotation. The position of an axis is best specified by its direction numbers, which are numbers proportional to the cosines of the angles made by the axis with the three coordinate vectors: the horizontal vector in the display plane, the vertical vector, and the vector perpendicular to the display plane, respectively (Snyder & Sisam, 1941). The eight fixed axes of rotation used in Exp. VI can be divided into three groups. Group 1 includes axes in the plane of the display: (0, 1, 0), the vertical axis; (1, 0, 0), the horizontal axis in the display plane; and (1, 1, 0), an axis at an angle of 45° with both the horizontal and vertical vectors in the display plane. Group 2 includes axes not in the display plane but perpendicular to one reference axis: (0, 1, 1), an axis tilted forward 45° from the vertical and 45° up from the axis perpendicular to the display plane; ($\sqrt{3}$, 0, 1) and (1, 0, $\sqrt{3}$), axes 30° and 60° back from the display plane, respectively, in a plane perpendicular to the vertical reference axis. Group 3 contains two skew axes that made acute angles with all three reference vectors: ($\sqrt{3}$, 2, 1) and (1, 2, $\sqrt{3}$), axes 30° and 60° forward from the display plane, respectively, and both at 45° from the vertical reference vector.

Two types of figures were used; six random dots and six random unconnected lines. Two replications of each figure type were intended to be made for each type of rotation, yielding 36 conditions. After the experiment had been completed, it was discovered that for axes (1, 1, 0) and (1, 2, $\sqrt{3}$) there were three dot figures and one line figure, while for axes ($\sqrt{3}$, 0, 1) and (1, 0, $\sqrt{3}$) there were three line figures and one dot figure, instead of two each. Sixteen *O*s, most of whom had served in the previous experiments, rated the displays for coherence in the usual way.

After the ratings had been obtained from all *O*s, 13 *O*s were tested again. This time *O* was asked to indicate the direction of the axis of rotation by setting a rod in a matching position. The *O* was instructed to make a setting, even if there did not seem to be a single fixed axis of rotation.

Results

The results of the coherence ratings are shown in Fig. 6. For the dot figures, all fixed axes but the familiar vertical lead to about the same level of coherence, and the tumbling dots are also at this level. Significantly more coherence is obtained by spinning about the vertical axis. For the line figures, the vertical axis also leads to relatively high coherence, but so do the other axes in the display plane, the tilted vertical axis, and the tumbling rotation. The other skew axes impart less coherence. The coherence ratings of the line figures support the hypothesis that the more complex axis locations are associated with less

[3] The author is indebted to Alice Wolf for running part of this experiment.

coherence. The three groups of axes defined above were formed on a priori grounds to represent three levels of complexity. When the ratings for each *O* are averaged across all line figures within each group of axes, we find that for 11 of the 16 *O*s the group averages are in the order 1, 2, 3, a preponderance significant at the .0001 level. Very little support for the hypothesis can be obtained from the ratings of the dot figures, since only the vertical axis stands out.

The results of the rod settings are shown in Fig. 7, where the proportion of setting within 15° and within 30° of the true axis are plotted for each axis. In order to plot the settings from the tumbling figures on the same figure, the median setting for the tumbling displays was taken as the "true" axis (the median was determined separately for dots and lines but the judgments from the two replications of each figure were pooled). The settings for the axes not in the display plane provide evidence for the reversals seen by *O*s. All of the true axes were in front of the display plane (the end of the axis above the origin of the display is used for this reference). Actually 35% of the settings had the axis in front, 50% in back, and 15% on the display plane. Thus the figures were seen at least as often with front and back reversed as in the programed orientation. For this reason, reversals were not counted as errors. There were two equally correct settings for all axes not in the display plane. On this account, the chance level for Group 1 differs from that of Groups 2 and 3. Chance levels are computed on the basis of a uniform distribution of settings over the surface of a unit sphere, and are shown in Fig. 7.

Figure 7 shows that the settings for the tumbling figures were very

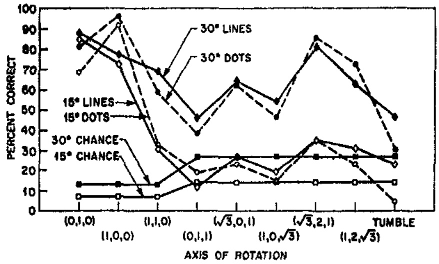

FIG. 7. Proportion of axis settings within specified angle of the true axis, in Exp. VI. (Two criteria of correctness are shown; 15° and 30°. Computed chance levels are shown for both criteria.)

inaccurate, in terms of the arbitrary "true" axes, indicating that the settings were quite variable. For the fixed axes, the stringent criterion of 15° error separates the vertical and horizontal axes from all the rest, and shows no differences among the rest. It also shows that setting the axis was a difficult task not accurately done by the *O*s. The sparse figures (only six elements in each), the short viewing time, and the tricky response device all contributed to the difficulty. Also, one or two *O*s occasionally set the rod at right angles to the true axis, apparently matching the direction of movement rather than the axis about which the movement occurred.

Measured by the liberal 30° criterion, the rod settings showed significant differences among the fixed axes, but no clear pattern emerges. Considering the three groups of axes described above, Groups 1 and 3 appear to have been matched with about the same accuracy but because of the differences in chance level, the settings for Group 1 would seem to be actually better. The axes in Group 2 were matched less accurately than the others. Individual differences in accuracy are huge. The best *O* had 97% of his settings within 30° of the true axis; the worst O only 19%; the other Os were fairly evenly distributed between these extremes, with a median of 78%.

The dot and line figures elicit quite different coherence ratings, and yet they yield rod settings of almost exactly the same accuracy. Indeed, Os reported that the axis of rotation was apparent in the dot displays even when the figures did not cohere. That is, even if some dots "broke away" perceptually from the figure, the direction in which the majority of the dots were rotating was still clear. In the case of dot figures rotating about axes in the display plane, about half the Os reported sometimes seeing the dots moving in 2-D, sliding back and forth on their straight paths (with sinusoidal velocity) rather than rotating in a 3-D circular path (with constant velocity). Nevertheless the proper setting for the rod was obvious.

There are other indications that matching the axis was psychologically quite different from judging coherence. The r between the average coherence rating of a figure and the number of errors made in matching its axis of rotation was only 0.16. The rank correlation between the number of ratings of "1" given by an individual and the accuracy of his settings was $-.45$.

Discussion

It is abundantly clear that the KDE alone is a very powerful factor in depth perception. Many of our Os saw every figure in 3-D; some Os reported occasionally seeing figures in 2-D, but the occasions were rare and fleeting, even with the meager figures that were used. The tendency to see depth in the 2-D projections of rotating 3-D figures is overwhelming. There is also a strong tendency for points or line segments undergoing the same 3-D rotation to be seen as parts of a rigid, coherent figure. Even randomly placed, unconnected points and lines form a rigid figure if they undergo the same 3-D rotation, while connecting the elements, or otherwise constraining them enhances the tendency to perceive a rigid figure.

The KDE is powerful, but it is not a *sufficient* condition for perceiving complete coherence. The majority of our figures were perceived as 3-D but nonrigid. The "1" rating was used less than half the time, and the "5" rating was seldom used, indicating that Os judged most figures to be partially coherent. Matching the axis of rotation in Exp. VI was not done very accurately, despite the omnipresence of the KDE. White and Mueser (1960) found that the spatial arrangements of elements were not accurately perceived even though the configuration was perceived as rigid and three-dimensional. The KDE seems to be more immediate than perceived rigidity, and both seem more immediate than accuracy of perception of unfamiliar random figures.

The role of perspective in the KDE is not determined. Gibson and his coworkers (1957, 1959) emphasize the importance of changes in perspective transformations. In our experiments, on the other hand, perspective was essentially irrelevant. The Os reported that reversals were common, and the axis-matching data of Exp. VI show that there was no agreement about which was front and which was back. (In retrospect, it would have been better to use parallel projection in our experiments, to make our statements about perspective unequivocal.) The truth must be that perspective is effective when it has a chance to be; perspective is very important when it is essentially the only clue to depth, but it is no more an essential feature of depth perception than is any other single factor. Braunstein (1960)[4] has data that confirm this supposition.

Some of the characteristics of figures that influence perceived coherence have

[4] M. Braunstein, personal communication, 1960.

been established. The number of elements is of prime importance, as are connections and constraint among elements. From *Os*' reports we know that isolated elements have a tendency to "break away" from the main body of the figure, and that lines that cross each other seem to enhance coherence. But our experiments did not include curved lines, solid figures, or familiar forms. Much remains to be learned about the properties of figures that are related to the KDE.

There is evidence of consistent individual differences across experiments. Twelve persons served as *Os* in all six experiments. For each experiment these *Os* were ordered according to the number of stimuli given a rating of 1. The similarity of the six resulting rankings of the 12 *Os* was evaluated by Kendall's coefficient of concordance, W. We found that $W = .60$, which is not only significantly different from zero at well beyond the .001 level, but also indicates very considerable consistency. The consistency of individual differences is all the more remarkable because the experiments were carried out at various times during a 3-yr. period. In each experiment, the percentage of "1" ratings given by the various *Os* varies over a wide range; the average range is 53 percentage points. How much of such large, consistent differences is due to differences in criteria for the "1" response, and how much to differences in perception cannot be determined from our data.

The subjective rating procedure served its purpose well. The ratings were reliable, and gave adequate measures of the major effects studied in these experiments. However, the distributions of ratings obtained in various conditions overlapped considerably, and we feel that a more sensitive measure is needed to investigate some of the finer points of the KDE. Also, individual differences in perception are confounded with individual differences in subjective scale values. To extract the individual differences which are known to be large, one must take enough data to establish firmly each *O*'s subjective scale, or else one must use an objective procedure.

How accurate is depth perception in the KDE? We may assume that when *O* saw a figure as rigid, he saw either a true 3-D figure or a complete front-back reversal of the true figure since there was only one rigid 3-D figure that would produce the 2-D display. But we have no other evidence that *O* saw the true figures, and indeed, the inaccuracy in the rod settings of Exp. VI suggests the possibility that depth is not perceived accurately. Accuracy of depth perception probably depends on the number of elements and the coherence of the figure, but the nature of this dependence is unknown.

There are many other unsolved problems. Can *O* discriminate between a rigid and a nonrigid 3-D figure, when perceived in the KDE situation? What happens with only one or two points or lines, i.e., what is the minimal stimulus for the KDE? Why are the more complex axes of rotation associated with less coherence? When is perspective important? Must all of the elements of the figure be continuously in view, as they were in these experiments? (Casual observation, plus everyday experience, strongly suggest that the answer is "No.") A wide field for research exists.

Finally, the role of the digital computer in this research deserves comment. Developing the computer techniques and camera techniques were difficult and time consuming, but without the computer, we would not have done the experiments at all. In our present setup, a film strip of 250 frames showing one figure rotating for 12.5 sec. can be produced in about 2 min., and there is complete assurance that all the elements in the figure will be of uniform size and brightness. Of course, KDE experiments can be done without computers, but the computer provides great flexibility in the kinds of experiments one can envisage and perform.

Summary

Six experiments examined the extent to which the kinetic depth effect produces per-

ceived coherence and rigidity of random figures. Subjectively rated coherence was greater with (*a*) more elements in the figure, (*b*) connections and constraints among the elements, and (*c*) less complex axes of rotation. The tumbling rotation was shown to be intermediate between simple and complex axes of spinning rotations. Speed of rotation was shown to have almost no effect. Individual differences were large. A high speed digital computer was essential for producing the stimuli for the experiments.

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