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Perception of Rigid Motion in Depth From the Optical Deformations of Shadows and Occlusion Boundaries

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Three experiments were designed to examine the abilities of observers to determine an object's 3-dimensional structure and motion from various types of optical deformations. Observers were required to discriminate whether pairs of moving ellipsoids were rotating rigidly about a single axis or nonrigidly about different axes that varied in slant. Discrimination thresholds were significantly influenced by whether the ellipsoids were intersecting or nonintersecting and whether they contained identifiable texture elements. Performance was unaffected by precession movements of the axis of rotation, by increasing the number of intersecting ellipsoids beyond 2, or by replacing the deforming silhouettes with the projected motions of cast shadows presented in isolation against a planar background. These findings indicate that observers can perceive structure from motion based on several different types of optical deformation, including the deformations of shadows and silhouettes that do not contain identifiable features on which most existing theoretical analyses are designed to operate.

A fundamental assumption for most computational models of the perception of structure from motion is that multiple views of an identifiable image feature must all correspond to the same physical point in three-dimensional space. There are numerous situations encountered in natural vision, however, for which this assumption is violated. For example, when a smoothly curved surface is viewed stereoscopically or in motion, the optical contour that bounds its projection will be systematically deformed, but the locus of surface points to which it corresponds will also be continuously changing. Analyses that assume projective correspondence over multiple views are of little use with this type of optical deformation even as a local approximation. Indeed, it is often the case that the optical motion of the bounding contour will be in one direction while the projected motion of any identifiable point on that contour is in the opposite direction (see Figure 1).

Ernst Mach (1886/1959) was probably the first researcher to investigate the visual perception of boundary deformations produced by rotating solid objects. He observed that when objects contain identifiable features such as sharp edges or corners, they can produce a compelling impression of rigid motion in depth. However, for smoothly curved objects such as eggs that do not contain any trackable features, the deforming silhouettes tend to be perceived as a nonrigid fluidlike motion. Similar observations were reported many years later by Wallach and O'Connell (1953).

The ability of human observers to perceive three-dimensional structure in the absence of feature motion has more recently been reexamined by Todd (1985). Like Mach (1886/1959) and Wallach and O'Connell (1953), he found that the optical projection of a single rotating ellipsoid is usually perceived as a nonrigid stretching motion. However, he also reported that if two intersecting ellipsoids rotate together, then the deforming silhouette produces a compelling kinetic depth effect, even for naive observers. Because this effect appeared to be attenuated for the projected motions of nonintersecting ellipsoids, Todd speculated that the motions of the intersection points in the image were a critical factor in determining perceived rigidity. It is important to recognize that the motions of these image intersection points do not correspond to the projected motions of any fixed set of points on an object's surface, and cannot therefore be successfully analyzed using traditional computational models that are based on an assumption of projective correspondence.

Subsequent psychophysical studies have not pursued this suggestion about the potential information from contour intersections and have concentrated instead on the perception of three-dimensional structure from the deforming silhouettes of individual ellipsoids (Beusmans, 1990; Cortese and Andersen, 1991; Pollick, Giblin, Rycroft, and Wilson, 1992; Pollick, Nishida, Koike, and Kawato, 1992). The important contribution of these studies is that they used more objective response measures than the spontaneous verbal reports used by Mach (1886/1959), Wallach and O'Connell (1953), and Todd (1985). By and large, however, the results have confirmed that observers are quite poor at making judgments of three-dimensional structure or rigidity from deforming silhouettes of single ellipsoids with no visible contour singularities.

For example, Pollick, Giblin, Rycroft, and Wilson (1992) asked observers to indicate whether the optical projections

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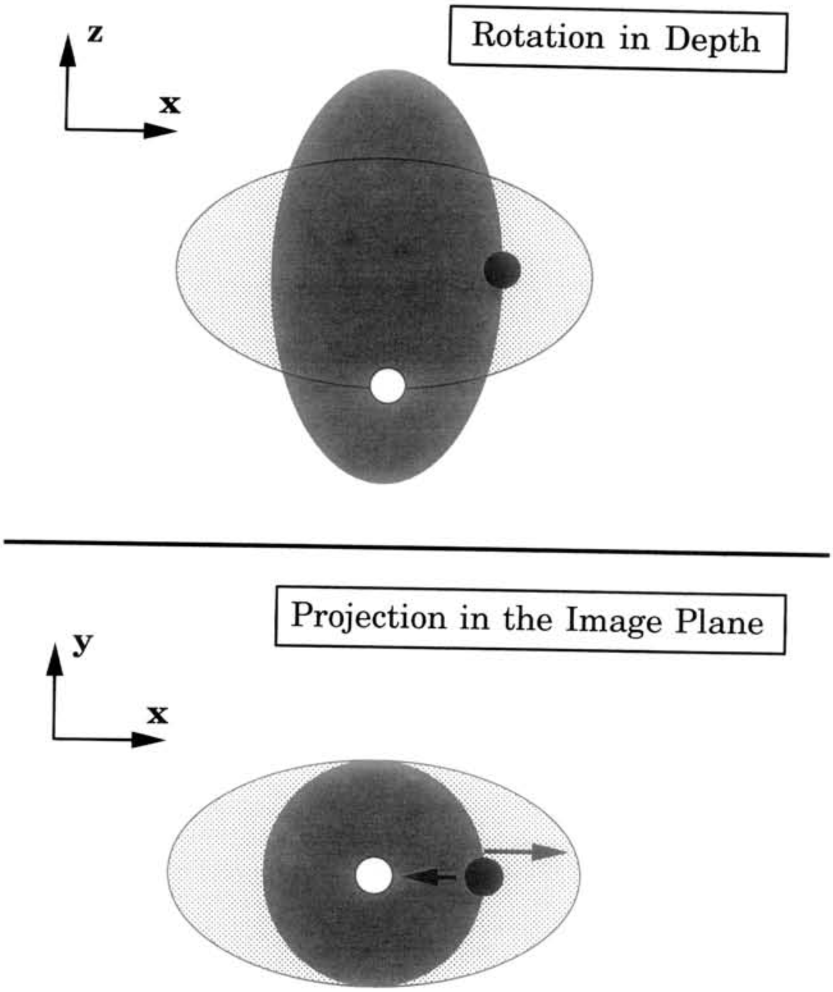

Figure 1. A rotating ellipsoid with a single identifiable point viewed both parallel and perpendicular to a display screen. The dark ellipse and the black dot show the optical projections of the surface and the point at one moment in time, while the light ellipse and the white dot show these same structures following a rotation of 90°. Note that when viewed in the image plane the occlusion contour of the ellipsoid moves in one direction, whereas the identifiable point on that contour moves in the opposite direction.

of rotating ellipsoids appeared as ''solid'' (three-dimensional) or ''flat'' (two-dimensional) objects. Although all of their displays simulated solid ellipsoids, 32% were perceived as flat ellipses. In another experiment, observers were instructed to report whether the depicted objects appeared two-dimensional or three-dimensional, and whether their motions appeared rigid or nonrigid. Only 37% of the displays were categorized correctly as moving rigidly in three-dimensional space.

In a related investigation, Beusmans (1990) asked observers to discriminate the rotations of solid (three-dimensional) ellipsoids and flat (two-dimensional) ellipses under a variety of conditions. Two of four observers reported that almost all of the displays appeared as flat ellipses. One other naive observer showed a general trend of increasing ''solid'' responses as the thickness of the simulated ellipsoid was increased, but his overall level of accuracy was only 51%. Beusmans himself was able to discriminate these forms with 90% accuracy. There was also a tendency of the observers in these experiments to systematically underestimate the slant of the rotation axis.

This latter finding has been examined more recently by Pollick, Nishida, Koike, and Kawato (1992). They used a pointing task to obtain judgments about the pattern of perceived motion from the projected silhouettes of solid ellipsoids rotating about a fixed axis at varying orientations with respect to the image plane. On any given trial, observers viewed a motion sequence and pointed one of their fingers so that it was parallel to the perceived rotation axis. The average error of these judgments was approximately 22° for experienced observers and 40° for naive observers.

In contrast to the studies described above, Cortese and Andersen (1991) have obtained reliable kinetic depth effects from the motions of individual ellipsoids. Their methodology differed from other investigations in two important respects: First, the projected silhouettes were defined by the accretion and deletion of background texture, as opposed to a continuous closed contour; and second, the simulated ellipsoids were not centered on the axis of rotation. There is some evidence to suggest that this latter difference may have had a significant influence on the observers' perceptions. In one experiment, which did include ellipsoids rotating about their centers, 25% of the observers reported that the displays appeared as nonrigid stretching transformations rather than as solid objects rotating in depth.

To summarize, the available psychophysical evidence indicates that the perception of structure from motion in the absence of projective correspondence can be achieved in some circumstances, but not others. Observers have reported compelling kinetic depth effects for displays depicting multiple intersecting ellipsoids (Todd, 1985) or with off-centered axes of rotation (Cortese & Andersen, 1991), but they often have difficulty interpreting the projected silhouettes of single ellipsoids rotating about their centers.

Theoretical Analysis of Boundary Deformations

The fact that deforming occlusion boundaries contain information about three-dimensional shape has not escaped the attention of applied mathematicians and computer vision researchers, and several models have been developed recently to take advantage of this information (Cipolla & Blake, 1990; Giblin & Weiss, 1987; Pollick, Giblin, Rycroft, & Wilson, 1992). Boundary contours in an image are formed by the projection of a set of points on an object's surface that separate visible from invisible regions (i.e., where the surface normal is perpendicular to the viewing direction). The locus of surface points that project to the boundary is often referred to as the *rim* (Koenderink, 1984). The rim is a space curve, which generally is nonplanar. Existing models of boundary deformations are designed to recover the metrical properties of points along the rim, such as their depths or curvatures. Using this type of approach, one could eventually measure the complete three-dimensional structure of an object as rotation causes the rim to slide over its entire surface.

An important limitation of the existing computational models for determining three-dimensional structure from boundary deformations is that they all require prior knowledge of how an object is moving relative to the observer (or vice versa). For example, Giblin and Weiss (1987) and Pollick, Giblin, Rycroft, and Wilson (1992) assume that the observer is moving along a great circle on a viewing sphere surrounding the three-dimensional object. This observer motion is optically equivalent to a stationary observer viewing a three-dimensional object that is rotating about a fixed axis, with some arbitrary slant and tilt. Because this assumption is necessary to recover information about shape from changing boundary contours, these algorithms cannot tolerate precessing axes of rotation whose orientation changes over time.

A similar approach also was adopted by Cipolla and Blake (1990). They developed a model that permits the recovery of surface curvatures even in the case of precession, but only when the motion of the observer is known precisely. When tested using images obtained from a camera mounted on a robot arm, their model functioned accurately when the exact camera motion was used in conjunction with the visual boundary deformations. However, they found that large errors in the recovered curvature magnitudes occurred when the camera's simulated motion differed even slightly from its actual motion.

Could any of these theoretical models be relevant to the perceptual analysis of boundary deformations by actual human observers? It is important to keep in mind that the available psychophysical evidence (e.g., Beusmans, 1990; Pollick, Nishida, Koike, and Kawato, 1992) does not suggest that observers are particularly accurate at judging a moving object's axis of rotation, as is required for these models to function effectively. It is still possible, however, that the display parameters investigated in previous studies have not been conducive to optimal performance. Thus, in an effort to shed new light on this issue, we designed the present series of experiments to measure the abilities of human observers to discriminate differences in the axes of rotation (a) for intersecting and nonintersecting ellipsoids, (b) with and without visible texture, and (c) with fixed or precessing axes of rotation.

Experiment 1

Method

Apparatus. Apparent motion sequences were displayed on a Silicon Graphics Personal Iris (4D/25 with Turbo graphics) workstation. The displays were viewed monocularly through a viewing hood. The viewing distance was 76.0 cm, such that the 1,280-pixel wide by 1,024-pixel high display screen subtended 25.22° x 20.29° of visual angle.

Stimulus displays. The stimuli for this experiment were orthographic projections of rotating solid ellipsoids defined by 648 connected triangular polygons arranged into a latticelike mesh. The ellipsoids were either textured, where every individual polygon had a randomly chosen color, or nontextured, where every polygon had the same color, thus forming a homogenous silhouette.

On each trial, two ellipsoids were displayed whose three semi-axes were randomly selected from a range between 0.6 cm and 5.0 cm (0.45° to 3.72°), subject to the constraint that the longest semi-axis on each ellipsoid would be at least twice as long as the shortest semi-axis. It is important to note that the objects generated by this procedure were not in general ellipsoids of revolution as have been used in previous investigations. Following the determination of its three semi-axes, each ellipsoid was randomly oriented relative to the fixed *x*, *y*, and *z* coordinate axes of the viewing space, and randomly translated away from the origin by an amount up to 1.7 cm so that its centroid would not coincide with the rotation axis. This is similar, but not as extreme, as the displacements used by Cortese and Andersen (1991). The two ellipsoids on any given trial either intersected or were separated in the two-dimensional image. In the nonintersecting displays, the ellipsoids were separated by sliding each object along its rotation axis (in opposite directions) by the minimum amount necessary to keep them from intersecting in the two-dimensional image. Examples of the four basic display types are shown in Figure 2.

We also manipulated the relative slants and tilts for the rotation axes of each ellipsoid, where slant is defined as the angle between the axis and the image plane, and tilt is the projected orientation of the axis in the image plane relative to the vertical. On any given trial, the two ellipsoids could move together as a globally rigid configuration with identical axes of rotation that varied in slant between ± 30°, or as a globally nonrigid configuration, in which the ellipsoids rotated about axes that differed in slant. The tilts of the two rotation axes were always identical, so that they would both project to the same line in the image plane. It is important to keep in mind that because the ellipsoids were oriented at random, their semi-axes were rarely (if ever) parallel to the rotation axis.

Each ellipsoid's axis of rotation was either fixed or precessing. For the fixed axis conditions, the ellipsoids rotated about axes that were stationary in three-dimensional space. In the precession conditions these rotation axes were themselves rotated about the observers' line of sight between adjacent frames of the motion sequence.

Using all possible combinations of the different stimulus manipulations, the displays were organized within a 2 x 2 x 2 factorial design (intersecting or nonintersecting ellipsoids, with or without visible texture, and with fixed or precessing axes of rotation). The ellipsoids were rotated 6° around their rotation axes between adjacent frames in the apparent motion sequence. In the precessing axis conditions, the axes of rotation rotated about the line of sight 1° between successive frames. Because of the precession of the rotation axis, 360 frames would be necessary in order for any given ellipsoid to return to its initial orientation. The stimulus displays were shown in continuous motion until the observer made an appropriate response. The individual frames of the apparent motion sequence were displayed at 20 Hz (each frame's temporal duration was 50 ms).

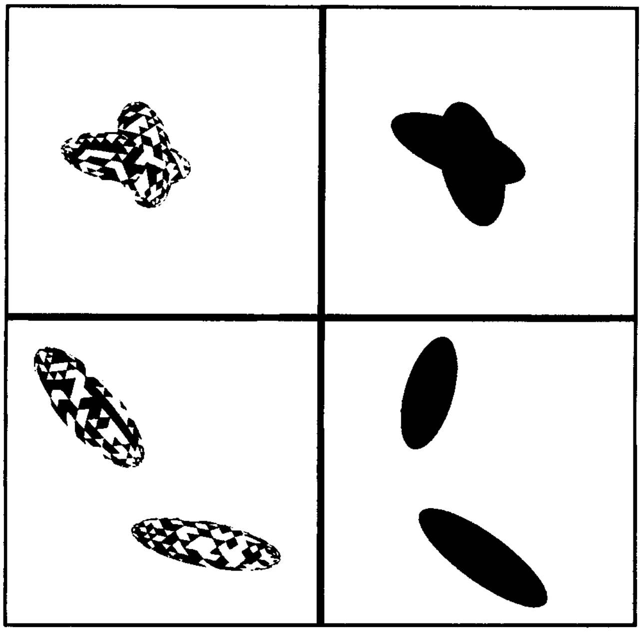

Figure 2. Examples of the four basic display types used in Experiment 1. Moving clockwise from the upper left, the examples include instantaneous optical projections of intersecting textured ellipsoids, intersecting nontextured ellipsoids, nonintersecting nontextured ellipsoids, and nonintersecting textured ellipsoids.

Procedure. The observer's task on any given trial was to discriminate whether the two ellipsoids rotated together as a rigid configuration (same axes of rotation) or as a nonrigid configuration (different axes of rotation). Observers made their responses using different buttons on the Silicon Graphics mouse. Auditory feedback (a short beep) was provided whenever a response was correct.

To assess the accuracy of these rigidity discriminations, we measured the threshold difference in slant for each condition necessary to determine whether the configuration of two ellipsoids rotated about the same or different rotation axes. Thresholds were obtained for each of the eight experimental conditions using an adaptive staircase procedure. The slant difference for nonrigid trials was initially set to 40°. This value was reduced by one increment amount whenever the observer made a correct response and was increased by three times the increment amount whenever the observer made an incorrect response. The increment magnitude was initially set to 5° and was halved on the first, third, and seventh reversals. This procedure is designed to converge at the 75% location of the observer's psychometric function (cf. Lelkens and Koenderink, 1984). The mean of the slant differences across 10 reversals was used as the estimate of the observers' thresholds. For the condition involving the separated silhouettes, the initial slant difference between the rotation axes was set to 75°, since pilot observation showed this condition to be particularly difficult. Five thresholds were obtained for each condition for each observer.

Observers. The displays were presented to three observers, including the two authors (J.F.N. and J.T.T.) and one other (H.F.) who was naive to the purpose of the experiment. All observers had normal or corrected-to-normal vision.

Results and Discussion

The individual results of all three observers are shown in Figure 3. An analysis of variance of these data revealed significant differences in the thresholds obtained for intersecting and nonintersecting ellipsoids, $F(1, 2) = 148.76$, $p < .01$, and for ellipsoids presented with and without texture, $F(1, 2) = 66.41$, $p < .02$. There were no significant differences between the fixed and precessing axes of rotation, and there were no significant interactions. Figure 4 shows the combined results collapsed over observers and the variations of precession to highlight more clearly the main effects.

The textured conditions were included in this experiment primarily to provide a standard reference with which to evaluate observers' performance for the deforming silhouettes. Because these displays contained numerous identifiable features, the three-dimensional structure and motion of the depicted ellipsoids could potentially be determined using traditional computational models that are based on an assumption of projective correspondence. Note in Figure 4 that in the intersecting textured condition, observers could reliably detect differences as small as 5° in the slants of the rotation axes. This high level of performance may be somewhat misleading, however, in that it was probably not based on a perceptual analysis of three-dimensional structure from motion. It is important to recognize that the intersecting ellipsoids actually passed through one another when they moved nonrigidly, producing accretion and deletion of tex-

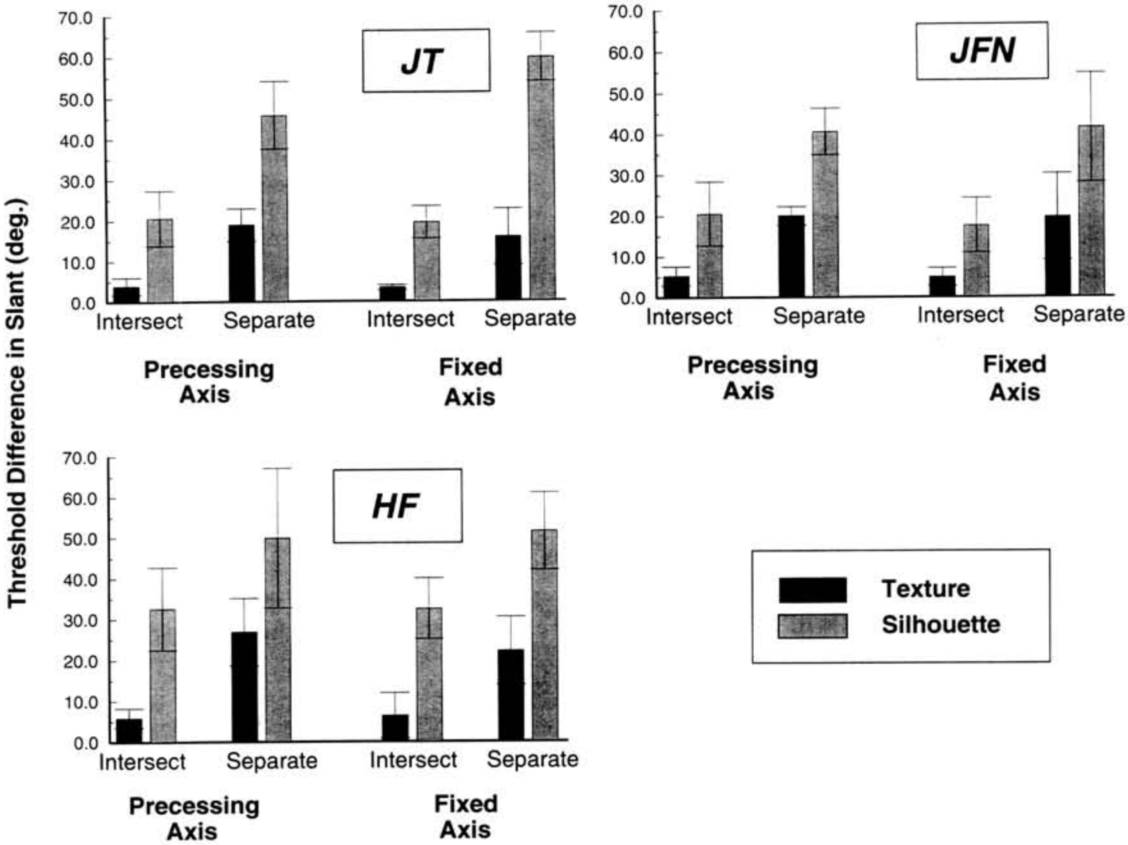

Figure 3. The slant discrimination thresholds of three observers (J.T., J.F.N., and H.F.) for all of the different conditions of Experiment 1. The error bars represent ± 1 standard deviation from the mean of five separate threshold measures.

ture at their intersection boundaries. All of the observers reported that they used this phenomenon whenever it was available as the primary basis for their judgments.

A better estimate of the observers' abilities to exploit the property of projective correspondence in performing this task is provided by the nonintersecting textured condition, in which additional information from accretion and deletion was unavailable. Note that the overall level of performance in that case was much less accurate: Observers could only detect differences in the slants of the rotation axes reliably when they were separated by a minimum of 21°. This result is similar to one reported previously by Todd (1982). When an individual texture element rotates about a fixed axis in three-dimensional space, its optical projection in the image plane will move in an elliptical trajectory, whose eccentricity is uniquely determined by the slant of the axis of rotation. Todd (1982) showed that observers have difficulty identifying variations of eccentricity in the trajectories of moving elements as nonrigid motion—a finding that is confirmed by the results of the present experiment.

Although this task may have been difficult in the nonintersecting conditions when the depicted surfaces were textured, it was nearly impossible when the texture information was removed. Indeed, for the nonintersecting ellipsoids without texture, the observers' discrimination thresholds increased dramatically to over 48°. All of the observers reported that many of the displays in this condition appeared to be undergoing nonrigid fluidlike motions rather than rigid rotation in depth—as has been reported previously by Mach (1886/1959), Wallach and O'Connell (1953), and Todd (1985). When evaluating this result, it is important to keep in mind that there were several sources of information available in these displays, from which it would have been theoretically possible to perform the task. Because all of the simulated objects were displaced away from the axis of rotation, the center of each projected ellipse would have moved in an elliptical trajectory, whose eccentricity could in principle have been used to determine the slant of the rotation axis for each object. The two authors who participated in this experiment were both aware that this information was available, but it is obvious from the data that they were unable to make use of it with any degree of accuracy. Another potential strategy for performing this task with fixed axis motions would be to use the algorithms of Giblin and Weiss (1987) or Pollick, Giblin, Rycroft, and Wilson (1992). However, given the extremely low levels of performance and the absence of any precession effects, it seems reasonable to conclude that these particular algorithms may be of little relevance to actual human perception.

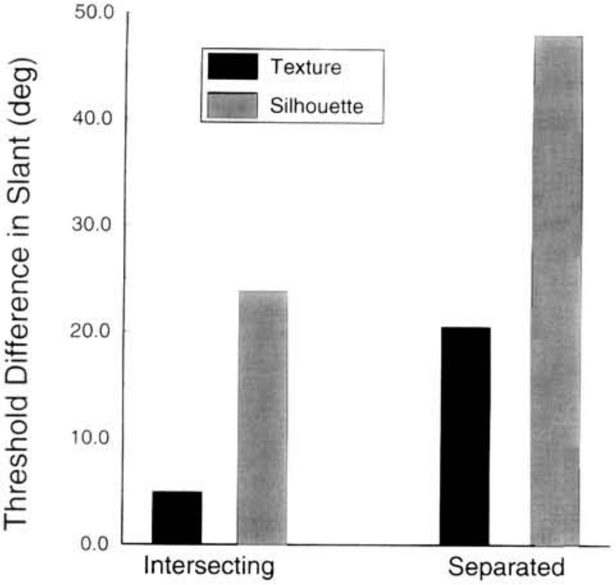

Figure 4. The slant discrimination thresholds from Experiment 1 collapsed over observers and the variations of precession. The textured and nontextured conditions are represented by black and grey bars, respectively.

In contrast to the performance obtained with nontextured ellipsoids in the separated conditions, the observers' discrimination thresholds were reduced by more than half when the ellipsoids were positioned so that they intersected one another. In addition, all of the observers reported that these intersecting displays produced much more compelling kinetic depth effects, which confirms the observation of Todd (1985). It is interesting to note that the overall level of performance for the intersecting silhouettes was almost identical to that obtained in the nonintersecting texture condition. Thus, although a threshold value of 24° may not seem particularly accurate when considered in isolation, the fact that this threshold is essentially the same for separated textured ellipsoids suggests that the optical deformations of intersecting silhouettes provide as much information for performing this task as does the projected motions of identifiable feature points. This suggestion is also supported by the observers' subjective impressions. For both of these conditions the displays usually appeared as pairs of individually rigid objects rotating about the same or different axes of rotation. For the separated silhouette condition, in contrast, the individual ellipsoids could sometimes appear to be rotating rigidly in depth, but they were more often perceived as elastic two-dimensional figures rotating and deforming in the image plane.

There are two important theoretical implications of these results that deserve to be highlighted. First, the relatively poor performance at detecting differences in the axes of rotation for both textured ellipsoids and silhouettes provides strong evidence that the perception of three-dimensional structure and rigidity in these displays cannot be based on a computational process that requires precise knowledge of the three-dimensional orientation of the axis of rotation, as has been proposed by Cipolla and Blake (1990), Giblin and Weiss (1987), and Pollick, Giblin, Rycroft, and Wilson (1992). Second, it also follows from this finding that the perceived three-dimensional structure of these displays—as specified by either the projected motions of identifiable texture elements or by the optical deformation of an object's silhouette—cannot entail a precise determination of the relative three-dimensional distances or orientations of moving ellipsoids or their individual surface points. Because relative three-dimensional distance and orientation changes for objects rotating about different axes, an accurate perception of either of these properties would make it possible to detect the nonrigid motion. Similar difficulties in detecting certain types of nonrigid deformations have also been reported by Norman and Todd (1993). Such findings are consistent with the arguments of Todd and Bressan (1990) and Todd and Norman (1991) that the visual perception of three-dimensional structure from motion may be primarily concerned with affine, ordinal, or topological aspects of object structure, and that Euclidean metric properties such as relative distance or orientation may be of secondary importance.

Why should the optical deformations of two intersecting silhouettes produce a more compelling kinetic depth effect than when the same two silhouettes are spatially separated? One possible explanation of this effect is suggested by the analysis of smooth occlusion contours proposed by Koenderink (1984) and Koenderink and van Doorn (1976, 1977, 1979, 1982). These authors have shown that the curvature of an occlusion contour in its optical projection is directly determined by the curvature of the surface region to which it corresponds, such that convex contours specify elliptic regions with positive Gaussian curvature and concave contours specify hyperbolic regions with negative Gaussian curvature. One important difference between the intersecting and nonintersecting displays of the present experiment is that the separated contours were always convex, whereas the envelopes of the intersecting contours contained concave regions that appeared and disappeared over time. This would have produced a repeating sequence of distinct generic views, which could be used to define an aspect graph of an object's three-dimensional structure as described by Koenderink and van Doorn (1977, 1979). When considered from this perspective, an individual ellipsoid is clearly degenerate, since it contains no hyperbolic regions and its optical deformation is restricted to simple affine transformations. Given that observers tend to perceive motion configurations with the simplest possible organization (see Johansson, 1950), it should not be surprising that these separated silhouettes were most often perceived as elastic two-dimensional figures rotating and deforming in the image plane. Because the optical deformations are more complex when two ellipsoids intersect one another due to the appearance and disappearance of contour concavities, the most economical encoding of motion in that case would be more likely to require a three-dimensional interpretation.

Experiment 2

Experiment 2 was designed to explore further how the complexity of a silhouette's optical deformations over time can influence its interpretation as a solid object rotating in depth. The complexity of these deformations was manipulated in two different ways: First, the number of intersecting objects in the rotating configurations was varied between two and four, in order to manipulate the number of concave regions in their deforming silhouettes that could appear and disappear over time. Second, we also included still another type of optical motion that arises from the deformations of cast shadows. We wondered in particular whether human observers could successfully interpret these shadow deformations, and whether their covariation with the deforming silhouettes would provide an additional constraint that might actually improve performance.

Method

The apparatus and procedure were identical to those used in Experiment 1. The stimulus displays were also similar except for the following changes: Either 2, 3, or 4 ellipsoids could be presented on any given trial. Two of the semi-axes on each ellipsoid were selected at random from a minimum of 1.33 cm to a maximum of 2.66 cm. The third semi-axis was constrained to be at least 1.75 times longer than the other two, with a maximum of 4.65 cm. Following the determination of an ellipsoid's shape, it was then rotated to a random orientation in three-dimensional space and displaced away from the origin along all three coordinate axes by a random amount up to 1.86 cm in each direction.

The homogenous background used in Experiment 1 was changed to a purple and white checkerboard pattern containing 400 rectangular elements (20 elements wide × 20 elements high across the entire display monitor). In some conditions, cast shadows of the rotating ellipsoids appeared on the background surface, which were generated by an infinite point light source at a horizontal slant of 60° relative to the image plane. The presence of a shadow in any given region changed the background white to a dim gray, whereas purple background regions were changed to a dark purple. Therefore, both the shadow and the background surface were visible in areas containing shadows (see Figure 5).

Because of the limitations of our computer graphics system, we were only able to display a maximum of four deforming contours simultaneously—including both the object silhouettes and their shadows—at a sufficiently rapid rate of 20 Hz to achieve a perceptually smooth apparent motion. Thus, we were restricted to seven possible experimental conditions: Silhouettes or shadows could be presented using rotating configurations composed of two, three, or four intersecting objects, and there was also a combined condition in which the silhouettes and shadows of two intersecting objects were presented together. The simulated ellipsoids used to generate these displays all oscillated back and forth about fixed axes (i.e., there was no precession). Each motion pattern consisted of 60 distinct frames presented in sequence, first in one direction, then in reverse order, until the observer made an appropriate response.

The rigidity of the depicted motions was manipulated in the same manner as in Experiment 1 by varying the relative slants of the depicted axes of rotation. For displays that contained more than two objects, this was defined conservatively as the maximum slant difference between the two most separated axes. In all conditions, the first ellipsoid's rotation axis had a vertical tilt and a randomly chosen slant within a 60° interval ± 30° from the frontoparallel plane. For globally rigid displays this same rotation axis was used for all of the other objects in the configuration. For globally nonrigid displays, in contrast, the ellipsoids rotated about different axes whose slants were spaced at equal intervals from one another. The maximum slant difference between the two extremes was varied adaptively from trial to trial to determine the discrimination thresholds in each condition. The displays were evaluated by the same three observers who participated in Experiment 1.

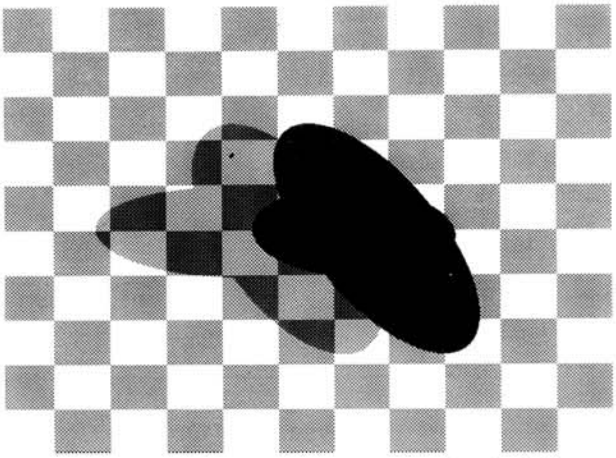

Figure 5. A typical display from the combined shadow and silhouette condition of Experiment 2, depicting two intersecting ellipsoids and their cast shadows against a planar background surface.

Results and Discussion

The individual results of all three observers are shown in Figure 6. It is clear from these data that the number of intersecting objects had no effect on the observers' discrimination thresholds—at least when defined by the maximum slant difference among all of the rotation axes in any given display. It should also be noted, however, that this particular definition of threshold is somewhat arbitrary. Had we plotted the results as a function of the average slant difference among the various rotation axes, then these same data could be used to support the claim that increasing the number of intersecting objects can significantly improve performance. With respect to the phenomenal appearance of the displays, all of the observers reported that their perceptions of three-dimensional structure from motion were equally compelling in all conditions, regardless of the number of objects depicted.

There were also no significant differences in the observers' judgments for displays containing different possible combinations of shadows and silhouettes. It is important to keep in mind when considering this result that shadows and silhouettes generally do not deform in the same manner. For the conditions used in the present experiment, in which shadows were cast by rotating ellipsoids onto a planar background surface at an oblique angle to the direction of

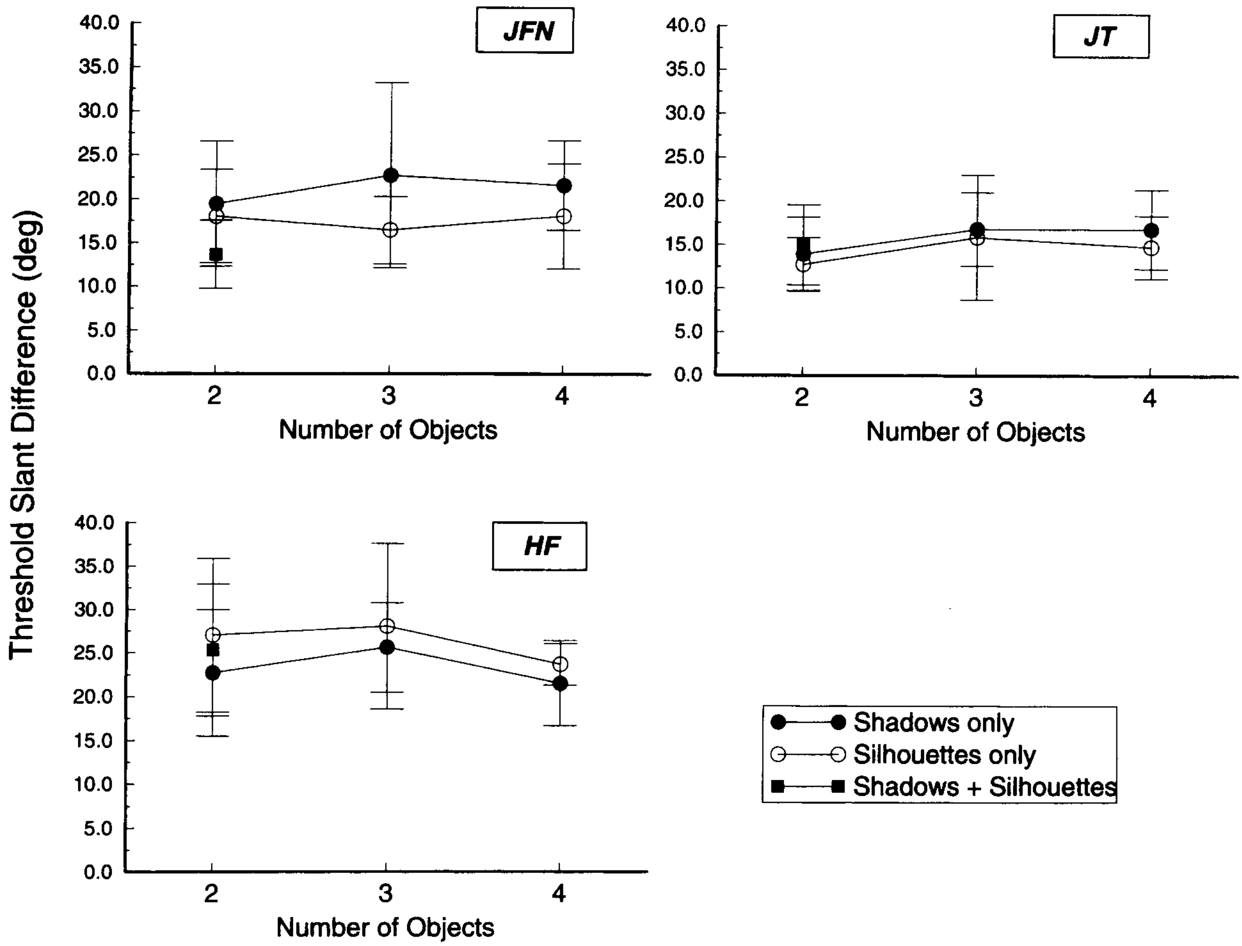

Figure 6. The slant discrimination thresholds of three observers (J.F.N., J.T., and H.F.) for all of the different conditions of Experiment 2. The results obtained for silhouettes, shadows, and both presented in combination are represented by open circles, filled circles, and squares, respectively. The error bars represent ±1 standard deviation from the mean of five separate threshold measures.

illumination, the two patterns of deformation are related by an affine transformation in the image plane. Consider, for example, the patterns produced under these conditions by a rotating sphere: Its silhouette would always be a circle, while its shadow would always be an ellipse (e.g. Todd & Mingolla, 1983).

Although the optical deformations of shadows and silhouettes may differ by an affine transformation, they seem to provide comparable information about an object's three-dimensional structure and motion. Note in Figure 6 that the observers' discrimination thresholds for shadow deformations presented in isolation were not significantly different from those obtained for the deformations of boundary contours. Moreover, all of the observers reported that the two types of deformation were phenomenally equivalent.

This last observation led us to wonder whether a deforming shadow would have a possible rigid interpretation if perceptually analyzed as though it were a silhouette. To address this question, it is useful to consider the envelope of silhouettes produced by a single rotating object over its entire trajectory. If the object rotates about a fixed axis, then this envelope will always have a bilateral symmetry about the optical projection of the axis of rotation (see Pollick, Giblin, Rycroft, & Wilson, 1992). This is demonstrated in Figure 7, which shows the envelopes of silhouettes produced for several pairs of ellipsoids rotating rigidly about randomly slanted axes with vertical tilts, as in the present experiment. Note that all of the envelopes have a vertically oriented bilateral symmetry. Now consider the envelope of shadows for a similar set of rotating objects as shown in Figure 8. If the direction of illumination is perpendicular to the projected axis of rotation, as was the case in Experiment 2, then the envelope of shadows will also have a bilateral symmetry, though it will be tilted in the image plane much like the envelope of silhouettes for an object rotating about a tilted axis. This apparent similarity between the deformations of shadows and silhouettes is somewhat misleading, however, because it depends on the particular direction of illumination. Figure 9 shows the envelope of shadows for a set of objects illuminated at a 49° slant relative to the image

Figure 7. The envelopes of silhouettes for pairs of ellipsoids rotating rigidly about a single fixed axis with a vertical tilt and a randomly selected slant. The envelope includes all regions of an image to which any part of an object projects over its entire trajectory. Because the envelopes of each object in a pair overlap one another, they are represented separately as transparent layers, depicted by light grey for one, dark grey for the other, and black in the region of overlap. Note that all of the envelopes have a vertically oriented bilateral symmetry that corresponds to the optical projection of the axis of rotation.

plane and a 49° tilt relative to the vertical. Note in this case that the envelopes are not bilaterally symmetrical and therefore cannot have a possible rigid interpretation as the deforming silhouette of objects rotating about fixed axes.

Are human observers sensitive to this difference? Unfortunately, the results of Experiment 2 do not provide a definitive answer to this question, since the shadow displays were generated using a special-case direction of illumination that mimics the symmetry properties of deforming silhouettes in a manner that is uncharacteristic of more unconstrained illumination conditions. Experiment 3 was designed therefore to determine empirically whether human observers can discriminate the deformations of shadows and silhouettes for arbitrary directions of illumination, when all other static sources of information for identifying these different contour types are removed.

Experiment 3

Method

The stimulus displays were identical to those used in the previous experiments with the following exceptions: They all depicted deforming silhouettes or shadows of two intersecting ellipsoids rotating rigidly about a single axis of rotation with a randomly selected tilt between ±180° and a randomly selected slant between ±30°. The shadows were simulated using a fixed direction of illumination at a 49° slant relative to the image plane and a 49° tilt relative to the vertical. In contrast to the displays of Experiment 2, for which the silhouettes were opaque and the shadows were transparent, both types of display in the present experiment were presented as homogeneous opaque blue regions against a purple and white checkerboard background. Because the shadow of an object is displaced relative to its silhouette, both types of configuration were shifted appropriately in the display screen so they could not be distinguished based solely on position. Moreover, because the shadow of a moving object is somewhat larger than its silhouette, the dimensions of the unseen ellipsoids used to generate the shadows were reduced by 15% relative to the silhouette condition, so that the displays could not be distinguished based solely on projected size.

Four observers participated in the experiment, including the two authors and two naive observers (J.S.T. and V.J.P.) who were unfamiliar with any details of how the displays were generated. Each observer viewed 100 displays of 50 shadows and 50 silhouettes presented in a random order. On each trial, their task was to identify the motion as a shadow or a silhouette by pressing the appropriate button on a handheld mouse. In an effort to achieve the highest possible levels of performance, all of the observers were provided with auditory feedback after each trial and participated in numerous practice blocks.

Results and Discussion

The percentages of correct responses for observers J.F.N., J.S.T., J.T.T., and V.J.P. were 57%, 58%, 52%, and 43%, respectively. From these data it is clear that the qualitative differences shown in Figures 7 and 9 between the optical deformations of shadows and silhouettes of intersecting ellipsoids rotating in depth cannot be discriminated by human observers with any degree of accuracy—even with practice and immediate response feedback after every trial. This is also consistent with the observers' phenomenological impressions. They all reported that the vast majority of

Figure 8. The envelopes of shadows for pairs of ellipsoids rotating rigidly about a single fixed axis with a randomly selected slant and a vertical tilt, cast upon a planar background from a direction of illumination with a 60° slant relative to the image plane and a horizontal tilt. Note that each of the envelopes has a bilateral symmetry, but that it does not correspond to the optical projection of the axis of rotation.

Figure 9. The envelopes of shadows for pairs of ellipsoids rotating rigidly about a single fixed axis with a randomly selected slant and a vertical tilt, cast upon a planar background from a direction of illumination with a 49° slant and a 49° tilt. Note that none of the envelopes has a bilateral symmetry and therefore cannot have a mathematically possible interpretation as a deforming silhouette of an object rotating rigidly about a fixed axis.

displays appeared as the silhouettes of rigid objects rotating in depth about fixed axes.

When evaluating these results, it is important to keep in mind that if a deforming shadow under the conditions of this experiment were mistaken for a silhouette, it would have no mathematically possible interpretation as a rigid object rotating about a fixed axis (see Figure 9). It is clear from the data, however, that the optical deformations of shadows and silhouettes were perceptually indistinguishable, and that both types of displays were equally likely to appear as rigid rotation in depth. When considered in conjunction with the results of Experiments 1 and 2, these findings indicate that observers can detect certain types of nonrigid deformations of an object from the optical motions of its bounding contour, but that they are relatively insensitive to others. That is to say, they can discern whether two intersecting ellipsoids are rotating about the same axis with a moderate degree of accuracy, but they cannot distinguish the projected motions of silhouettes from the deformations of shadows against a planar background.

Why might these tasks vary in difficulty? When considering this issue, it is interesting to note that similar qualitative distinctions among different types of nonrigid deformation have been studied previously for the perception of three-dimensional form from the projected motions of identifiable feature points (see Norman & Todd, 1993; Todd, 1982; Todd & Bressan, 1990; Todd & Norman, 1991). This research has shown that moving objects can be perceptually represented within broad equivalence classes defined by their affine properties, such that human observers have difficulty detecting within category structural variations or deformations (i.e., those that are related by an affine transformation along the line of sight).

Based on the results of the present series of experiments, it seems reasonable to speculate that a similar type of representation may also be used for objects that are visually specified by the optical deformations of shadows or occlusion contours, though the precise geometric properties that define the boundaries of perceptually distinct equivalence classes in this case have yet to be determined. One thing we can conclude with certainty, however, is that the perceptual distinction between rigid and nonrigid motion in these displays could not have been based on the symmetry properties of the envelopes of their optical deformations (cf. Pollick, Giblin, Rycroft, & Wilson, 1992). Note in Figures 7 and 9, for example, that the envelopes produced by shadows and silhouettes are qualitatively different, yet the empirical results indicate that these two types of displays are perceptually indistinguishable. Now consider the envelope of silhouettes produced by a nonrigid configuration of objects rotating about axes that differ in slant by 30° (see Figure 10). Note in this case that the envelopes are qualitatively similar to those produced by rigid configurations (see Figure 7), yet these motions can be discriminated with a high degree of accuracy.

General Discussion

A fundamental fact of ecological optics is that contours in a visual image can be produced by several different environmental causes, including variations over space in surface reflectance (e.g., texture), surface orientation (e.g., shading), or the pattern of illumination (e.g., cast shadows). Although this may appear at first blush to be a trivial observation, it has important theoretical consequences for the computational analysis of three-dimensional structure from motion. When objects move or are viewed stereoscop-

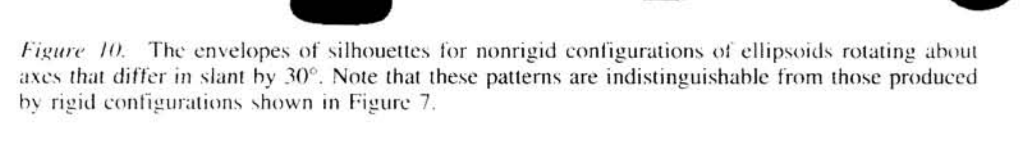

Figure 10. The envelopes of silhouettes for nonrigid configurations of ellipsoids rotating about axes that differ in slant by 30°. Note that these patterns are indistinguishable from those produced by rigid configurations shown in Figure 7.

ically, the different types of optical contours can undergo different types of deformation, and analyses that are designed to be used with one type generally will not be appropriate for others.

Most previous research on the visual perception of structure from motion has been exclusively concerned with the optical displacements of identifiable features, such as reflectance contours or the edges of polyhedra, which satisfy the condition of projective correspondence. During the past decade there have been numerous theoretical analyses of this type of optical motion that have demonstrated how it is mathematically possible to determine an object's Euclidean three-dimensional structure provided that certain other minimal conditions are satisfied. For an arbitrary configuration under orthographic projection, the computation requires that the depicted object must be rotating rigidly in depth and that the pattern of projected motion must include at least three views of four or more noncoplanar points (see Bennett, Hoffman, Nicola, & Prakash, 1989; Huang & Lee, 1989; Ullman, 1979). In the absence of additional constraints, these conditions are both necessary and sufficient to allow a unique determination of Euclidean metric structure. If an arbitrary rotating configuration contains fewer than three orthographic views or fewer than four points, its three-dimensional structure will be mathematically ambiguous with an infinity of possible rigid interpretations.

During the past several years, however, there has been a growing amount of evidence that these theoretical limitations may have little or no relevance to human vision. Using a wide variety of converging operations, this research has shown that two-frame apparent motion sequences presented in alternation provide sufficient information to obtain compelling kinetic depth effects, and that there are only negligible improvements in performance on objective response tasks when the length of an apparent motion sequence is increased beyond two frames (Norman & Todd, 1993; Todd & Bressan, 1990; Todd & Norman, 1991). Since the determination of Euclidean structure requires a minimum of three distinct views, it follows from this result that moving objects must be perceptually represented using some other less constrained geometry.

There is additional evidence to indicate that the relevant geometry in this context is affine. This was first suggested by a theoretical analysis of Todd and Bressan (1990), which showed that affine structure can be computed from two-frame apparent motion sequences—that is to say, with only two views, an object's three-dimensional structure can be specified up to an indeterminate affine stretching transformation along the line of sight (see also the related analysis of Koenderink & van Doorn, 1991). There have also been numerous empirical studies that have confirmed the psychological validity of this analysis. The results of this research have shown that perceptual performance is critically dependent on the specific aspect of an object's structure that an observer is asked to judge. Tasks that are theoretically possible based on an analysis of affine structure (e.g., object discriminations) invariably produce high levels of performance, whereas those that are theoretically impossible based on an analysis of affine structure (e.g., three-dimensional angle discriminations) invariably produce low levels of performance (Norman & Todd, 1993; Todd & Bressan, 1990; Todd & Norman, 1991).

It is interesting to consider the results obtained for textured ellipsoids in Experiment 1 within this general theoretical perspective. Of particular relevance in this regard is that the intersecting conditions produced much higher levels of performance than did the nonintersecting conditions. For intersecting ellipsoids the required discriminations could be performed based on the topological structure of the depicted surface texture. When the objects rotated nonrigidly about separate axes, this topological structure was altered at the boundaries of intersection (i.e., the adjacency relations among neighboring texture elements were destroyed), but when they rotated rigidly about a common axis, the topological structure remained invariant. This information was not available in the nonintersecting conditions because there were no intersection boundaries in the texture to alter. Performance in that case presumably required a more difficult computation of the specific slant of each rotation axis, or the relative three-dimensional orientations of the depicted ellipsoids, and the observers' discrimination thresholds were over four times larger than those obtained for the intersecting conditions.

Smooth Occlusions

A second type of optical motion encountered in natural vision that does not satisfy the condition of projective correspondence involves the deformations of smooth occlusion contours. Theoretical analyses of this type of motion have shown that it can also provide potential information about an object's Euclidean metric structure under certain conditions, which include rotations in depth about a fixed axis (Giblin & Weiss, 1987; Pollick, Giblin, Rycroft, & Wilson, 1992) or rotations about a moving axis whose motions are known precisely (Cipolla & Blake, 1990). The results obtained in the present series of experiments provide strong evidence, however, that these analyses are not used by actual human observers.

There are several basic findings that support this conclusion. First, it should be noted that observers are not particularly accurate at judging an object's axis of rotation from its deforming silhouette as is required by current theoretical analyses. In Experiment 1, for example, the slant discrimination thresholds were 24° for intersecting ellipsoids and over 48° for nonintersecting ellipsoids. There were also no significant effects of precession as would be expected on the basis of the analyses of Giblin and Weiss (1987) and Pollick, Giblin, Rycroft, and Wilson (1992). The primary stimulus factor that seemed to affect performance for these displays was the appearance and disappearance of local concavities in the boundaries of the deforming silhouettes (cf. Koenderink & van Doorn, 1977, 1979). The absence of these changes in the optical deformations of individual ellipsoids presented in isolation is probably why they were most often perceived as nonrigid stretching transformations in the image plane. Note, however, that this is a mathematically degenerate condition that is uncharacteristic of most natural objects. We have informally examined the optical deformations produced by a wide variety of rotating three-dimensional forms, and the only ones we have found that do not produce compelling kinetic depth effects are objects such as eggs or ellipsoids that are completely convex.

When evaluating these results, it should also be kept in mind that performance was no worse for the intersecting silhouettes than it was for the separated textured ellipsoids that satisfied the condition of projective correspondence. Thus, it would appear that for this particular task the deformations of smooth occlusion contours provide just as much perceptually relevant information as any other type of optical motion. It remains to be demonstrated, however, whether this finding can be generalized to tasks involving other aspects of an object's three-dimensional structure (e.g., Todd & Norman, 1991).

Cast Shadows

Another type of optical deformation that can violate the assumption of projective correspondence is produced by the motions of cast shadows. Shadow deformations can be subdivided into two distinct categories: (a) those produced by an observer's motion with respect to a fixed scene; and (b) those produced by the motions of other objects or their sources of illumination. Let us first consider the case where a fixed scene is viewed from multiple vantage points (e.g., as in binocular vision), such that all visible objects maintain a constant relation with their sources of illumination. When an observer moves within a static environment, shadow borders remain bound to fixed positions in three-dimensional space, which satisfies the condition of projective correspondence. Thus, they can be analyzed using existing algorithms to determine the three-dimensional structures of the background surfaces on which they are cast.

A very different pattern of deformation occurs, however, when an object moves relative to the light source. A shadow of a moving object will itself move over the background surface, which violates the assumption of projective correspondence. Nevertheless, the results of the present experiments show clearly that human observers can successfully analyze this type of deformation to distinguish between rigid and nonrigid motions of an otherwise invisible object—at least in the special case where shadows are cast upon a planar background surface. Although shadow deformations in that case can be demonstrably different from the deformations of smooth occlusion boundaries, they are perceptually indistinguishable as shown by the results of Experiment 3. It is probably best to be circumspect in drawing any conclusions about the generality of this result. For the more general case of arbitrarily curved background surfaces, the shadow deformations will be influenced by the shape of the background in addition to the shape of the moving object. It remains to be determined whether human observers can successfully interpret such a complex event.

Smooth Shading

It is interesting to note in passing that one other type of optical motion occurs frequently in natural vision, for which object motion and observer motion produce distinctly different patterns of deformation. This type includes the changing patterns of color and shading on smoothly curved surfaces. To appreciate the structure of image shading, it is useful to consider a set of points on a surface that all have the same luminance. For a smoothly curved surface with homogeneous reflectance, these points will be aligned along continuous space curves, which are sometimes referred to as isoluminance contours or isophotes (Koenderink & van Doorn, 1980). There are several different factors that can influence how these isophotes deform over time within a visual image. Most previous analyses of shading deformations have focused exclusively on observer motion relative to matte (Lambertian) surfaces, which maintain a fixed relation with their sources of illumination (e.g., Horn & Schunk, 1981; Nagel, 1981, 1987). The optical deformations of the isophotes in that case satisfy the condition of projective correspondence and can therefore be analyzed using existing algorithms to determine a surface's three-dimensional structure from motion or stereopsis.

Existing analyses of three-dimensional structure from intensity-based motion or stereo will not work, however, when an object moves relative to the light source or for surfaces that contain specular highlights, because the isoluminance contours under those conditions will move over an object's surface, thus destroying the property of projective correspondence. Although there have been several demonstrations reported in the literature that human observers can perceptually interpret all of these different types of shading deformations (Blake & Bulthoff, 1990, 1991; Bulthoff & Mallot, 1988; Todd, 1985), the precise mechanisms by which this is accomplished have yet to be revealed.

Conclusions

There are many different ways that optical contours can deform in natural vision, depending upon the particular environmental phenomena by which a contour or its motion are produced. Image contours can occur due to discontinuities of surface reflectance (texture), discontinuities of illumination (cast shadows), discontinuities of surface orientation (sharp corners), smooth variations of orientation for Lambertian surfaces (i.e., Lambertian isophotes), smooth variations of orientation for specular surfaces (i.e., specular isophotes), or smooth occlusions, and all of these different contour types can deform due to motions of the surface itself or motions of the observer.

Figure 11 provides a summary of all of the different categories of optical deformation that have been described. The rows of this table represent different types of optical contours, whereas the columns are used to distinguish observer motion from object motion. Note that some of the

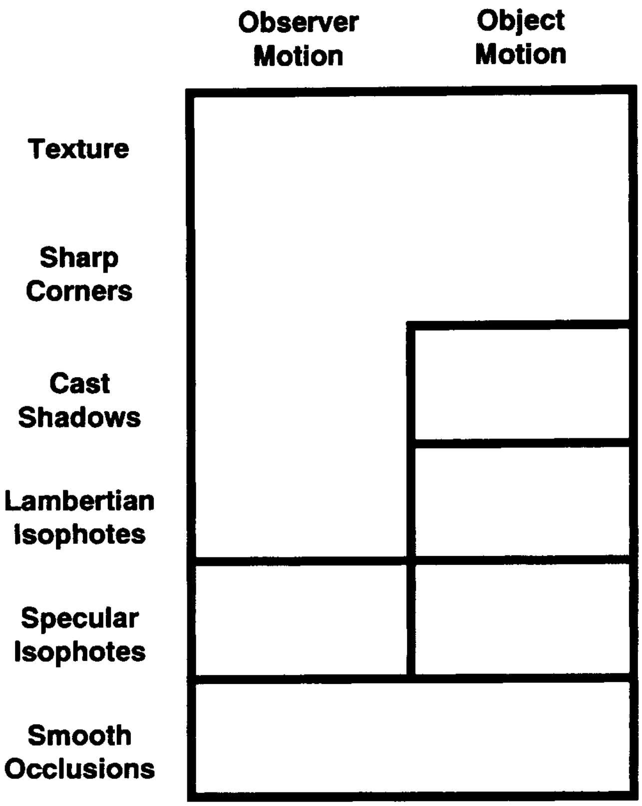

Figure 11. The categories of optical deformation defined by object motion and observer motion for different types of image contours. Note that some of the borders between cells in this table have been removed. These open areas define classes of deformation that are formally equivalent.

borders between cells in this table have been removed. These open areas combine classes of deformation that are formally equivalent. For example, the deformations of texture, sharp corners, cast shadows, and Lambertian isophotes caused by observer motion and the deformations of texture and sharp corners caused by object motion are all formally equivalent in that they satisfy the condition of projective correspondence. Although this one general category has been investigated extensively, our knowledge of the others is quite limited, both with respect to the formal geometric properties of the optical deformations they produce, and how these deformations are perceptually analyzed by human observers. The available evidence suggests that the perceptually relevant information provided by motion can only specify an object's three-dimensional structure within relatively broad equivalence classes, as opposed to a precise representation of Euclidean metric structure. For the projected motions of identifiable feature points, these equivalence classes seem to be defined by their affine properties, but it remains to be determined whether a similar form of representation is also used for the other types of optical deformation identified in Figure 11 that do not satisfy the condition of projective correspondence.

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P&C Board Appoints Editor for New Journal: *Journal of Experimental Psychology: Applied*

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Areas of interest include applications of perception, attention, decision making, reasoning, information processing, learning, and performance. Settings may be industrial (such as human–computer interface design), academic (such as intelligent computer-aided instruction), or consumer oriented (such as applications of text comprehension theory to the development or evaluation of product instructions).