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Spatial Layout, Orientation Relative to the Observer, and Perceived Projection in Pictures Viewed at an Angle

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Judgments of the spatial layout of a three-dimensional array of pictured dowels remain relatively constant as viewing angle changes, whereas judgments of their orientation relative to the observer (perceived orientation) vary These changes in perceived orientation as viewing angle changes, called the differential rotation effect (DRE), also occur for stimuli such as the eyes in portraits, which are not extended in pictorial space Thus, the mechanism for the DRE does not depend on the extension of pictured objects in depth The DRE is decreased when back-illuminated pictures are viewed in the dark so that the picture plane is not visible This result suggests that the DRE depends on information that defines a pictured object's direction relative to the picture plane The difference in the way spatial layout and perceived orientation are affected by changes in viewing angle suggests that it is important to distinguish between these two attributes of pictures In addition, another attribute, the picture's projection, should be distinguished from spatial layout and perceived orientation When these distinctions are not made, the result is confusion, particularly when discussing whether or not pictures viewed at an angle appear distorted

A scene depicted in linear perspective and viewed from the correct station point can, by duplicating the geometrical array of the original scene, create a perception similar to the perception of the original scene Many investigators have noted, however, that changing the geometrical array by viewing a picture from an incorrect station point does not cause a corresponding distortion in the observer's perception of the picture (Haber, 1980, Pirenne, 1970; Rosinski & Farber, 1980). This contention, however, is only partially correct. One attribute of pictures, the spatial layout of objects in the picture, does remain relatively constant with changes in viewing angle; however, another attribute, the orientation in which pictured objects point relative to the observer, is far from constant with changes in viewing angle (Goldstein, 1979).

These findings pose a potential paradox. On one hand, the orientations of pictured objects relative to the observer change as an observer's viewing angle changes, while on the other hand, the perceived spatial layout of these objects remains relatively constant One purpose of the present article is to investigate this paradox in more detail by having observers make both orientation-relative-to-the-observer and spatial layout judgments on a picture of known spatial layout so that these two attributes can be compared with each other and with the actual spatial layout. Observers viewed a picture of a triangular arrangement of vertical dowels at different viewing angles and judged both the spatial layout of these dowels (Experiment 1) and the orientations of pairs of dowels relative to the observer (Experiment 2) (For brevity, orientation relative to the observer will be referred to as *perceived orientation*)

Following these two experiments, I will look more closely at possible mechanisms responsible for orientation perception by asking how perceived orientation is affected by (a) the extension of pictured objects in pictorial space (Experiments 3 and 4) and by (b) visibility of the picture plane (Experiment 5).

Experiment 1

In this experiment, a person's ability to reproduce a picture's spatial layout is measured by having observers judge the locations of three vertical dowels arranged in a triangular layout when a picture of these dowels is viewed from different angles.

Method

Observers Five undergraduates at the University of Pittsburgh who were naive to the purpose of this experiment were observers

Stimulus A line drawing of the picture used in these experiments is shown in Figure 1 The actual stimulus, which did not include the letters shown in the figure, was a 4 × 5-in (10 2 × 12 7 cm) black and white photograph of three dowels on a homogeneous white surface, in front of a homogeneous white background The dowels were painted with black-and-white horizontal stripes to make them easy to differentiate from the ground plane and from the background The 3 375-in (8 572 cm) high dowels, when photographed from a distance of 46 in (116 84 cm), resulted in an image 1 125 in (2 86 cm) high in the photograph

Procedure Observers viewed the picture monocularly from a distance of 15 in (38 1 cm), with head fixed in position by a chin rest The picture was placed on a plane that was rotated to present the picture at viewing angles of 20°, 45°, 70°, 90°, 110°, 135°, and 160°, with viewing angles presented in random order *Viewing angle* is defined as the angle between the picture plane and the observer's line of sight when looking straight ahead A viewing angle of 0° means that the picture plane is parallel to the observer's line of sight, with the right edge of the picture

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I wish to thank Sam Choi, Ang Franzetta, and Paul Haber for running subjects for some of the experiments I also thank Frank Valentich for building the apparatus

I regret that reprints are not available

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closest to the observer A viewing angle of 90° means that the picture plane is perpendicular to the observer's line of sight, and a viewing angle of 180° means that the picture plane is parallel to the observer's line of sight, with the left edge of the picture closest to the observer (See Figure 2 of Goldstein, 1979, for further details)

Because binocular viewing results in two different viewing angles, one for each eye, the pictures in this and all subsequent experiments were viewed monocularly, with the line of sight intersecting the picture's center of rotation Monocular viewing made unambiguous determination of viewing angle possible Pilot experiments, in which monocular and binocular viewing were compared, showed that results were identical for both viewing conditions

Pictures were continuously on view so that observers could see the pictures as they were rotating to each new viewing angle The constant visibility of the pictures, the visibility of the edges of both the picture and the rotating plane on which they were displayed, and the contrast between the black plane on which the pictures were displayed, and the white border of the picture made the viewing angle and changes in viewing angle obvious to the observer

As the observers viewed the picture from each angle, they judged the spatial layout of the dowels by arranging three discs on a piece of 8½ × 11-in (21 59 × 27 97 cm) paper to duplicate the positions of the bases of the dowels in the picture The edges of the paper on which the observers arranged the discs were clearly visible, and the paper was positioned between the observer and the picture so that the back edge of the paper was 2 in (5 08 cm) below and 2 in in front of the picture Observers were given unlimited time to position the discs on the paper, but on most trials they completed the task in less than a minute

Results

The averaged results for all 5 observers, labeled *layout condition* in Figure 2, show both the locations of points A, B, and C for viewing angles of 20°, 90°, and 160° and the actual layout of the dowels The data for all 5 observers were combined by scaling side BC to the same length for all observers, and in Figure 2 this side is set equal to side BC for the actual layout [1] The data for the other viewing angles are not included, but the triangles for the omitted views fall in an orderly sequence between the 20° and 160° triangles. Comparison of the averaged, scaled triangles with the actual spatial layout indicates that at all viewing angles observers underestimate the distance between A and B, and this result is also apparent in the raw unscaled data for each of the individual observers This underestimation of the distance between objects extended in depth has also been reported for three-dimensional objects in an environmental setting (Wagner, 1985).

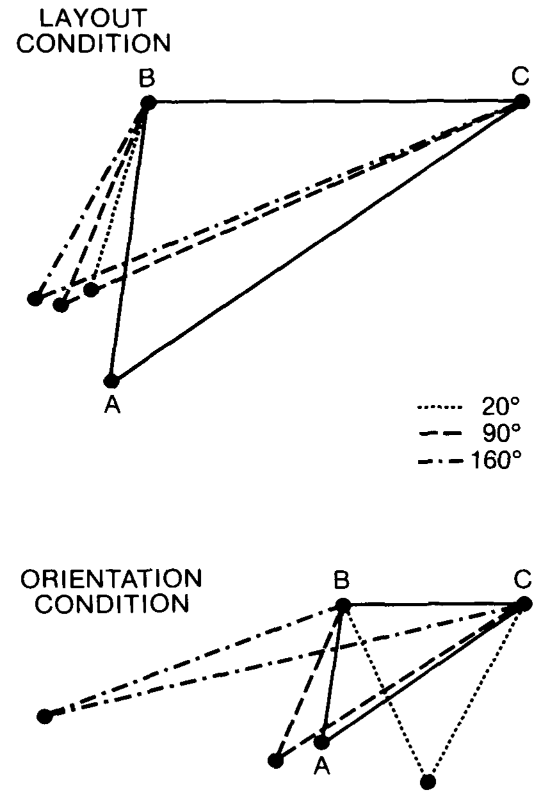

Figure 2 Results for Experiment 1 (layout condition) and Experiment 2 (orientation condition) (The points marked A, B, and C represent the actual layout of the dowels shown in Figure 1 as seen from above) Layout condition Triangles represent the average layouts produced by 5 observers in response to the stimulus in Figure 1 when viewed at angles of 20°, 90°, and 160° Orientation condition Triangles calculated from the results in Figure 3 (Average of judgments made by 5 observers Standard error of the mean for Experiment 1 ranged from a low of ±1 1° for angle C to a high of ±5 5° for angle B Variability for Experiment 2 is indicated in Figure 3)

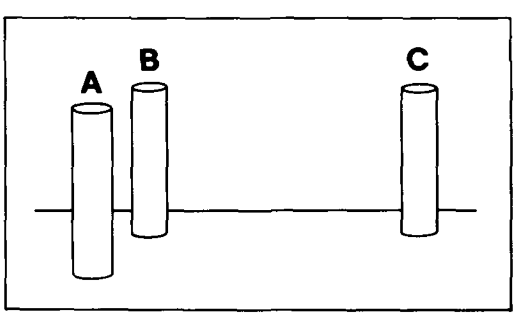

Figure 1 Line drawing traced from the photograph that served as the stimulus for Experiments 1 and 2 (For the actual stimulus the letters were omitted and the dowels had horizontal black and white stripes to clearly differentiate them from the background The actual aspect ratio of the stimulus was 4½ × 3½)

The most important result for our purposes is that observers' perception of spatial layout changes only slightly as viewing angle is varied between 20° and 160°. The same result also occurs for each individual observer.[2]

[1] Side BC was used as the "anchor" in comparing the perceived layouts to the actual layout because of side BC's lack of extension in depth and its orientation parallel to the horizon line and to the lower edge of the picture These properties enabled our observers to judge the separation and orientation of dowels B and C more accurately than for pairs AB and AC, which were extended in depth (cf Wagner, 1985)

[2] The relative constancy of the spatial layout judgments shown in Figure 2 is not an artifact of the procedure, in which observers knew they were seeing the same picture throughout the experiment This was shown by eliciting layout judgments from a different group of observers using the following procedure. The observers viewed pictures of four different arrangements of the three dowels, the picture in Figure 1 and three additional pictures These pictures were presented in random or-

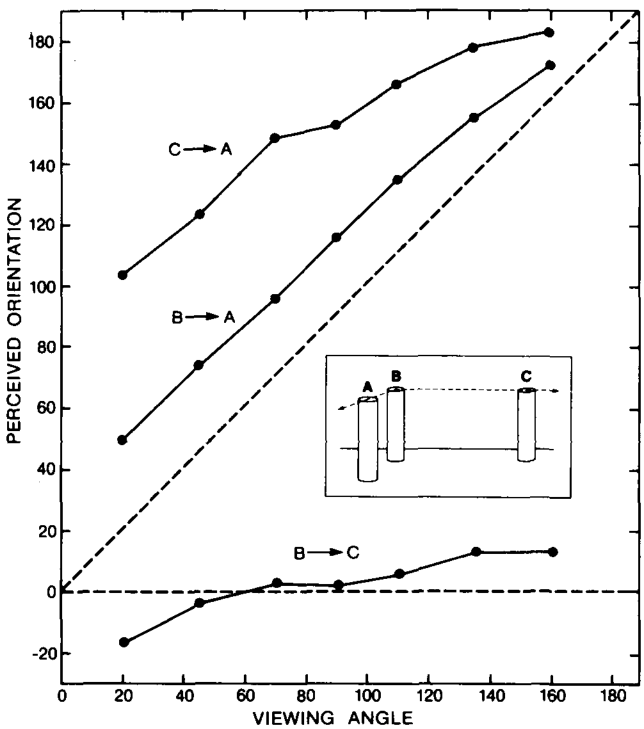

Figure 3 Perceived orientations of the directions defined by pairs of rod stimuli (see insert) at viewing angles of 20°, 40°, 70°, 90°, 110°, 130°, and 160° (Each point is the average data from 5 observers who made two judgments at each viewing angles Standard error of the mean ranged from a high of ±6.3° for pair BC to a low of ±3 2° for pair BA)

Experiment 2

In this experiment, the effect of changes in viewing angle on the perception of the orientations of pairs of dowels relative to the observer is demonstrated by having observers judge the direction defined by extending imaginary lines between pairs of the dowels in Figure 1, as shown in the inset to Figure 3.

Method

Observers The observers were the same as for Experiment 1

Stimulus The stimulus was the same as for Experiment 1

Procedure Observers viewed the picture from the same angles as in Experiment 1, and at each angle they set a pointer to match the directions defined by extending imaginary lines from dowels B to C, from B to A, and from C to A The pointer was mounted just below the picture and rotated around the picture's axis of rotation *Perceived orientation* is defined as the angle between the setting of the pointer and the picture plane If the pointer is set so that it is parallel to the picture, pointing to the right, the perceived orientation is 0°; if the pointer is set perpendicular to the picture, the perceived orientation is 90°, and if the pointer is set so that it is parallel to the picture, pointing to the left, the perceived orientation is 180° (See Figure 3 of Goldstein, 1979, for further details)

Results

Figure 3 shows the relation for perceived orientation versus viewing angle for the direction defined by each of the pairs of dowels. These results demonstrate the differential rotation effect described by Goldstein (1979). That is, objects that define directions close to perpendicular to the picture plane (such as the line between dowels B and A) change their perceived orientation more with changes in viewing angle than do objects that define directions that are more parallel to the picture plane (such as the line between B and C). For the change in viewing angle of 140° that occurred between the 20° and 160° viewing angles, the perceived orientation of B → A changes 123°, C → A changes 79°, and B → C changes 29°.

To facilitate comparison of the results for Experiments 1 and 2, the perceived orientations for each pair of dowels was used to determine triangular layouts at each viewing angle This layout was constructed by first setting side BC to an identical size for all observers and then determining the angle between B → A and B → C from the perceived orientations of B → A and B → C This angle, marked B in the plot labeled *orientation condition* in Figure 2, defines the directions of sides BA and BC of the triangle. The direction of side CA was determined by calculating angle C from the perceived orientations of B → C and C → A, thereby completing the triangle.

The triangles calculated using this procedure are shown for viewing angles of 20°, 90°, and 160°. As for the layout condition, the data for the other viewing angles have been omitted for clarity, with the omitted triangles falling in an orderly sequence between the 20° and 160° triangles. In marked contrast to the relative constancy of the triangles in the layout condition, these triangles differ greatly from each other. When the picture is viewed straight on (viewing angle = 90°), the resulting triangle almost matches the actual layout of the dowels, but the triangles from more extreme viewing angles are distorted compared with the actual layout and differ greatly from one another. (The closest match to the actual layout is achieved for the 70° viewing angle [not shown], which results in a triangle that almost exactly matches the actual layout of the dowels)

Discussion of Experiments 1 and 2

A comparison of the results for Experiments 1 and 2 illustrates large differences in how spatial layout and perceived orientation are perceived in a picture viewed at an angle. The perception of spatial layout changes only slightly with changes in viewing angle, whereas the perception of orientation relative to the observer changes dramatically with changes in viewing angle.

The large differences in the triangles derived from the orientation task for different viewing angles are a manifestation of the differential rotation effect—that is, the fact that the change in perceived orientation with changes in viewing angle is different for objects with differing orientations Pictured objects that point directly out of a picture, such as Uncle Sam's finger in the

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der at viewing angles of 20°, 90°, and 160°, with some observers seeing the 20° view first, some seeing the 90-degree view first, and some seeing the 160° view first The display was masked from view as pictures and viewing angles were changed Under these conditions, the relative constancy of perceived spatial layout shown in Figure 2 was replicated, both for the picture in Figure 1 and for the additional pictures

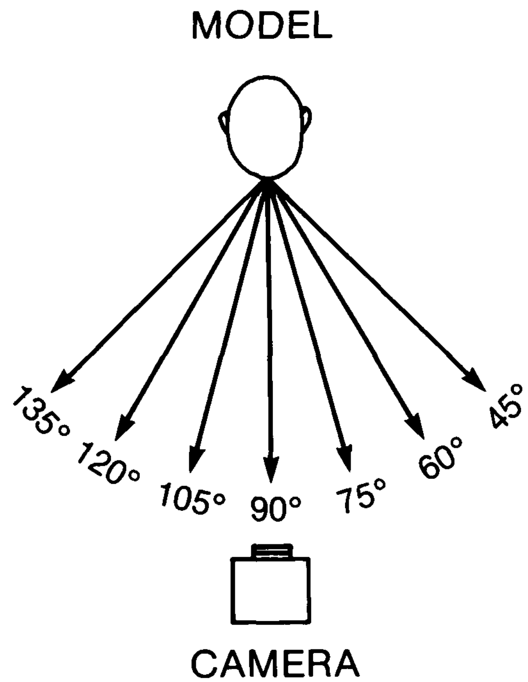

Figure 4 Top view of setup for producing photographs of faces with different gaze directions and head orientations (In Experiment 3 the model sat facing the camera [head orientation = 90°] and, keeping her head stationary, looked at targets located at 45°, 60°, 75°, 90°, 105°, 120°, and 135° These directions specify the gaze direction of the resulting photographs In Experiment 4, the same procedure was used, but, in addition, pictures were taken with the model's head turned to face the 45°, 60°, and 75° targets These directions specify the head orientations of the resulting photographs)

"Uncle Sam Wants You" recruiting poster, appear to "rotate" so that they maintain a constant direction relative to the observer, pointing directly at the observer no matter where the observer is positioned relative to the picture. Objects that point to the side, however, rotate less, and do not, therefore, maintain a constant direction relative to a moving observer.

Why does the differential rotation effect occur? One possibility is that the amount of rotation is a function of the perspective information that causes us to perceive an object in depth. Objects that appear to extend forward and back into the picture, like Uncle Sam's finger or the line connecting dowels A and B (considering this pair of dowels as an "object"), rotate more, whereas objects that have less extension in depth, like the pair of dowels B and C, rotate less The results of Experiments 3 and 4 show that the differential rotation effect cannot be explained in these terms, because it also occurs for pictures of human faces, stimuli in which information about direction is provided, not by perspective information but by the position of the pupil in the eye socket

Experiment 3

In this experiment, the effect of changes in viewing angle on a portrait's perceived gaze direction is measured for a portrait that appears to be looking directly at the observer and for six portraits that appear to be looking to the left or right of the observer

Method

Observers Seven observers included the author, 3 undergraduates who were doing other projects in the laboratory, and 3 undergraduates who were recruited from the introductory psychology subject pool at the University of Pittsburgh

Stimuli The stimuli were seven photographs of a human face, which were obtained by photographing a female model Seven different *gaze directions* were created by photographing the model, positioned 45 in (114 3 cm) from the film plane of a 4 × 5-in (12 7 cm) view camera with Polaroid back, and taking photographs as she looked at each of seven targets The 90° target was the lens of the camera, and the other targets were discs located at eye level positioned every 15° as shown in Figure 4 For gaze directions of 45°, 60°, and 75° the model looked to the left of the camera, and for gaze directions of 105°, 120°, and 135° the model looked to the right of the camera Line drawings made by tracing photographs for the 45°, 90°, and 135° gaze directions are shown in Figure 5 The length of the model's head was 9 in (22 86 cm), and the image of her face in the photograph was 3 in (7 62 cm) high

Procedure The procedure was identical to that described by Goldstein (1979) except that photographs of faces were used as stimuli instead of line drawings of rods Observers viewed each portrait monocularly from different viewing angles and at each viewing angle judged the perceived gaze direction by setting a pointer, which was mounted just below the picture and which rotated around the picture's axis of rotation, to match the direction the portrait appeared to be looking *Viewing angle* is defined in the same way as for Experiment 1 *Perceived gaze direction* is equivalent to *perceived orientation* as defined in Experiment 2

Results

Figure 6 is a plot of perceived gaze direction versus viewing angle, with gaze direction as the parameter. The curve for the 90° gaze direction (pupils centered) falls along the diagonal, which indicates that perceived gaze direction always matches the observer's viewing angle This confirms the common observation that when a straight-on face is looking directly at an observer, its eyes will "rotate" to follow the observer so that they appear to be looking directly at the observer no matter where he or she is relative to the picture As the viewing angle is changed from 20° to 160°, the perceived gaze direction for the 90° face changes from 22° to 159°, a *total rotation* of 137°. The faces with other gaze directions, however, rotate less for the same change in viewing angle For example, as the viewing angle

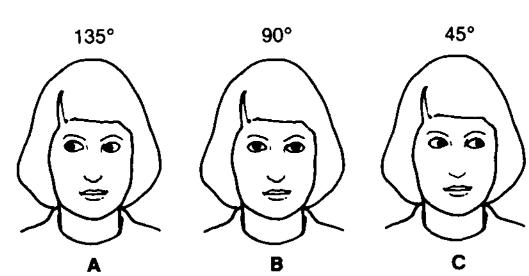

Figure 5 Drawings of three of the face stimuli used in Experiment 3 (These line drawings were traced from the photographs that were used as stimuli Numbers under each face indicate gaze direction)

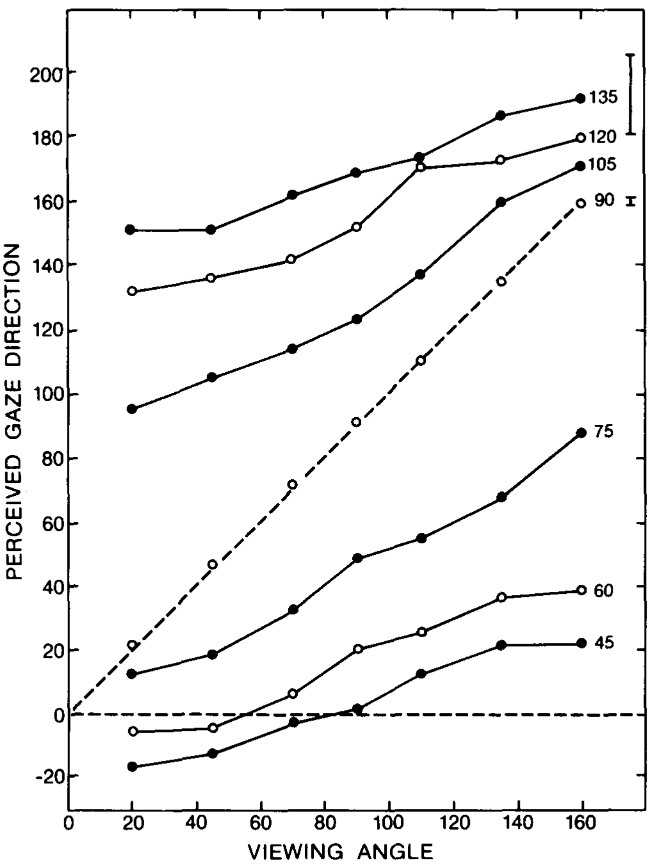

Figure 6 Perceived gaze direction for each of the face stimuli at viewing angles of 20°, 40°, 70°, 90°, 110°, 130°, and 160° (The number to the right of each curve is the gaze direction of the face Each point is the average data from 7 observers who made two judgments at each viewing angle Plus or minus one standard error of the mean for the 135° curve [maximum variability] and the 90° curve [minimum variability] is indicated by the bars opposite the curves)

is changed from 20° to 160°, the perceived gaze direction for the face with a 45° gaze direction changes from −16° (the negative direction indicating that the face appears to be looking in back of the right side of the picture) to 22°, a total rotation of only 38°.

The relation between *total rotation* and gaze direction is plotted in Figure 7 This result, which is qualitatively similar to the result shown in Figure 5 of Goldstein (1979), shows that the differential rotation effect occurs for pictures of faces.

Experiment 4

This experiment is identical to Experiment 3 except that gaze direction was measured for both a straight-on face and for three additional faces with heads turned in a counterclockwise direction

Method

Observers Four observers included the author and 3 undergraduates who were doing other projects in the laboratory

Stimuli The stimuli in this experiment were photographs of a model's face produced as described in Experiment 3 except that in addition to photographing the model as she was directly facing the camera, photographs were also taken of three additional *head orientations* A total of four different head orientations were, therefore, used For the 90° head orientation, shown as a line drawing on the left of Figure 8, the model directly faced the camera For the 75°, 60°, and 45° degree head orientations, the model's face was rotated in a counterclockwise direction by having her face the 75°, 60°, and 45° degree targets (see Figure 4) The line drawing on the right of Figure 8 shows a head orientation of 60°.

Gaze direction is determined, as in Experiment 1, in terms of the targets at which the model was looking. Thus, turning the head affects the position of the pupils, but the gaze direction indicates where the model is looking, independent of head orientation That is, no matter what the head orientation, a 90° gaze direction indicates that the model is looking directly at the camera This is illustrated by the 60° head orientation of Figure 8 The gaze direction of 90° results in the pupils' being positioned off-center, but the model appears to be looking at the camera

Procedure The procedure was identical to the procedure for Experi-

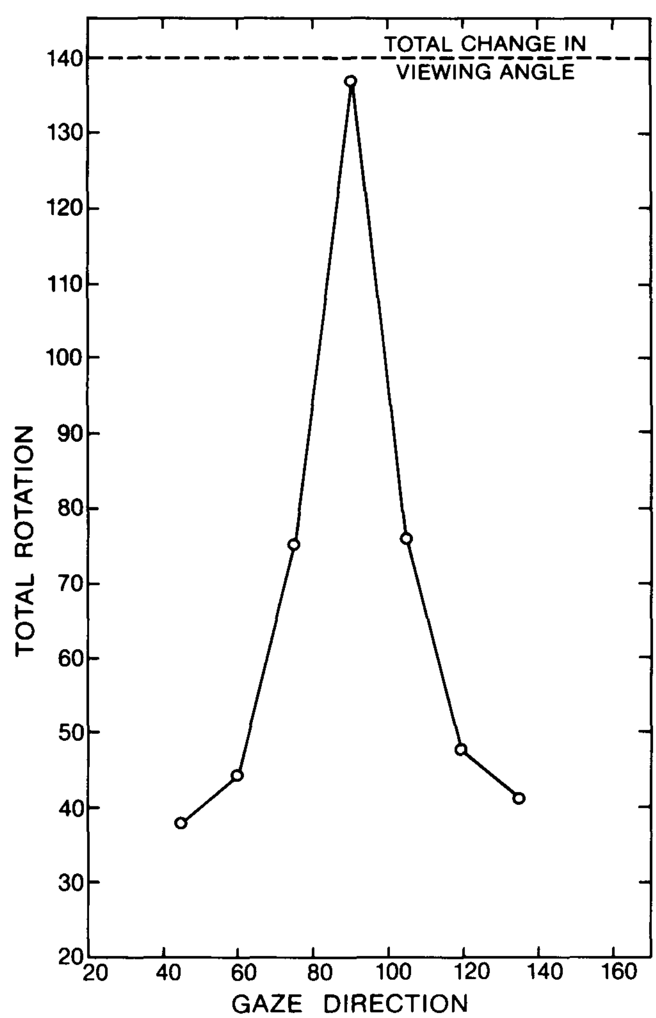

Figure 7 Relation between the total change in perceived gaze direction that occurs when the viewing angle changes from 20° to 160° and gaze direction, derived from the data in Figure 6

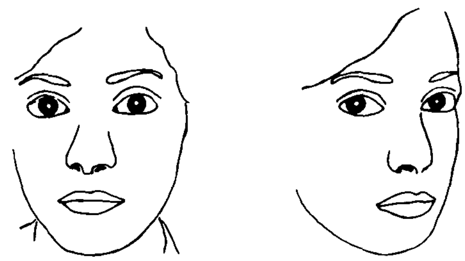

Figure 8 Line drawings traced from photographs of two of the stimuli used for Experiment 2 Left 90° head orientation, 90° gaze direction Right 60° head orientation, 90° gaze direction

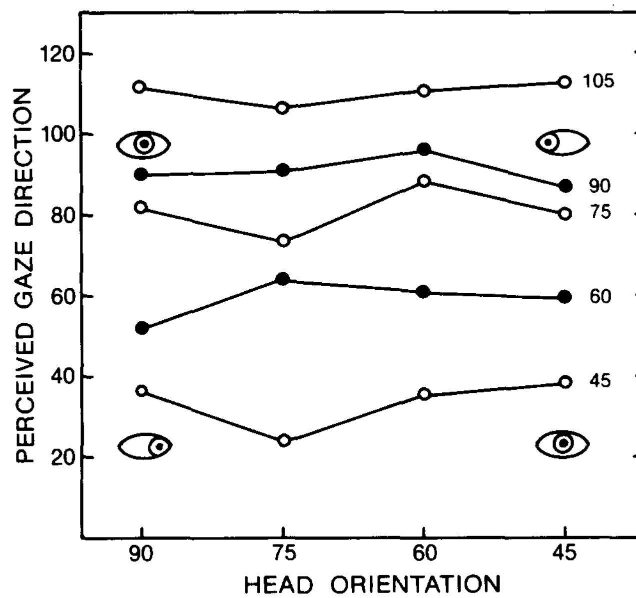

Figure 10 Perceived gaze direction versus head orientation, for five different gaze directions. (Gaze direction is indicated by the numbers to the right of each curve Eyes show pupil positions for 90° and 45° head orientations with gaze directions of 45° and 90°)

ment 3 except each of the faces was presented with a small piece of white paper covering the right eye of the photograph This was done because Noll (1976) has shown that when a model's head is turned and she is looking at an observer, the model's farther eye (in our case, the model's left eye) appears to be looking at the observer, while her nearer eye appears to be looking away from the observer Reflecting Noll's result, our observers reported that it was more difficult to estimate where the faces were looking when both of the photograph's eyes were visible than when just one eye was visible.

Results

The results of this experiment are similar to the results of Experiment 3 When the head is turned to the side, rotation occurs for all gaze directions, but rotation is greater when the model is looking either toward the observer (90° gaze direction) or just to the observer's right (70° gaze direction). This result is summarized by the plots of total rotation versus gaze direction in Figure 9. The total rotation for this face is less than for the one used in Experiment 3, but the qualitative result—a peaked function for the relation between total rotation and gaze direction—is similar.

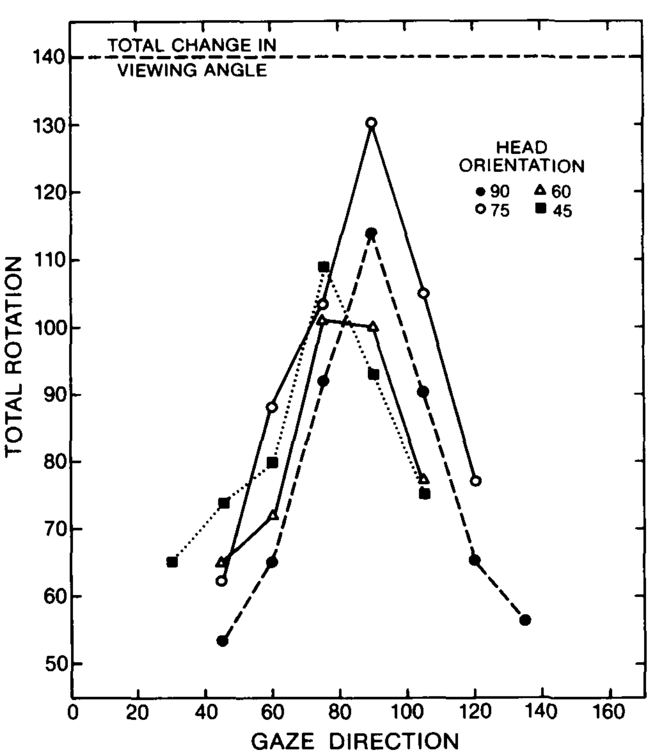

Figure 9 Relation between the total change in perceived gaze direction that occurs when the viewing angle changes from 20° to 160° and gaze direction, for four different head orientations

In Figure 10, perceived gaze direction is plotted versus head orientation, with gaze direction as parameter, for a viewing angle of 90°. The data are plotted in this way to show that the perceived gaze direction is relatively constant for a given gaze direction, independent of head orientation A similar result occurs for the other viewing angles

Discussion of Experiments 3 and 4

Previous investigations of gaze direction have measured an observer's ability to judge where live models (Anstis, Mayhew, & Morley, 1969, Cline, 1967; Gibson & Pick, 1963) or television portraits (Anstis et al , 1969) are looking. The present experiments present the first measurements of the relation between a photographed face's direction of gaze and the degree of "following" or "rotation" that occurs with changes in viewing angle. The major finding of these experiments is that the differential rotation effect previously observed for representations of three-dimensional objects such as pointing fingers, cylinders, or objects in scenes, all of which are extended in depth, also occurs for pictures of faces, stimuli in which information for direction is indicated by the position of the pupil in the eye socket. Thus, whatever mechanism is responsible for this following effect, it does not depend on the extension of pictured objects in depth

Rather, the extent of rotation appears to depend on the direction of extension out of the picture, no matter whether this direction is determined by three-dimensional objects that are extended in pictorial space or by objects that are essentially flat like portraits. The 90° face provides the most obvious example of direction being determined by two-dimensional information because the front view of the face has little depth and direction being determined by the left–right position of the pupils in the eye sockets.[3]

The present results also confirm Noll's (1976) finding that in faces turned to the side, observers take head turn into account in judging perceived gaze direction But most important for our purposes is the finding that the differential rotation effect occurs for all head orientations. The differential rotation effect is, therefore, a general phenomenon that occurs not only for representations of three-dimensional objects extended in pictorial space but also for portraits that directly face the observer and for portraits in which the head is seen at an angle.

It has been shown that extension of an object in space is not necessary for the differential rotation effect, but the question remains What controls the portrait's rotation? The answer that is usually given for portraits like the one in Figure 5b, which always appears to be looking at the observer, has been stated by Gombrich (1972) as follows

> In a painting, an object with a pronounced aspect such as a foreshortened gunbarrel, a pointing finger, or human eye will continue to show the same aspect from whatever side we look at the picture If these objects were not painted, but real, any move on our part would, of course, show them from a different side and reveal a different aspect, since we fail to produce this change, we instinctively assume that the object is still pointing at us and must therefore have moved (p 142)

Thus, for the portrait that is looking straight ahead, the pupils always appear centered, and these centered pupils provide information that signals "being looked at" However, the situation for portraits that look to the side is somewhat more complex.

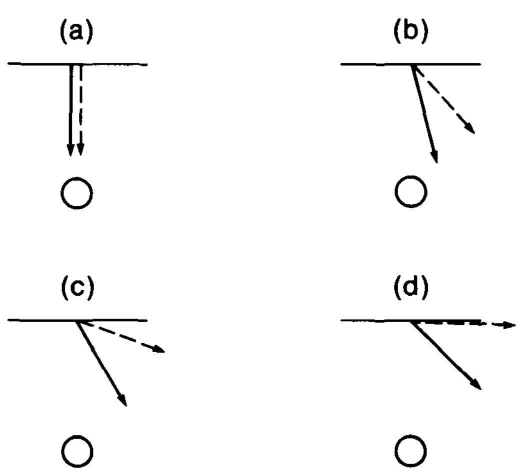

Figure 11 Gaze direction (solid line) and perceived gaze direction (dashed line) for an observer at 0 viewing a face with head orientation = 90° Panel a Gaze direction = 90°; perceived gaze direction = 91° Panel b Gaze direction = 75°, perceived gaze direction = 49° Panel c Gaze direction = 60°, perceived gaze direction = 21° Panel d Gaze direction = 45°, perceived gaze direction = 2° (Based on the data in Figure 3)

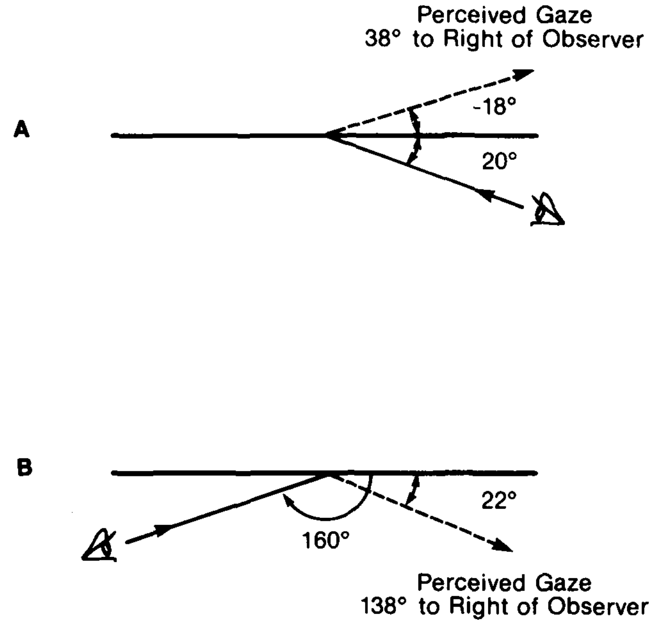

Figure 12 Perceived gaze direction (dashed line) for an observer viewing a portrait with a gaze direction of 45° at viewing angles of (Panel A) 20° and (Panel B) 160° (The picture plane is indicated by the horizontal line Based on the data in Figure 6)

One of the complexities of portraits that look to the side is the fact that the portrait's angle of gaze is overestimated This result, which was originally reported by Anstis et al. (1969), is illustrated in Figure 11 for the case of an observer, at O, who is viewing the picture straight on (viewing angle = 90°). In Figure 11a, when the portrait is looking directly at the camera (gaze angle = 90°), the gaze direction (solid line) and perceived gaze direction (dashed line) match. However, when the portrait is looking off to the side as in Figure 11b (gaze angle = 75°), Figure 11c (gaze angle = 60°), and Figure 11d (gaze angle = 45°), the perceived gaze direction is far to the right of the actual direction of the model's gaze. A similar result occurs for the rod stimuli used by Goldstein (1979)

Further complicating the situation for portraits looking to the side is that although the pupil's "aspect" is perceived as relatively constant at different viewing angles, this constant aspect does not signal a constant gaze direction relative to the observer, as Gombrich hypothesized for portraits that always look directly at the observer. We can appreciate this by referring to Figure 12, which shows the perceived gaze direction relative to the observer for a portrait with a gaze direction of 45° when viewed from two angles. When the portrait is viewed from the far right (viewing angle = 20°), the portrait's gaze is perceived to be 38° to the right of the observer, but when the portrait is

[3] Although the position of the pupils in the eye socket can be considered two-dimensional information, the observer's judgment of direction is based on the knowledge that the position of the pupil indicates the degree of rotation of the three-dimensional eyeball

viewed from the far left (viewing angle = 160°), the portrait's gaze is perceived to be 138° to the right of the observer Analogous results occur for all oblique gaze directions

This change in the direction of a portrait's gaze relative to the observer, which is a manifestation of the differential rotation effect, means that Gombrich's explanation for the rotation effect holds for objects that are pointing directly at the observer but not for objects that are pointing off to the side The problem with Gombrich's explanation, however, may be not that it is wrong but simply that it is incomplete. It is true that the position of the eyeball (or, more correctly, the position of the eyeball in combination with the orientation of the head) does signal a specific direction of gaze relative to the observer. However, the position of the eyeball also signals a specific direction of gaze *relative to the left and right sides of the picture* Thus, a portrait such as the one in Figure 5c is looking both to the right of the observer *and* toward the right side of the picture, and as the observer moves to the left, the portrait continues to look to the observer's right, but is constrained from following the observer fully because it also contains information that indicates that it is looking toward the right side of the picture. Portraits that appear to be looking toward the left or right side of the picture appear to be constrained from fully rotating to follow an observer to the extent that they are perceived to be looking to the side Portraits that look more toward the front appear to be constrained less, so that the 90° portrait (Figure 5b), which is free of such constraints, is free to totally follow the observer no matter where he or she is in relation to the picture.

If the information about the direction of gaze relative to the left or right side of the picture, does, in fact, decrease the following effect, then elimination of this information should increase the amount of following. This hypothesis was tested in Experiment 5 by making the picture plane invisible. To accomplish this, the experiment was run in the dark, with the stimulus made visible by using back-lit transparencies of line drawings, which appeared in the dark as white line drawings floating in space

Experiment 5

Method

Observers Four undergraduates who were working on other projects in the laboratory served as observers

Stimuli Face stimuli were not used in this experiment because our observers found judging the direction of a portrait's gaze to be very difficult when a back-illuminated line drawing of the portrait was viewed in the dark The reason for this difficulty is that when the portrait is viewed in the dark, the projective changes that occur at oblique viewing angles become much more obvious than when the portrait is viewed in the light, and the portrait therefore appears distorted at these viewing angles Thus, judging the direction of a portrait's gaze, a difficult task when the portrait is viewed in the light, becomes more difficult and increasingly variable when the portrait is viewed in the dark. Therefore, instead of faces, a line drawing of two vertical cylinders similar to those used in Experiments 1 and 2 was used as the stimulus (Figure 13) A black-on-white line drawing of the cylinders was used when the stimuli were viewed in the light, and a back-lit negative prepared from this line drawing was used when the stimuli were viewed in the dark The observer's task was to set the pointer, which was made visible in the dark by coating it with fluorescent paint, to match the direction defined by an imaginary line connecting the left and right cylinders (See Figure 13) Although projective deformations are also obvious when this stimulus is viewed obliquely in the dark, judging the direction defined by the two cylinders is easier and less variable than judging the direction of gaze

Procedure The procedure was similar to that in Experiments 3 and 4 Observers viewed the picture monocularly from different viewing angles and judged the direction defined by the two cylinders by setting the pointer mounted just below the picture plane This procedure was carried out in the light and in the dark, using the same procedure in both cases, except that in the dark the subjects closed their eyes as the picture plane was being rotated to a new position so they would not see the projective changes of the stimulus that occur during this rotation

Results

The open circles in Figure 13 shows the relation between viewing angle and perceived orientation for the stimuli when viewed in the light. A total change in viewing angle of 150° results in a total change in perceived orientation of only 60°, a result similar to that observed for any stimulus that is oriented obliquely to the picture plane (Goldstein, 1979; Experiment 2 in this article) and similar to the result for the portraits looking to the side (Figure 6). The filled circles show the same relation for the stimuli when viewed in the dark. When viewed in the dark, these stimuli rotate 113°, almost twice as much as when viewed in the light, although still less than the rotation that would be expected if the change in perceived orientation matched the change in viewing angle (dashed line).

Discussion

The results of Experiment 5 show that eliminating perception of the picture plane increases the amount of rotation for pic-

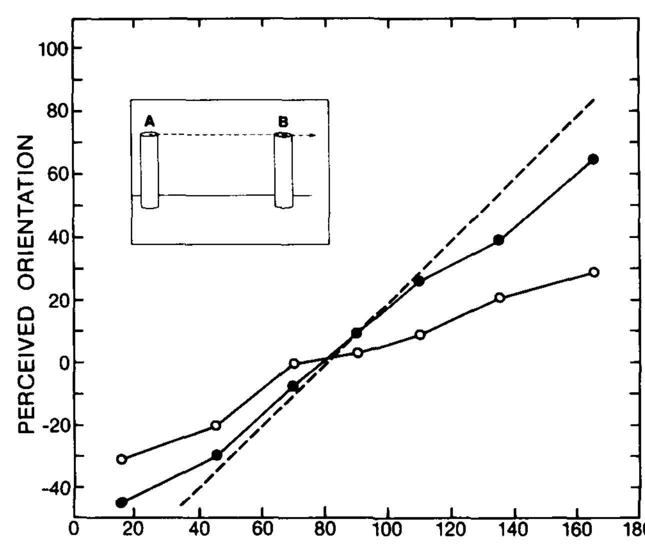

Figure 13 Perceived orientation versus viewing angle for the stimuli shown in the inset when viewed in the light (open circles) and in the dark (filled circles) (The dashed line indicates the result that would occur if the change in perceived orientation matched the change in viewing angle Each point is the average data of 4 observers who made two judgments at each viewing angle Standard errors of the mean for the light condition ranged from a high of ±11 5° for the 15° viewing angle to ±4 5° for the 90° viewing angle, and for the dark condition from ±13 6° for the 165° viewing angle to ±4 6° for the 90° viewing angle)

tured objects that define a direction oblique to the picture plane. Objects that define a direction that is perpendicular to the picture plane are not affected by this manipulation because they already rotate maximally; that is, for a change in the viewing angle of 150°, these objects rotate 150° both in the light and in the dark.

The increase in rotation that occurs for obliquely oriented objects when viewed in the dark does not, however, result in the maximum possible rotation, as indicated by the fact that the data diverge from the dashed line in Figure 13. The reason for this failure to rotate fully may be that even though viewing the stimuli in the dark eliminates perception of the picture plane, projective information contained in the image of the back-lit stimuli provides some cues to the picture's orientation.

Even though maximal rotation was not obtained in the dark, the results of Experiment 5 are consistent with the idea that a complete explanation of the rotation effect must take into account the fact that the constant aspect characteristic of pictured objects means that a picture contains information that simultaneously signals two different directions: (a) a direction relative to the observer and (b) a direction relative to the left or right side of the picture. These two directions are not necessarily the same and, in fact, become quite different when the observer views the picture from, say, the far left when the pictured object defines a direction far to the right This difference appears to be the reason that obliquely oriented objects rotate less than would be expected if only their aspect relative to the observer were controlling their perceived orientation.

One remaining question is why the rotation of stimuli that are pointing straight out of the picture is not inhibited by the fact that they contain information indicating that they define a direction perpendicular to the picture plane Perhaps the fact that these stimuli are perceived to point directly at the observer causes observers to focus their attention on this aspect of the stimulus information and to ignore the conflicting information indicating their direction relative to the picture plane.

General Discussion

It has often been said that pictures define a dual reality—the reality of the three-dimensional space depicted in the picture and the reality of the two-dimensional surface on which the picture exists. The experiments reported here show that this property of pictures leads to another dual reality: Changing viewing angle has only a small effect on the perception of the layout of objects in pictorial space, but it has a large effect on the perception of the object's orientation relative to the observer

The lability of perceived orientation is most apparent for objects that define directions parallel, or nearly parallel, to the picture plane In contrast to objects that define directions perpendicular to the picture plane and that rotate so they constantly point at a moving observer, objects not directed perpendicularly to the picture plane rotate too little to maintain a constant orientation relative to the observer and, therefore, take on different orientations as the observer changes position relative to the picture.

The results of Experiments 3, 4, and 5 support the idea that the reduced rotation of these objects is due, not to the objects' lack of extension in pictorial space, but is rather due to the fact that the direction defined by these objects is compared with the left-to-right axis of the picture plane. According to this idea, such an object is constrained from fully rotating because no matter where the observer is, this object must continue to point either toward the left or the right side of the picture.

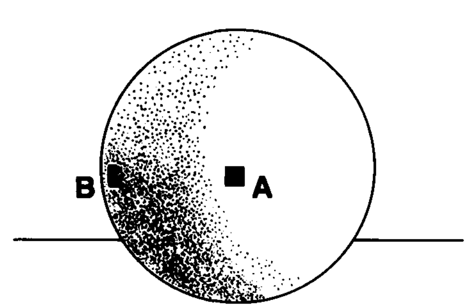

Figure 14 A line drawing of the sphere stimulus. (The actual stimulus was a photograph Observers judged the perceived orientation of the sphere at points A and B. The actual stimulus showed only one of the points, either point A [actual orientation = 90°] or point B [actual orientation = 150°], and did not include the letters)

The picture plane's constraining effect on rotation means that perceived orientation is not determined solely by the geometrical information provided by the picture. This conclusion is supported by the fact that when viewing a pictured object from certain angles, the perceived orientations of parts of the object are inconsistent with the object's geometry. For example, consider the sphere in Figure 14. When 3 observers viewed a photograph of this sphere from an angle of 20° (far to the right of the picture), their average judgment of the orientations of the sphere at points A and B was 25° and 153°, respectively. This 128° difference in orientation cannot, however, be predicted from the sphere's geometry. The maximum separation that two visible points can have on the circumference of either a sphere or the ellipsoid which the sphere becomes when viewed at an angle of 20°, is 180°. The maximum separation between point A, which is in the center of the sphere/ellipsoid, and another visible point, is 90° The observed difference of 128° between the perceived orientations of points A and B far exceeds both the theoretical limit of 90° and the points' actual separation of 60°. The perceived orientation of these points on the sphere cannot, therefore, be solely determined by the picture's geometry.

This sphere experiment replicates, with a different stimulus, the results of Experiment 3, in which observers made judgments of gaze direction for different positions of the pupil in the eye socket. Consider, for example, our observers' judgments of perceived gaze direction for the 90° and 135° stimuli when viewed from an angle of 20° (Figure 6). These two stimuli represent a difference in the position of the eyeball of only 45°, but the difference in perceived gaze direction is 128°. (At a viewing angle of 20°, the perceived gaze directions of the 135° and 90° stimuli are 151° and 22°, respectively.) Perceived gaze directions, or orientations, relative to an observer, therefore bear little resemblance to the actual physical orientations of objects in the picture.

In contrast to the noncorrespondence between judgments of perceived orientations relative to the observer and the physical orientations of objects, our observers' judgments of spatial lay-

Table 1
Properties of Three Attributes of Pictures

Attribute	Example	Is Attribute Sensitive to Viewing at an Angle?	Is 3-D Illusion Necessary?
Spatial layout	The house is in the middle of the field and is perpendicular to the road	Slightly Reproduction of layout stays relatively constant with changes in viewing angle (Figure 2)	Yes *Space*, or *layout*, as defined here, implies three-dimensionality
Perceived orientation	If extended out of the picture, the house is pointing over my right shoulder	Yes "Differential rotation effect" (Figures 2 & 3)	No Occurs for representations of both 3-D objects and faces (but object must define a direction which can be extended out of the picture)
Projection	The picture of the house appears narrow when viewed at an angle	Yes Perception is directly related to the changes in projection that occur with changes in viewing angle Identical pictures viewed from different angles appear different	No Occurs for representations of both 2-D and 3-D objects

out do bear some resemblance to the actual layout of objects in the picture. Although this correspondence between judged spatial layout and actual spatial layout is by no means perfect in the present experiments (cf. Figure 2), the spatial layout of a picture of three dowels is reproduced with greater accuracy if depth information is enhanced by placing the dowels on a textured ground and photographing them from a higher viewpoint (Goldstein, 1986)

It is clear from the results of the experiments reported in this article that the pictorial attributes of perceived orientation and spatial layout have different properties and must, therefore, be distinguished from one another in any research on the perception of pictures The importance of making this distinction is nowhere more important than in considering one of the problems addressed at the beginning of this article—whether pictures appear distorted when viewed at an angle.

Clearly, one attribute (perceived orientation) changes drastically with changes in viewing angle, whereas another (spatial layout) changes only slightly, and we can also add a third attribute to this list: the perception of the picture's projection on the retina This attribute of pictures does change with changes in viewing angle, although these changes are usually unnoticed by most observers. The fact that changes in projective information go unnoticed has been noted by many authors. For example, Haber (1980) seems to be referring to projective information when the states that "One can move around while looking at any scene, without the scene appearing to change, even though each successive retinal pattern undergoes massive changes" (p. 19)

The fact that these projective changes are not noticed does not mean, however, that it is not possible to perceive them. One reason that people have difficulty in perceiving projective changes has been proposed by Rosinski and Farber (1980), who suggest that "observers cannot judge that a scene is distorted unless they know what it is supposed to look like. This information is not available at the incorrect viewing point" (p. 150)

According to this idea, an observer could perceive these distortions if two views of the scene from different station points were available for comparison, and this can easily be accomplished by obtaining two identical copies of a picture and positioning them at right angles so that one can be viewed straight on, and the other at an angle When this is done, the distortions in the picture viewed at an angle become obvious, with objects in this picture appearing compressed compared with objects in the other picture

The projective changes that occur when viewing pictures at an angle may pass unnoticed not only because of the absence of a comparison view from the correct station point but also because of the stability of the picture's spatial layout This possible linkage between the two attributes of picture is implied (although not explicitly stated) by Rosinski and Farber's (1980) statement that "We perceive a pictorial representation of space veridically, even when the geometric projection to the eye is greatly distorted. Moreover, pictures apparently look the same regardless of the viewing point" (p 149). The first sentence of this quotation refers to the constancy of spatial layout, which has been empirically demonstrated in Experiment 1, whereas the second sentence appears to refer to the difficulty in noticing projective changes Perhaps the constancy of spatial layout directs attention away from distortions in projective information that cause pictures viewed at different angles to appear different. If this is so, we would predict that changes in appearance caused by changes in projective information would be more easily detected in pictures that contain little depth information, as in abstract art or drawings of two-dimensional geometrical figures Although this comparison remains to be made, Thouless' (1931) classic experiments on "phenomonal regression to the real object" clearly shows that observers perceive a circle at an angle as an ellipse Thus, Thouless' results, although usually cited to illustrate our failure to perceive an object's projective shape, also provide evidence that pictures of two-dimensional geometrical objects do look different when viewed at an angle.

Some of the properties of the three attributes of pictures discussed here—spatial layout, orientation relative to the observer, and projective information—are summarized in Table 1 The examples in this table refer to how a person might describe a perspective picture of a house that is depicted as perpendicular to a road

The importance of distinguishing among these three different attributes of pictures cannot be overemphasized, because a failure to make this distinction can lead to confusion, especially when discussing how pictures are perceived when viewed at an angle. For example, consider the following excerpts from Pirenne's (1970) discussion of the effects of viewing a picture at an angle

With reference to the viewing of portraits at an angle, he states.

> When as is most often the case, ordinary pictures are seen binocularly from a position different from the center of projection, they do not as a rule give a noticeably deformed view of the scene represented (p 97)

With reference to architectural drawings viewed at an angle, he states·

> For most observers deformations of this kind are neither obvious or striking Many people only notice such deformations when their attention has been drawn to them, and then only after some practice, even if they use one eye only (p 157)

And this is Pirenne's suggestion of a possible mechanism to explain the difficulty we have in perceiving distortions in pictures viewed at an angle.

> In general, therefore, the fact that many find it difficult to see the deformations theoretically predicted for a spectator who is not at the correct position, must be explained by an intuitive process of psychological compensation which is based both on the spectator's awareness of the surface of the picture, and on his preconceived ideas regarding the components of the scene presented
>
> It is the existence of these processes which must largely explain that pictures in perspective can be used as widely as they are as *representations* of complicated scenes or objects, even for purely practical purposes (p 162)

The problem is that in each of these excerpts it is unclear to which attributes Pirenne is referring. His reference to the absence of a "noticeably deformed view" of portraits in the first excerpt seems to refer to projective information. However, Pirenne's references to architectural drawings in the second excerpt and to "pictures in perspective" and "complicated scenes or objects" in the third excerpt leave open the possibility that these statements refer to an observer's perception of spatial layout

Pirenne's lack of explicitness makes it difficult for us to know exactly which attributes of pictures he is concerned with (projective shape? spatial layout? orientation relative to the observer?), and it also limits his ability to analyze these properties. Consider, for example, the issue of deformation. A theme throughout Pirenne's discussion is that pictures are deformed when viewed at an angle, but that this deformation is hard to notice. If Pirenne is concerned solely with projective deformation, then he is on solid ground. But one wonders whether Pirenne's statement that deformations are difficult to notice is based solely on his observations of the projective attribute of pictures. Is it possible that he is influenced by the fact that deformations of spatial layout do not occur? Is he lumping together the two phenomena of (a) projective deformations that are difficult to perceive and (b) spatial deformations that do not occur and then attempting to study them? The answers to these questions are not obvious from Pirenne's discussion, but if he is combining these two attributes, confusion is bound to be the result For example, Pirenne's idea of a compensation mechanism based on our perception of the surface of the picture may hold for perception of projective changes but may be less important for perception of spatial layout, which might be more profitably analyzed in terms of identifying information for spatial layout that remains invariant with changes in viewing angle

The confusion that can occur by ignoring the fact that different attributes of pictures have different properties, especially with reference to how these properties change with changes in viewing angle, argues that it is important to distinguish among these attributes. Although some of the mechanisms responsible for the properties of the various attributes remain to be determined, distinguishing among them is the first step in uncovering these mechanisms, and making these distinctions will, at the least, help us to know what we are talking about.

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