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The role of surface attraction in perceiving volumetric shape

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Abstract. Rock [1973, *Orientation and Form* (New York: Academic Press)] showed that form perception generally depends more on the orientation of a stimulus in world coordinates than on its orientation in retinal coordinates. He suggested that the assignment of an object's 'environmental orientation' depends on gravity, visual frame of reference, and the observer's ability to impose orientation along one axis or another. This paper shows that the assignment of environmental orientation and perceived 3-D form also depends on the relationship between an object and retinally adjacent surfaces in the scene to which it might be attached. Whereas previous examples have demonstrated effects of orientation on 2-D form, we show that orientation can affect the perceived intrinsic 3-D shape of a volume.

1 Orientation and form

This paper makes two contributions to the literature on the effect of orientation on form perception. First, most previous studies have investigated the effect of stimulus orientation on 2-D form perception (eg Humphreys 1983; Palmer 1980, 1985; Palmer and Bucher 1981, 1982; Rock 1973). For example, Goldmeier (1937) showed that a square has a different phenomenal 2-D shape than a diamond, even though these stimuli differ only by a rotation in the image plane. In contrast, we investigate here the effect of stimulus orientation on the perception of 3-D volumetric shape.

Second, Kopfermann (1930) showed that phenomenal shape is also influenced by the geometrical relationship between a figure and its spatial context (see also Goldmeier 1937; Koffka 1935, page 185; Palmer 1983, 1985; Rock 1973). For example, a 'diamond' can be perceived as a tilted square when it is embedded in a tilted rectangle (see figure 1). In this paper we show that the 3-D shape seen in a silhouette depends on the orientation of the silhouette relative to the 3-D surfaces with which it has optical contact (ie the surfaces to which it is adjacent in the retinal image). For example, the 3-D shape seen

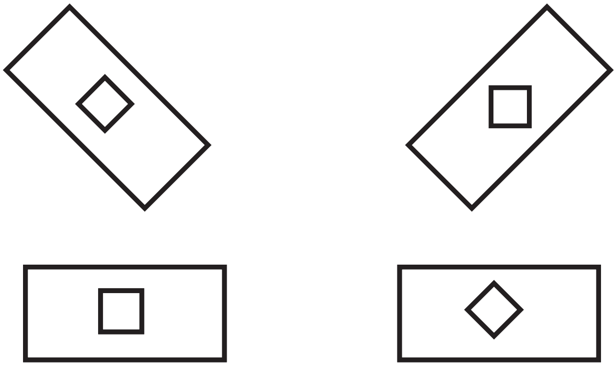

Figure 1. Note that the inner shapes are seen as diamonds or squares depending on the context provided by the surrounding rectangles (after Kopfermann 1930).

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in a silhouette whose basal contour is in optical contact with a 'ground' surface will generally appear to attach and conform to that surface along that contour.

When an object is rotated in the world, several factors change at once: First, the retinal projection of the object is rotated; second, the object is rotated relative to gravity; and third, the object is rotated relative to the global visual frame of reference (such as the walls of a room). The first factor will be called 'retinal orientation', whereas the latter two jointly determine 'environmental orientation', according to Rock (1973). Thus, an object's environmental orientation is determined by the axis or direction in the environment that best specifies the top and bottom of the object in that context. Rock (1973) gives evidence that, for most stimuli, it is environmental orientation that determines phenomenal form, rather than retinal orientation.

2 Surface formation, attraction, and conformation

Albert (1995, 1999) suggested that perceptual 3-D objects tend to be 'attracted' to other perceptual surfaces, such as ground surfaces, even in the absence of other explicit evidence for these surfaces. This tendency can affect the perceived relative depths of objects in 3-D scenes. For example, a simple line-drawing containing a few properly placed cubes can induce an 'illusory' ground plane on which the cubes appear to rest (also see Gibson 1950, 1979).

In figure 2 the front and bottom faces of the two blocks appear to be roughly coplanar and at the same depth, as if they were resting on a common ground plane. However, when figure 2 is rotated by 90° counterclockwise the perceived relative depths of the blocks change dramatically (Albert 1995; also see Jepson and Richards 1993). Now the smaller block appears to sit in front of the larger block. In this orientation, attachment of both blocks to a common ground plane would require the large block to be seen as much farther away than the small block. Perhaps the visual system is unwilling to infer such a large depth difference without more evidence. Yet the large block *does* appear substantially further away (relative to the small block) than it did in the original orientation, suggesting that it is being 'attracted' to a potential ground surface. In fact, most observers report one of the following three percepts: (i) the front face of the large block appears to be roughly coplanar with the rear face of the small block, (ii) the bottom face of the large block appears to be roughly coplanar with the top face of the small block, or (iii) some intermediate percept between (i) and (ii). In addition, if figure 2 is rotated clockwise rather than counterclockwise, then the perceived depth difference between the blocks is diminished, suggesting that attraction to an inferred ground plane enhances the perceived depth in the case of counterclockwise rotation.

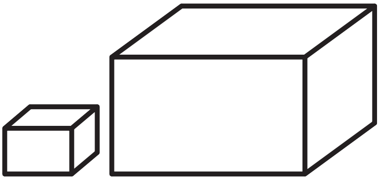


Figure 2. For most observers the perceived relative depth of these blocks is somewhat multistable, and the preferred 3-D arrangement depends on the orientation of the figure. However, most of the perceived 3-D arrangements are such that some pairs of faces of the blocks (one on each block) are perceived to be roughly coplanar in 3-D. See text for further details.

The surface attraction hypothesis suggests that a silhouette perceived as a volume should tend to attach and conform to other surfaces in the scene with which it is in optical contact. This may be an adaptive heuristic designed to favor 'physically stable' interpretations of sparse or ambiguous stimuli. Albert (1995) suggested that this tendency may result from relatively automatic processes of surface formation, rather than from higher-level inferences based on a strictly obeyed physical stability constraint.

For example, in figure 3 most observers perceive the circles that are close to the front face of the cube as coplanar with that face, and those that are close to the rear face of the

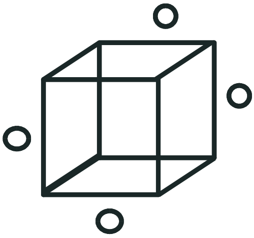


Figure 3

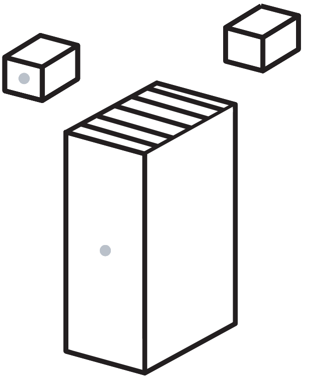


Figure 4

Figure 3. Each of the circles around the Necker cube appears to be coplanar with either the front or the rear face of the cube. The circles that are close to an edge belonging to the front face of the cube appear coplanar with the front face. Those that are close to an edge belonging to the rear face of the cube appear coplanar with the rear face.

Figure 4. The bottom faces of the small blocks appear to be approximately coplanar with the top of the big block. This is not readily explained by the hypothesis that human vision uses a constraint of physical stability (Albert 1999).

cube as coplanar with the rear face (Albert 1999). However, since these faces of the cube are not perceived to extend beyond the edges of the cube, the coplanarity of the circles with these faces cannot be explained by a physical stability constraint. Similarly, in figure 4 the bottom faces of the small blocks appear to be approximately coplanar with the top face of the big block. However, the top face of the big block does not appear to extend out into 3-D space in such a way that it could be in physical contact with the small blocks. Nor do all three blocks appear to rest on a common 'ground' plane.

Albert suggested that the mechanisms underlying surface formation and attachment in these displays might be related to those that underlie surface formation and attachment phenomena in stereopsis (Mitchison and McKee 1985) and structure-from-motion (Hildreth et al 1995). Surface formation mechanisms in those domains are generally believed to be relatively low-level and automatic. On the other hand, we do not believe that surface formation effects in our stimuli are completely cognitively insulated either. Kanizsa's (1955) illusory figures are widely believed to be mediated partly by low-level mechanisms (von der Heydt et al 1984), and partly by higher-level visual and cognitive factors (Albert and Hoffman 2000; Hoffman 1998; Petry and Meyer 1987). Perhaps the surface formation, attraction, and conformation phenomena presented in this paper are also mediated at multiple processing levels.

3 The present study

In this paper we investigate the role of surface formation and attraction on the perception of 3-D volumes from silhouettes. A volume is a connected region of 3-D space enclosed by a surface (Tse 1999). The stimuli that will be tested in experiment 1 are shown in figures 5 and 6. To most naïve observers the phenomenal 3-D forms of these two 'rocks' resting on the ground surface are very different, as shown below. Figure 5 tends to be perceived as having a 3-D form similar to figure 7, whereas figure 6 is generally perceived as similar to figure 8. However, the silhouettes of the rocks shown in figures 5 and 6 are identical except for a 90° rotation in the image plane.

The effects of orientation on 3-D volumetric form (eg figures 5 and 6) are different, and perhaps more dramatic than the well-known 2-D effects (eg figure 1). In the 2-D case these effects may have more to do with the coordinate systems used to describe

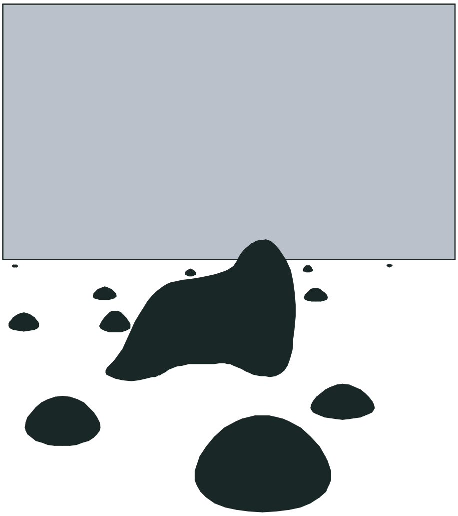


Figure 5. A 'rock'. The bottom contour of the 'rock' appears to arch away from the observer in the middle, adhering to the illusory orientation of the 'ground' surface. This makes the 'rock' appear somewhat concave in the middle.

the figures, rather than with the *intrinsic shapes* of the figures. For example, if a square and a diamond are each described in relation to their vertical axis of symmetry, then different figural *descriptions* would result. However, most observers would agree that each figure can also be described as "a four-sided polygon with all sides of equal length and all angles of equal size", suggesting that the two figures are perceived to have the same internal geometry. On the other hand, for most observers the intrinsic 3-D geometry of the 'rock' perceived in figure 5 appears to be quite different from that in figure 6. In other words, no imaginary 3-D rotation of the rock seen in figure 5 would allow it to be 'superimposed' (in a 3-D sense) on the rock seen in figure 6. Of course, some observers do see the rocks in figures 5 and 6 as having the same intrinsic 3-D shape. However, as reported below, in a between-subjects design, naïve observers shown figure 5 generally prefer the shape depicted in figure 7, whereas those shown figure 6 generally prefer the shape depicted in figure 8.

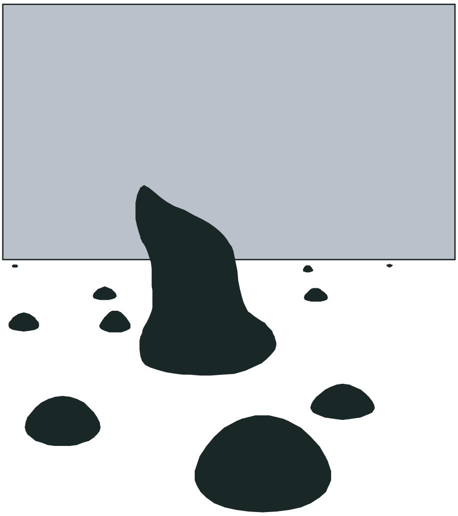


Figure 6. The same silhouette and surrounding scene as in figure 5, except that the silhouette of the 'rock' has been rotated 90° clockwise. For most observers the perceived intrinsic shape of the 'rock' is quite different here than in figure 5. The bottom contour appears to bulge towards the observer in the middle. The corresponding contour in figure 5 (the contour on the right) does not bulge forward in the middle to the same degree, if at all. Similarly the contour on the left in figure 6 does not appear to arch away from the observer in the middle to the same degree as the corresponding contour in figure 5 (the basal contour).

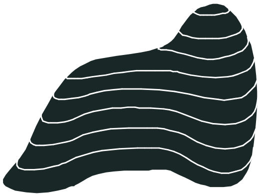


Figure 7

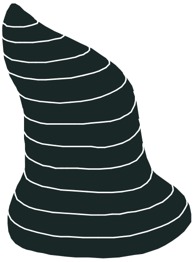


Figure 8

Figure 7. 'Surface contours' drawn on the 'rock' of figure 5 to illustrate the phenomenal shape reported by most observers.

Figure 8. 'Surface contours' drawn on the 'rock' of figure 6 to illustrate the phenomenal shape reported by most observers. Note that this shape is *intrinsically* different from the one in figure 7. In other words, no imaginary 3-D rotation of the 'rock' in figure 7 could allow it to be 'superimposed', in a 3-D sense, on the 'rock' in figure 8. In contrast, the shape changes seen in figures 1 and 2 may be primarily due to differences in the coordinate systems that the visual system uses to describe them.

3.1 *Stimuli*

Simple silhouettes that create the impression of volume were used. This eliminated effects of other cues to 3-D form perception such as texture gradients, linear perspective, patterns of shading, and shadows. All stimuli were static achromatic pictures presented on paper and were freely viewed by the observers.

3.2 *Observers*

Sophisticated observers can change the assignment of environmental orientation or the top – bottom object axis at will. For example, one can will to see a diamond (whose top is the uppermost vertex) to be a square that is tilted 45° (whose top is now one of the upper sides of the diamond). Similarly the set of equilateral triangles shown in figure 9 can be seen to be pointing in any of the three directions defined by the vertices and natural axes of symmetry (Attneave 1968; Palmer 1980; Palmer and Bucher 1981, 1982). Because of this ability to bias axis assignment with experience or will, the experiments reported here used naïve observers, each of whom made only a single perceptual judgment.

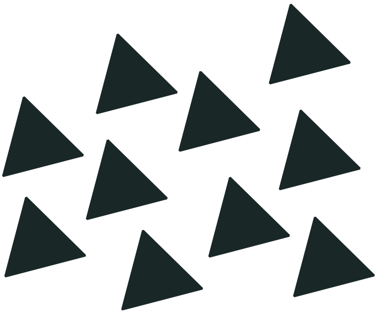


Figure 9. There are three possible directions in which these triangles could be seen as 'pointing'. The direction closest to the vertical axis appears to be preferred. Note that at a given time, all triangles tend to point in the same direction (after Palmer 1980).

3.3 *Method*

The experimenter sat at a table in the entrance hallway to the Psychology building at Harvard, and asked passers-by between the ages of approximately 17 and 70 (who had no knowledge of the purpose of the experiment) if they would participate in a "thirty-second experiment" without remuneration. Each observer in experiment 1 was shown either figure 5 or figure 6. Each observer in experiment 2 was shown either figure 13 or figure 14.

The experimenter pointed to the target silhouette in the stimulus. The observer's task was to report which parts of the boundary of this silhouette appeared to be regions where the surface of the perceived 3-D blob was *gradually* changing its orientation, curving away from the observer (as along the sides of a cylinder). This was to be contrasted with regions where the surface appeared to be *abruptly* changing its orientation (as along the top or bottom edges of a cylinder), or regions where the 3-D surface did not appear to be curving away from the observer at all (as along the bottom contour of a pole penetrating into the ground). The experimenter used a small 'espresso' cup to illustrate these concepts to the observer.

The experimenter then presented the observer with two roughly pear-sized clay models, one of which was molded to correspond to the object seen in figure 7, and the other molded to the object seen in figure 8. Both models were viewed by the observer from an angle such that the projected retinal contours approximated those of the target silhouettes in the stimulus. The left/right order of the models was pseudo-randomized across trials. To reinforce the surface curvature concepts presented earlier, the experimenter indicated the parts of the rim on each model where surface orientation was changing smoothly or abruptly, as had been done with the espresso cup. Our dependent variable was the observer's response as to which clay model best matched the qualitative 3-D shape and surface curvature he/she perceived in the target silhouette. Each observer made a judgment about only one stimulus.

The instructions to observers in these experiments emphasized the perceived qualitative 3-D shape and surface curvature along the rim. In an earlier pilot study observers were simply asked to report which clay model was 'most similar' to their perception of the silhouette. Unfortunately, debriefing indicated that observers were often using metrical criteria to compare the models to the stimulus. These criteria were irrelevant to the qualitative 3-D shape differences we were trying to measure. For example, observers would sometimes say that they chose a particular model because the other model appeared a little taller or shorter than the silhouette in the stimulus. The clay models (which were formed by hand) projected metrically similar, but not identical, retinal contours to those projected by the target silhouettes. However, since the perceived surface curvature along the rim is sufficient to discriminate between the different 3-D shape percepts, the protocol described above seemed well-suited to testing our hypothesis.

4 Experiment 1: Form perception in a matching task

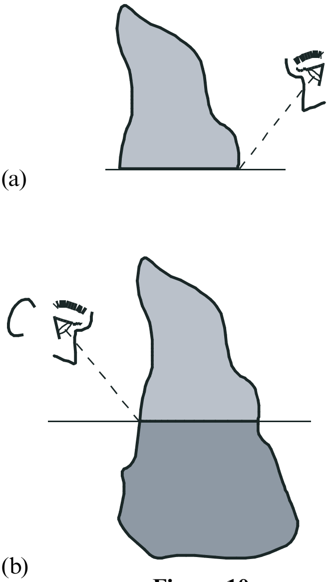
In this experiment observers were asked to select the clay model that best matched their 3-D shape percept of the target silhouette.

4.1 *Results*

For figure 5, 18 out of 22 observers (82%) selected the model corresponding to figure 7. For figure 6, 21 of 22 observers (95%) selected the model corresponding to figure 8. Thus 39 of 44 observers (89%) perceived the 3-D shape suggested by attraction of the basal contours of the blobs to the 'ground' surface ($p = 7.0258 \times 10^{-8}$ by the binomial test).

4.2 *Discussion*

The results of experiment 1 show that 3-D shape perception can be influenced by optical contact between an object's basal contour and an inferred ground surface on which it might be resting. If the object is assumed to lie flat on the ground, then each point along its basal contour must have the same depth as its point of optical contact with the ground. Consequently, the basal contour of the 'rock' appears to be concave in figure 5 and convex in figure 6 (see figure 10a). Similar considerations apply under the interpretation that the rock is erupting from below, like the tip of an iceberg jutting out of the ocean's surface (see figure 10b). This shape information along the basal contour seems to 'propagate' across the entire surface of the rock (see also Tse 2000).



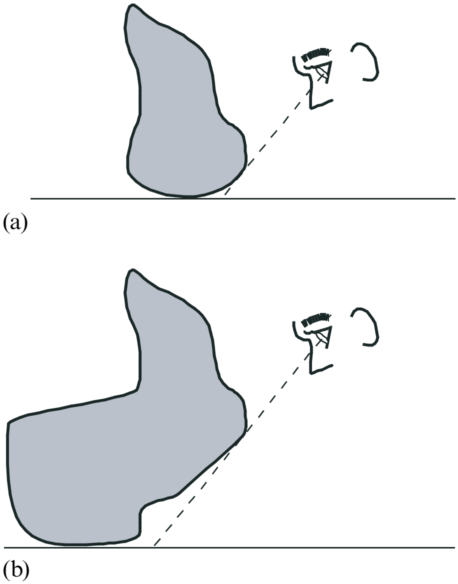


Figure 10 **Figure 11**

Figure 10. Attachment of the basal contour to the ground surface in figure 6 does not determine whether (a) the 'rock' has an abrupt change in surface orientation, with the ground surface continuing smoothly underneath it, or (b) the ground plane has the abrupt change in surface orientation, with the surface of the rock continuing smoothly down into the ground (like the tip of an iceberg jutting out of the ocean). Similarly for figure 5.

Figure 11. If the basal contour is not seen as attached to the ground surface, it could be seen as (a) very near the ground surface or (b) considerably above the ground surface. An ecological explanation why interpretation (a) might be preferred to (b) is that (a) is a more physically stable interpretation than (b); ie the rock in (b) could be easily knocked over by an outside force, so it would be unlikely to be seen in that orientation very often.

On the basis of ecological considerations Tse and Albert (1998) proposed that vision can segment the boundary of a silhouette at points of abrupt change in its contour curvature. This carves out the basal contour of the rock in figure 6 as one boundary segment. We suggest that attraction of this contour to the illusory 'ground' surface causes the percept of an abrupt change in the surface orientation of either the rock (as in figure 10a) or the ground surface (as in figure 10b) *before* the complete 3-D percept is constructed. Such contours may subsequently be more likely to 'propagate' shape information to the silhouette's interior. In addition, the *convexity* of a boundary segment may facilitate surface attachment and propagation of shape. This may explain why some observers in experiment 1 saw the percept in figure 8 when viewing figure 5.

In figure 10b the rock penetrates the ground, and the ground conforms to the surface of the rock. So the *ground* has a surface-orientation discontinuity where it meets the rock, and it 'owns' the basal contour of the silhouette, not the rock. Since this contour is the projection of a smooth curve conforming to the surface of the rock, it may function as a 'surface contour' for the rock (Knill 1992; Stevens 1981).

Under the interpretation of figure 6 shown in figure 11a, the basal contour of the rock is raised slightly above the ground surface, rather than attached to it. In this case the basal rim is not a locus of *discontinuity* in the surface orientation of the 'rock' (or the ground surface), but just a region of relatively high surface curvature.

Perhaps because there is no information in figure 6 about the shape of any possible 'hidden region' of the rock's surface lying between the basal rim and the ground surface (as shown in figure 11b), the visual system prefers the interpretations shown in figures 10a and 11a. It prefers to assume that this hidden region is very small, or nonexistent, rather than to 'guess' its shape (ie "no news is good news"; Grimson 1981). Ecological considerations based on physical stability also suggest that maximally conforming objects would be preferred (Tse 1998), since objects will generally be most stable when they maximally conform to the surfaces that support them.

Since it is not clear whether the rocks of figures 5 and 6 are perceived to have sharp edges along their bases (eg figure 10a) or just regions of very high surface curvature, it seems more accurate to speak of the visual system as having a tendency towards 'surface attraction' and conformation (Albert 1995; Tse 1998) rather than strict 'surface attachment'. This term also better captures how this tendency may interact with other visual and nonvisual information about shape, as discussed earlier in relation to figure 1. We propose that, in the absence of evidence to the contrary, perceptual objects will tend to rest upon, protrude from, or adhere to other objects and surfaces. Contrary evidence might include a shadow indicating that an object arches up from the ground surface, or an observer's prior knowledge and experience. For example, an observer who had previously seen figure 6 might interpret figure 5 as a "Hershey's kiss" lying on its side with its basal contour arching up from the ground surface.

There are many examples (eg Koenderink 1984) where a silhouette is seen as a volume that touches the ground surface only along a line or a point (see figure 12). For example, when the 'bump' silhouette in figure 12 is rotated by 180° a 'bowl' can be seen, although the bowl may appear less compelling than the bump. (Note that surface attraction favors a relatively flat object on the ground, or even a hole in this case.) The 'bump' was constructed by gluing two half-ellipses with different eccentricities together, with the lower half having greater eccentricity than the upper half. The boundary of this silhouette has curvature discontinuities at the two points where the half-ellipses meet. Compare this with the flat appearance of the 'pancake' silhouette in this figure. The pancake (or ellipsoid) has no curvature discontinuities, since it is just a single ellipse (Tse and Albert 1998).

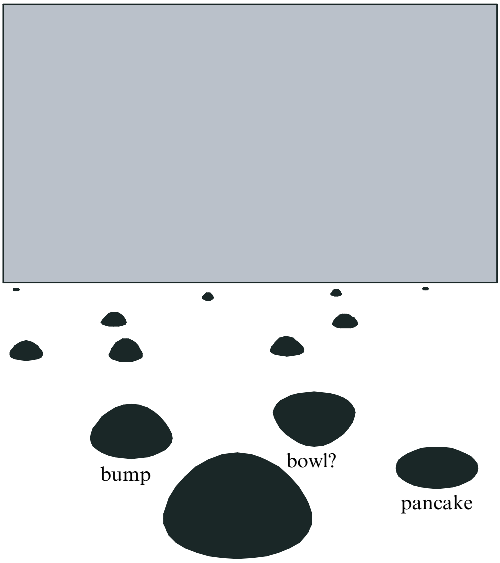


Figure 12. Both a 'bump' and a 'bowl' can be seen in this figure, although the bowl interpretation is less compelling to naïve observers.

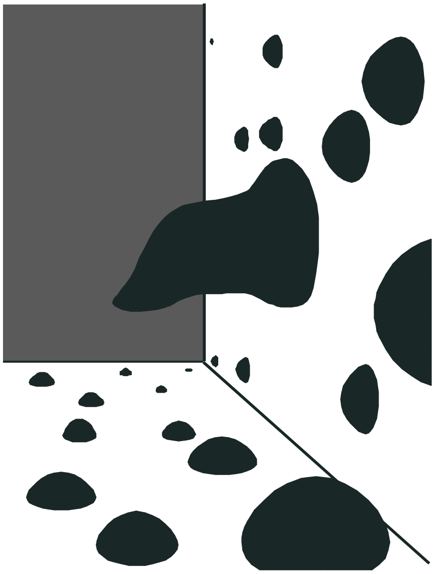


Figure 13. Attraction/attachment to surfaces with orientations that do not even approximate a 'ground' surface influence the perceived shape of a volume. Here the 'rock' attached to the 'wall' is perceived to have a similar *intrinsic* shape as the rock in figure 6.

5 Experiment 2: Base 'on the wall'

In experiment 1 the rocks appeared to rest on a ground plane. Thus the perceived 3-D form may either be due to the way the rocks are perceived to conform to their 'surface of attachment', or due to some other factor confounded with environmental orientation, such as the presumed direction of gravity. In this experiment we show that 3-D form can also be influenced by surfaces that do not have a ground-plane orientation. The rocks in figures 13 and 14 appear to be attached to a 'wall'. Informal observation suggests that the same qualitative shape changes seen in figures 5 and 6 also occur in these figures, although the effect may not be quite as strong. This might be expected, given the special ecological significance of ground surfaces for terrestrial animals.

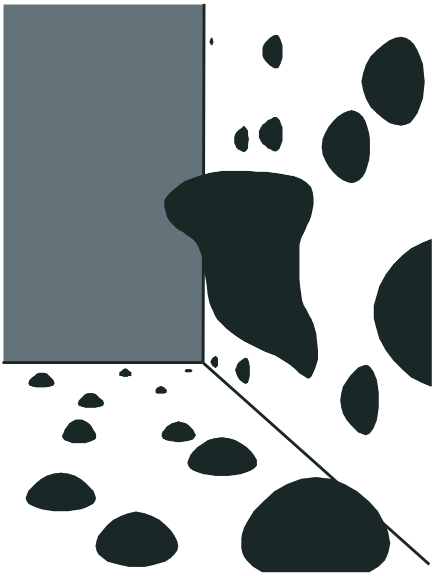


Figure 14. Here the rock attached to the 'wall' is perceived to have a similar *intrinsic* shape as the 'rock' in figure 5.

5.1 *Results*

For figure 13, 18 of 21 observers (86%) selected the model corresponding to figure 8, whereas for figure 14, 18 of 21 observers selected the model corresponding to figure 7 ($p = 1.4144 \times 10^{-6}$ by the binomial test).

6 General discussion

The results of these experiments support the hypothesis that volumes tend to attract and conform to surfaces with which they have optical contact (Albert 1995; Tse and Albert 1998), and that these surfaces can strongly affect the perceived overall shape of a volume. (On the other hand, these silhouettes generally induce or support the *formation* of these surfaces in the first place.) A further example is shown in figure 15, in which identical silhouettes placed in optical contact with different surfaces can be perceived to have very different 3-D shapes. The arms of the 'croissant' placed on the ground plane appear to come forward, whereas the arms of an identical silhouette placed in front of a cylinder appear to bend slightly back. Similarly, in figure 16 the volumetric shape of the 'rock' seen inside the Necker cube depends on which interior face of the Necker cube best approximates a 'ground-plane' orientation. When the interpretation of the Necker cube changes, so does rock's. Perceived orientation and surface attachment can also influence other perceptual attributes, such as transparency. For example, in figure 17 one hemisphere appears transparent while the other appears opaque, even though they are identical except for a 180° rotation in the image plane.

Figure 15. The 'croissant' on the right appears to curve away from the observer in the middle, owing to attachment of the basal contour to the ground surface. The 'croissant' on the left appears to curve somewhat towards the observer in the middle, owing to attachment to the cylinder.

Figure 16. If you see the 'rock' as contained within the Necker cube its shape flips when the Necker cube flips.

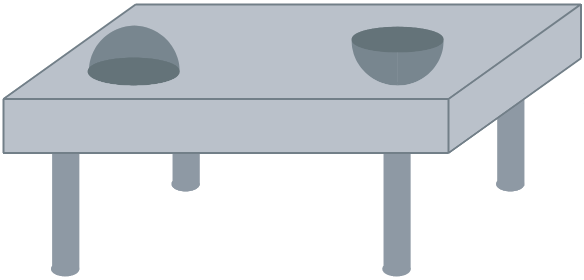


Figure 17. The hemisphere on the left appears transparent while the one on the right does not. The hemispheres are identical except for a 180° rotation in the image plane. Thus, surface attraction/attachment can influence perceptual transparency.

Finally, although the primary aim of this paper has been to investigate the influence of orientation and surface attraction on perceived 3-D form, surface attachment also plays a critical role in the 2-D form effects reviewed earlier. Kopfermann (1930) showed that the perception of the quadrilaterals in figure 1 as squares or diamonds is affected by the orientation of the surrounding figure. However, in figure 18a each quadrilateral can be seen as either a rectangle or a diamond depending on the face of the block to which it appears to be attached, even for a fixed interpretation of the Necker block. When a quadrilateral appears to be attached to one of the large side faces of the cube, it looks like a 'Post-it' glued along only one edge. However, when it appears to be attached to the front or the rear face of the cube, it looks like a diamond in the plane of that face. These two interpretations can be seen without multistability in figure 18b.

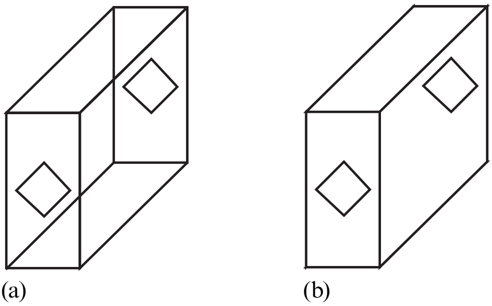


Figure 18. In (a) a quadrilateral is perceived as a diamond when it is seen as attached to either the front or the rear surface, but as a rectangular 'Post-it' when it is seen as attached to one of the large side surfaces. These percepts are illustrated in (b).

7 Conclusions

Rock (1973) suggested that environmental orientation and perceived 2-D form is determined primarily on the basis of gravity, overall visual frame of reference, and an observer's ability to intentionally choose one reference axis or another. The experiments presented here suggest that the assignment of environmental orientation also depends on the surrounding surfaces to which an object might be attached, and that surface attraction and conformation strongly affect the perception of 3-D form from silhouettes.

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