PSYCHOLOGICAL SCIENCE

Research Article

The Perception of Doubly Curved Surfaces From Anisotropic Textures

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ABSTRACT—***Most existing computational models of the visual perception of three-dimensional shape from texture are based on assumed constraints about how texture is distributed on visible surfaces. The research described in the present article was designed to investigate how violations of these assumptions influence human perception. Observers were presented with images of smoothly curved surfaces depicted with different types of texture, whose distribution of surface markings could be both anisotropic and inhomogeneous. Observers judged the pattern of ordinal depth on each object by marking local maxima and minima along designated scan lines. They also judged the apparent magnitudes of relative depth between designated probe points on the surface. The results revealed a high degree of accuracy and reliability in all conditions, except for a systematic underestimation of the overall magnitude of surface relief. These findings suggest that human perception of three-dimensional shape from texture is much more robust than would be reasonable to expect based on current computational models of this phenomenon.***

In a remarkable book that was first published more than 50 years ago, Gibson (1950a) introduced the concept of texture gradients as a potential source of optical information for the perceptual specification of three-dimensional (3D) surface structure. At about the same time, a similar concept was also emerging within a new school of painting called optical art, especially in works of Victor Vasarely and Bridget Riley. This important new insight had an immediate impact on the study of human perception, and it inspired a succession of theoretical models and empirical investigations that continues today.

Although numerous computational analyses have been developed for determining 3D shape from texture, they are all based on a common conceptual foundation: It is assumed that the pattern of texture on a physical surface has some form of underlying regularity, and that distortions of that regular structure within a visual image can be attributed to variations in the surface geometry (e.g., depth, slant, or curvature). For purposes of the present discussion, it is useful to categorize textures into two general classes that we refer to, respectively, as blob textures and contour textures. Blob textures are those that contain patterns of discrete shapes such as polka dots or flagstones, whereas contour textures contain patterns of extended lines, as in wood veneer or striped cloth.

The earliest computational analyses of 3D shape from texture were designed primarily for blob textures, based on an assumption that the sizes and shapes of these blobs on a physical surface are approximately uniform. Texture gradients are defined in this context by changes in the optical projections of these blobs within a visual image, including various scalar properties such as density, foreshortening, or scaling (e.g., see Cutting & Millard, 1984; Purdy, 1958; Stevens, 1981a).

Other models have been designed to exploit statistical regularities in surface texture rather than focus on individual texture elements. For example, one common approach is to assume that variations in reflectance on a visible surface are statistically isotropic—that is, approximately equal in all directions. When this assumption is satisfied, it is possible to estimate the local orientation of a surface from the foreshortening of texture in its optical projection (see Blake & Marinos, 1990; Brown & Shvaytser, 1990; Clerc & Mallot, 2002; Davis, Janos, & Dunn, 1983; Gårding, 1993; Knill, 1998a; Witkin, 1981). Another popular strategy is based on a much weaker assumption that the texture on a physical surface has a constant area or density (Aloimonos, 1988; Kanatani & Chou, 1989; Super & Bovic, 1995). Although this approach is more ecologically valid for natural textures than are analyses based on an assumption of isotropy, it fails to exploit potential information in the pattern of projected shape changes in an image. This deficiency has recently been addressed in an algorithm developed by Malik and Rosenholtz (1997). Their model assumes that the texture on a physical surface is statistically homogeneous—that is, it is invariant over translation—and it estimates the 3D shape of a surface by measuring local affine deformations of the texture within neighboring patches of a visual image. This algorithm works well for planar or singly curved surfaces, but it is not easily generalized to doubly curved surfaces, except in the special case where curvature is approximately the same in all directions.

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Analyses of contour textures typically involve assumptions quite different from those that are employed with blob textures. For example, it is sometimes assumed that the contours on a physical surface are constrained to be lines of principal curvature (Stevens, 1981b) or surface geodesics (Knill, 2001). An important limitation of these models is that they are valid only for singly curved surfaces. Tse (2002) has suggested a potentially more general approach, which assumes that the contours carve up a surface into a series of parallel planar cuts. This is indeed a common procedure for generating contour patterns in mechanical drawing and optical art, though it is also possible to create perceptually compelling displays of 3D shape from texture that violate this assumption (see Knill, 2001; Todd & Oomes, 2002; Todd & Reichel, 1990).

Numerous psychophysical studies have investigated how various aspects of surface texture influence observers' perceptions of 3D structure, but almost all of these studies have focused on planar surfaces (e.g., Attneave & Olsen, 1966; Gibson, 1950b; Knill, 1998b, 1998c; Phillips, 1970; Rosenholtz & Malik, 1997; Tibau, Willems, Van Den Berg, & Wagemans, 2001) or surfaces that are curved in only one direction (e.g., Buckley & Frisby, 1993; Cumming, Johnston, & Parker, 1993; Cutting & Millard, 1984; Knill, 2001; Zaidi & Li, 2002). The research described in the present article was designed, therefore, to examine the perception of 3D shape from texture in the more general case of doubly curved surfaces (see also Reichel & Todd, 1990; Todd & Akerstrom, 1987; Todd & Reichel, 1989, 1990). The specific goals of this research were twofold: (a) to investigate the importance of texture isotropy in the perceptual analysis of blob textures and (b) to compare perceptual performance for surfaces depicted with blob textures and with contour textures.

METHOD

Apparatus

The experiment was controlled using a Macintosh G4 computer with a 21-in. monitor. The spatial resolution of the monitor was 1280 × 1024 pixels; the display area subtended 38.5° × 25.8° of visual angle when viewed at a distance of 57 cm.

Stimuli

Four randomly shaped objects were created by performing a series of sinusoidal perturbations on a sphere at random positions and orientations (see Todd, Norman, Koenderink, & Kappers, 1997). Procedural volumetric textures for these objects were created using 3D Studio Max 4.0 by Kinetix and its Darktree 2.0 texture plug-in by Darktree Studios. The process for creating a volumetric texture is analogous to carving an object out of a solid material, such as wood or marble. Consider, for example, one of the possible stimulus objects, presented in the upper left of Figure 1. The texture in this case was created from a densely packed hexagonal lattice of spheres. Where the surface cuts through a sphere it is colored black, and where it cuts

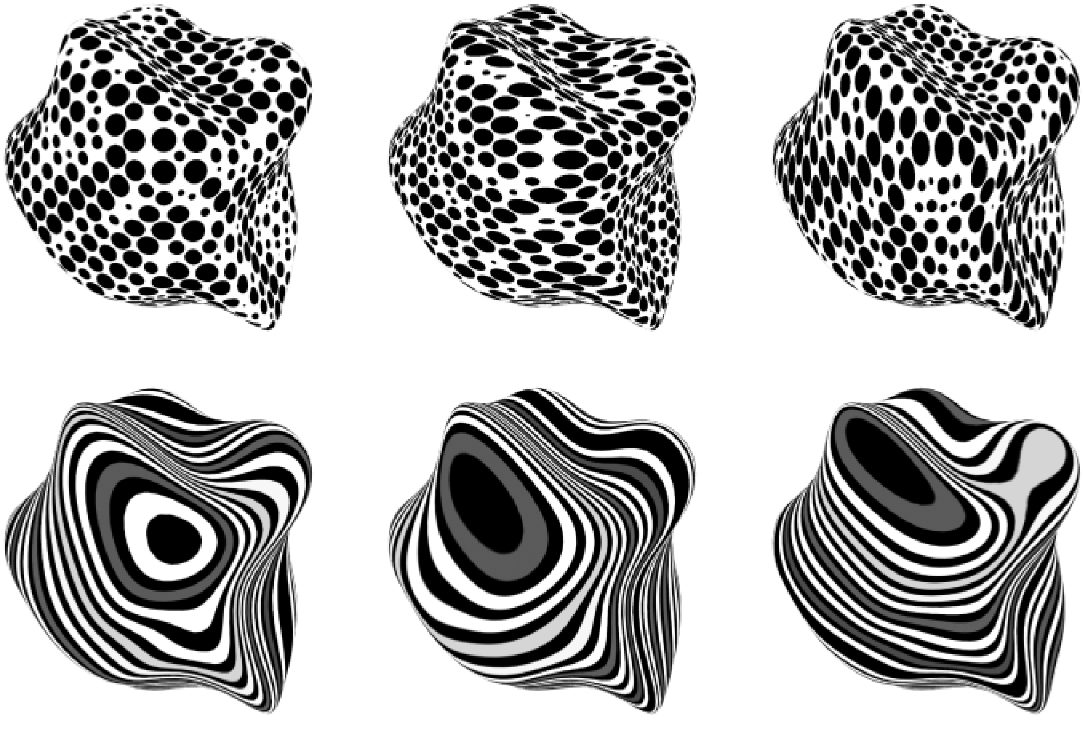

Fig. 1. One of the stimulus objects used in the present experiment with its six possible patterns of texture. The top row shows the three possible volumetric blob textures. In the left-most illustration, the texture is composed of a three-dimensional hexagonal lattice of spheres, which produces a pattern of circular polka dots on the surface that is roughly isotropic. The textures shown in the middle and right illustrations were created by stretching a hexagonal lattice of spheres by a factor of 2 in either a horizontal or a vertical direction, thus producing a volume of parallel ellipsoids; in addition to being anisotropic, these textures are globally inhomogeneous. The bottom row shows the three possible planar-cut textures in different orientations. From left to right, the planar cuts are perpendicular to the line of sight, slanted 30° to the left, and slanted 30° upward. These textures are also both anisotropic and globally inhomogeneous.

through the space between spheres, it is colored white. This produces a pattern of circular polka dots that is roughly isotropic over the entire surface.

In order to investigate the perceptual significance of texture isotropy, we used two anisotropic blob textures, which are illustrated in the upper middle and right examples in Figure 1. These textures were created by stretching a hexagonal lattice of spheres by a factor of 2 in either a horizontal or a vertical direction, thus producing a volume of parallel ellipsoids. The resulting distribution of surface markings on these objects was globally inhomogeneous. That is to say, the black blobs that occurred on the physical surface could have aspect ratios that varied continuously between 1 and 2, depending on how each local region was oriented relative to the principal axes of the ellipsoids. In most instances, however, these variations were spread out over relatively large areas, so that the inhomogeneities could be negligible within sufficiently small local neighborhoods.

We also employed three different contour textures that are illustrated in the bottom row of Figure 1. These were created from a volume of alternating light and dark rectangular slabs, which produced a series of parallel planar cuts through the surface (see Tse, 2002). These rectangular slabs could have a fronto-parallel orientation, as in the lower left example in Figure 1, or they could have a 30° slant in either the horizontal or vertical direction, as shown in the lower middle and right examples. It is important to note that the widths of the stripes on the physical surface varied systematically, depending on how each local region was oriented relative to the rectangular slabs. Thus, these contour textures were both anisotropic and globally inhomogeneous.

Procedure

Two different response tasks were employed in order to measure observers' perceptions of 3D structure. One procedure, called the near-far task, was designed to assess the ordinal structure of observers' perceptions. On each trial, an image of a textured surface was presented together with a set of red and yellow dots that could be moved along a single horizontal scan line with a handheld mouse. Observers were instructed to mark each local depth minimum on the scan line with a red dot and each local depth maximum with a yellow dot. Once all of the depth extrema on that scan line were appropriately marked, the trial was terminated by pressing a mouse button, and a new display was presented.

A second procedure, called the profile task, was also employed in order to assess the relative magnitude of perceived relief in different surface locations. On each trial, an image of a textured surface was presented, and one of its horizontal scan lines was marked by a row of five to eight equally spaced red dots. An identical row of dots was presented against a blank background on a separate monitor; each of the dots could be moved up and down with a handheld mouse. Observers were instructed to adjust the dots on the second monitor in order to match the apparent surface profile in depth along the designated scan line (see Koenderink, van Doorn, Kappers, & Todd, 2001). Once they were satisfied with their settings, they initiated a new trial by pressing a mouse button.

To summarize the overall experimental design, we used six textures applied to four randomly shaped objects. We probed four different scan lines for each object-texture combination, and each of these scan lines was repeated on three separate trials. Five different observers, 3 of the authors (A.K., J.K., and J.T.) and 2 naive observers, performed both response tasks for these stimuli over a series of six experimental sessions. All of the observers had normal or corrected-to-normal visual acuity and wore an eye patch over their nondominant eye.

RESULTS

Let us first consider the results from the near-far task. For every scan line in every condition, each subject marked either a single near point

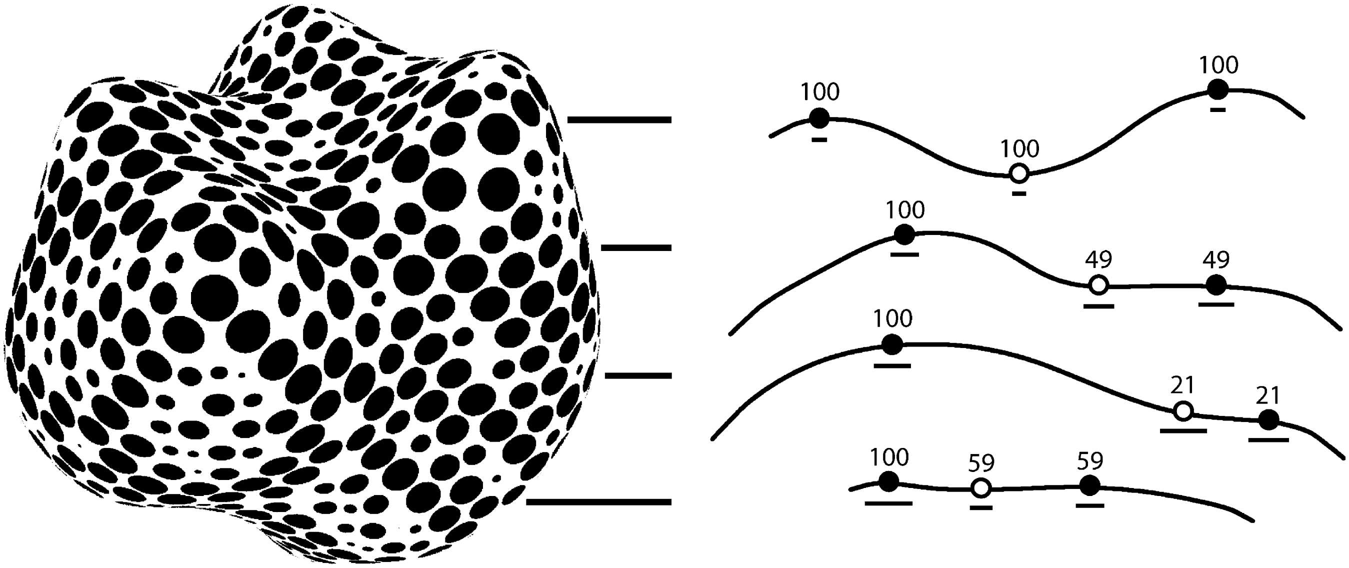

Fig. 2. Results for one of the stimulus objects. The illustration on the left shows the object with four horizontal bars indicating the locations of the four scan lines observers were required to judge. The solid curves on the right show the actual depth profiles for these scan lines. The dots on each profile show the average positions of the judged near points (solid dots) and far points (open dots) over all of the different observers and conditions; the numbers just above the dots show the percentage of possible trials on which each point was marked; and the horizontal bar below each point depicts the standard error of the mean.

or a single far point between two near points. In almost all instances, these responses were closely clustered—even among different observers—so it was easy to determine appropriate correspondence relations for subsequent regression analyses. Over 93% of these responses were in the general vicinity of an actual near point or far point on the object's surface. Observers failed to mark about 7% of the actual extrema, and about 7% of their responses were false alarms.

To get a better sense of the nature of these errors, it is useful to consider a specific example. Figure 2 shows the average positions of the judged near and far points on the actual depth profiles for one of the possible stimulus objects. It is interesting to note that on any given trial, both the misses and the false alarms always occurred in pairs consisting of one near point and one far point. Examples of misses can be seen in the second and fourth scan lines from the top, which contain very shallow concavities that the subjects failed to detect on 51% and 41% of the possible trials, respectively. False alarms were generally placed near inflexion points on the surface depth profile. Some typical examples are shown on the third scan line from the top, which subjects marked incorrectly on 21% of the trials. The misses and false alarms also revealed clear variations in response criteria among the different observers. Those who had misses seldom made false alarms, and those who made false alarms seldom had misses.

The left panel of Figure 3 shows the average judged position of each depth extremum as a function of the ground truth. It is clear from this figure that the observers' judgments were highly accurate. Indeed, their responses were almost perfectly correlated with the actual locations of the near and far points ($r^2 = .985$). There were also high correlations among the judgments obtained for each pair-wise combination of textures (average $r^2 = .940$) and for each pair-wise combination of observers (average $r^2 = .949$).

A similar pattern of results was obtained on the profile task. The right panel of Figure 3 shows the average judged depth as a function of the ground truth for each adjacent pair of probe dots on the four stimulus objects. Note that the observers' judgments were highly correlated with the overall pattern of surface relief ($r^2 = .902$), but that the magnitude of depth scaling was systematically underestimated. Although there were high correlations among the different observers (average $r^2 = .865$), there were large individual differences in the magnitude of perceived relief. The proportion of judged depth relative to the ground truth was .25, .41, .46, .50, and .62, respectively, for the 5 different observers. An analysis of the judgments for the six different textures revealed that they, too, were highly correlated (average $r^2 = .909$), and that there were no significant differences in the magnitude of depth scaling.

DISCUSSION

Considered as a whole, these results indicate that the accuracy and reliability of perceived 3D shape from texture depend on the particular aspect of 3D shape an observer is required to judge. With respect to the perception of 3D metric structure, observers underestimated the depths of the stimulus objects by more than a factor of 2, which is consistent with the results of many previous studies. However, observers' judgments of local depth extrema and the relative depths of different surface features were almost perfectly accurate. This suggests that patterns of optical texture—like other sources of visual information such as motion (Todd & Norman, 1991) and shading (Koenderink et al., 2001)—may provide perceptually useful information about 3D shape only within some family of possible interpretations.

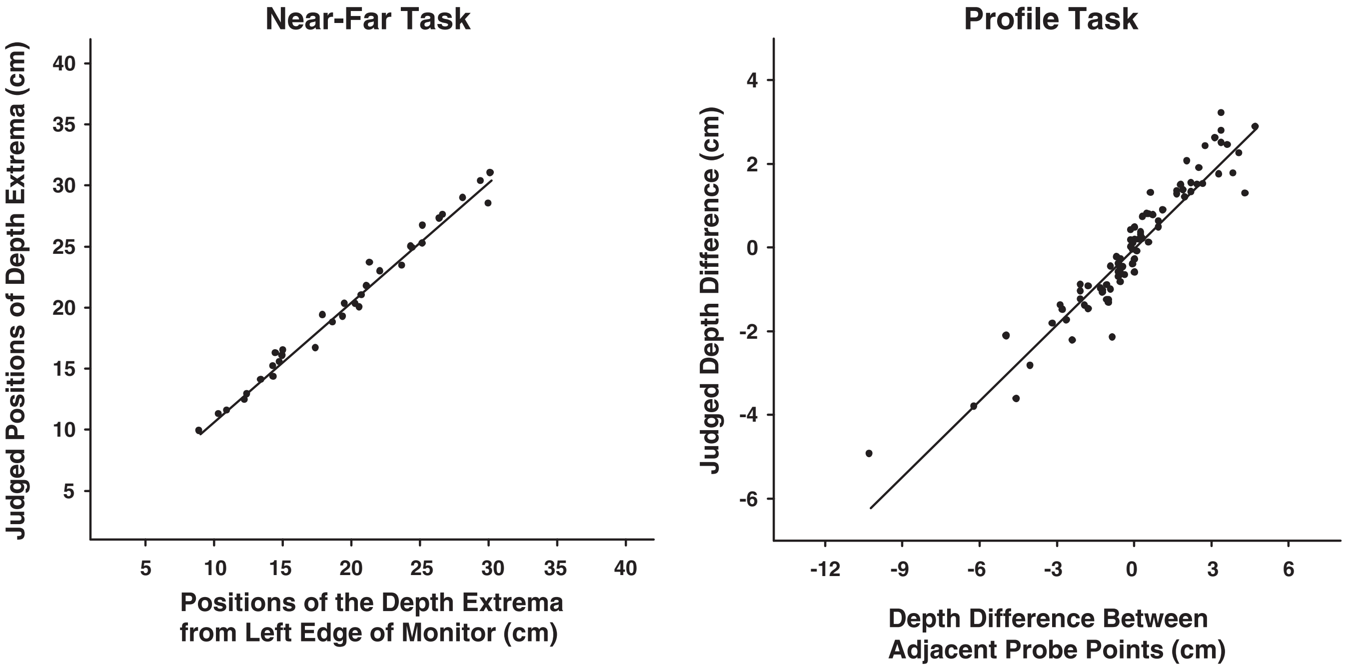

Fig. 3. Average judgments over all observers and textures as a function of the ground truth. The left panel shows the judged positions of the depth extrema on all of the different scan lines for the near-far task. The right panel shows the average judged depth for each adjacent pair of probe points on the profile task.

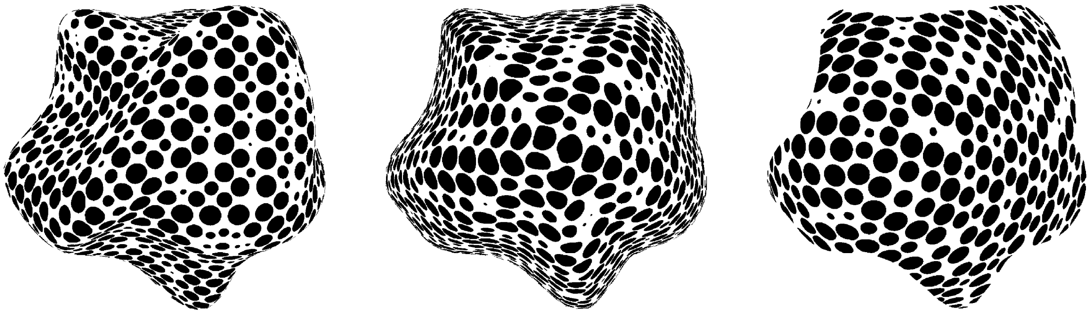

Fig. 4. Three different surfaces with polka-dot textures. Because these surfaces all have identical bounding contours, the variations in their apparent three-dimensional structure can only be due to the patterns of optical texture. It is also interesting to note how the patterns of texture provide information about the nature of the bounding contour. For the two objects on the left, the boundary appears as a smooth occlusion contour, whereas the object on the right appears to have been shaped by a cookie cutter.

In evaluating the effects of texture in this experiment, it is useful to consider another potential source of visual information that has been described previously in the literature: Koenderink and van Doorn (1982) have shown mathematically that an object's smooth occlusion contours can specify the sign of surface curvature in their immediate local neighborhoods. However, this information would be of minimum value for the tasks employed in the present study, because occlusion contours cannot reveal the pattern of curvature within interior regions of a surface, nor can they indicate the precise locations of near and far points. There are in fact an infinity of possible 3D surfaces that are mathematically consistent with any given occlusion boundary. Consider, for example, the three objects with polka-dot textures depicted in Figure 4. All of these objects have identical bounding contours, yet their apparent surface structures are quite different because of variations in the pattern of texture.

Texture Isotropy and Homogeneity

Given the importance of isotropy and homogeneity constraints for current computational analyses of 3D shape from texture, it is surprising that there has been so little research to investigate the psychological validity of these constraints, and the few experiments that have examined this issue have been contradictory. For example, Knill (1998c) found that slant discrimination thresholds were significantly lower for isotropic textures than for anisotropic textures, but that this effect was diminished when the texture elements were rectangular rather than elliptical. Todd and Akerstrom (1987) found that elongating texture elements perpendicular to the direction of slant increased the apparent depths of ellipsoid surfaces, but Cumming et al. (1993) obtained the opposite effect for judgments of cylindrical surfaces.

Perhaps the most interesting experiment on this topic is the one performed by Rosenholtz and Malik (1997) on the perceived orientations of planar surfaces. If a texture is systematically elongated or compressed at an oblique angle to the direction of slant, then an analysis based on an isotropy constraint would produce a predictable pattern of errors in the estimated slant direction. Rosenholtz and Malik found that human observers did indeed make errors in the predicted direction, though these errors were significantly smaller than what would be expected if the judgments had been based entirely on an assumption of texture isotropy, and there were large individual differences among observers. One potential problem with this study, however, is that perceived slants were measured by having subjects adjust the 3D orientation of a circular disk until it appeared to fit within the tangent plane of the depicted surface. Although this is a technique that we have used ourselves in many previous experiments (e.g., Koenderink et al., 2001; Todd et al., 1997), there is some ambiguity in this task when it is employed with textured surfaces. Should the gauge figure fit best on the surface, or should it fit best within the texture? Because of the task's ambiguity, subjects may have adopted different response strategies.

It is important to note that the same basic reasoning used by Rosenholtz and Malik (1997) is also applicable to the present study: If observers' perceptions had been based on an assumption of texture isotropy, then the anisotropic textures would have produced large changes in the apparent locations of the local depth extrema. When observers judged surfaces with anisotropic blob textures, for example, they would have located apparent near and far points in regions where the aspect ratio of the texture elements was at a local minimum along the designated scan line. That clearly did not occur. Indeed, the judged positions of the near and far points were almost perfectly accurate in all conditions, and there were no detectable differences between the judgments for the isotropic and anisotropic textures.

The most theoretically interesting aspect of these data is that observers could achieve accurate performance on the near-far task for textures that were both anisotropic and globally inhomogeneous. Although this might appear at first blush to provide negative evidence for the gradient-based approach of Malik and Rosenholtz (1997), that may not necessarily be the case. Consider, for example, the anisotropic blob textures depicted in Figure 1. Because the aspect ratios of the physical surface markings change relatively slowly in these stimuli, the qualitative structure of the gradient field is primarily determined by local variations of surface curvature. This suggests that a gradient-based approach could produce a 3D interpretation of these stimuli that is at least qualitatively accurate, which is, after all, the limit of what human observers can do. The contour textures depicted in Figure 1 would likely pose greater difficulties for a gradient-based approach, but those stimuli could potentially be analyzed using a planar-cut constraint (Tse, 2002).

Blobs Versus Contours

On the basis of experiments with sinusoidally corrugated surfaces, Zaidi and Li (2002) recently argued that contour textures aligned in the direction of maximum curvature are the only textures that provide information about the direction of surface slant or the sign of surface curvature. The results of the present experiment provide clear evidence that this conclusion is incorrect. None of the textures employed in this study had a preponderance of energy along lines of principal curvature, yet observers were almost perfectly accurate in their judgments of the sign of curvature.

How, then, do we account for the poor performance obtained by Zaidi and Li (2002) for polka-dot textures and sinusoidal surfaces? One possibility is that some form of information provided by doubly curved surfaces is not available in images of surfaces that are curved in just one direction (see, however, Fig. 15 of Todd & Oomes, 2002). A more likely explanation, we suspect, may involve the fundamental limitations of gradient-based analyses of 3D shape from texture. In order to measure gradients of optical texture, it is necessary to compare the image statistics in two neighboring regions (Malik & Rosenholtz, 1997), but there are some inherent trade-offs in this process. Ideally, these regions should be as large as possible in order to obtain the best possible estimate of their statistical structure. However, it is also important that the texture in each region be approximately homogeneous, which is unlikely to be the case if the regions are too large. Because of this trade-off, there are several aspects of surface geometry or texture that could affect perceptual performance. For example, performance could be impaired if the surface orientation changes too rapidly, if the texture is too sparse, or if its variance is too large. The analysis of texture may also involve some form of long-range smoothing process (e.g., Grossberg & Mingolla, 1985, 1987), so that performance may be affected by overall image size (see Knill, 1998b).

Under optimal conditions, as captured in the paintings of Vasarely or Riley, gradients of optical texture are one of the most powerful sources of information for the visual perception of 3D surface structure, but there are many combinations of surface geometry and texture that seem to provide no such information whatsoever (e.g., stucco surfaces or high-frequency-noise textures). Our own anecdotal observations suggest that the regularity of a texture may be particularly important for conveying the impression of 3D surface structure, so that displays look best when texture elements all have approximately the same shape and are arranged in a regular pattern. The results of the present experiment suggest, however, that the distribution of these elements need not be isotropic—at least not in the case of doubly curved surfaces. How it is possible to obtain accurate judgments of 3D shape from texture patterns that are both anisotropic and globally inhomogeneous presents an interesting theoretical problem for future research.

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