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Ratings of Kinetic Depth in Multidot Displays

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Subjects saw kinetic depth displays whose shape (sphere or cylinder) was defined by luminous dots distributed randomly on the surface or in the volume of the object. Subjects rated perceived 3-D depth, rigidity, and coherence. Despite individual differences, all 3 ratings increased with the number of dots. Dots in the volume yielded ratings equal to or greater than surface dots. Each rating varied with 3 of 4 factors (shape, distribution, numerosity, and perspective), but the ratings either between trials or between conditions were often uncorrelated. Object shape affected rigidity but not depth ratings. Veridically perceived polar displays had slightly lower rigidity but higher depth ratings than parallel projection displays. (Reversed polar displays were always grossly nonrigid.) The interaction of ratings and stimulus parameters requires theories and experiments in which different KDE ratings are not treated interchangeably.

When a two-dimensional (2-D) projected image corresponds to a three-dimensional (3-D) object that is rotating, viewers frequently perceive an object with depth. Because rotation induces apparent 3-D depth even when isolated still views of the object fail to induce perceived depth, the phenomenon is called the *kinetic depth effect* or KDE (Wallach & O'Connell, 1953). In this article, experiments are discussed that consider the perception of dot displays, in which each stimulus consists of illuminated dots on an otherwise invisible object. It will be demonstrated that there are a number of partially decoupled aspects to the perception of these displays under motion: (a) Coherence, whether all dots in the display are seen as constituting a single object; (b) depth, the amount of 3-D depth seen in the display; (c) rigidity, whether those illuminated dots that are perceived as constituting a coherent object also are perceived as maintaining their relative 3-D positions (rigid appearance) or as changing their relative positions (nonrigid, rubbery appearance).

There is a large body of literature examining the function of various kinds of stimulus variables in the kinetic depth effect. Some of the classic stimulus variables include the number of elements defining the stimulus, element shape, occlusion, perspective, correspondence, element density, and rotation speed. The effects of these stimulus variables were examined by a variety of dependent measures: global "goodness" judgments (Andersen & Braunstein, 1983; Braunstein, 1962; Braunstein & Andersen, 1984; Green, 1961; Petersik, 1980), qualitative motion categorization (surface, rotary, oscillatory; Caelli, 1979, 1980), judgments about objective rotation direction (Braunstein, 1962, 1977; Petersik, 1979, 1980), perceived curvature or shape (Braunstein & Andersen, 1984; Todd, 1984), and proportion of corresponding elements across frames (Lappin, Doner, & Kottas, 1980). One question that arises is whether the choice of dependent measure is of no consequence: Are all these measures simply reflections of a unitary aspect of the kinetic depth percept? In order to answer this question, we examined the independence of the three aspects of the percept listed above by collecting three separate responses on every trial in experiments that varied some important stimulus variables.

As a concrete example, consider an early set of experiments by Green (1961). He examined, among other factors, the importance of the number of stimulus elements on the KDE. Subjects were asked to rate displays on a scale that combined the notions of rigidity and coherence, as defined here. The label goodness is used here to describe Green's combined rating scale, in order to distinguish it from our use of the distinct labels rigidity and coherence (which Green used interchangeably). Green demonstrated that the number of stimulus elements was a potent factor in determining the goodness of a perceived object under various forms of rotation; generally, the more stimulus elements, the higher the rated goodness, with the largest increments occurring with the number of elements under 32. In principle, the increment in goodness could have reflected some unspecified weighting of coherence and rigidity. It is not clear whether numerosity affected one or both of these aspects of the percept primarily, nor is it clear how it affected perceived depth of element trajectories.

Here we investigated element numerosity, as well as a number of other factors that may vary in viewing 2-D projected images of objects. In particular, we examined one image projection factor (parallel projection versus perspective projection, with projection distance at three times object radius) and three object factors (the number of elements representing an object, from 4 to 80 elements; whether the elements representing the object were entirely on the surface or distributed throughout the volume; and the strength of density cues

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to depth in a still frame, by using different forms). Our aim was to determine the effect of these KDE stimulus variables on ratings of coherence, depth, and rigidity.

Our results corroborate some findings of previous investigators, for example, that the number of dots in the object and the presence of polar perspective can add to the strength of KDE. However, we also show that these stimulus variables do not generally affect all three aspects of the KDE percept equally and that there are many subtleties and complexities in the KDE.

Method

Because of the large number of stimulus variables, the study was divided into three separate experiments. The experiments were conducted with the same subjects and with the same procedures, except as noted.

Subjects

There were 4 subjects in the experiments, including 2 of the authors of this article and 2 students. The students were paid for their participation. Three subjects had normal or corrected-to-normal vision; subject CFS could be corrected only to 20:40.

Apparatus

All stimuli were computer generated, and the display and response collection was computer controlled. Experiment 1 and a pilot experiment used a point/vector display controller (Kropfl, 1975) and an HP1304A display monitor. Display resolution was 1024 × 1024 pixels. Experiments 2 and 3 used a raster display controller, Adage RDS-3000, and a Conrac 7211C19 RGB color monitor. Display resolution was 512 × 512 pixels. Experiment 1 used binocular viewing in a completely dark room. In Experiments 2 and 3, subjects viewed the stimuli monocularly through a reduction tube, with an aperture slightly larger than the stimuli. Hence, weak stereo cues to flatness may have been present in Experiment 1, but not in Experiments 2 and 3.

Stimuli

Stimuli consisted of random white dots scattered on the surface or throughout the volume of invisible spheres and cylinders. The probability distribution used for dot placement was uniform across the surface (or through the volume) in each case, but choices of dots were constrained so as to fill the surface or volume fairly evenly by partitioning into equal-area (or equal-volume) segments and putting equal numbers of dots in each segment. Five stimulus parameters were varied. First, there were two types of objects, a sphere of diameter 2° of visual angle and an upright cylinder of height 2° of visual angle and cross-sectional diameter 2° of visual angle. The number of dots was varied from 4 to 80. These dots were either positioned on the surface or in the volume of the object being simulated. Stimuli were either presented in parallel projection (i.e., with no perspective) or with an exaggerated amount of polar perspective (corresponding to a viewing distance of three times the object radius, far smaller than the actual viewing distance). All stimuli were rotated about a vertical axis through the center of the simulated object. Stimuli were either rotating front–left or front–right, although this distinction is only meaningful for the stimuli with polar perspective. Single-frame views of some sample stimuli are shown in Figure 1.

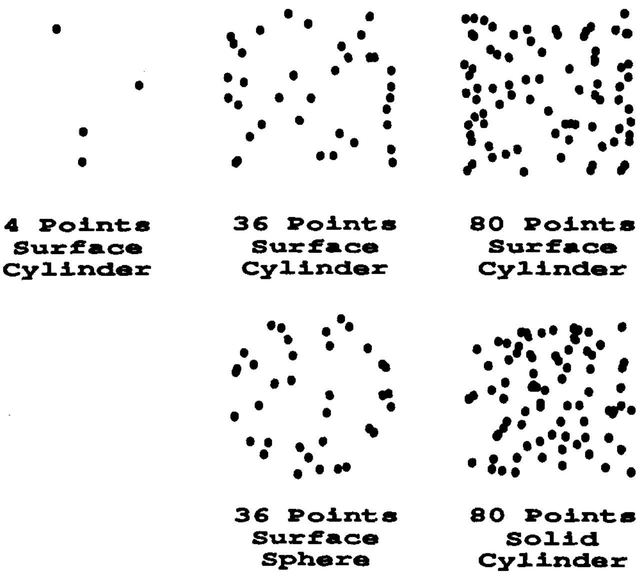

Figure 1. Single frames from some sample stimuli varying in numerosity, distribution, and form.

Procedure

On each trial, the subject was shown a fixation target, which then disappeared and was followed shortly by one rotation of the stimulus. (See Table 1 for details of rotation speeds, etc.) After the stimulus presentation was complete (approximately 2 s), four responses were required of the subject. First, the subject indicated the direction of rotation of the object (front–left or front–right). These responses were used in polar projection displays to determine whether the subject perceived the object in the veridical or the reversed mode. Then, three different ratings of the percept were required: depth, coherence, and rigidity.

Depth rating. The subject indicated the amount of depth perceived in the stimulus on a scale from 1 to 5. Given that all stimuli were based on objects rotating about a vertical axis, depth was related to an inferred "top view" of the stimulus. The subject was shown the top views (Figure 2) to facilitate his or her rating. The most depth, 5, was associated with a perceived circular path for each dot; the least depth, 1, was associated with no perceived depth and hence an oscillatory linear path for each dot.

Coherence rating. The next rating, also on a scale of 1 to 5, was of the perceived coherence of the multidot display. A rating of 5 indicated the greatest coherence (i.e., all the dots held together as one object). A rating of 4 indicated that a few dots did not cohere; 3 indicated that the display broke up into two distinct objects (segmentation); 2 indicated that three or more objects were perceived; 1 indicated there was no perceived coherence whatsoever.

Rigidity rating. Perceived rigidity was rated on a scale from 1 to 5, with a 5 indicating one or more totally rigid objects, and lower numbers indicating more and more nonrigidity or "rubberiness."

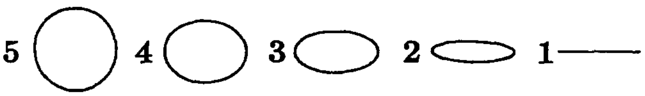

Figure 2. The inferred top views of the stimuli that were used to define the five levels of perceived depth ratings.

Subjects judged all three aspects of each percept. This allowed us to relate the three aspects on an individual trial basis. Had the three judgments been collected separately, the relation between the three judgments would have been available only at the level of the mean data.

Designs

Experiments 1, 2, and 3 differed in the factors varied and in the display devices used. Table 1 summarizes the design and viewing conditions for each experiment. All designs were fully crossed in each included factor. Left and right veridical rotation direction was also a factor in each experiment. Stimulus order was randomized within block and each block consisted of one token of each stimulus type, yielding 64 stimuli per block in Experiment 1 and 32 stimuli per block in Experiments 2 and 3. A different random token of each stimulus type was generated for each of six blocks per experiment. A pilot experiment yielded no effect on any response ratings of object size (2° of visual angle vs. 4° of visual angle); 2° of visual angle was used subsequently. The polar perspective manipulation was defined with respect to object radii, so that the object size manipulation also varied the mismatch between actual and appropriate viewing distance for the degree of perspective. This and some of the current work was originally reported in Landy, Dosher, and Sperling (1986).

Results

The results for Experiments 1 and 2, pooled across subjects, are shown in Figure 3. There were significant individual differences, discussed below, and so statistical analyses were performed as within-subject analyses of variance (ANOVAS). The 12 trial-type replications that resulted from collapsing over rotation direction and test block formed the random factor. These replications represented responses to 12 distinct, randomly generated stimuli of each type. Table 2 lists the significance levels associated with each rating, factor, subject, and experiment, along with a qualitative coding of the direction of the results. Table 2 thus gives a quick summary of the consistency both between subjects and within subjects across experiments. Table 3 summarizes the results of previous related experiments. Notice that the current set of experiments include factors and ratings that are either unrepresented in the literature or represented by a questionable combined measure.

Numerosity. In Experiment 1, in which the number of dots ranged from very small to moderate in number, all three ratings for 3 of the 4 subjects were increased by increasing the number of dots. The 4th subject showed a very different behavior (e.g., see Figure 4). The four-dot stimuli yielded very high depth ratings for this subject. The subject mentioned afterward that the stimuli reminded him of organic chemistry drawings and yielded a vivid percept.

In Experiment 2, in which the number of dots was moderate to large, the effect of the number of dots was less dramatic. Depth ratings increased slightly and saturated at these high numerosities. At these larger levels of numerosity, the effects of numerosity on coherence and rigidity were small: There were no significant effects on coherence ratings and numerosity was related to rigidity ratings for only 2 of 4 subjects. In summary, by increasing dot numerosity, all three ratings increased, up to a point, and then saturated. Depth ratings appeared to increase and saturate in a continuous manner, whereas coherence and rigidity ratings were high for all but the sparse displays (eight or fewer elements). These findings are in general agreement with those of Green (1961) over similar ranges of numerosity. However, Green's judgment was one of overall goodness and more nearly agrees with the depth judgments reported here.

Intensity. In Experiment 3, in which the intensity of displays was increased from 0.86 to 42.7 μcd/dot, there was no significant effect on ratings (with the exception of a single subject on a single rating). We ruled out an effect of varying display types in which overall stimulus intensity (contrast) varies in the visible range. (But see Dosher, Landy, & Sperling, in press, for manipulations of intensity very near to threshold, which do affect kinetic depth performance.)

Form. For conditions in which a spherical shape was directly contrasted with a cylinder (Experiment 1), the sphere was rated more rigid than the cylinder by all subjects and more coherent by 3 of the 4 subjects. The higher rigidity ratings for spheres overall was actually due to a strong interaction between form and perspective: Rigidity ratings were differentially lower for cylinders under perspective. The sphere gives less representation to dots that are substantially affected by the projection factor (far from the axis of rotation), and the increase in perceived nonrigidity may have resulted

Table 1
Experimental Factors and Conditions

Experiment	Numerosity	Form (cylinder or sphere)	Distribution (surface or volume)	Perspective (parallel or polar)	Luminance
1	4, 8, 16, 36	both	yes	yes	1.45 μcd/dot[a]
2	36, 48, 64, 80	cylinders	yes	yes	3.02 μcd/dot[b]
3	48	cylinders	yes	yes	0.86, 3.02, 11.52, 42.72 μcd/dot[b]

[a] Point plot display, resolution 1024 × 1024 pixels; 36 new frames per 360° rotation (or 10° per frame); 60 ms per new frame, or 2.16 s per full rotation; dark room; binocular free viewing; viewing distance 1.1 m; object diameters 2° visual angle (parallel perspective).

[b] Raster display, resolution 512 × 512 pixels; 36 new frames per 360° rotation (or 10° per frame); 66.67 ms per new frame, or 2.4 s per full rotation; dim room (8 cd/m^2) with light-tight viewing hood; monocular viewing through a reduction aperture; viewing distance 1.6 m; object diameters 2° visual angle (parallel perspective).

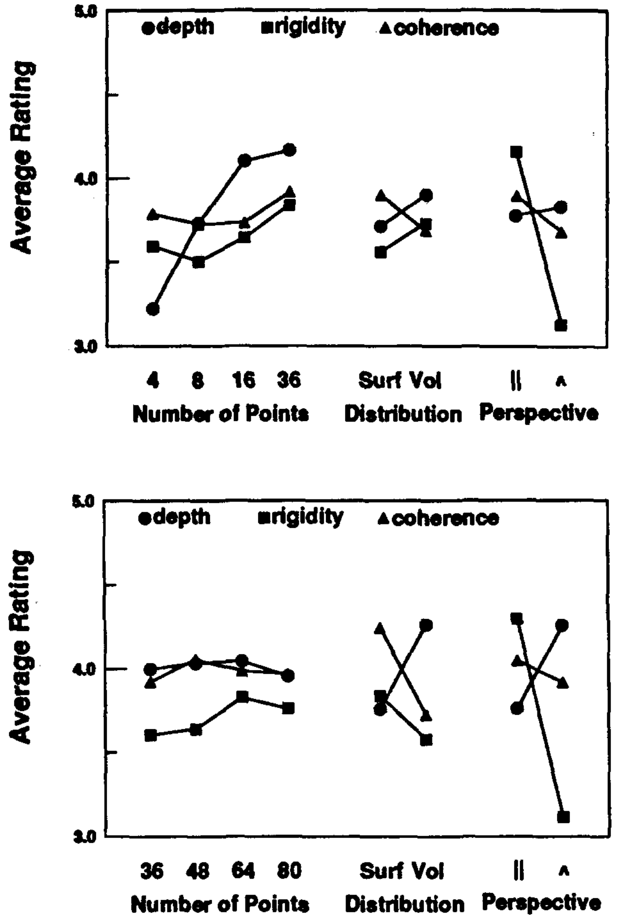

Figure 3. Response data for all ratings and stimulus manipulations in Experiments 1 (upper panel) and 2 (lower panel), pooled across subjects. (The parameter is the particular rating made: perceived depth [circles], rigidity [squares], and coherence [triangles]. In each panel, the first set of curves is for the number of dots in the stimulus, the second for the effect of distributing the dots across the surface or throughout the volume of the object, and the third for the effect of perspective transformation [parallel or polar].)

in object breakdown (segmentation, incoherence) in some cases. Braunstein and Andersen (1984) also compared spheres to cylinders. They used each form as the base for elliptical distortions and found that sensitivity to minor axis variation (flatness of the elliptical orbits) was slightly greater when the base form was a cylinder than when the base form was a sphere. However, this was a cross-experiment comparison with different groups of subjects in the different conditions.

Distribution. The effect of dot distribution (in the volume or on the surface) was generally small with significant individual variation (see Figures 3 and 4 and Table 2). Close examination of Table 2 suggests that distribution was more important when numerosity was large and when there was reduced single-view shape information (i.e., for the cylinder, Experiments 2 and 3). In these conditions, distribution in the volume increased depth ratings for 3 of the 4 subjects and might have improved coherence for some subjects as well.

Green's (1961) overall goodness measure showed slightly higher scores for surface representations than for completely random placements in the volume of a cube, but an enormous benefit for point representations with regular placements in the volume. Our random sampling incorporated partition equality and hence represented a compromise between Green's random and regular conditions. Dots in the volume might have increased depth ratings because a range of intermediate velocities was represented in the cylinders, whereas in surface representations of cylinders, all dots were traveling at more nearly the same velocity, except at the edges of the object. To the extent that differential velocity supported depth segregation (Braunstein & Andersen, 1981), representation of intermediate velocities may have been useful. The ability of distribution to strongly affect the kinetic depth percept may have also depended on the unavailability of other strong cues to shape such as perspective, texture density, or contour (see the discussion of Figure 5 below).

Perspective. For all subjects, the rigidity ratings were decreased by adding polar perspective. The effect of perspective on coherence was small and depended on the subject. A collateral analysis of the polar perspective trials that sorted those occasions on which the perceived rotation direction disagreed with the intended rotation direction found that most, but not all, of the decrease in rated rigidity with polar projection occurred when the observer perceived the stimulus in the reversed mode (see also Gregory, 1970; Schwartz & Sperling, 1983). Thus, when polar displays were perceived in their reversed mode, they appeared grossly nonrigid; when polar displays were perceived veridically, they appeared slightly less rigid than the corresponding parallel displays.

Neither our polar stimuli nor our parallel stimuli were viewed at the appropriate viewing distance. The parallel stimuli would have to be viewed from infinity; the polar stimuli from 6 cm; the actual viewing distances were in the range 1 m in the various experiments. (Had we produced appropriately projected objects for the 1 m viewing distance, they would have been negligibly different from the actual parallel stimuli. When viewed at the appropriate viewing distance of 6 cm, our polar displays possessed little depth—largely a consequence of the large scale.) The greater mismatch between appropriate viewing distance and the actual viewing distance for polar stimuli conceivably might have accounted for the fact that veridically perceived polar stimuli received slightly lower rigidity ratings than parallel stimuli. But this distance mismatch does not bear on the overwhelming cause of nonrigidity in polar displays—that stimuli are perceived in reversed mode. Even the secondary effect of polar projection on rated rigidity may have depended only weakly on projection/viewing distance mismatch. As noted previously, a pilot study in which object size was varied by a factor of 2:1 (producing a change between projected and actual viewing distance of 2:1) had no significant effect on any rating. Finally, Cutting (1987) found little impact of mismatch between simulated and actual viewing distances.

The rigidity and coherence results reported here agree with the reported relationship between the amount of perspective and the ability to infer the intended rotation direction (Braun-

Table 2
Significant Factors in Experiments

Experiment/ Subjects	Numerosity	Form	Distribution	Perspective	D × P
Depth judgment					
1	(small numbers)				
MSL	+,***	ns	+,***	ns	**
BAR	+,***	ns	+,***	+,**	*
CFS	+,***	ns	+, ns	ns	ns
RHS	U,***	+,**	−,**	ns	ns
2	(large numbers)				
MSL	~,**	—	+,***	+,***	***
BAR	~,**	—	+,***	+,**	*
CFS	~,*	—	+,**	ns	†
RHS	~,***	—	−,***	ns	ns
3					
MSL	—	—	+,**	+,***	†
BAR	—	—	+,*	+,*	*
CFS	—	—	+, ns	+,*	†
RHS	—	—	−,*	ns	ns
Coherence judgment					
1	(small numbers)				
MSL	+,***	+,*	ns	−,***	***
BAR	+,***	ns	+,**	+,**	*
CFS	+,***	+,**	ns	−,***	ns
RHS	+,***	+,**	−,***	−,**	ns
2	(large numbers)				
MSL	ns	—	ns	ns	ns
BAR	ns	—	+,***	+,***	***
CFS	ns	—	−,**	−,***	ns
RHS	ns	—	−,***	−,***	ns
3					
MSL	—	—	+,*	ns	†
BAR	—	—	+,**	+,*	**
CFS	—	—	+,*	−,*	ns
RHS	—	—	−,**	−,*	*
Rigidity judgment					
1	(small numbers)				
MSL	+,*	+,**	+,†	−,***	**
BAR	+,***	+,**	+,**	−,***	ns
CFS	+,**	+,**	+,†	−,***	ns
RHS	X,***	+,*	+,*	−,***	*
2	(large numbers)				
MSL	ns	—	ns	−,***	ns
BAR	~,**	—	+,**	−,***	ns
CFS	~,*	—	−,**	−,***	ns
RHS	ns	—	−,***	−,***	ns
3					
MSL	—	—	ns	−,***	ns
BAR	—	—	+,*	−,***	ns
CFS	—	—	ns	−,***	ns
RHS	—	—	ns	−,**	ns

Note. The p values (see below) are the significance of corresponding F values from an analysis of variance for each subject treating rotation direction and tokens of stimuli as the random factor. The symbols ~, +, and − indicate the pattern of the effect and can be referenced to the legend list below for each factor. See the text for a discussion of the interaction of distribution and perspective. Numerosity: +, increasing with number of points; ~, saturates with large number of points; U, U-shaped function of number of points. X, highest for smallest and largest number of points. Form: +, sphere > cylinder. Distribution: +, volume > surface. Perspective: +, polar > parallel. D × P = interaction of distribution and perspective. ns = not significant. Dashes = not applicable.
† $p < .100$. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table 3
Summary of Related Results

Judgment type	Numerosity	Form (cylinder or sphere)	Distribution (surface or volume)	Perspective (parallel or polar)
Depth	=Petersik, 1980			+Braunstein, 1962 =Petersik, 1980
Coherence	−Braunstein, 1962			
Rigidity	=Petersik, 1980			−Petersik, 1979 −Braunstein, 1977
Combined	+~Green, 1961	−Braunstein & Andersen, 1984	−Green, 1961	−Braunstein, 1962 =Braunstein, 1977

Note. The symbols ~, +, and − indicate the pattern of the effect and can be referenced to the note for Table 2. The symbol = indicates no effect. A summary of some relevant factors in prior experiments follows: Braunstein (1962), dots in volume of cube, $N = 2–6$, depth and coherence/rigidity judgments; Braunstein (1977), dots in volume of sphere, $N = 1{,}000$, varied perspective in horizontal and vertical dimensions, direction and coherence/rigidity judgments; Braunstein & Andersen (1984), dots on surface of sphere or ellipses, $N = 140–160$, shape and quality judgment; Green (1961), dots or line elements in volume or on surface of cube, $N = 4–64$, goodness rating (combined segmentation and rigidity); Petersik (1979), dots in volume of sphere, $N = 4–45$, depth and direction rating; Petersik (1980), dots in volume of sphere, $N = 5–60$, depth and direction rating.

stein, 1977; Petersik, 1979). The difference in the effect of perspective on rated rigidity and on rated coherence may explain the inconsistent results of Braunstein, who found that perspective decreased a combined rating of coherence and rigidity in one study (1962), but had no effect in another (1977).

Perspective generally increased the rated depth (shape) of the percept (although not all contrasts were significant, see Table 2). A prior study by Braunstein (1962, see Table 3) also found that perspective improved a "strength of depth" rating. Petersik (1980) found that depth judgments were not affected by perspective. However, this same study found no effect of numerosity ($N = 5–60$) on depth, which suggests that the experiment had insufficient power.

Interaction of Perspective and Distribution. By adding polar perspective, the rated depth was increased. Distributing dots throughout the volume of the object had the same effect. However, when the two were combined, a further increase was not achieved. This interaction between perspective and dot distribution is illustrated in Figure 5, and the significance levels for each subject are listed in Table 2. (Here again, the effect of distribution was greater in high-numerosity cylinders, Experiments 2 and 3.) As suggested above, some factors such as distribution may be more likely to control the percept in the absence of other strong cues to shape.

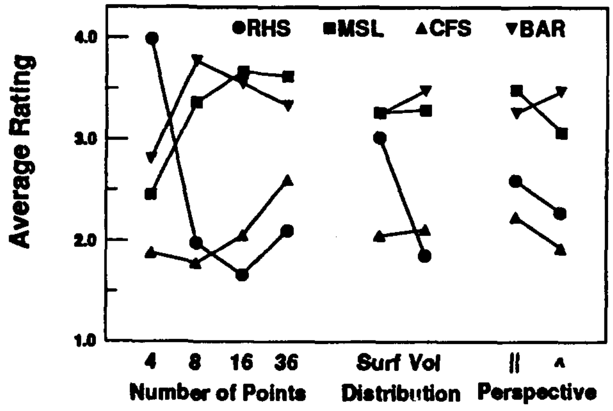

Figure 4. Coherence ratings in Experiment 1. (The parameter is the particular subject. Note the large individual differences.)

A Large Individual Difference. Occasionally, individual differences were very striking. An example of this is shown in Figure 4. Here the coherence ratings for all conditions of Experiment 2 are shown for individual subjects. Subject RHS was the only subject for whom the increased number and distribution of dots in the volume of the object decreased the coherence of the kinetic depth percept. Individual differences presumably occurred in earlier studies, but were undetected because prior studies collected few observations from each subject and performed cross-subject analyses. For another example of large individual differences in KDE, see Dosher, Sperling, and Wurst (1986).

Three Ratings Are More Informative Than One. So far, we have described the empirical results with respect to manipulations of dot numerosity, perspective, and so forth. What was perhaps most important was the added information gained by having multiple ratings of the stimuli. These ratings, each of which can be (and has been in the literature) construed as a measure of the "strength" of a KDE percept, did not necessarily covary. In many cases, as we have seen, an experimental manipulation had a different effect on different ratings. For example, shape significantly affected mean ratings of rigidity, but had little or no effect on depth ratings. At high numerosity, further increases in numerosity continued to increase depth ratings, but did not affect coherence ratings, and so forth.

Correlations Between Ratings. It was also possible to do a finer-grained analysis of the three ratings that looked beyond the means to the correlations on a trial-by-trial basis. Table 4 gives the trial-by-trial correlations pooled over conditions and subjects. Seven of the nine correlations in Table 4 are between −0.12 and +0.19; and the two highest correlations are still

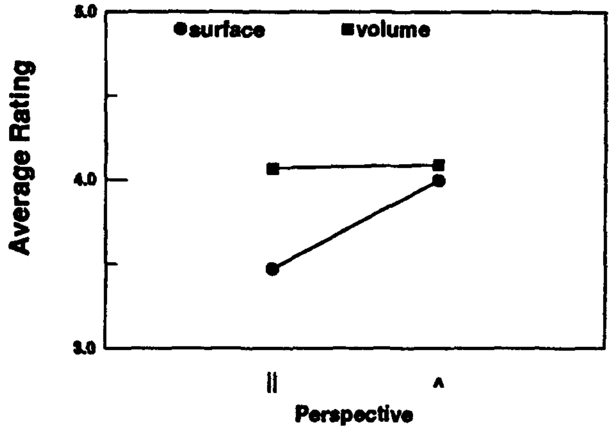

Figure 5. Interaction between perspective transformation and dot distribution in Experiments 1 and 2 (pooled).

rather low, with each relationship accounting for only about 12% of the variance. Although the subjects were affected somewhat differently by some of the experimental factors, on the whole, different subjects tended to use the ratings quite similarly. Such low correlations between ratings clearly rule out a simple, single factor interpretation that would require high positive or high negative correlations between each pair of ratings. For every subject, at least two of the three interrating correlations are low. Obviously, the rated qualities of kinetic depth percept reflect at least two underlying dimensions. Although the experiments were not designed in a way that would expose the KDE depth percept to multidimensional analysis, they were sufficient to bring this inherent multidimensionality to the fore. The fact that different ratings weigh differently on these dimensions cannot continue to be overlooked in KDE research.

Discussion

Wide Range of Percepts. The KDE for a multidot display is quite rich. When viewing a stimulus with a small number of dots, there generally are many possible stable percepts. Even though the whole was geometrically derived from a rigid object, perceptually, subgroups of dots form clusters, and each subgroup appears to move independently in 3-D, acting as a separate object. Groups of two or three dots can be perceived as moving independently in the plane, or as a 3-D and rigid configuration, or as a nonrigid 3-D configuration similar to the Ames window (as in Gillam, 1975, 1976, in which line segments were used rather than dots). In short, groups of dots do not necessarily cohere as single objects, even when they are being perceived in depth and when a unitary rigid 3-D interpretation is available. Even when dots are correctly perceived as parts of one coherent object, there is a range of possible percepts that differ in shape, in depth, and in perceived rigidity. The perceived coherence, shape, and rigidity have a complex and partially decoupled relationship.

Table 4
Correlations Between Judgments: All Subjects

Judgment types	Experiment 1	Experiment 2	Experiment 3
Depth–rigidity	.05	−.12	−.01
Depth–coherence	.08	.07	.16
Rigidity–coherence	.36	.35	.19

Decoupled Aspects of Percepts. Some degree of decoupling between aspects of a KDE percept has been known since Braunstein (1962) varied perspective in KDE displays and observed an inverse effect on mean judgments of depth and of combined rigidity/coherence. However, it has implicitly been assumed that the manipulation of rigidity by perspective was a special case. The current experiments demonstrate that this decoupling between the various aspects of the percept is not restricted to the independent variation of perceived rigidity but is quite general because different factors affect different judgments. In terms of mean ratings in our experiments, rated depth was significantly affected by numerosity, distribution, and perspective. Rated segmentation was affected primarily by numerosity; this effect reflected a division between sparse and dense levels of numerosity (above or below 16 elements). Secondarily it was affected by form and perspective. Rated rigidity was primarily affected by perspective and numerosity. Additionally, correlations among the three ratings were low and sometimes negative when measured on a trial-by-trial basis.

Experiments in the literature on multidot KDE have used as the dependent measure either ratings or paired comparisons on some judgment dimension (see Table 3). The judgment dimensions either selected from a variant of the three ratings used here or combined two or more in one rating. Conflation of the dependent measure may, in part, explain some of the inconsistencies in the literature noted above. In particular, the combined coherence and rigidity ratings of Braunstein (1962, 1977) may account for the inconsistent effect of perspective in those studies.

Importance of Independent Factors. Our experiment manipulated a number of factors within a subject, factors that previously had been examined in separate experiments or had been chosen arbitrarily as fixed factors that happened to differ, along with the dependent measure, between studies in the literature. Shape, distribution, and numerosity have usually varied haphazardly between experiments. For example, Braunstein (1962, 1977) found inconsistent patterns of perspective on a rigidity–coherence judgment using 2–6 dots in the volume of a cube and 1,000 dots in the volume of a sphere, respectively. Braunstein (1962) and Petersik (1980) found inconsistent patterns of perspective on depth judgments using 2–6 dots in the volume of a cube and 4–45 dots in the volume of a sphere, respectively. It has been difficult to know whether the structural and numerosity factors explained the inconsistency in patterns.

The results of our experiments can be viewed as filling in Table 3 with a self-consistent set of data and providing previously unavailable data in the empty cells. The results clearly separate three important aspects of a kinetic depth percept: depth (shape), coherence, and rigidity. Because our stimulus parameters are manipulated within subject, cells are directly comparable. A number of our results are similar to Green (1961), Braunstein (1962, 1977), and others. In other cases, in which inconsistent findings were reported, we suggested explanations based on confounded dependent measures. Typically, inconsistent results between KDE experiments result from judgments that combine component aspects (e.g., depth, coherence, rigidity) in unspecified, but probably different weightings.

Nonmotion Cues to Depth in KDE Displays. There are two classes of cues to object structure in our displays: static cues such as density and 2-D object contour and dynamic or motion cues that depend either on optic flow or on changing interpoint distances. Based on our data, the greatest likelihood of perceiving the veridical shape occurs with perspective images of spheres (rather than cylinders), with high dot numerosity, and with dots in the volume (rather than on the surface).

High dot numerosity guarantees a good representation of the 2-D contour of the sphere and of 2-D density cues. Even when the 2-D contour is not as suggestive, as in the case of the cylinder, the density cues that become visible with high numerosity may be important in providing static cues to shape. (In the case of surface distribution of elements, the 2-D density will increase toward the edges, whereas in volume distribution of elements, the density cue is reversed, as in Figure 1.) The presence of 2-D cues to shape, whether from contour or density, may constrain the perception. High element numerosity also minimizes the likelihood of atypical clumping or grouping characteristics likely in low numerosity figures, which then are likely to cause grouped or segmented (i.e., incoherent) percepts.

Perspective may simply serve as an additional cue to depth organization. Alternatively, the exaggerated perspective used here may be especially effective because it slightly increases the proportion of elements moving in the same direction, yielding a display similar to that arising from an image with occlusion, and possibly allowing stronger input to an optic flow analysis at high numerosity (J. Todd, personal communication, March 1987).

Distribution in the volume provides a range of velocities in any local area and may support a full depth percept by relating distance from the axis of rotation to dot velocity. Dot fields of different velocity, whether adjacent or superimposed, tend to segregate in depth (Braunstein & Andersen, 1981).

Percept Description Versus Objective Task Measures. An alternative to the measurement of one or another aspect of the kinetic depth percept by rating is to conceptualize a different sort of question. In rating, we ask about various aspects of the percept itself. An alternative is to ask whether a percept, whatever its subjective appearance, is adequate to support objective performance on a particular kind of judgment, such as a judgment of shape. Some attempts have been made in this regard. For example, Todd (1984) required subjects to make objective curvature judgments under various levels of nonrigidity in the kinetic depth image. Lappin et al. (1980) required subjects to make objective, paired-comparison judgments of the degree of correspondence in two-frame displays. We investigated one possible objective measure of having perceived shape from a kinetic depth display (Dosher, Landy, & Sperling, in press; Landy, Sperling, Dosher, & Perkins, 1987; Sperling, Landy, Dosher, & Perkins, 1989). This objective measure requires subjects to identify the object perceived from among a large lexicon of possible objects and offers an attractive alternative to the elaboration of subjective methods under study here.

Relation to Models. Three classes of computational models have been proposed to account for the kinetic depth effect based on motion cues: those deriving shape from optic flow fields (Clocksin, 1980; Koenderink & van Doorn, 1986), those deriving analytic solutions by assuming rigidity from m views of n points (Hoffman & Bennett, 1985; Ullman, 1979), and those based on maximizing rigidity in interpoint distances (Hildreth & Grzywacz, 1986; Landy, 1987; Ullman, 1979, 1984). Usually, flow-field models are applied to objects composed of densely packed points, and interpoint-distance models are applied to images composed of less than a few dozen points. Interpoint-distance models apply geometric computations to the 2-D image-plane positions of the given points to compute a 3-D object that is either totally rigid (Ullman, 1979) or a 3-D object that deforms minimally between adjacent frames (Landy, 1987; Ullman, 1984).

We will illustrate the problems that rigidity models have with data such as ours by considering, as an example, the incremental rigidity algorithm of Ullman (1984). When an n-point 3-D object undergoes rotation, the algorithm takes as its input a sequence of frames that represent the 2-D image-plane x, y projections of the n points. For each frame, the algorithm outputs an estimated depth value z for each point plus one overall fidelity score. The computation consists of a gradient descent in the space of depth values z to maximize the fidelity criterion. This criterion measures the deformation (nonrigidity) in the recovered 3-D object between the current frame and the prior frame.

To evaluate such an algorithm as a psychological model, one must associate quantities produced by the algorithm with aspects of human perception. We have shown here three aspects of performance that are partially separable in performance measures: segmentation, depth, and rigidity. Consider what happens in the case of four-point displays. Ullman's (1984) algorithm, like most others, simply assumes element correspondence and figural segmentation as prior processes. For four-point objects, the incremental rigidity algorithm would have recovered the veridical single object with rigid depth assignments for all nonperspective images in the experiment. On the other hand, only 1 of our 4 subjects regularly perceived four-point displays as unitary; for the other subjects, these were usually perceived as two or more objects moving independently. This grossly violates the segmentation assumed by the Ullman model.

The algorithm's estimated depth values seem a plausible basis for predicting human depth judgments, and the algorithm's fidelity score seems a plausible basis of rigidity judgments. An immediate problem is that perspective-dependent modulations in position of elements on the image plane are treated as noise by this (and most other) algorithms (Sperling & Dosher, 1987), although our subjects' depth percepts are improved by moderate amounts of perspective. The problems surrounding predictions with parallel and perspective projections are particularly enlightening. Detailed consideration (Dosher & Sperling, 1988; Sperling & Dosher, 1987) showed that a class of models including Ullman's (1984) exhibit unrealistic properties because they do not incorporate any perspective transformation, whereas the models would require a flexible perspective transformation to deal with perceptual facts. Parallel perspective algorithms, such as Ullman's, when applied to perspective images, such as those in our experiments, yield flattened depth estimates in relation to nonperspective images. On the contrary, for our human observers, perspective increased depth ratings slightly.

Predictions of perceived rigidity based on the fidelity criterion are the most problematic aspect of Ullman's (1984) algorithm. When the image is produced by perspective transformation, parallel-perspective rigidity algorithms (e.g., Ullman) cannot distinguish between veridical and reversed depth 3-D recovered objects—they yield precisely equal rigid and nonrigid solutions. For our subjects, reversed depth perceptions are grossly more nonrigid than the veridical ones, a powerful perceptual fact that is beyond the scope of this class of models.

Purely geometric algorithms that yield explicit solutions to 3-D objects given *m* views of *n* points (Bennett & Hoffman, 1985; Hoffman & Bennett, 1985; Ullman, 1979; Webb & Aggarwal, 1981) fare much worse than the incremental rigidity algorithm. Again, segmentation is simply assumed. The algorithms yield exact solutions under certain conditions in which the stimuli represent rigid objects. The outputs here are exact solutions or the fact that a solution failed. An exact solution must be rigid, so the model cannot predict any particular nonrigid percept, nor does it have computational by-products that can support rigidity–nonrigidity judgments, partial depth, or incomplete segmentation.

We conclude that, although many existing algorithms are of great interest as a possible basis for robotics solutions to the structure-from-motion problem, they are inadequate as psychological models. Our experiments suggest that a successful psychological model must identify at least three separable aspects of recovered objects that can serve as a basis for the three separable, measurable aspects of kinetic depth perception.

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Call for Nominations

The Publications and Communications Board has opened nominations for the editorships of the *Journal of Experimental Psychology: Animal Behavior Processes, Contemporary Psychology,* the Personality Processes and Individual Differences section of the *Journal of Personality and Social Psychology, Psychological Assessment: A Journal of Consulting and Clinical Psychology,* and *Psychology and Aging* for the years 1992–1997. Michael Domjan, Ellen Berscheid, Irwin Sarason, Alan Kazdin, and M. Powell Lawton, respectively, are the incumbent editors. Candidates must be members of APA and should be available to start receiving manuscripts in early 1991 to prepare for issues published in 1992. Please note that the P&C Board encourages more participation by members of underrepresented groups in the publication process and would particularly welcome such nominees. To nominate candidates, prepare a statement of one page or less in support of each candidate.

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