Picture perception is array-specific: Viewing angle versus apparent orientation

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The amount that a pictured lattice appears to be swung from its frame changes with subjects' viewpoint, in contrast with previous experiments using insufficient range of rotation. Also, this effect is shown to be independent of the physical slant of the picture surface, though not necessarily of border-shape information. Analysis of depicted headings which rotate with viewpoint, with respect to the picture plane, although the angle between these headings in virtual space hardly changes, relates these data to specific geometric properties of the perspective array *as seen from the different viewpoints*. Data show differential rotation of differently oriented features within a single depicted object, in a way that is dependent on task instructions. It is proposed that in picture perception, contradictory cues are resolved by combination.

We ordinarily view pictures from a wide range of viewpoints other than that from which they were created, without appreciable distortion or misunderstanding. It has been held that, if picture perception were strictly determined by constraints in the perspective array, distortion would be noticed, since the array, for all views except from the original station point and direction of view, specifies a distorted scene (Cutting, 1986; Kubovy, 1986; Pirenne, 1970; Rosinski, Mulholland, Degelman, & Farber, 1980). Pirenne and Kubovy each claim that an appreciation of the flat-panel nature of the picture enables the viewer, by a process of perceptual compensation, to see and interpret the picture from almost any oblique viewpoint as if viewing it from the station point. Failures of compensation are assigned special causes, for example, full-face portraits "follow us" because an anticipated visual instability is not realized, in that we maintain eye contact despite our moving relative to the painted face (Kubovy, 1986). Other effects (column paradox, distortion of spheres) are considered to occur when the visual system loses track of the center of projection, as in wide-angle pictures (Pirenne, 1970).

Such compensation, as a strict mechanism, is inconsistent with Goldstein's (1979, 1987) convincing demonstration that some things about a picture will change markedly with the angle of view, while others will not. Goldstein (1987) distinguishes three properties in terms of what hap-

pens to them: perceived orientation (heading), which shifts with viewpoint in differential amounts for objects of different original headings; spatial layout, which remains relatively stable; and projection, which causes horizontal compression of objects and scene, in views from the side. Two of these properties pose a problem: No satisfactory mechanism has been proposed to explain why the pictured scene should appear stable in layout, while its components are seen to rotate differentially! Compensation might explain scene stability; it cannot account for rotation. On the other hand, *differential* rotation seems to be a difficulty for explanations based on the array. Changes in the array might rotate the scene, but if some parts rotate faster than others, the scene itself should fragment, or at least visibly warp. Goldstein (1987) concludes that "perceived orientation is not determined solely by the geometric information provided by the picture." But what, then, would be the mechanism?

The answer given here, as a preview, is that geometry does determine space, in pictures as elsewhere. And the scene does fragment, in the sense that the specific geometric properties of the array, that is, the projected lengths and angles of object contours, when pictures are seen from the side, yield not one but many sets of perspective information (i.e., cue sets) concerning orientation, all sets distorted and often grossly contradictory from one to another, from which the viewer must determine a perception. (Some of the distortions become apparent in the conventional definition of virtual space as being affine-transformed [Cutting, 1987], but the simultaneous existence of different possible interpretations of the same geometry does not.)

The present experiments sought to identify differing sets of perspective cues that exist geometrically and therefore are available for perception, to specify the geometric disagreement among cue sets identified, and to consider how they, or other, less precise cues, might be combined into the resultant perception, and to identify higher-order fac-

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tors which could direct this combination. Before all this, however, the Rosinski et al. (1980) finding against object rotation with viewpoint will be reexamined, and an attempt made to show directly that perceived object orientation can be independent of known picture-plane slant, though it is not always.

EXPERIMENT 1

Rosinski et al. (1980) failed to find rotational shifts in object orientation under normal viewing conditions (their Experiment 2), and concluded that their subjects, when judging orientation, had successfully compensated perceptually for the angular relation of their viewpoint to the picture surface. The stimulus was a lattice, depicted as pivoted about a vertical axis by different amounts. This two-dimensional lattice provides strong cues to its depicted orientation in the extent to which it fills the width of the picture, and in the angle formed between the frame and the lattice top or bottom edge. If either of these border relations is salient, that information, and not compensation for the picture plane, could be why the lattice's correct orientation was perceivable from oblique viewing angles. The possibility could be tested by extending the range of viewing angles and depicted orientations of such a stimulus, since the lattice-width to frame-width ratio, especially, becomes a less conspicuous cue to orientation as the lattice is swung further away from the frame, and since any rotation with viewpoint which does occur despite inhibiting factors will be more detectable at extremely oblique viewpoints.

Method

Subjects. Of 12 unpaid volunteer subjects with normal or corrected vision, 11, including the 2 males, were psychology junior or senior students at the University of Pittsburgh at Johnstown, and 1 was a retired teacher.

Apparatus and Procedure. Stimuli and procedure strongly resembled Rosinski et al.'s (1980) Experiment 2 (illustrated in Kubovy, 1986), except that this lattice was hinged to the black field's framing border at the right edge (vs. their central vertical pivot). The 10.6 × 22.8 cm wide lattice (five white vertical bars alternating with five black) was depicted at swing angles of 15°, 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 165° to the 17.7 × 22.8 cm frame, a 90° lattice being flat in the plane of the field and smaller or greater angles indicating that the lattice is swung away from or toward the observer respectively. Station point was 46 cm in front of and normal to the frame. Stimuli were full-scale printed copies of perspective drawings that had been individually drafted on an Apple Macintosh Plus computer. Subjects sat unrestrained 46 cm from the center of pictures placed at eye height, to view them from positions of 30°, 45°, 90°, 135°, and 150°, with 90° representing a normal, frontal view, and smaller or greater angles representing positions facing the picture from left or right respectively. Swing angles and positions were in random order per subject, and the pictures, rather than subjects, were repositioned at the different viewing angles. A 30-cm-long pointer, attached to a protractor and pivoted at the center, was placed on the table before the subject at each position. With the pointer, subjects indicated the angular amount that the lattice appeared to have been swung away from or toward them out of the plane of the black field, which was depicted on the pointer's base as a radial line in the direction of field (picture-plane) slant. The room was diffusely well-lit from above.

Results and Discussion

Figure 1 shows that extending the ranges of viewing positions and swing angles beyond those of Rosinski et al. (1980) has produced a clear pattern of phenomenal rotation with viewing position. A 9 (depicted swing) × 5 (viewing position) × 12 (subjects) repeated measures ANOVA showed significant effects of depicted swing [$F(8,88) = 213.61, \alpha < .001$], of viewing position [$F(4,44) = 26.39, \alpha < .001$], and of swing × position interaction [$F(32,352) = 5.89, \alpha < .001$]. The interaction reflects the differential nature of rotation (Goldstein, 1979, 1987). In particular, subjects saw the 90° lattice very much as depicted (flat in the picture plane) regardless of viewing position, presumably because coplanarity is such a strong, unambiguous two-dimensional cue to orientation, whereas rotation was evident, as predicted, between extremes of viewing angle when there was also considerable depicted lattice swing from the picture plane. Within the ranges of Rosinski et al. (which were 30° to 150° swing, 45° and 135° viewing), it was expected that strong lattice-to-frame relational cues (angles the lattice top and bottom edges make with the frame, relative widths of lattice and frame) would inhibit rotation. That did seem to happen, though not over the entire range expected. Swing angles of 60° to 135° were observed as relatively invariant from the 45° through 135° viewpoints. In the arrays, the proportion of lattice width to picture width is nearly invariant over viewpoints. However, lattice-to-frame angle is not constant except for the 90° depiction, and may well have contributed to the rotation that did occur. (Subjects reported having used the lattice-to-frame cues.) Interestingly, differential rotation was unidirectional with respect to viewpoints away from 90°, occurring only when it was counter to the substantial amount of regression to the picture plane (Goldstein, 1979) that was present. Most probably, whenever the large difference in their widths

Figure 1. Judged lattice swing as a function of depicted swing, at the different viewing positions, in Experiment 1.

made it clear that a lattice was not depicted in or even nearly in the plane of its background, that width differential was too obvious a cue to be diminished by other, perspective cues tending to rotate the lattice coplanar with its ground.

EXPERIMENT 2

A case for array-determined picture perception has not yet been made. The lattice rotations perceived in Experiment 1 may well be due to indications for lattice orientation in the specific central projection to the viewer, which indications change with viewpoint. However, the rotations were clearly weak, for example, when compared with Goldstein's (1979) for similarly oriented stimuli. While they may have been weakened in extent by border-relation information, as suggested, alternatively it could be that something about the orientation of the picture surface per se, perhaps some measure of (at least partial) compensation for viewpoint (Pirenne, 1970), muted rotation. If, however, the same rotational pattern results from a given array, whether that array is from a picture surface seen at a slant or else from a picture of that surface constructed from the slant (oblique) viewpoint but presented frontally, then it must be information in the array itself (which in this case must include the field frame for the lattice), rather than information about the orientation of the picture surface per se, which determines these object-rotation effects.

Method

Subjects. There were 12 unpaid volunteer student subjects with normal or corrected vision, all psychology juniors or seniors at the University of Pittsburgh at Johnstown. Two were male.

Apparatus and Procedure. Stimuli and procedure strongly resembled those in Experiment 1, but with these differences: Perspective drawings were prepared of those Experiment 1 stimuli which had depicted 15° and 165° of lattice swing, in the aspect those depictions would have from each of the five viewpoints of Experiment 1. Figure 2 shows an example. Viewing was always normal to the picture plane, from the station point at 46 cm. Subjects were asked to judge the horizontal angles, away or toward themselves from the picture surface, formed by the black field and by the lattice. They expressed their judgments (20 in all, for the 10 stimuli) by adjusting a movable radial line on the pointer's base to show the apparent angle of the black field from the picture's surface, and then moving the pointer itself to show the swing of the lattice.

Results and Discussion

From the difference between subjects' pointer and line settings, observed lattice-from-frame swings were derived for each stimulus. Figure 3 shows that the effect of depicted viewpoint on this perceived swing was virtually the same as for the physically differing viewpoints in Experiment 1, except that, with respect to the judgments of Experiment 1, some regression of judged angles toward the picture plane was consistently present in Experiment 2.

This result was not foregone, since distortion is far more evident in pictures of pictures than in pictures of real scenes (Pirenne, 1970, pp. 96-99), which fact suggests

Figure 2. One of the pictures shown to subjects in Experiment 2. It corresponds with the 15° lattice stimulus of Experiment 1 as projected in perspective to the 45° viewing position.

a possible difference in perceptual mechanism. But it is only when the "second-order" picture does not present the array one would expect from a depicted real object that it seems distorted. And from Experiment 2 it appears that, given the same projected perspective array in either case, perception is the same. The only perceptual difference found, additional regression of swing angle toward

Figure 3. Judged lattice swing as a function of viewpoint, whether at different actual viewing positions (Experiment 1) or in frontally viewed pictures made from those positions (Experiment 2). Standard errors of the mean judgments shown here for Experiment 1 ranged from 3.42° at $165^\circ/90^\circ$, swing/viewpoint, to 10.55° at $165^\circ/150^\circ$. For Experiment 2, this range was from 2.77° at $15^\circ/135^\circ$ to 6.39° at $165^\circ/150^\circ$.

the field plane, is probably attributable to real differences in incidental cues, for example, the projections of the rectangular stimulus cards (picture planes) themselves, when their orientation does (Experiment 1) or does not (Experiment 2) agree with the projection to the viewer of the black field from which the lattice is hinged. Cutting (1987) found that Euclidean rectification, his term for the use of cues to the slant of the screen surface, did not account for his subjects' judgments of whether stimuli depicted in cinematic motion represented rigid or nonrigid objects. The present data extend that finding to the perception of direction in static pictures.

It is tempting to conclude that picture-surface slant is irrelevant. But what is really established is that only the projective-geometry indications (border shape) of that slant matter, when they conflict with genuine surface orientation. What effect if any that border will have on perceived orientation might well depend on the picture. And whether the textural and other cues in a boundless surface could be effective in some conditions was not tested.

Wallach and Slaughter (1988) suggest that because the relative duration of the two possible Necker-cube interpretations is manipulable with viewing angle for real cubes and not for pictured ones, picture and real-space perceptions differ in process. That conclusion is only supported here with respect to a minor effect, regression of swing angle toward the picture plane.

EXPERIMENT 3

Frame relations may inhibit rotation, but if array cues cause it, there is the question of what kind of cues they are. It would be helpful if some consistent relation between actual perceptual judgments and specific information in the picture were found. Winslow Homer's painting, *The Fog Warning*, was chosen for several reasons: (1) It is an accurate perspective of sufficient complexity. (2) The objects within it appear to rotate strikingly with viewing-angle changes. (3) These rotations are not explainable as maintained eye contact (Kubovy, 1986) or other recognized exceptions to compensation. (4) The painting contains objects of well-understood general size and shape. This matters to perceptual judgments and also permits a confident reconstruction of virtual space behind the picture. (5) Excellent, large-sized reproductions are widely available.

Method

Subjects. There were 23: the experimenter and another psychologist, a community member, 3 cognitive psychology graduate students, and 17 students who received points toward their grade in an undergraduate course in psychological research methods at the University of Oregon. Ages were from 18 to 60; 13 subjects were female. All reported normal or corrected vision. None but the two psychologists knew the hypotheses.

Apparatus and Procedure. Subjects stood at each of seven positions along a table to view a 42×66 cm (20°×31° visual angle when seen orthogonally from 1.2 m) multicolored reproduction of *The Fog Warning* (Figure 4), which was centered on a long wall of a 3.8×6.9 m diffusely well-lit room so that the painted horizon

was 1.6 m above the floor. The seven positions were at these polar-coordinate horizontal distances from the painting's center (with 90° representing a normal, frontal view, and smaller or greater angles representing positions facing the picture from left or right respectively): 14°, 2.3 m; 30°, 2.4 m; 45°, 1.7 m; 90°, 1.2 m; 135°, 1.7 m; 150°, 2.4 m; and 166°, 2.3 m. Subjects were admitted to the room, through one of two doors, directly to either the 30° or 150° position without having seen the picture from any other angle. The pointer of Experiment 1 (minus the radial line that had indicated field slant) was placed on the table before the subject at each position. The subject was instructed, at each position, to aim the pointer in the direction the dory was pictured as headed (boat angle), with respect to a perpendicular to the picture face, that is, to try to judge from that viewpoint what direction the dory would have if the picture were viewed frontally (from 90°). The judgment, then, was of the correct relation between real and virtual space, as intended by the artist. In the same manner, the subject was then instructed to indicate the direction from man's position in the dory to the mother ship on the horizon (ship angle). From the initial position, subjects were led to the remaining positions in counterbalanced order.

Results

A horizontal parallel to the picture plane, seen from in front of the picture to be headed rightward, is reported as 0°; a perpendicular to the picture plane headed away from the observer into virtual space is 90°, and so forth. (Thus, heading angles increase with counterclockwise rotation.) Figure 5 shows a large and regular shift in judged headings from position to position, and also a small but systematic change, with position, in the perceived amount of the difference between boat's present heading and the direction from the boat to the ship (= difference angle). Solely for the purpose of the ANOVA to test for these effects, subjects were divided into two groups, according to the position at which they first saw the picture, as a control for any influence of presentation order. In an ANOVA comparing first-position judgments of 10 subjects at 30° with 10 at 150°, for viewing position, $F(1,18) = 22.31$, $\alpha < .001$; for boat-angle judgment versus ship-angle judgment, $F(1,18) = 208.38$, $\alpha < .001$; for position × difference angle interaction, $F(1,18) = 4.50$, $\alpha < .05$. (Due to an earlier-than-planned termination of data collection, only 10 subjects had their first view from 150°.) The differences in heading judgments for a given position, depending on whether a subject saw that position first or later, turned out to be negligibly small in any case, compared to the heading rotation observed between positions: These mean differences between the two groups in judgments of boat or ship angle at the same position, whether 30° or 150°, were not consistent in direction, and ranged between 3.7° and 5.1°. Of 16 subjects who were asked after their judgments were completed to look at the painting while walking by it, 15 found the dory to rotate as they did so.

Projective Analysis and Discussion

Homer's ability to make an accurate perspective drawing is beyond question. Yet it was not taken for granted that he did so. A plan and elevation of the scene in *The Fog Warning* were reconstructed (Figure 6) using a tech-

Figure 4. *The Fog Warning*, by Winslow Homer, American, 1836-1910. Oil on canvas, 30×40 in. (76.2×121.9 cm). Otis Norcross Fund. 94.72. Courtesy, Museum of Fine Arts, Boston.

Figure 5. Perceived boat- and ship-angle headings, from subjects' judgments and from estimates by calculation, as a function of viewing angle, in Experiment 3. (Calculated headings are means of separate headings indicated by different cues.)

nique which amounts to a reversal of the "projection" method of mechanical perspective drafting. The method is described in Ramsey and Sleeper (1988, p. 798). (This reconstruction method also resembles that of La Gournerie [Pirenne, 1970], though subsequent attempts here to describe virtual space for oblique viewing will depart from his assumptions.) To reconstruct the appropriate virtual space in this way required that two dimensions be established: A "station point" was fixed at the subjects' 90° viewpoint (1.2 m from the reproduction), and the doryman's actual sitting height was assumed at 91 cm, the mean for civilian United States males (Van Cott & Kincade, 1972). Those determinations place the doryman (depicted at 6° visual angle) at 8.7 m from the observer. "Imaginary" lines are then projected from the specified station point through points in the picture which define contours (schematized per Figure 6), and extended into the plan and elevation views of virtual space. Then, along these projection lines in virtual space, are located the points defining those particular contour endpoints and corners which will yield a symmetrical boat and oar set of appropriate proportions. This is an iterative but straight-

Figure 6. Schematic reconstruction of the spatial layout of the scene represented in Winslow Homer's *The Fog Warning*. Lines represent the oars exclusive of both blades, as only one blade is visible in the painting.

forward drafting procedure providing a single solution to virtual-space layout; at the 1/25 scale used, it defines the boat orientation well within 1° of uncertainty. (The phenomenal impressions that the doryman is not sitting quite in the center of his seat, and that the dory not only pitches up but also tilts slightly side-to-side, are confirmed in the reconstructive layout.) The doryman is found to be depicted in a 5 × 1.6 m (as schematized) dory headed away at 112° (boat angle), its bow pitched up 21° in the waves, with the oars each angled 4° sternward from the handle out, with respect to a perpendicular to the boat's long axis, all as shown in Figure 6. The symmetry and appropriateness of these dimensions attest that subjects' viewpoint at the 90° position was satisfactory to veridically perceive a fully realistic scene. To produce the same array and thus a picture of the same visual angle, Homer's station point would have to have been 2.2 m back from his painting at its original, larger size. While the fact that the reconstruction succeeded as well as it did suggests that Homer's station point was indeed not far from the one used here, adjusted for scale, it is not Homer's viewed scene which is defined, but the virtual space in which the objects represented could be veridically perceived by the present subjects.

(As with any consistent representational transformation from 3-D to 2-D [Hagen, 1986], a central projection is in principle entirely reversible. But, just as is true of orthographic [metric] projection and other transformations, a scaling factor must be specified. And in central projection, size parallel to the picture plane must be specified separately from distance in depth, because that relation, for any given set of objects within the picture, is specific to a particular projection, whence the two dimensions needed above. Whenever the real sizes of depicted objects and at least one depth can be known or inferred, reconstruction is possible.)

From an uncountable multitude of contour lines and specific indications of size and shape which could be used in different combinations to produce sets of perspective cues, four prominent cue sets to boat orientation were identified, and these were evaluated for their effect at the different viewing positions. The sets each consist of contour lines and/or points in the (schematized) depiction which, taken as a set, would specify a heading for the dory. Broadly described, the first three sets each function by specifying in some way a particular distance from the subject-observer to the dory, which distance is employed along with points defining the long axis of the dory and an assumption about dory length to define the dory's orientation (boat angle). (Distance works to specify heading in this way: Array lines from the station point through contour points on the depiction surface [picture plane] spread laterally as they proceed into virtual space. Thus, as the boat is indicated to be at a further depth into virtual space, the depicted horizontal distance between bow and stern will represent a relatively larger lateral [than depth] component of the real boat length, requiring that the boat appear to be swung further leftward from a heading away from the observer. This does assume that the

observer sees a boat of the same length at each viewing position.) By contrast, in Set 4, the relative projected length of the two oars (minus both blades, since one is not fully depicted) is a cue which orients the oars and therefore the boat (defined as perpendicular to a line joining the oar blades) without determining its distance to the observer. (Total picture-plane extent of oar length could have specified distance, but the proportional difference in projected length between the two oars, which was the cue, in itself did not.) None of the sets related the picture to its border.

Sets 1, 2, and 3 were each found to dictate an approximation of full rotation with viewpoint, and thus were highly redundant. Set 4, however, describes an orientation that is relatively unchanging with viewpoint (consistent with Goldstein's, 1979, 1987, finding for objects aligned nearly parallel with the picture plane). In the case of each cue set, there was an excellent fit with judged boat angle at 90°, and with the graphic reconstruction of the scene from that viewpoint. As well as lending confidence to the procedures for determining the virtual spaces for Sets 3 and 4 (the convergence of Sets 1 and 2 at 90° with the overall 90° reconstruction is tautological), this further confirms that 90° viewing was approximately from the original station point, and is also evidence that, at least at 90°, subjects' boat-heading judgments were in accord with perspective cues. (The word *cue*, used here, means perceptual information in a portion of the projected array which permits some particular interpretation of an item of depiction. It has no further theoretical implication.)

The purpose in describing the cue sets is to establish that they exist as perceptible information about object orientation in virtual space; whether subjects used any or all of them is a further matter. Sets 1 and 2 were graphically reconstructed for all viewpoints (Figure 7), employing the same procedure that was described for the reconstruction of the frontally viewed (90°) scene, except made simpler in each case by the fewer contour-point constraints which were involved, and done at 1/50 scale. All scene layouts were by the author. Set 1 determined distance in the same way as for the 90° scene, by the doryman's real sitting height versus visual angle. This, with a 5-m dory length specified between the bow point and the stern center notch, determined a boat angle for each viewpoint. It should be noted that, since the central five viewing positions are (intentionally) the same perpendicular distance in front of the picture plane, and since the doryman's sitting height per se is a single vertical dimension and is in this case not constrained by relation to other depicted features, the man is in each of these five positions located the same perpendicular distance behind the picture, that is, 8.7 m measured orthogonally from the doryman through the picture plane to a plane which includes the five observer viewpoints, exactly in the relation of pure affine shear. Specifying a boat length, however, prevents the bow and stern from appearing at the affine-shear distance in virtual space. (Constraints on room arrangement prevented locating the 14° and 166° positions at the pure-

Figure 7. Experiment 3, reconstruction of boat position in virtual space at 135° viewing, from each of Cue Sets 1 and 2.

shear distance.) For Set 2, a schematic rectangle was constructed on the 90° layout (where such could accurately be determined) from the stern width to a forward place of equal schematic-boat width (see Figure 6); the rectangle was then employed to conveniently establish the degree of perspective taper along the portion of boat length represented in the rectangle, at each position. When projected into virtual space, this taper specifies a proper-length rectangle at a specific distance behind the picture plane, and the angular orientation indicated by the long sides of this rectangle specifies a boat heading. The fact that these projections actually form rectangles (and of fixed length) in virtual space means that they will not be found to be at the distances which an affine transformation would specify for them.

In neither Set 1 nor Set 2 was it possible to assume a constant width for the boat, due to horizontal compression. This is symptomatic of the fragmenting and fracturing of such cues which occurs under perspective distortion. If constant width is added to what has already been assumed for either cue, then the boat will not fit the array or else it will be at such a great distance and pitch-up that, in Set 1, it will become relocated out from beneath the fisherman in it—not a likely perceptual outcome. It is impossible, except at 90° (where all the cues do and should agree), to veridically see in the picture a dory that is at a single specified distance, heading, pitch, length, and width, all at once and in accord with all the locating cues. Each cue set represents an independent partial

geometry of the projection which does not agree with that of any other set.

Sets 3 and 4 were calculated from trigonometric equations (in Appendix); Set 3 was then verified graphically at the 90° and 150° positions, and Set 4 was graphically checked at each position. Set 3 assumed a 5 × 1.6 m dory at all positions except 14° and 166°, where horizontal compression caused a problem with even this modest assumption. At these two positions, the projected length/width ratio was so great that a boat this short in length would not fit the array at any pitch. At these extremes, at an assumed pitch of 70°, the ratio determines that an 8.2-m boat heads 39° left of the line of sight, at a distance from the observer of 62 m. These are the only positions, and this the only cue set, for which the original assumptions fail to provide a solution and must be arbitrarily revised. Notice that Set 3 is the only one which explicitly preserves (for the five central viewpoints) the length/width proportions of the dory. Data (to be presented) suggest that observers do preserve this.

At all oblique viewpoints, Set 3 located the dory considerably further along a line of sight from the observer than did Set 1 or Set 2. (In interpreting the horizontally compressed array, constant length and width are only compatible with greater pitch-up; higher pitch in turn means that the boat's vertical projection is that of a greater proportion of its true length, that is, is a greater height in virtual space, which means the boat is "really" further away.) Set 4 required no constraints of absolute size or distance, but the oars were assumed to be of equal length in virtual space, with the oar of greater projected length appearing closer as a function of that difference in projected length. Their not quite being in a single line but forming a slight bend (172° included angle in the horizontal plane, at 90°), blades sternward, had to be considered, as this influenced the array-permissible interpretation of the length ratio as projected.

It has been objected that this cue analysis is unconventional, which it is. In reconstructing virtual space as seen from nonstandard viewpoints, it is customary to define that space as affine transformed from the standard view (Cutting, 1986, 1987; Rosinski & Farber, 1980). This homogenous linear transformation produces an unambiguous matrix of virtual object points to fit the perspective array as projected to any specified viewpoint. Because it does, it is handy in computing or drafting a perpendicular slice through the projection, to represent what geometric array is actually seen. (It was used here for that purpose, and also, as mentioned, to locate the doryman in Cue Set 1.) The transform is generated by simple rules which guarantee that, though distorted from the virtual space of standard or station-point viewing, the affine-transformed space will within itself have a wholly consistent geometry. The difficulty with this affine transform (not to be confused with affine projection to the picture surface [Hagen, 1986]) as a model of picture perception, is that it entirely removes from consideration the possi-

bility of alternate *optical surrogates* (Hochberg, 1986, p. 22-5) in virtual space, that is, different objects with identical array configurations. And it seems very likely that the perspective array is really seen as something other than its affine-shear transform. In affine space, to preserve an internal geometric integrity consistent with the shifted array, the virtual objects themselves become markedly distorted in size and shape. Right angles become acute or obtuse, and diagonals to the line of sight change in length. Our dory, for example, at the 150° position would become 10 m long and pitch up only 9°. The fact that affine virtual space is always available to the observer as an interpretation does not justify the assumption that it is used, because it so often violates strong expectations concerning the shape and extent of the depicted objects. Instead, it is in keeping with (1) the fact that gross distortion is seldom noticed (Kubovy, 1986; Pirenne, 1970), (2) the notion of ecological validity (Brunswik, 1956), and (3) data to be presented, to suppose that observers see as preserved the prominent, defining dimensions of depicted objects. But distortion is inevitable with nonstandard viewing; not all the dimensions and angles (of realizable objects) can be preserved in any array-compatible layout. Fragmented, partial cues, each preserving specific salient features, are the result.

A corollary problem with affine space concerns the amount of rotation which the virtual-space layout will predict. Affine-shear geometry predicts that there is no oblique angle in front of the picture from which observers could see an object which had been depicted from the station point as heading into the picture (away from the observer), for example, the dory in this experiment, as phenomenally heading *out* of the picture instead into space in front of the picture. Yet Cue Set 3 makes just such a prediction for 166° viewing (the other sets do not), and Goldstein's (1979) data with unidirectional stimuli show clearly that observers regularly will make such "impossible" judgments at extremely oblique angles, when unidirectional stimuli are used. This form of reversal should not be confused with a more genuinely unlikely kind. No cue set predicts, nor do subjects ever report, that the dory heads *toward the observer* at an oblique viewpoint. The latter reversal would genuinely violate prominent constraints in the perspective array, for example, superposition, whereas the former merely challenges a constructive convention (affine transformation) which, though mathematically sound, has nothing necessarily to do with perception. Inasmuch as affine shear distorts recognizable sizes and shapes into forms unlikely to be seen, cannot account for the simultaneous existence of contradictory dimensional indications, and cannot in principle predict phenomenal heading reversals with respect to the picture plane, it is an unlikely a priori candidate to explain rotation with viewpoint.

The mean of boat headings derived from the four identified boat-cue sets fit the subjects' actual perceived/judged orientations better at each oblique viewing position than did any single-cue heading (see Figure 8). Among the de-

Figure 8. Perceived boat-angle headings, from subjects' judgments and from estimates by calculation, as a function of viewing angle, in Experiment 3.

fined sets, the best fits were obtained by combining the means of Set 4 with those of any other one cue set. The case of Sets 3+4 is shown in Figure 9. In general, it appeared that *the mean of two cues, one indicating complete rotation with the line of sight, and one indicating complete heading invariance, could predict an observer's boat-heading judgments*. Figure 10 shows this to be the case. It would at first seem that this simple formula could not be generally useful because object rotation is differential

Figure 9. Perceived boat-angle headings, from subjects' judgments and as calculated from pitch and from oar-length cue sets (Sets 3 and 4), as a function of viewing angle, in Experiment 3. (Because of the extreme distortion at the 14° and 166° viewpoints of pitch cues based on projected boat shape, separate assumptions involving 70° pitch and a longer boat were used to calculate boat heading from pitch at those viewpoints, for this figure only. Over a substantial range of assumed pitches for these two positions, overall two-cue fit with subjects' judgments is about as good. Fit at other positions is entirely unaffected.)

Figure 10. Subjects' judgments of boat- and ship-angle headings, together with estimates of these as the means of two hypothetical cue sets, one indicating full rotation and one indicating full invariance, versus viewing angle, in Experiment 3.

across object orientations (Goldstein, 1979). But, for depictions of real objects having substantial extent in all horizontal directions, the nonrotation of an axis closely paralleling the picture plane will almost always be compensated by strong rotation of an orthogonal axis which points into or out of the plane. Except for predicting the rotation of poles, rifle barrels, and oars, then (for which a single cue may suffice), the formula may turn out to be a useful approximation. It does appear that some simple combination or choice among partial cue sets is apt to govern each instance of off-angle perception, if such cue sets are indeed involved in that perception.

The same simple formula (heading rotation = $\frac{1}{2}$ angular shift in position) applied to the ship angles predicted their judged rotational increments, but consistently overestimated absolute judged headings (Figure 10). Revising the position-shift angle to include an array-correct allowance for horizontal compression did not materially affect the prediction. A likely explanation for the discrepancy between judgments and calculation is that subjects' underestimate of ship angle (overestimate of its difference in heading from the line-of-sight), observed at 90°, extended to other positions as well. It is as if subjects grossly underestimated the distance to the ship, in making judgments. (A hierarchical reason for this will be suggested.)

The ship angle is seen to rotate slightly less than the boat. This mean rotational difference is small enough (11°, over a 152° change in viewing angle) to go unnoticed by observers, who would thus see the within-picture layout as unchanging. In general, object relations do remain stable under viewpoint shifts (Goldstein, 1979, 1987) because headings of all object axes will be seen to rotate in the same direction; viewpoint must change through large angles before differential rotation distorts the directional relations among pictured objects suffi-

ciently to be noticed. Scene stability is thus a natural concomitant of rotation, not a paradoxical countereffect.

A border cue may have prevented the ship angle from appearing to rotate more than it did. (Differential rotation [Goldstein, 1979] would predict the ship angle to rotate more than the boat angle, based on their relative depicted headings.) There is a strong cue to constancy or stability of ship heading in the virtually invariant proportion between the ship's distance along the painted horizon and the total distance between the picture's edges.

EXPERIMENT 4

Experiment 3 demonstrated the existence of sets of geometric cues which conflict with each other in the rotation they represent at oblique viewpoints, and showed that these cues could be made to account for observers' judgments of depicted orientation. But did subjects really use the cues? If their judgments differed, in the predicted direction, depending on whether their attention was directed to rotational or nonrotational cues, that would suggest the cues were effective. Homer's picture (Figure 4) was again employed to test this.

Method

Subjects. The 17 subjects were 13 United States Army commissioned officers, one warrant officer, one noncommissioned officer, and two civilians. All were male students in a University of Southern California extramural graduate program in systems management. Four were helicopter pilots currently flying; all reported normal or corrected vision. Ages ranged from 22 to 38 years.

Apparatus and Procedure. Subjects sat at a table to view a 14.6×22.9 cm nonglossy monochrome reproduction of Winslow Homer's *The Fog Warning* (Figure 4) from a position which duplicated the visual angle and projected array of the 150° position in Experiment 3. Thus, the line of sight was at 30° to the picture plane, from the right side, and viewing distance was 84 cm horizontally to the center of the depicted horizon. The picture was mounted on a platform above the table, to place the horizon approximately at eye height for all subjects.

Each subject was asked to make separate judgments of (1) the plan-view orientation of the dory, with respect to the picture plane, that is indicated by its hull (long axis), disregarding any other sources of information, (2) the orientation to the picture plane of a "best-fit" straight line (imaginary) extending along the pair of oars (e.g., a line between the blades), and (3) the angle (oar-crossing angle) formed between the dory-hull long axis and the best-fit line along the oars, that is, the angle at which the oars, ignoring the slight bend between them, would cross the boat. To accomplish this, subjects used a pair of 29-cm pointers of different colors pivoted about a common center and mounted on a circular base. Pointers represented boat axis versus picture plane, oar axis versus picture plane, or boat axis versus oar axis, as appropriate. The task order was counterbalanced among subjects. Next, subjects were asked to identify the "correct" boat among five numbered plan-view outline shapes presented, that were drawn in different length to width proportions and oriented vertically in a horizontal row on a sheet of paper. The boat-length/width ratios were (1) 1.5:1, (2) 2.5:1, (3) 3.33:1, (4) 5.0:1, and (5) 7.0:1.

Results and Discussion

Azimuth from the picture plane, whether of boat or oars, is reported as were the boat angles in Experiment 3,

that is, a 90° boat is headed directly into the picture, and 90° oars are parallel to the picture plane in such a way as to indicate a 90° boat heading. Counterclockwise rotation increases heading. The oar-crossing angle is expressed as the included angle from the point of the bow to the "best-fit" line along the right oar (in the man's left hand).

Over all subjects, mean boat (length axis) orientation was 162.6° and mean oar direction (converted to boat angle) was 126.9°; standard errors of the means were, respectively, 4.1° and 4.8°. At the comparable 150° position in Experiment 3, mean judged boat angle was 135.8°, that is, an intermediate value, when subjects were not directed to differentially attend to cues (though this comparison is very tenuous, given differences in subjects, pictorial scale, and chromaticity). The mean oar-crossing angle, judged directly, was 102.2°, with standard error 3.5°. This is less than the oar-crossing angle implied by the separate mean judgments of boat and oar headings, which is 125.7°. All these data are what would be expected if subjects used different cues for the different tasks. Subjects saw the oar-crossing angle at nearly its depicted size (90°, as reconstructed, Figure 6) when that angle was attended to (nine indicated it to be within 4° of a right angle), but that perception did not prevent judgments of boat (length) direction and oar direction, attended to separately, from being incompatible. It appears that there are, for the same viewing position, different perceptually effective cues indicating different amounts of rotation, and that, to some extent at least, they may be attended to selectively. However, the two mean judged headings only differ by 35.7°, which is much less than the individual cue-set calculations of Experiment 3 would predict. For Set 3 versus Set 4, for example, that difference is 90.2°, making the obtained difference only 40% of what might have been expected. This suggests either that the cues used are not completely separable perceptually, are not adequately represented by Set 3 versus Set 4, or that some unknown factor is also functioning.

There were strong individual differences, suggesting that cues may have been much more separable for some subjects than for others. The discrepancy in oar-crossing angle, between direct judgments of that angle and its calculation from judged headings, ranged from 0° to 74°, with no reversals but with five subjects reporting 6° or less. The judgments of these five, then, unlike the other 12, either were not at all influenced by having their attention redirected between cues, or not very much. (This way of comparing subjects eliminates the problem that some of them *directly* saw the oar-crossing angle as markedly obtuse.) Four subjects spontaneously reported difficulty in separating cue information, but only one of these did not show a substantial cue-dependent effect.

Dory Shape 3, which proportioning agrees with the 90° reconstruction in Experiment 3, was chosen as correct by nine subjects; five chose Shape 2, and three chose Shape 4. This bears on what rotational cue subjects might have used. If subjects "saw" affine shear, the exact boat

proportion seen would depend on whether and by how much they interpreted the depicted length and width indications to represent nonorthogonal dimensions, as they would under that transform, but in no case could the judged ratio be less than about 6.7:1, or twice the modal ratio reported here. Cue Sets 1 and 2 (Experiment 3) also indicate a long, narrow boat at this position, but Set 3 preserves the true (reconstructed) dory proportions that were also most often seen, and therefore that cue set may have been used by subjects in their judging.

From Experiment 3, it is appropriate to consider Set 4, the difference in projected oar length, as the nonrotational cue here. But a more plainly visible if less precise cue exists. The depiction of the oars extends nearly the full width of the picture, and they are painted nearly flat in that plane (at 22° from it). Their extent nearly from border to border remains obvious at any viewpoint, and may be a strong border-relation cue to coplanarity. From far aside, the observer can still tell the correct width of the picture, which is also the depicted length of the oars. Had they been angled further from the frame, the relation of depicted length to real length and therefore to orientation might have been less clear, and the frame relation less obvious. (At the same time, the oars' aspect with respect to the viewer is markedly foreshortened when viewed more obliquely, by an amount that, in absolute size, is much greater than if the oars had been shown on end pointing toward us. As a dynamic cue which, if effective at all, can only be so during the observer's movement by the picture, the foreshortening should not have mattered here, except that subject-observers were unrestrained, and doubtless experienced it at least mildly.) Set 4, by contrast with the border relation, seems to be subtler. Other than that, they should both equally indicate nonrotated oars, and so are indistinguishable by these subjects' performance.

There are many sources of information, some of it equally available to any viewpoint, that the oars cross the boat at a right angle. A prominent cue is that the man's hands are on oar handles which are in line and nearly touch. Conversely, explanation based either on affine shear or partial cues could account for the obtuseness of the mean judged oar-crossing angle. In no way, however, can affine shear (as the only cue) explain the discrepancy between that angle as judged directly, and as inferred from heading judgments. Nothing suggests that affine-transformed space was seen; it might have been, but then something else would have to account for the way that subjects judged boat shape.

EXPERIMENT 5

If projective cues are really responsible for rotation or its lack, then attending separately to rotational versus nonrotational cues ought to affect rotation more strongly than it did in Experiment 4. The difficulty may be, however, that, for most people, it is perceptually impossible to fully separate cues that are simultaneously present in a depiction. This might be tested with a variation on

some data of Goldstein (1987). He shows that subjects viewing two dots, one dot at the center and one near the circumference along a ball's "equator," the dots presented singly on pictures of the ball (his Figure 14) and viewed from aside, misjudge the relative angular location between the dots in a way wholly inconsistent with the geometric depiction.

Goldstein (1987) argues from this against complete reliance on projected geometry, in that the rotation with viewpoint of certain objects is inhibited by comparison of the object's orientation with that of the picture plane. But, considering Experiment 2, it seems that the picture plane per se does not much affect orientation judgments, though its border can. And in Experiment 4, a manipulability of perceived orientation was predictable from very specific geometric information, the partial cues previously identified in Experiment 3. The case for geometric-array-determined perception would be made stronger, however, if it could be shown that, not only is the effect of a difference between cues much greater when they are separable, as was so for Goldstein's dotted ball (each dot considered as a separate cue), but that the dotted-ball presentations are genuinely comparable to Experiment 4, in that, when both dots are simultaneously present, the angle between them is judged veridically. This would argue for the differential effect of task requirements on cue salience, rather than the failure of geometric determinants to direct the perception of pictures.

Method

Subjects. The six volunteer subjects with normal or corrected vision were an economics professor, a retired teacher, an undergraduate senior in engineering, and three psychology seniors. Three subjects were female.

Apparatus and Procedure. The three stimuli were similar to Goldstein's (1987) Figure 14 except they were perspective line drawings. Each depicted a 15.2-cm ball with one or two 1.9-cm square dots on it, either one dot directly in the center of the ball as drawn, one dot drawn as if swung 60° horizontally leftward along the circumference from that direction, or both dots present. Subjects viewed the pictures from 160° (i.e., 20° from the right-hand side) and from 46 cm away, the distance of the station point. They each saw the two-dot picture first, then the others in random order. For the two-dot condition, they were asked to indicate the radial angle between the dots (with reference to the center of the ball), using the pointer arrangement from Experiment 2; for single-dot presentations, they indicated the dot's direction from the picture plane.

Results and Discussion

When subjects judged each dot alone, they perceived mean orientations of 147.5° for the center dot and 32.8° for the side dot, which represents an included angle between the dots of 114.7°, a much greater angle than could veridically be inferred from the depiction. Goldstein (1987) found similarly for these conditions of presentation. However, when subjects viewed both dots at once, their mean included-angle judgment was 67.7°, acceptably close to the actual depicted separation of 60°. Standard errors of the means were 9.72° for both dots, 11.91° for the center one, and 9.05° for the side.

It is probable that when subjects saw the dots singly, they used proximity to the circumference, along with observed slant of the picture (judged from the trapezoidal projection of its border), to orient the side dot, but tended to interpret the center dot as pointing toward themselves, since "pointing toward" was highly salient for the center dot but not the side dot. However, when observers had the different task of determining how far apart the dots were, in angular measure, their perceptual strategy was appropriately different; it was to use the same type of cue (distance along the equator of the slanted picture) to orient each dot, despite greater salience of a different cue for one of the dots. This suggests that, when partial cues conflict, the choice among them will depend on the requirements of the perceptual task at hand. To account for performance, it seems necessary and sufficient to know two things: the partial geometries being projected, and the observer's perceptual decision strategy.

If it can be expected that, each seen alone, the center dot will rotate fully and the side dot hardly at all (Goldstein, 1987), then the expected difference between their included angle as directly observed (two-dot condition) and as inferred from separate directional judgments for each dot seen alone will be 70°, the amount by which the picture has been slanted from a frontal view. The obtained difference was 47°, that is, two-thirds of the expected value. This does suggest, compared with Experiment 4, that when cues are visually, as well as attentionally, separated, their differential effect is stronger. It is not strong enough, however, altogether to preclude the operation of other, unidentified factors on rotation.

(It would have been a more direct stimulus comparison with Experiment 4 to have presented isolated portions of Homer's composition. However, the patent artificiality and attention-begging nature of showing a rowboat without oars—let alone the reverse of that—seemed to prevent the idea from being a good one for the present purpose.)

EXPERIMENT 6

Experiments 4 and 5 have demonstrated that when features of a single depicted object are separately attended to, some will rotate more than others, suggesting that partial-geometry cues (Experiment 3) may be differentially effective. It remains to be established that subjects specifically used one or another of the cue sets identified for the seascape stimulus. Truly, that may be very difficult to establish with certainty, considering the wide individual differences obtained and the facts that the cue sets identified do not exhaust the perspective information nor need cue use be mutually exclusive. But there is already a suggestion, in the shape that subjects in Experiment 4 saw the boat to be, that Set 3 may have been salient there. And Set 3 indicates other things than just rotation. It specifies a boat of the same canonical proportions as those which were graphically reconstructed, and which were modally judged as correct from 150°, and it also predicts that a strong pitch-up will be seen by an observer mov-

ing from the frontal (90°) viewpoint sideways to any other. If the rotation, constant shape, and increased pitch all were seen, that would specifically implicate Cue Set 3, since both of the other rotation-inducing cues would indicate a narrowed boat and neither would indicate an appreciable increase in pitch.

Method

Subjects. The 10 subjects consisted of 8 United States Air Force commissioned officers, including three pilots, enrolled in a University of Southern California extramural graduate program in systems management, a retired teacher, and the experimenter. One subject was female.

Apparatus and Procedure. The apparatus of Experiment 4 was used, except that the 29-cm pointer was mounted above a 25-cm circular platform in such a way that it pivoted about two axes to indicate azimuth and pitch simultaneously. At each viewing position, the pointer was repositioned on the table to be directly in line between the subject and the picture; the pointer's pivot point was 15 cm below the level of the depicted horizon. Subjects viewed the picture as they did in Experiment 4, from the 150° position and a distance of 84 cm, and also saw it frontally from a 42-cm viewing distance. The subjects, not the picture, were moved from position to position, in counterbalanced order. As in Experiment 4, these positions were intended to be comparable, in visual angle and array geometry, to the corresponding (i.e., 90° and 150°) positions of Experiment 3.

At each position, subjects were asked to align the pointer, with respect to both azimuth and pitch, with the direction that they saw the dory to be oriented, from that viewpoint. Azimuth was read from markings on the circular platform; pitch was measured with a separate protractor, applied to reference lines on the pointer and its vertical post, after the pointer was aligned.

Results and Discussion

Azimuth headings have been converted to the boat-angle reporting convention of Experiment 3. A bow-up pitch is positive, from 0° when the dory is horizontal in space. Mean judged boat angles were 118.7° at the 90° position, 172.6° at 150°. Mean judged pitch was +22.8° at 90°, +28.8° at 150°. Standard errors of the means, in the order listed, were 1.3°, 1.2°, 1.4°, and 2.6°.

Mean rotation between positions was over twice as much as between the comparable viewpoints in Experiment 3, fully as if there had been complete reliance on rotational (vs. rotation-inhibiting) cues. There are several possible causes of this. The smaller, monochrome picture may have degraded the already less visually prominent oars cue until it was not as salient as before. Framing cues could have been effective in some unidentified way, and more so for the larger picture. But a far more likely cause is that the attention of these subjects was differently directed. In this experiment, subjects did not estimate with respect to the picture's orientation, as they did in Experiment 3, but judged azimuth with explicit reference to their own viewpoint. Doing this, their attention would be drawn to the leftward position of the bow of the dory, as a criterion virtually mandating full rotation; moreover, the judgment of azimuth and pitch were combined, and pitch depends on, and brings attention exclusively to, the dory's long axis, the basis of the rotation-inducing cues. This explanation is reinforced by the effect

on rotation of explicitly redirecting attention, especially in Experiment 4 where the very same picture was used, and comparable full rotation was judged when boat-hull cues were exclusively attended.

Overall, the small increase in upward pitch at the 150° position, over that at 90°, is scant evidence that subjects used Cue Set 3, which calls for a 27° increase. Nonetheless, Set 1 would indicate only a 2° increase, and Set 2 a 9° decrease, so that the 6° mean increase actually observed, the full rotation, and the preservation of dory shape (this in Experiment 4), do favor Set 3 over any other set of geometric information identified, including the affine-shear construction which would indicate a decrease in upward pitch, and is now even less likely perceptually than before.

There are revealing individual differences. Three subjects saw exactly the same pitch at both positions, and two saw only 1° increase at 150°, while the rest all reported substantial increases. This suggests that subjects may have dichotomously attended either Set 1 or Set 3 as the primary cue. The cues are lawful; their selection may be less predictably so. (Four of the five who saw virtually no difference in pitch viewed the 90° position first. However, the effect of presentation order, between those who did and did not see an increase, failed of significance [$F(1,8) = 3.71, \alpha > .05$].)

GENERAL DISCUSSION

At first it would seem that the rigid relation between lattice and frame, in Experiments 1 and 2 here, and in Rosinski et al. (1980), is a rare event, making these stimuli laboratory curiosities. But many depictions show objects "laid out flat" in the picture plane, or nearly so, in a way that is clearly evident from any viewpoint. For one thing, their width, with respect to the picture width, remains visibly constant. And these *are* the objects which do not rotate (Goldstein, 1979). In the different case, when objects are visibly angled to the frame, that trigonometric complication renders horizontal extent a less simple cue, and probably a less discernible one (unless object and frame are visibly hinged, for example, which is a laboratory exception). At the same time, the more foreshortened their horizontal lengths are in the frontally viewed depiction, the more stable will be the objects' apparent aspect toward or away from the observer, since their horizontal extents and, for that matter, the angles those lengths make with the picture's top and bottom borders, are changed by much smaller absolute amounts under compression due to viewpoint shift. And stable apparent aspect, accepted as veridical by the viewer, is what defines the presence of rotation; the objects follow us. So the picture plane, or rather the picture frame which is more certainly effective, sometimes does and sometimes does not influence object orientation. For objects having a relatively invariant visible relation to the frame, that relation will, or at least can, inhibit rotation. But where any such apparent relation changes, or is vague, depiction-array geometry that is independent of the frame must

decide the object's orientation. If that geometry, under viewpoint shift, maintains an aspect with respect to the observer instead of with respect to the frame, rotation ensues. It is as if the picture either "captures" the object by showing it in full extent, or fails to, in which case it is free to rotate. The examination of the nonrotational (oars) cue in Experiment 4 is suggestive of this. But it is not an all-or-nothing situation; these two opposing tendencies, and other indications, often exist at once, and their conflict must be resolved. There could be a kind of loose, symbolic geometry, with the different cues having simple, directional valences.

On the other hand, a large number of geometrically exact directional indications exist in a pictured scene, and these, too, mutually conflict at oblique viewpoints. They do so complexly, but those discovered virtually indicate either full rotation or none at all. There are even anti-rotational cues (Set 4, Experiment 3) of this kind which, unlike the relative-width cues just described, have no dependence on the border. Judgments of shape and other properties under oblique viewing in Experiments 4 and 6 are consistent with reliance on one of the exact cues identified in Experiment 3, though not conclusively. More work, perhaps much more, is needed to decide the exact nature and utility of the directional indicators. Perhaps people use all the kinds there are.

While precise or sloppy cues might be seen, observers apparently do *not* see an affine-sheared space which distorts both angular and linear proportions within the picture. Consider a summary comparison, affine space versus a combination of Cue Sets 3 and 4 from Experiment 3. Both alternatives would predict that the boat-hull and oar-length directions would rotate differentially, as they are in fact seen to do (Experiment 4). Set 3 preserves the shape of the boat (Set 4 is irrelevant to boat shape and pitch). But the affine-transformed boat would elongate to about twice the length-to-width ratio that was depicted, and that was seen from aside (Experiment 4). Set 3 predicts an increase in bow pitch with obliqueness of view; affine space a decrease. Observers saw an increase or no change, never a decrease (Experiment 6). Affine space predicts that observers will never, from any angle, see something that was depicted as heading into the picture, as heading out of it—yet this does repeatedly happen, at extreme obliquity (cf. Goldstein, 1979, Figure 4), and Set 3 predicts it. Affine space also does not predict contradiction; the oars should cross the boat at the same oblique angle whether that angle is visually estimated directly or from headings, but they are not seen to do so (Experiment 4). Altogether, combinations of independent cues or "spaces" in the same projective array seem to predict performance, while affine-sheared virtual space does not, whenever those predictions differ for situations considered here. The transformation of the projective array itself is such that any space, be it partial-cue, affine, or other, that genuinely fits the array, must have strong commonalities with any other, so that they would predict alike in many ways. Thus, Cutting (1988) might loosely

account for Goldstein's (1987) results, without validating affine space as that which is seen. That Cutting's analysis badly underpredicts the amount of rotation Goldstein (1987) found at extremely oblique views is due to the same inherent rotational limitation of affine-geometric space that prevents it from predicting object-heading reversals with respect to the depiction surface.

Selection among available cues can depend on the salience and the priority of higher-order, *event-related* cues, which constitute awarenesses of the nature of depicted objects and events. While such higher awareness derives from the geometric information available, it is itself categorical and does not appreciably distort or disorganize under viewpoint change. It is clear at all viewpoints, for example, that the boat is a fishing dory, and this information strictly constrains the boat's length within a certain appropriate range. Event cues may also explain why the oars in Experiment 4 are seen relatively square with the rotating dory, despite the fact that boat-geometry projections will dictate rotation while the oar projections will not: That the doryman's hands are together and the oars in line does not geometrically dictate squareness in just any object; it does, however, if the object is recognized as a rowboat. And in Experiment 3, that the doryman appears to look over his shoulder at the ship may account for the consistent underestimation of ship angle (even at 90°, Figure 5) as an underestimate of ship distance; the doryman's head (his eyes are not clearly visible) seems turned more obliquely, that is, to a closer place along the array line from observer to ship, than the ship's depicted size would indicate its position to be. This is despite the fact that the doryman's gaze, independent of its purpose, need not locate anything. The fact of "hinging," in Experiments 1 and 2, could also be considered an event cue, as well as a geometric one. It is these superordinate, "narrative" cues which *direct* or force the integration of locational cues and cue sets in some effective combinational compromise, and may even distort them. The event cues could also contribute to or be responsible for scene stability (Goldstein, 1987) generally, by concentrating attention on properly comparable cues to relations wholly within the depiction, as in Experiment 5. As in ordinary perception (Brunswik, 1956), we would expect the salience of cues to depend on the differential subjective probability that each is ecologically valid. The event cues assist that implicit probability estimation.

From what is known, three points, amounting to a model, can be made:

1. What is seen as being in the virtual space of the picture is determined in the first place by geometric properties of the perspective array being projected from depicted features to the observer's eye. The salient features may be represented as independent, partial-geometry cues or sets of cues to the position and/or orientation of complex depicted objects. Cues to orientation may, but will not always, include some which involve a discernible geometric relation between the depiction and its border; such

cues are characteristically nonrotational. The cue sets are apt to be mutually contradictory, except in the array projection to the station point.

2. The amount of apparent rotation for any particular feature is determined by the proportion in which the observer attends to relevant cue sets which do or do not induce rotation. The cues are perceptually combined into an effective resultant.

3. The proportion in which conflicting cue sets are combined, or whether one cue is attended to and another ignored, can depend on higher-order information of two kinds: cues to the categorical nature of objects and events depicted, and particular requirements of the perceptual task at hand.

The idea that picture perception is array-specific is not new. Leonardo da Vinci held such an opinion (Kubovy, 1986, p. 52 ff.), and Cutting (1986, p. 31 ff.) has applied to pictures his theory that vision generally is directed by determinants in the array. Both Cutting (1988) and Goldstein (1988) speculate that virtual-space geometry may combine with other factors, such as awareness of the picture's orientation, to produce rotation. What the present study provides is a mechanism, the partial cue, by which the perception can proceed as it does (including frame effects) and still be array-directed.

In an array-determined model, the classic anomalies are explained about as they often have been. Portraits follow us because of the stable predominance of "facing toward" cues. The column paradox and the apparent distortion of spheres seen in the corners of pictures (Pirenne, 1970) seem to be caused by the observer's losing track of the station-point relation of objects located at wide angles, and thus attending only to local cues. But now these accounts cohere with that for picture perception generally.

Border cues may be implicated in the data of Ellis, Smith, and McGreevy (1987). They found that the rotation of a depicted pointer was more differential (there is less rotation of leftward- and rightward-depicted pointers vs. those aimed at the observer) when the pointer was elevated (or depressed) 30° than when it was horizontal. When elevated or depressed, the projection of the pointer's vertical angle varies more with viewpoint, at least for those azimuth conditions where the pointer's horizontal extent approaches being parallel to the picture plane, the same conditions for which they observe greater inhibition of rotation for the elevated pointer. They point out that this greater variability of projected angle increases information about the amount of picture-plane reorientation being undergone, permitting more accurate (less rotated) judgments when it is present. But the trapezoidally projected border would seem of itself to provide plenty of evidence for the picture's orientation. And unless observers were relying on memory instead of immediate perception, something else seems important; the apparent relation *between* picture plane (frame) and pointer is the perception in question. The vertical angle might still be effective; its greater change (when pointer is elevated) with viewpoint indicates greater reorientation, which should more agree with the increasingly/decreasingly trapezoidal

frame, resulting in less apparent rotation between the two. Alternatively, or perhaps in addition, when the pointer is elevated, its projected length to oblique viewpoints more nearly preserves its length projected frontally, so that elevated pointers depicted at shallow angles to the picture plane will continue to have an appreciable length, relative to the overall size of the picture, at oblique viewpoints. The pointer could thus appear relatively "flatter" in the picture plane at all viewpoints, and not rotate as much. Either account implies projective cues relating depiction to border.

Cutting (1987) has suggested that distortions are ordinarily not noticed at oblique cinematic viewpoints because local information, for example, the projected size of corner angles, is changed so little that perception is unaffected. This is probably quite true; however, it is more global integrations of length, aspect, etc., which seem to distort our judgments of spatial direction (a lot) and spatial layout (a little), though we remain unaware of the distortion.

Increasingly, resultant performance is an issue in picture perception, as when perspective displays are considered for aircraft cockpits (McGreevy & Ellis, 1986). Analyzing the display cues and their differential salience should contribute to understanding that performance; however, efforts toward prediction must contend with the strong individual differences observed.

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APPENDIX

Cue Sets 3 and 4 were derived by calculation. In Set 3, to obtain the desired horizontal boat azimuth angle, B , from the line of sight at each viewing position, first the ratio on the picture plane of the vertical projection of boat length to the horizontal projection of boat width was measured as 1.239, with the boat schematized as in Figure 6. Considered as it is seen normal to the line of sight, that ratio increases with obliquity of viewpoint. Yet, as defined, it must represent the components normal to the line of sight of the same full-size boat dimensions in virtual space. This representation is veridical only if the boat pitch-up increases also. Pitch angle thus is defined in terms of viewpoint: $\sin \text{pitch} = .3763/\sin A$, where A is the viewing angle, and the constant represents the cross-multiplication of the depicted and real vertical-length to horizontal-width ratios already described. At the observer's distance, d , from the center of the boat, defined for this cue set, not only boat width but all lateral dimensions have spread along array lines to their full real extent in virtual space. Thus, the horizontal component of boat bow-to-stern distance, measured in the picture plane, represents a constant lateral extent (normal to the line of sight) for all viewpoints, that is, 1.75 m per the 90° reconstruction. This dimension, and the horizontal component of real boat length, define azimuth thus: $\sin B = .355 \cos \text{pitch}$. The observer's distance, d , depends on pitch, vertical boat height in the picture plane, and viewing distance to the picture, p , thus: $d = 17.08 p \sin \text{pitch}$, where the constant is the ratio of the full real length of the boat to the picture-plane size of its vertical extent in projection. Geometers will notice a simplification in these Set 3 calculations: Projective spread along the depth that the boat's length extends in virtual space has been ignored, in the trigonometric relations defined. It is as though the array was centrally projected through the picture plane along the line of sight to a normal plane at d , from which plane the boat itself was constructed in depth by parallel projection along the line of sight, somewhat in the manner of a Chinese landscape scroll (Hagen, 1986, pp. 261-262). (No such projective violations are

involved in the graphic reconstructions. For Set 3, as for all sets, reconstructive layouts are valid central projections.) This simplification seems justified in that the projective discrepancies it produces are relatively slight and local, and their effects tend to cancel each other; in any case, these equations appear quite robust; for example, for the 150° viewpoint, calculated values of pitch, observer distance, azimuth, and the length and width of the boat all agree within 1% with the values as graphically reconstructed.

The following approximate formulae define azimuth B (Figure 11) per Cue Set 4, for viewpoints left of 90°: $\tan B = g(r-s)/2rs$, where

$$r = g \tan R + \frac{g \sin Z(\tan R - \tan S)}{2 \tan S} - g \sin Z \tan^2 R$$

and

$$s = g \tan S - \frac{g \sin Z(\tan R - \tan S)}{2 \tan R} - g \sin Z \tan^2 S.$$

(Views from the right require the same equations but with several sign reversals.) Angle Z was entered as 4°, from the reconstruction in Figure 6. Graphic-layout verifications revealed three things: (1) The calculated headings are array-correct in terms of this cue. (2) Horizontal compression causes Z to decrease either side of 90° viewing, to about 1° at the extreme side views, for the calculated values of B . (3) A range of combinations of B and Z will fit the array. The least counterrotation (most rotation) occurs with B at minimum values, which require that $Z = 0$. Even the *minimum* B , which averages 13° less than B , works strongly against rotation. Applied in Cue Set 4, it would have yielded 9° net total rotation between the 14° and 166° viewpoints.

In the foregoing equations, as in the graphic method used for all sets, it is assumed that there is no perspective convergence in the vertical direction. This simplifying assumption is the conventional one, and is entirely appropriate here, but would not be in some cases, for example, a scene viewed from above.

Figure 11. Diagram used with calculations of boat angle from Cue Set 4, projected oar lengths (minus blades). Proportions are exaggerated for illustration.