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Illusory volumes from conformation

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Abstract. The purpose of this paper is to offer demonstrations of 'illusory volumes' in the spirit of the illusory flat surfaces described by Kanizsa. These demonstrations of illusory volumes exploit a new cue to the recovery of surface curvature from ambiguous images: conformation. In assuming conformation, the visual system assumes that the surface of a volume conforms to the curvature of its neighboring, underlying, or supporting surface, in the absence of image cues to the contrary. Demonstrations that exploit the assumption of conformation provide several insights into the nature of the inferential processing that underlies contour, surface, and volume formation. In particular, these demonstrations imply that the visual system does not calculate local surface curvature, illusory contours, or occlusion relationships before it analyzes global surface relationships.

1 Introduction

Several authors (eg Kanizsa 1976; Michotte et al 1964) have offered demonstrations that the visual system links image fragments up into larger regions. When those fragments are taken to be the visible portions of an occluded object, the object is said to 'amodally complete' behind the occluder. When the completed object lies in front of its inducers, the object is said to 'modally complete'. Perhaps because traditional demonstrations (Kanizsa 1955, 1976; Koffka 1935; Matthaei 1929; Schumann 1904) such as the Kanizsa rectangle (figure 1) could be constructed by laying flat pieces of paper one on top of another, research on amodal and modal completion phenomena may have been unnecessarily constrained by an emphasis on flat-surface relationships. In the natural world, occlusion happens between curved and irregular surfaces that are the visible portions of volumes. The key fact that distinguishes a volume from a surface is that a point can lie inside or outside a volume, whereas a point can only lie on or off a surface (Tse 1998a). The purpose of this paper is to offer examples of illusory volumes (such as spheres) rather than just illusory surfaces (such as rectangles), and to explore what these demonstrations might reveal about the nature of the inferential processing that underlies contour, surface, and volume formation.

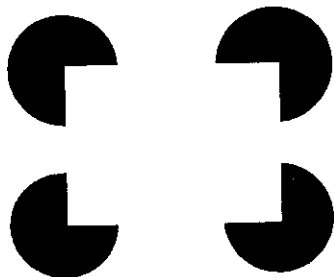


Figure 1. The Kanizsa rectangle.

2 Methods

The goal of this paper is not to parameterize the factors that lead to illusory-volume percepts, but to demonstrate their existence. As such, an 'instant psychophysics' approach was used.

Ten subjects (three psychology graduate students and seven lay persons) who were naive regarding the aim of the task were told "Describe in detail the objects that you see here" when shown the various demonstrations included in this paper. Subjects sat in an office chair and viewed stimuli printed on standard 8.5 inch \times 11 inch paper. They viewed the stimuli by holding them in their hands at a comfortable distance, which on average was approximately 60 cm. Stimuli were typically drawn to fit into an 8 cm \times 8 cm imaginary square region in the center of the page. All demonstrations included in this paper were spontaneously judged to be volumes rather than flat surfaces by at least seven of the ten subjects tested. Stimuli that failed to evoke a volume percept in at least seven of the ten subjects have not been included here.

3 Illusory volumes

Any cue that can alone be used to generate a volume percept is a sufficient cue to volume. It should be possible to exploit any sufficient cue to volume to create illusory volumes if by 'illusory volume' we mean a percept of a volume inferred from visual input that is more minimal or ambiguous than the input that would be cast upon the retina by a real volume. Of course, all visual input is ambiguous and requires inference. In this sense, even a photograph of a ball would count as an illusory volume, since we see volume and 3-D depth relationships where there is in fact only a 2-D surface. But we reserve the term 'illusory' for those cases that reveal the nature of visual inference by making information that is not explicitly specified in the image perceptually explicit. The Kanizsa rectangle, for example, counts as an illusory surface because the illusory surface and contours that are perceived are not explicitly specified in the image by a visible bounding contour. Demonstrations in this paper count as illusory volumes because volumetric form is explicitly and unambiguously perceived even though only implicitly and ambiguously specified by contour-curvature cues in the image.

It has been shown that illusory volumes can be generated with many 'structure-from- x ' cues. In recent years much has been learned about structure-from-motion (eg Ullman 1979) and structure-from-stereo (eg Carman and Welch 1992; Gregory 1970; Julesz 1971; Marr and Poggio 1977). Other cues to 3-D layout and shape include occluding contours (eg Koenderink 1984), surface contours (eg Knill 1992; Todd and Reichel 1990), perspective, motion parallax, shading, shadows, highlights, and texture gradients. Contours, like shading, or motion parallax, offer information only about the sign of surface (ie Gaussian) curvature (Beusmans et al 1987). In this regard, contours are not as rich a source of information about surface curvature as stereo or motion, which can in principle yield precise surface curvature at all points on a visible surface. Nevertheless, occluding contours seem sufficient to generate a volume percept. This may be because our visual system settles for an imprecise representation of surface curvature, and/or because it makes additional assumptions to constrain surface curvature solutions compatible with image contour cues. One such prior assumption appears to be the assumption of conformation.

4 The assumption of conformation

Most demonstrations in this paper consist of silhouettes where black regions correspond to the visible surfaces of a volume. Because silhouettes were used, the only traditional cue to volume available in the image was given by the shape of the occluding contour. Occluding contours are the self-occlusion contours projected from the 'rim' of an object. The rim lying on the surface of a volume, relative to a particular viewpoint, is the set of points where the observer's line of sight 'grazes' the surface. For a volume with a smooth surface (ie differentiable as many times as necessary) the rim is comprised of a set of smooth curves and loops that divide the visible and self-occluded surfaces of the volume.

The informativeness of contour curvature is made evident in certain drawings (Hogarth 1981; Koenderink 1984), such as the ones in figure 2. The rectangle in 2a looks flat because its lack of contour-curvature cues to volume is assumed not to be an accident of viewpoint (Grimson 1981). That is, a slight shift of viewpoint in an arbitrary direction will not lead to a radical change in image structure. If we assume a 'non-accidental' or 'generic' viewpoint, a straight (curved) line in the image projects from a straight (curved) line segment of rim in the world (compare Lowe 1987). Figures 2b and 2c look volumetric because the curvature cues implicit in the occluding contour imply that they are projected from a nonplanar object. The nature of these contour-curvature cues will not be discussed in detail here (but see Tse 1998b).

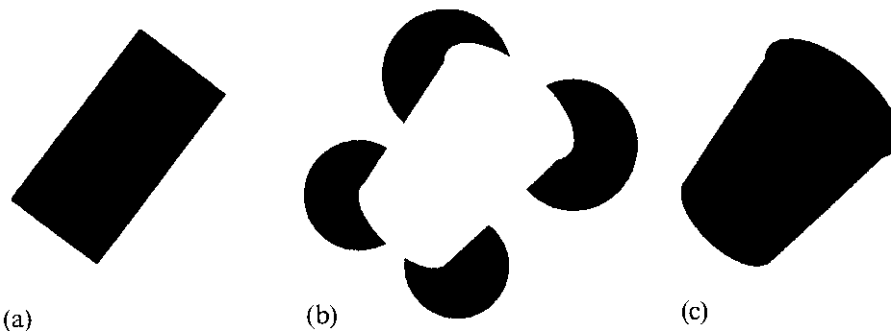


Figure 2. The rectangle in (a) looks flat because there are no contour-curvature cues specifying that the image was projected from a nonplanar surface. Cases (b) and (c) look volumetric because they do have such contour-curvature cues.

Brady and Grimson (1981) and Stevens (1981, 1986) generated illusory volumes using line drawings where lines correspond to 'surface contours' (eg scratches or lines on the surface). The geometrical relationship between surface contours and surfaces must be constrained for the visual system to be able to recover 3-D surface form from the 2-D image projections of its surface contours. Stevens (1981, 1986) and Knill (1992) have argued that the visual system is biased to attribute most, if not all, of the curvature of a surface contour to the underlying surface curvature (see also Todd and Reichel 1990). This is equivalent to an assumption that a surface contour could have arisen from an intersection of a plane with the curved surface because the surface contour has no more curvature than is afforded it by the underlying surface.⁽¹⁾

An assumption similar to this 'planar cut' assumption for surface contours also appears to apply to volumes and their surfaces. The visual system appears to attribute most if not all of the curvature of a volume's surfaces to the curvature of the surface that supports or underlies it (Tse and Albert 1998; Albert and Tse 1998). This assumption of conformation may also arise because of the visual system's implicit knowledge about physical stability in the world; a stationary object must be attached to a supporting surface in the terrestrial environment to counteract gravity and will tend to be supported by a stable interface between surfaces so that the object does not tip over. Thus, for example, the ambiguous black blobs in figure 3 appear to most observers to be croissant-shaped volumes resting on a flat surface whose arms, relative to the central portion, come toward the reader, whereas the identical black blobs in figure 4 appear to conform to the underlying cylindrical surface, causing the arms to appear to curve away from the reader.

⁽¹⁾ Note that this 'planar cut' assumption is weaker than the assumption that a surface contour is a line of principal curvature, as suggested by Stevens (1981), and is also weaker than the assumption that a surface contour is treated as a geodesic, as suggested by Knill (1992). This is because a surface contour corresponding to a locus of intersection between *any* plane and a curved surface will have a curvature entirely due to the surface curvature of the curved surface. In most cases, such contours will be neither curves of principal curvature nor geodesic curves.

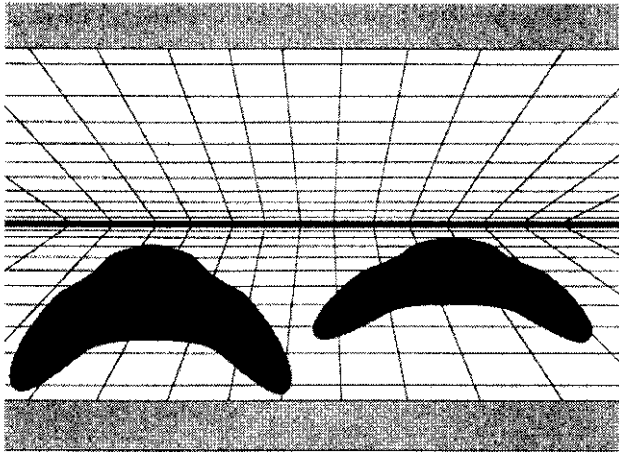


Figure 3. Note that the 'arms' of the black blobs seem to come toward you.

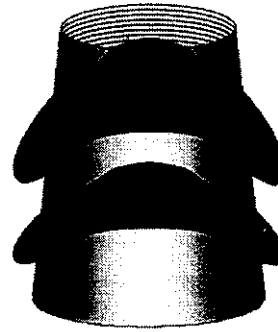


Figure 4. Here the same blobs in image coordinates appear to have arms that curve slightly away from you. This is because the blobs are now conforming to a different underlying surface.

5 Illusory volumes from conformation

This tendency to attribute the curvature of a volume's surfaces to the underlying or supporting surface is exploited in figure 5 to create an illusory volume. Figure 5 appeared to be a volume wrapped around an illusory post to seven of ten observers. For the subjects who perceived a volume wrapping around a post, the volume appeared to be comprised of a closed, approximately tubular surface. Three subjects spontaneously used the word 'worm' to describe their percept. For the three subjects who did not perceive an amodally completing volume, the black regions appeared flat. Two of these subjects said they saw something like a 'yin yang' symbol, and the third said she saw a flat 'S' with a part missing. All three of these subjects were able to see this figure as a worm wrapped around an illusory pole when this interpretation was suggested to them, and found it difficult not to interpret the figure as a volume once they had done so. For most subjects the shape-from-contour system seems to be invoked quite automatically by the nature of the contour relationships of the image themselves. But ambiguous images such as this may fail to invoke this system for some subjects.



Figure 5. A volumetric worm wrapped around an illusory pole.

Since the worm was perceived to be tubular, its occluding contour must project from a rim that does not lie directly on the surface of the illusory pole (Tse and Albert 1998). If the worm's rim did lie directly on the pole, there would be a surface discontinuity there, and the worm would not appear tubular. However, the portions of the rim closest to the supporting surface might be taken to correspond to a surface contour of the supporting surface that has been 'lifted off' the surface. It seems that what conforms to the underlying pole surface here is not the worm's surface where it meets the pole so much as the entire volume. Thus an assumption of surface conformation may follow from more general assumptions of volume conformation and surface smoothness.

In addition to cues to conformation, another cue to 3-D form in figure 5 is the pair of discontinuities in the first derivative taken along the otherwise smooth contours of the

black regions. Points of deep concavity or convexity can lead the visual system to assume the existence of an occluding edge (eg Kellman and Shipley 1991). Once occlusion has been assumed for the two black 'halves', the two elements can complete behind the illusory 'occluding' post.

Note that points of deep concavity or convexity do not necessarily lead the visual system to assume the existence of an occluding edge. Whether such a discontinuity is interpreted in this way depends on its context. Occlusion cannot be determined solely on the basis of local cues. The generation of an illusory volume depends on the global pattern of the visible portions of an object or objects, a point Kanizsa (1974) and Rock (1987) made for illusory contours. Although the two 'stars' shown in figure 6a possess the same illusory 'post'-defining edges (figure 6c) as the 'worm' of figure 6b, observers who have not seen figures 5 or 6b consistently report seeing two stars. This may be because in a context like the stars, where there are several pointed regions that must be interpreted as points of the object, the one pointed region that might indicate occlusion is instead taken to be just another point of the object, rather than an implicit T-junction.

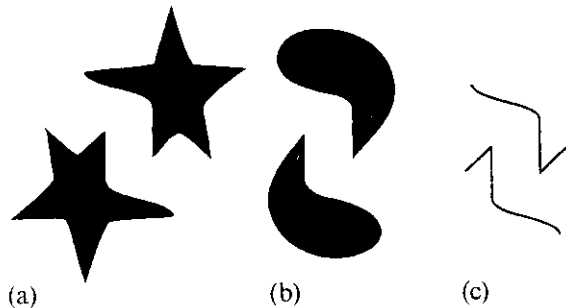


Figure 6. Observers who have not seen (b) consistently report seeing two stars in (a), although both figures possess the same illusory 'post'-defining edges (c).

Other examples where occluding contour curvature and tangent discontinuities generate illusory volumes can be seen in figures 7–9. As in figure 5, the black regions in these examples are not taken to be reflectance differences or surface contours of the underlying surface, but rather are taken to comprise a volume that lies on top of and conforms to the underlying illusory surface. The underlying surface is in turn defined by the shape of that which conforms to it, permitting the formation of illusory volumes. Most observers say that figure 7 looks like a sphere grasped by an amorphous object that is partly occluded by the illusory sphere.⁽²⁾



Figure 7. The illusory ball shown here could also be interpreted as a flat white figure lying on a black background, even though most observers have an initial preference for the volumetric interpretation.



Figure 8. An illusory pole embraced by an amodally completing person.

⁽²⁾ Note that this example reveals the visual system's bias to interpret ambiguous images as volumes, because all observers tested ($n = 10$) reported seeing a sphere even though the drawing is also compatible with a 2-D interpretation. A flat white 2-D angel-like figure lying over black objects can also be seen; Note the 'wings' in the upper right and lower left.

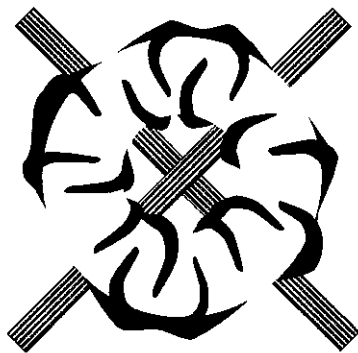


Figure 9. An illusory lifesaver.

The sphere is a particularly interesting volume because there is no contour-curvature cue in the occluding contour projected from a sphere that can distinguish it from the occluding contour projected from a disc standing in the frontoparallel plane. Since a circular occluding contour is not what distinguishes the perception of a spherical volume from the perception of a disc, it must be that other cues to volume lead to the percept of a sphere. However, these figures do not exploit any traditional cue to volume other than the shape of the occluding contour. The new 'cue' here is conformation, suggesting that conformation (as inferred from image cues such as contours) is a sufficient cue to volume.

In figure 10a, the illusory figure is presumed to conform to the black rings, accounting in part for its spherical appearance. The illusory figure also looks like a sphere because its bounding contour is a circle, and a circle is consistent with a spherical interpretation. (Ten out of ten subjects reported seeing a sphere here.) Note that the rings (which are presumed to be circles that project ellipses in the image) may imply a circular cross-section of the sphere at the equator which can then be used to propagate shape information toward the polar regions (Tse 1998b). A similar example is shown in figure 11. (Again ten out of ten subjects reported seeing a sphere surrounded by black curved bars.) In these examples both the occluding contour and conformational

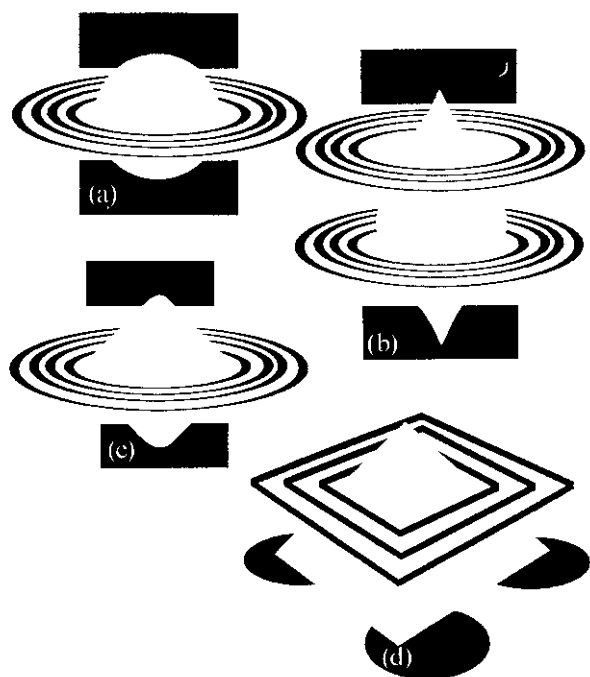


Figure 10. Various illusory volumes generated by conformation 'at a distance' and occlusion cues.

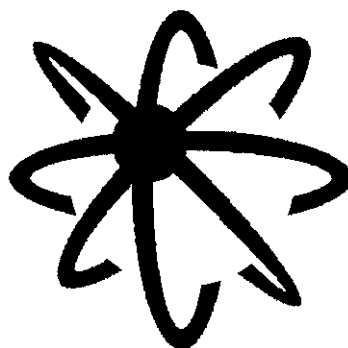


Figure 11. An illusory sphere generated by conformation at a distance.

cues imply a sphere, but in other cases the conformational and contour-curvature cues may constrain each others' possible volume solutions. Thus figure 10b appears to be shaped like a Christmas tree ornament, whereas figure 10c appears to be primarily conical, even though they conform to similar rings. Figure 10d appears to most observers to be an illusory pyramid. (Seven of ten observers reported seeing a pyramid, whereas the other three reported a flat trapezoidal illusory surface.)

6 The contour of penetration

The locus of intersection between two interpenetrating volumes is the set of all points where the surfaces of the two volumes intersect. For volumes that have everywhere smooth surfaces, the locus of intersection is a smooth loop lying on the surfaces of both volumes. The image projection of a locus of intersection is a 'contour of penetration' (COP). COPs specify a special class of surface conformations, where a surface that is penetrated by another conforms around the penetrating surface. The COP is typically a smooth curve in the image that can only be distinguished from a similarly shaped occluding contour on the basis of global cues to occlusion and surface layout. Therefore, COPs, unlike T-junctions or other discontinuities in the first derivative taken along the image contour, cannot be thought of as low-level features of the image. Rather, they indicate occlusion and penetration at a higher level of representation, where surface layout has been analyzed.

COPs can serve as an occlusion cue because the penetration of one object by another generically leads to the creation of surface orientation discontinuities in 3-D (Beusmans et al 1987; Hoffman and Richards 1985). The smooth convex conicality of the bases of the spikes in figure 12a (see also Idesawa 1993) is a cue that they intersect a surface because, as proven in Tse and Albert (1998), the COP projected from the locus of intersection of two intersecting smooth closed surfaces generically has no first-order image discontinuities where it meets the occluding contour projected from the penetrating volume.⁽³⁾ In contrast, the concavity at the bases of the distal spikes is a cue that they are occluded by a surface because, as Hoffman and Richards (1985) have shown, first-order image discontinuities arise generically when one surface occludes another surface that is further in depth.

Note that the perceived curvature of the surface of the illusory volume can be made to seem 'bumpy' by changing the COP from the arc of an ellipse to some other curve, as in figure 12b. This follows because, on assuming a non-accidental view and intersection, only a volume whose planar cross-section is an ellipse (or circle) will give rise to a planar and elliptical locus of intersection. Simple geometry dictates that under orthographic projection only an ellipse will generically project onto an ellipse (of perhaps different aspect ratio). Thus, if either the penetrating surface deviates from this 'conicality' or the penetrated surface deviates from flatness, the orthographic image projection of

⁽³⁾ Claim from Tse and Albert (1998) is reproduced here for the reader's convenience: For points where the locus of intersection of two interpenetrating volumes meets the rim of either volume, the tangent lines of the projected contours will be identical.

Proof: Since the line of sight of the observer grazes the surface at all points on the rim, the eye of the observer lies in the tangent plane to the surface at rim points. Therefore, in the projection to the retinal image, the tangent plane at a rim point collapses to a line L, since the tangent plane is viewed 'edge on'. Consider a differentiable curve D on the surface passing through a rim point R. The tangent line to D at R must project either to L, or to a single image point on L. In the latter case the tangent line coincides with the observer's line of sight, implying that the observer has an accidental view. It follows that the tangents to two such curves D1 and D2 on the surface which intersect at R will both project onto L in the image, assuming a generic view. Since the locus of intersection of two smooth surfaces is a smooth curve contained in both surfaces, any junction of that locus with the differentiable curve specified by the rim itself will not generically project first-order discontinuities onto the retinal image (page 457).

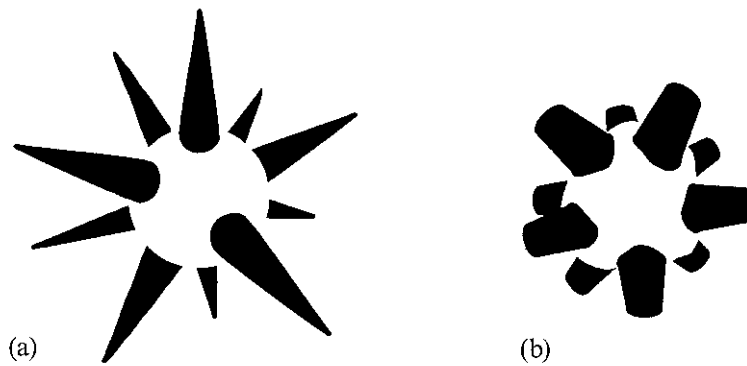


Figure 12. The illusion of a sphere in (a) is induced by the rounded COPs of the spikes. In case (b), the induced surface appears 'bumpy' because the contours of penetration are irregularly curved.

the locus of intersection (ie the COP) will not be an ellipse or an arc of an ellipse. There will therefore be places along the COP that appear irregular. These places will indicate either a deviation from flatness of the penetrated surface or a deviation from conicality of the penetrating surface.

Thus, the contour curvature of a COP is a cue to both the surface curvature of the penetrating surface and that of the penetrated surface, because a COP is projected from a locus of intersection that lies on both surfaces. If a COP has regions of rapid curvature change, then either the penetrating surface, the penetrated surface, or both may be perceived to have 'bumps' and 'dents'. This does not mean, however, that the visual system calculates a precise value of surface curvature using the COP. For example, in figure 13 volume A appears to penetrate and amodally complete through volume B. Note that the locus of intersection cannot be planar or elliptical given the irregularity of the COP that it projects (indicated by arrows in figure 13). This, however, does not mean that A is not cylindrical or conical in the vicinity of the locus of intersection. The irregularity of the COP might be entirely due to the bumpy surface of B. Or, it might be due to bumps on the surface of A. Moreover, the point where the COP begins and the occluding contour of A ends is not specified precisely by the information in the image. Since there are many combinations of A's surface curvature and B's surface curvature that could give rise to a given irregular COP, a solution to the problem of recovering surface curvature is underdetermined. Interestingly, the unspecifiability of surface curvature does not keep the visual system from completing A amodally through B. This implies that amodal completion can take place in the absence of a precise representation of surface orientation and layout. It seems that the visual system simply settles for less than a perfect representation of surface orientation and layout, and that this fact is not normally noticed by us.

The notion that the visual system does not calculate a precise map of surface orientations is an important one supported by the work of several recent authors (eg Koenderink et al 1992, 1994, 1995, 1996; Reichel et al 1995; Todd and Norman 1995). Todd and Norman (1995) conclude that our representation of 3-D structure is not metrical, insofar as relative depth and surface orientation are not precisely represented by the visual system. What then can account for our phenomenal impression that the

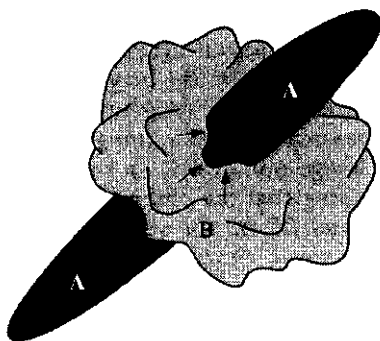


Figure 13. Note that A appears to amodally complete through B even though the contour of penetration fails to specify a precise surface curvature for either A or B. The arrows indicate the irregular contour of penetration in the image.

surfaces of A or B in figure 13 have definite surface orientations that vary smoothly over the surface? One possibility raised by Todd and Norman (1995) is that surface smoothness is conveyed by other properties, such as smooth variations of shading, texture, motion, or disparity. Another possibility is the notion that 'an ambiguous representation is not the same as a representation of ambiguity'. We simply may not represent surface geometry metrically, and so do not notice information that is 'missing'. That is, we may not notice the ambiguity in our representations of depth and surface orientation because surfaces have definite layout in the world. This allows us to gather more precise information about surface layout when we need it without having to represent it explicitly or precisely (compare O'Regan 1992).

7 COPs and volume formation

As a final example of illusory-volume formation based on the COP conformation cue, figure 14 shows a case where COPs are a strong cue to surface penetration and occlusion. All subjects tested reported seeing a 'sea monster' ($n = 10$). Note that any single one of the sea monster's three fragments viewed in isolation would not induce a strong percept of volume or of an illusory 'water' surface. Taken together, however, these fragments not only generate an illusory water surface at a particular slant relative to the viewer, they also tell us about the sea monster's tubular form. This is an instance where there is completion in spite of the fact that there are none of the traditional cues necessary for amodal surface completion. There are no traditional surface-based cues indicating that the sea monster's discrete visible portions link up under an illusory water surface. There is no good continuation or 'relatability' between contours that link (Kellman and Shipley 1991) and there is no explicit occluding surface creating unbounded surfaces (eg Nakayama et al 1989, 1995). In order for there to be amodal completion, the individual portions must be seen as potential parts of a larger volume. Indeed, only as 'potential volumes' (ie volumes that are consistent with image cues) could the parts then complete into a volume. If the parts were just considered to be potential flat surfaces, they would not complete at all since there are no traditional surface cues to completion. The possibility of occlusion by 'water' can only be considered once the COPs are taken as cues to discontinuities in surface orientation. That is, occlusion can only be entertained at a level where potential volumes consistent with image cues are considered (Tse 1998a).

Note that the interpolated water surface can stay the same, as in figure 15, even when the left-hand COP belonging to the middle segment is lowered substantially in the visual field. The interpolated water surface seems to have to do more with the curvature of the COP than its location. The interpolated water surface is quite different from the surfaces that are interpolated in traditional displays such as the Kanizsa rectangle of figure 1 because the water surface is unbounded. Indeed, it seems to be a slanted ground plane that is generated in the absence of any texture cues.



Figure 14. A sea monster.



Figure 15. The induced water surface remains the same as in figure 14 even though the left side of the central portion of the sea monster has been extended downward.

8 Illusory volumes and illusory contours

Figures 16a and 16b are bistable figures like the Necker cube. Under one interpretation one can see an illusory pole surrounded by partially occluded black rings. In this case, which most observers perceive first, the pole is specified by illusory contours that seem to pass under the portions of the black rings in the foreground. Presumably we see an illusory pole rather than a flat illusory rectangle because the curvature of the black rings is attributed to the underlying surface curvature of the pole as predicted by the assumption of conformation. For this reason the pole in figure 16a appears to have an approximately circular cross-section, whereas the pole in figure 16b appears to have a squarish cross-section. The illusory contours seen here are difficult to account for in terms of lateral interactions among similarly oriented contour-tuned cells that respond to contours in the image, as posited in current theories of illusory-contour formation (Field et al 1993; Grossberg and Mingolla 1985a, 1985b). It would seem that illusory contours must be generated after surface layout and occlusion relationships have been analyzed. This point is made more strongly when we consider the alternate perceptual interpretation of figures 16a and 16b. If the depth of each ring is reversed, so that the gap now lies toward rather than away from the reader, the illusory pole disappears, and we are left with a percept of a floating column of rings or 'bracelets' with a gap in front. Remarkably, with the disappearance of the occluding-pole interpretation, the illusory contours also disappear. Thus illusory-contour formation does not precede depth assignment and volume formation. Illusory contours are not derived directly or automatically from image cues such as similarly oriented lines or aligned line terminators.

Illusions such as the Kanizsa rectangle (figure 1) are important because of what they might reveal about the mechanisms underlying contour and surface interpolation. Kanizsa emphasized the enhanced brightness of his illusory figures, their illusory borders, and their depth segregation. While emphasis has traditionally been placed on the formation of illusory contours, several authors have argued that illusory contours may merely be a by-product of surface formation (Brady and Grimson 1981; Kellman and Shipley 1991; Petry and Meyer 1986). It is often assumed on the basis of examples such as the Kanizsa rectangle that illusory-surface formation and illusory-contour formation go hand in hand. However, figure 17 shows that illusory contours are neither necessary nor sufficient for the formation of an illusory volume. Figure 17a shows an illusory volume where the modally completing white surfaces of the volume do not seem to have well-specified illusory contours where they meet the white background. Here, modal surface completion seems to take place not because of good contour continuation, but because the black regions correspond to surfaces of a single object that conform to one another. Conversely, figure 17b is an example where a clear illusory contour forms in the absence of surface or volume formation, or occlusion (compare Purghé 1995). Thus, volume formation and illusory-contour formation are independent; neither is necessary nor sufficient for the formation of the other.

9 Conformation as a bottom-up cue to amodal completion

A distinction is usually made between top-down and bottom-up contributions to perception. The top-down contribution comes from knowledge about the world and the influences of attentional modulation. The bottom-up contribution, on the other hand, is entirely stimulus driven, and derives higher-order representations from a succession of largely automatic information-processing stages. Early stages of visual perception are concerned with detection of key features and invariants in the image that succeeding stages of processing can then use as input. In this framework, the front end of the visual system is imagined to be based on various 'filters'. The filter approach finds strong support in the receptive-field tuning properties of early neurons. Recently it has become clear, however, that there are aspects of vision that are not likely to be reducible

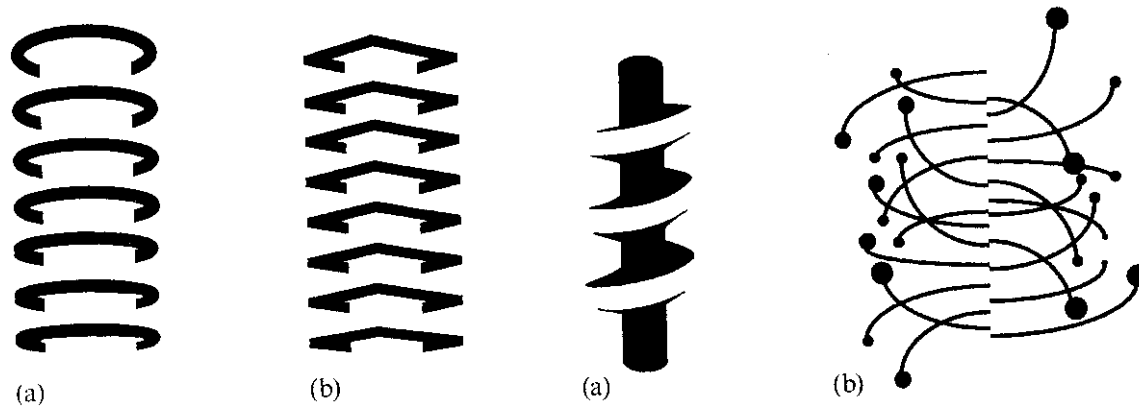


Figure 16. (a) A reversible figure. Under one interpretation an illusory pole is surrounded by rings. Note that the illusory contours of the illusory volume complete under the inducers. However, if the gaps in the rings are brought to the front, the illusory contours disappear, and one sees a column of 'bracelets' with the gaps in front. (b) A similar reversible figure with square rings. Note that under the illusory-pole interpretation the pole in (a) appears to have a round cross-section and the pole in (b) appears to have a rectangular cross-section.

Figure 17. (a) A modally completing screw generated by the conforming shapes of the black regions. Note the extreme weakness if not the entire lack of illusory contours here. (b) A strong illusory contour generated without illusory surface or volume formation.

to the responses of filters. In particular, the visual system appears to construct internal representations, such as surfaces (Nakayama et al 1989) and volumes (Tse 1998a), from initial filter outputs. These 'mid-level' representations may be taken as input by attention and other higher-order processes (He and Nakayama 1992, 1994).

It is possible that mid-level representations such as volumes may themselves be generated in an entirely bottom-up fashion. For example, in the model proposed by Tse (1998a), volume formation begins with the formation of 'potential volumes' that could have given rise to local image cues to volume. These primitives then mutually constrain one another in order to generate maximally closed curved surfaces or volumes. Since we regularly perceive the 3-D form of unfamiliar objects, volume completion must be a primarily bottom-up process that is not dependent on object knowledge. Several authors (Gerbino and Salmaso 1987; He and Nakayama 1992, 1994; Sekuler and Palmer 1992; Shimojo and Nakayama 1990) have offered evidence that occluded parts of an object are represented rapidly, before they could be subject to top-down or attentional processing. Kanizsa (1979) offered several demonstrations that amodal completion can occur in a stimulus-driven manner. For example, he showed that a horse could appear elongated, even though we know cognitively that a horse could not really be that long, as shown in figure 18. The same point can be made for curved and closed surfaces, as demonstrated here with an elongated cat. Conformation can therefore act as a bottom-up cue that overrides object knowledge, which suggests that volume formation and amodal completion are primarily stimulus-driven processes.

10 Conformation and top-down influences in volume formation

Conformation can be exploited to show that there are top-down contributions to volume formation as well. It is commonly pointed out that attending to one aspect of an image versus another can alter the perceived organization of the whole image. This point is often made with the use of the famous Rubin (1915/1958) face-vase (figure 19). Attending to the faces turns them into figure, and the rest into ground. Once the faces are figure they come to 'own' the ambiguous border between the faces and the vase.

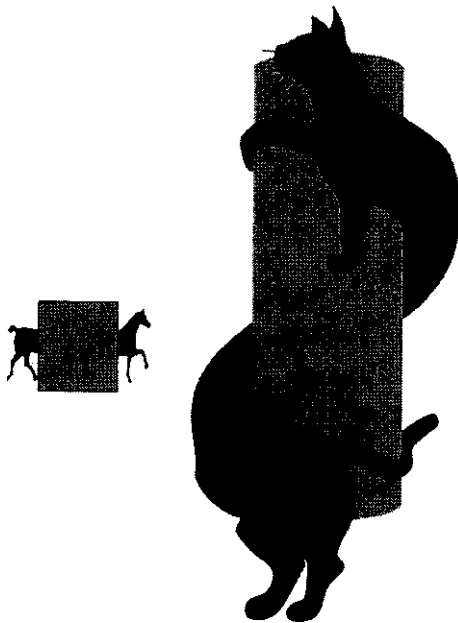


Figure 18. Kanizsa used an 'elongated horse' to make the point that amodal completion can override object knowledge. The same point can be made for the volume realm with an 'elongated cat'.

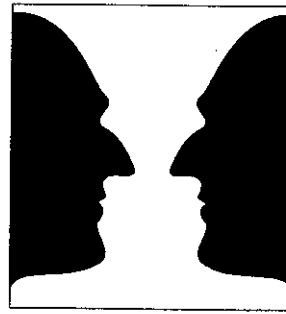


Figure 19. The Rubin face-vase.

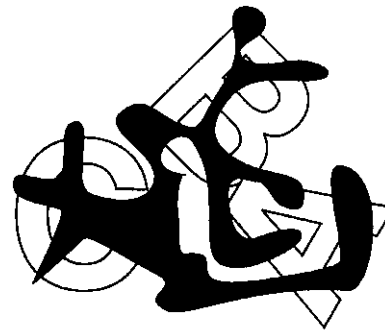


Figure 20. Amodal completion of some letters.

Border ownership is a key factor in determining surface-occlusion relationships (Nakayama et al 1989; Nakayama and Shimojo 1992). With no accidental alignment of surface edges, the border between two image regions can only project from or belong to one of those surfaces. The surface that owns the border is taken to occlude the surface that does not own the border. The occluded surface can then continue behind the occluding surface and link up with other occluded surfaces because it is 'unbounded' on the side where it does not own its border.

What does it mean to be a figure? Is a figure a surface, a volume, or even a (recognized) object? A figure can probably be any of these things depending on the stimuli used. However, all figures may have some attributes in common. One characteristic of a figure in traditional displays, like the Rubin face-vase, is that a figure tends to have maximally closed borders. Thus, in a traditional amodal completion display, we can make a figure out of an amodally completing object by attending to it. Even though all its borders are not visible in the image, upon amodal completion borders tend to close up. For example, when we attend to the occluded letters in figure 20, they seem to have closed borders even though those borders are partially occluded. There therefore seems to be a tendency for the visual system to attain a level of representation where borders are closed, at least for attended regions. But closed borders might just indicate a collection of overlapping flat surface patches that do not close into volumes.

In less 'flat' displays, attaining closed borders may not be possible. For example, how would borders be closed in figure 21? Since any contours that might link together are occluded by the object itself, closure is only possible at the higher level of representation of surfaces. At this level, a figure has a closed surface (and is therefore a volume). As argued elsewhere, surfaces may undergo maximal closure as part of the process of volume formation (Tse 1998a). In the volume domain, a figure owns image borders that correspond to the rim (or edge) of a surface. This follows intuitively because a surface can only belong to a single volume at a time.

In figure 22—a volumetric generalization of Rubin's face-vase—the central pattern can be seen as a wine glass (left) in front of a black region, or as a black worm

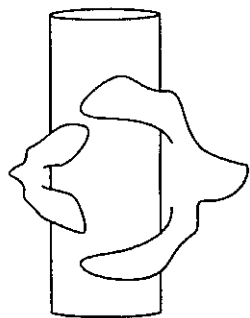


Figure 21. Amodal completion in the absence of closable borders.

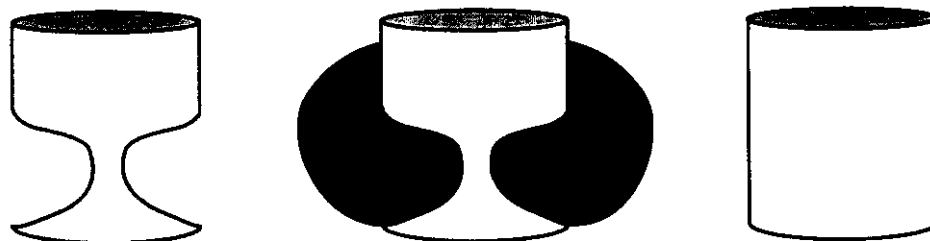


Figure 22. The center figure can be seen either as a wine glass in front of a black background or as a black worm wrapped around a white cylinder.

conforming around a cylinder (right). If the wine glass is attended and made into the figure, it owns the ambiguous image borders. These correspond to rim points from which the surface of the wine glass can be interpolated. Attending to the worm, conversely, eliminates the possibility of a wine glass (assuming no accidental alignment of surfaces in the world), because there is now no surface available to support the wine-glass interpretation. Another example of this can be seen in figure 23, where an octopus can be seen clinging to a rock. If the octopus is in front, it is white and the rock is gray. If the octopus is clinging from behind, it is gray and the rock is white. Finally, figure 24 shows an example that can be interpreted either as a woman holding a sack, or a 'seal' clinging to a buoy.

Note that both ways of seeing the image involve amodal completion. Which case is seen depends on 'mental set' or how one attends to the image. Amodal completion and volume formation are therefore not entirely preattentive or cognitively impenetrable processes.

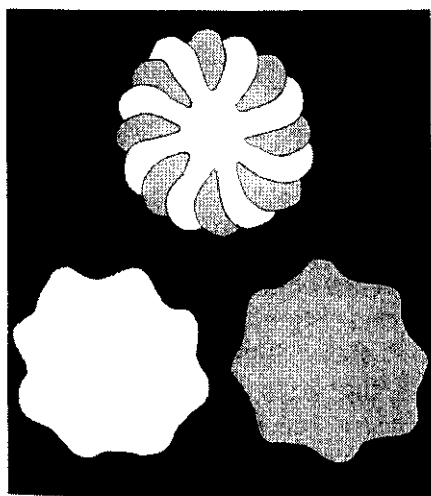


Figure 23. Is the octopus hugging the gray rock or the white rock?

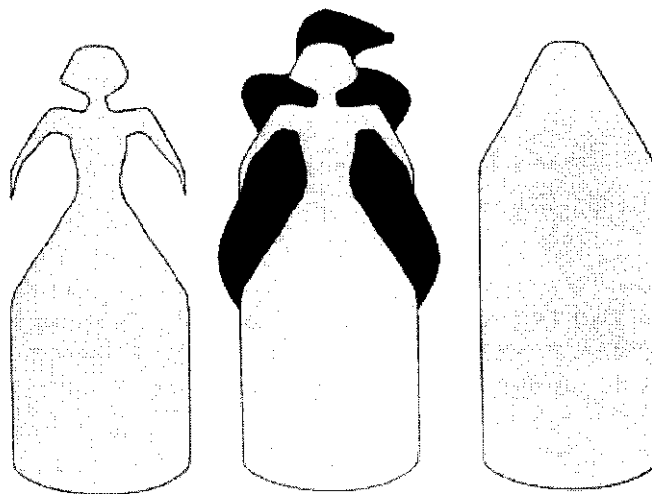


Figure 24. This can be seen as a woman holding a large sack or as a seal hugging a large buoy or missile.

11 Discussion

Unlike Kanizsa's illusory rectangle, the illusory surfaces demonstrated here seem to be closed surfaces with a definite inside and spatial extent. Since a volume, by definition, is a surface plus the inside that it encloses, these are examples of illusory volumes rather than illusory surfaces. This paper has offered some examples where illusory volumes were generated by exploiting the visual system's assumption of conformation. Like the Kanizsa rectangle, these illusory figures may reveal certain inferences that the visual system makes when constructing a percept based on ambiguous image cues. More specifically, the following several insights into the nature of visual processing have emerged as a consequence of using conformation as a cue to constructing illusory volumes:

(i) Conformation (as revealed by visible contour relationships in the image) is a sufficient 'cue' to surface and volume formation for the same reason that surface contours are a sufficient cue. It appears that the visual system assumes that the overall curvature of the surface of a volume is not in excess of the curvature of the surface that appears to support or underlie it, in the absence of image evidence to the contrary.

(ii) Conformation is not a 'direct' image cue to volume, because image cues must be processed up to a level where surface layout is analyzed before conformation can play a role in generating illusory volumes. Thus illusory volumes are not generated directly or piecemeal from local image cues, but are constructed 'holistically' in the context of global cues to surface curvature and closure. Indeed, as figure 14 makes clear, potential 3-D volumetric forms must be considered before the pieces of the sea monster can link up behind an illusory water surface. They could not link up as flat surface fragments because there is no occluder specified in the image behind which those flat surface fragments could link.

(iii) Similarly, analysis of occlusion relationships does not take place before an analysis of surface layout, at least for these types of images. This follows because COPs, unlike T-junctions or discontinuities in the first derivative taken along the image contour, cannot be thought of as image features. Rather, they indicate occlusion at a higher level of representation, where surface tangent discontinuities and closure into volumes come into play.

(iv) Amodal completion can take place even when a precise specification of surface orientation and layout is impossible in principle. Thus, completion processes do not require a precise representation of surface curvature (see discussion of figure 13).

(v) Illusory-contour formation does not proceed independently of depth assignment or volume formation. Thus, illusory contours are not derived automatically from image cues such as similarly oriented lines or aligned line terminators (see discussion of figure 16). Moreover, volume formation and illusory-contour formation are independent (see discussion of figure 17).

(vi) Rubin's (1915/1958) face-vase drawing implied that figure formation involves attention, and that what is attended as figure comes to own all its borders, whereas the relatively unattended ground does not own its image borders with the figural region. In this paper a new class of drawings (figures 22, 23, and 24) has been introduced that generalizes Rubin's insight to the realm of volumes. Reversible volumes provide evidence that a figure in the 3-D realm is not typically a flat surface that owns all its edges, but rather a volume that owns all its surfaces. More precisely, a figure owns image borders that correspond to rim points from which surfaces, especially closed surfaces, can be interpolated. In this domain, changing the figure-ground relationship entails a change in occlusion relationships and even the shapes of the completed volumes. These demonstrations therefore provide evidence that volume formation and completion phenomena are not entirely stimulus-driven or preattentive processes.

12 Conclusion

Illusory volumes and image cues that exploit the visual system's assumption of conformation have revealed some interesting things about the inferential nature of visual processing. In particular, the visual system does not appear to calculate local surface orientation, illusory contours, or occlusion relationships before it analyzes global potential volume relationships. Rather, the visual system comes up with a 3-D scene interpretation based on multiple ambiguous image cues sampled globally across the image. These image cues may be consistent with many potential volumes which can then constrain one another globally in the process of 3-D scene interpretation. Interpretations are further constrained by top-down processing and various priors, such as the assumption of conformation. Therefore a simple feedforward or bottom-up account of local interactions among, for example, similarly oriented line terminators or image contours cannot account for the emergence of a volume percept, amodal or modal completion, or illusory-contour formation. Analyses of visual processing that acknowledge the importance of global interactions, prior assumptions, and top-down constraints in the construction of a percept are essential.

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