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View Direction, Surface Orientation and Texture Orientation for Perception of Surface Shape

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Abstract

Textures are commonly used to enhance the representation of shape in non-photorealistic rendering applications such as medical drawings. Textures that have elongated linear elements appear to be superior to random textures in that they can, by the way they conform to the surface, reveal the surface shape. We observe that shape following hache marks commonly used in cartography and copper-plate illustration are locally similar to the effect of the lines that can be generated by the intersection of a set of parallel planes with a surface. We use this as a basis for investigating the relationships between view direction, texture orientation and surface orientation in affording surface shape perception. We report two experiments using parallel plane textures. The results show that textures constructed from planes more nearly orthogonal to the line of sight tend to be better at revealing surface shape. Also, viewing surfaces from an oblique view is much better for revealing surface shape than viewing them from directly above.

Key words: Surface shape perception, textures, visualization, shape from texture.

1 Introduction

In scientific visualization it is common for researchers to generate curved surfaces, either directly from data, or from a theoretical model. The goal of non-photorealistic rendering in support of scientific visualization is to determine the best method for displaying a surface so that its shape can be perceived and the most common way of doing this is to construct an artificial lighting model to generate shape-from-shading cues. Surface texture is also a potentially rich source of information about a surface's shape and this leads to the problem of constructing textures, which when mapped onto the surface of a three dimensional object, will best help reveal surface shape. There are two components to this problem. One concerns the perceptual characteristics of a texture that will optimally reveal surface shape features. The other concerns the algorithms required to efficiently generate such a texture. In the present paper we are concerned with the perceptual issues. We begin with a review of research relevant to shape perception from shading and texture.

1.1 Shape from Texture

Most shape from texture studies assume that a texture is composed of independent elements, or *texels* [1, 4]. Gibson was the first to stress the value of texture as a depth cue and performed the first perceptual experiments. Gibson regarding the "terrain extending to the horizon" as a fundamental surface, devised an experiment which displayed textured planes at varying degrees of slant. Each plane was textured with either a regular grid pattern, or an irregular grass pattern. He found that slant judgments increased fairly consistently with increases in the actual slant of plane; however, observers also consistently underestimated the amount of slant [4]. A number of further studies have verified these results [3, 11]. The way that a texture changes with distance can be broken up into three distinct components, *compression, density* and *perspective*, assuming a uniformly textured surface [2]. *Compression,* also called foreshortening, refers to the fact that the shape of a texel will change due to the orientation of the surface relative to the image plane. *Density* refers to how tightly packed texels are in the image plane. The density increases with both distance and the obliqueness of the view. The *perspective* depth cue is the scaling of texels with distance from the viewpoint. Cumming, et al [2] carried out an experiment to determine which of compression, density, and perspective is most useful in the perception of surface shape displayed in stereo and textured with a set of different colored ellipses. By varying the shape and position of the ellipses, all eight possible combinations of the three texture cues were considered. They reported that for curved surfaces viewed stereoscopically, 97% of the variance in perceived surface shape could be accounted for by the compression depth cue. The perspective and density cues were ineffective at revealing surface shape in this case.

1.2 Oriented Textures

Textures made up of elongated texture elements are far more capable of conveying shape than random textures, particularly if the texture elements are oriented to reveal surface shape. One example is the shape following hache marks commonly used in cartography and medical illustration [16]. It has been suggested that the optimal way for an elongated texture to reveal surface shape is for the texture to be oriented with principal curvature direction at each point on the surface [6, 8, 9]. Principal curvature direction is the direction, for a point on the surface, in which the surface changes most rapidly. Li and Zaidi, [14] suggest that "Veridical *ordinal depth* is seen only when the projected pattern contains changes in oriented energy along lines corresponding to projected lines of maximum curvature of the surface." [italics ours]. Ordinal depth refers to the rank ordering of distances from the viewpoint. Concerning their conjecture, it is worth noting that a scientist is likely to be more interested in the shape of a surface than the *ordinal depth* of points on the surface.

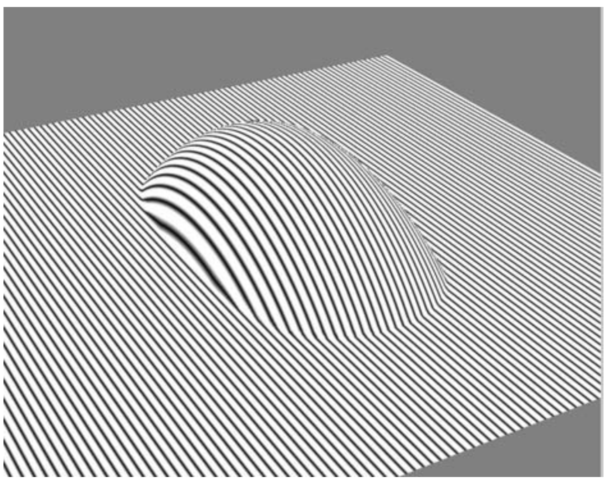

Figure 1: A portion of a toroidal surface projecting from a plane. Contours on the surface of the toroid are at right angles to the principal curvature direction.

It is easy to demonstrate that aligning contours with the principal curvature direction cannot always be the optimal solution. For example, consider in the case of a toroidal surface viewed in perspective from its center; in this case the lines of principal curvature will be all be parallel on the picture plane and thus uninformative. Moreover, it is possible to see shape from oriented texture where the texture contours are *orthogonal* to principal curvature direction. Figure 1 shows a section of a toroid extending out of a plane with contours on the toroid that are orthogonal to the principal curvature direction, yet the shape of the surface appears quite clearly.

It seems plausible that in optimally orienting surface textures to show surface shape, it is necessary to take viewpoint into account as well as other factors, such as principal curvature direction. Figure 2 illustrates how view direction can interact with texture orientation in affecting perceived surface shape. In both views the same sinusoidal surface is viewed from an oblique angle. In Figure 2a the texture contours follow the principal curvature direction but because of the particular viewpoint, are quite uninformative. In Figure 2b the texture contours are oblique to the principal curvature direction but seem to show the sinusoidal undulations better, although the overall slant of the surface appears reduced.

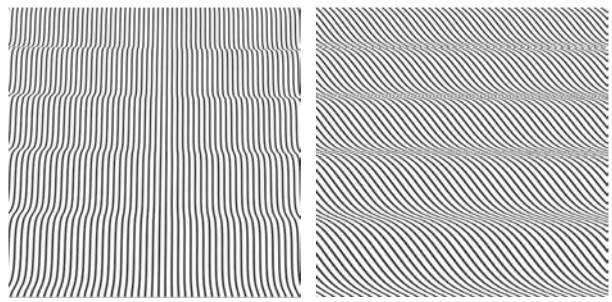

Figure 2: A sinusoidal surface, (a) with contours following the principal curvature directions, (b) with contours at 45 degrees to the principal curvature direction.

In order to understand the relationship between view direction and texture contour orientation we turn to the class of textures defined by the intersection of parallel planes with a surface [12]. Over small areas, textures consisting of elongated parallel contours, such as hache marks can be locally defined in this way. Figures 1 and 2 both show examples of globally defined parallel plane textures.

We conjectured that for optimal perception of surface shape it is undesirable for the line of sight to have a shallow angle with the orientation of the planes texture (as in Figure 2a), and that biasing the orientation of the parallel planes away from the line of sight will improve perception of surface shape. We are agnostic on the issue of the perception of ordinal depth.

2 Shape from Shading Combined with Texture

It seems likely that employing both shading and oriented texture is likely to be most effective in revealing surface shape, thus we must consider how these two factors interact. A number of studies have shown humans can use shape-from-shading information quite effectively to perceptually reconstruct the shape of smoothly shaded surfaces [10]. However, contours can dramatically alter how shape-from-shading information is perceived. Figure 3a and Figure3b show two patterns with exactly the same gray-scale gradient pattern from left to right but different border shapes (adapted from Ramachandran [17]). As can be seen, the boundary contours dramatically alter the perceived shape of the surfaces.

Internal contours can similarly perceptually constrain the perceived shape of the surface as Figure 3c and Figure 3d illustrate. If these contours are fine then they make up a linear texture. Although in the case of this example the texture appears to dominate shape-from-shading information it must be supposed that normally these two types of information are mutually reinforcing.

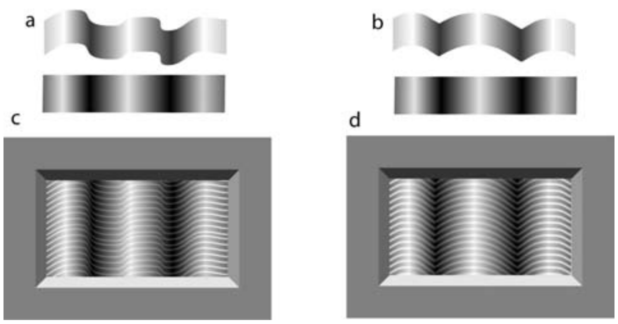

Figure 3: (a) and (b) both have the same gray scale profile, but different border contours. (c) and (d) have one gray scale profile for the thin lines and another for the wider lines. In both examples the contours determine the shape of the surface.

2.1 Measuring Perceived Surface Orientation

Two degrees of freedom are required to specify the orientation of a surface normal. The most common representation used in perceptual experiments is to represent orientation in terms of *slant* and *tilt* [10]. Slant refers to the angle between the normal of the surface at some point and line of sight and thus ranges from 0 to 90, whereas tilt refers to the rotation of the cursor about the line of sight and thus ranges from +/- 180 degrees. The relationship between slant and tilt is illustrated in Figure 4. One obvious problem in slant and tilt measurements is that when the slant is close to 0 degrees a large error in measured tilt angle can correspond to a small angular distance between the estimated normal vector and the actual normal vector. Therefore we chose instead to decompose angular errors into X-axis rotation and Z-axis rotation as illustrated in Figure 5. We define X-axis error as the angle between the normal vector and the glyph vector when projected onto the y-z plane. Similarly Z-axis error is the angle between the normal vector and the glyph vector when projected onto the x-y plane. Since we are interested in the x-y plane. Since we are interested in the perception of the shape of terrain surfaces (as opposed to fully rounded objects), these coordinates seem more appropriate.

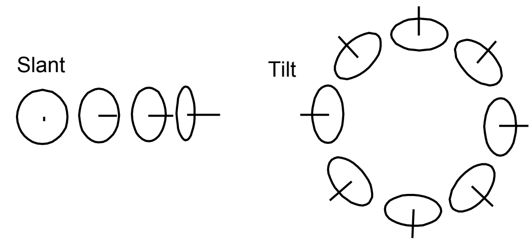

Figure 4: Slant and tilt.

2.2 Factors in Surface Shape from Texture

Given that oriented textures can reveal shape, the following variables may be important.

1) Orientation of texture planes with respect to the viewpoint.
2) Orientation of texture planes with respect to the surface.
3) Orientation of viewpoint with respect to the surface.
4) Orientation of illumination with respect to surface/texture/viewpoint. Texture orientation, the illumination direction and the viewpoint may all interact in determining perceived shape.

Considering the possible interactions between these variables presents a huge factorial problem. In our first experiment we focused on the orientation of parallel plane textures with respect to viewpoint for an artificial terrain surface tilted at 45 degrees to the line of sight as illustrated in Figure 5. In experiment 2 we examined the effect of orientation of the viewpoint with respect to both the surface and orientation of the parallel plane textures with respect to the surface.

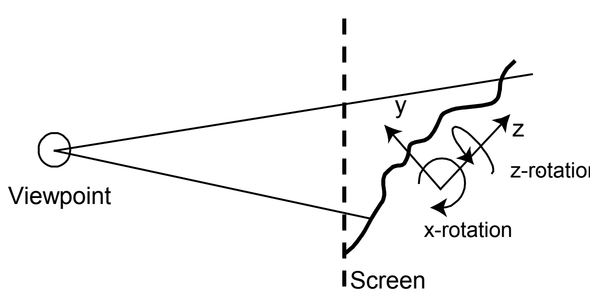

Figure 5: Angular error was defined in terms of rotation about the X-axis and rotation about the Z-axis as shown.

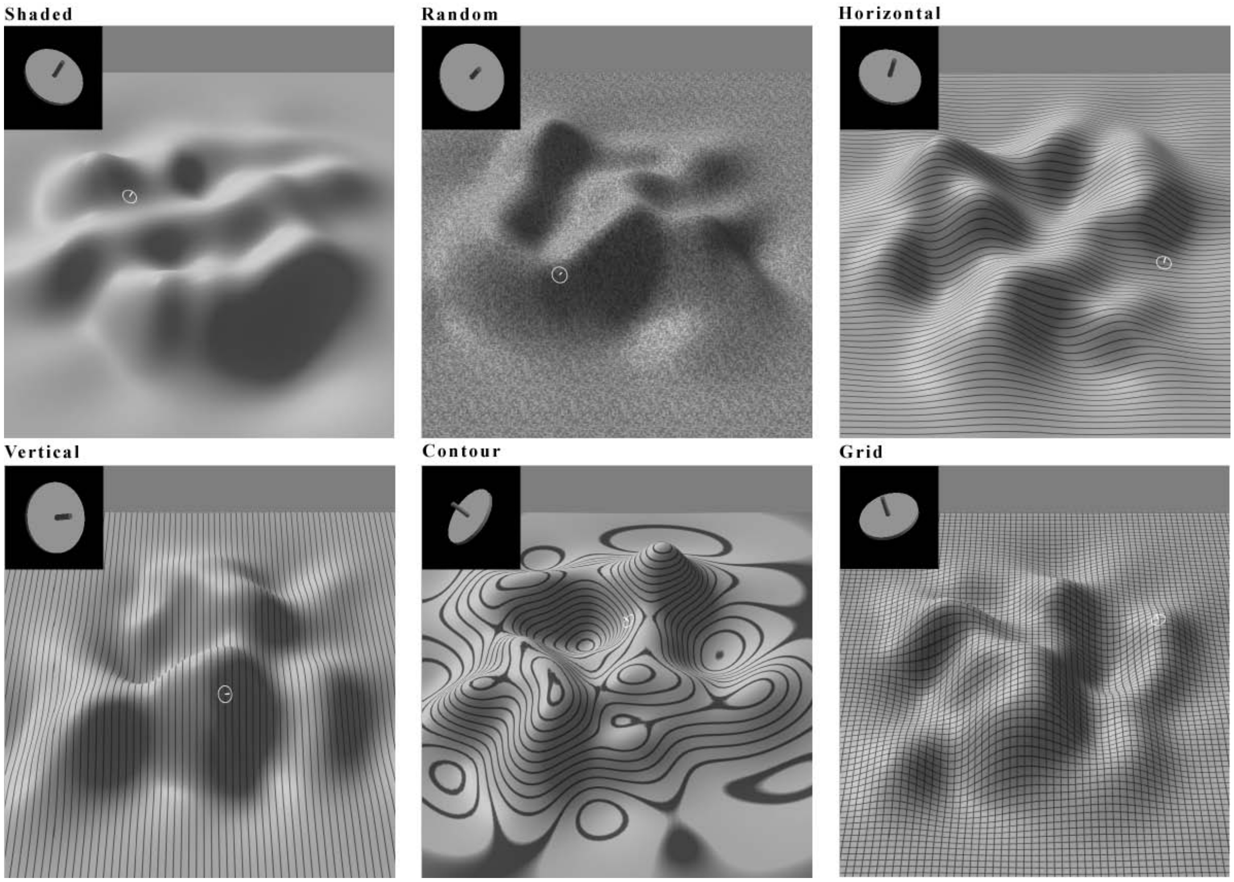

Figure 6: Examples of the six different textures used in Experiment 1.

3 Experiment 1

The goal of the first experiment was to conduct a preliminary evaluation of the effect of parallel plane textures at different orientations, and to compare these with no texture and a random particle texture. The task was the estimation of the surface normal. The six different texture conditions are listed below and illustrated in Figure 6.

1) No texture (Shaded)
2) Random particle texture (Random)
3) Oriented planes orthogonal to z direction (Horizontal)
4) Oriented planes orthogonal to x direction (Vertical)
5) Oriented planes orthogonal to y direction (Contour).
6) Grid combining 3 and 4 (Grid)

For texture 4 (Vertical) the view vector lies in the texture planes. We therefore predicted that it should be the worst at revealing texture along with the condition 1 (Shaded) and condition 2 (Random).

Textures 3 (Horizontal) and 5 (Contour) both have texture planes oriented at 45 degrees to the line of sight while texture 6 (Grid) combined textures 3 and 4. Because in these conditions the texture planes were more nearly orthogonal to the line of sight we predicted smaller errors.

In summary, we predicted that conditions 3, 5 and 6 should afford better estimates of surface orientation than textures 1, 2 and 4.

3.1 Method

Generating the Test Surfaces

Our test surfaces were constructed as regularly gridded height fields 100x100. Smooth random terrains were constructed by summing 50 gabor functions having the general form.

$$f(x,y) = k\cos(2\pi x/w)e^{-\frac{x^2+y^2}{2\sigma^2}}$$

These were randomly varied in center positions, the amplitude (*k*) and the width *w* as well as the orientation. Six different examples are shown in Figure 6.

Lighting and Rendering

The surface was illuminated using both Lambertian and specular shading components. In all cases the illumination was the same, from the upper left at infinity, defined by the vector (-1,1,-1) To avoid artifacts due to aliasing of the texture lines we anti-aliased by rendering at three times the final resolution then averaging blocks of 9 pixels.

Viewing conditions

The perspective parameters were set up assuming a viewpoint 65 cm from the screen. The viewport width was 23.5 cm giving a 20.5 degree field of view. The test surface was displayed tilted at 45 degrees about the X-axis and scaled so that the left and right boundaries of the test surface were not available to provide a linear perspective cue as illustrated in the examples shown in Figure 6.

Method for Evaluating Surface Orientation

To assess the ability of texture to reveal surface orientation, a series of test point locations were randomly selected in a central square region of the test surface. This region was half the width and depth of the overall surface. A test was carried out to determine if a test point was visually occluded and if this was the case an alternative point location was randomly selected. A new set of test points were defined for each new surface.

We used the test glyph developed by Koenderink and Van Doorn [10] to measure perceived surface orientation. This consists of a circle, with a line extending from it as illustrated in Figure 4. But because this could sometimes be seen ambiguously we added a much larger 3D version of the glyph in the upper left hand corner of the test window as illustrated in Figure 6. The smaller test glyphs were drawn in white as shown and these can just be seen in Figure 6. To draw the test glyphs the Z-buffer test was disabled so that occlusion of parts of the glyph could not be used as a spatial cue.

To adjust the glyph subjects moved the cursor left and right to rotate it about the Z-axis and up and down to rotate it about the X-axis. When the subject was satisfied with the orientation setting they depressed the space bar to advance to the next trial.

3.2 Procedure

For each of the texture conditions a different surface was randomly generated and the subject was asked to judge the orientation at 5 test points on the surface in turn. The 6 textured surface conditions were given in a different random order for each subject. This set of 6 conditions was repeated a total of 4 times, in different random orders, with new random surfaces, yielding 20 settings per condition and a total of 120 settings per subject.

3.3 Subjects

There were 14 subjects, mostly undergraduate and graduate students who were paid for participating.

3.4 Results from Experiment 1

Figure 7 summarizes the results of the first experiment in terms of the absolute mean difference between the surface normal at a test point and the vector defining the center-line of the orientation glyph. An ANOVA revealed a significant main effect of texture conditions ($F(1,5) = 20.9$; $p < 0.0001$). Overall the rank ordering of the textures was as we predicted. The Grid, Horizontal and Contour textures resulted in smaller errors than the Random, Shaded and Vertical textures. To discover which conditions differed significantly a Tukey test of honestly significant differences (HSD) test was applied. The results of this are also illustrated in Figure 7. Confirming our hypothesis, the Grid, Horizontal and Contour textures resulted in smaller errors than the Vertical texture and Shading only condition. However, the difference between the Contour and Random conditions failed to reach significance. The Grid pattern texture was significantly better than all others.

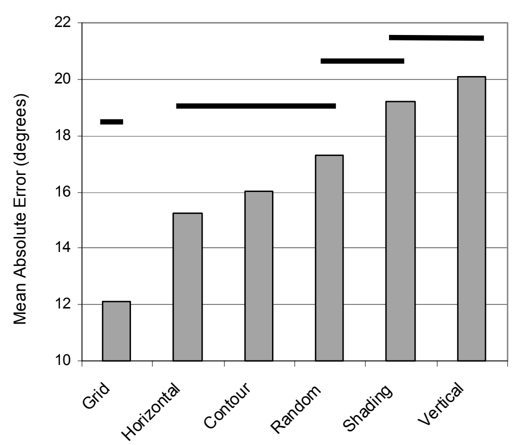

Figure 7: Summary of results from experiment 1. The different textures are ordered in terms of mean absolute error from best to worst. The horizontal black bars show groups of not-significantly –conditions according to Tukey's Honestly Significant Difference (HSD) test.

To determine if the error was isotropic, or biased according to the view direction we separated out the error into two components, rotation about the X-axis and rotation about the Z-axis. The results, as illustrated in Figure 8, show that errors were substantially larger about the X-axis, compared to about the Z-axis.

3.5 Discussion of Experiment 1

The results confirmed our hypotheses that parallel plane textures will be least effective when the texture is constructed such that the line of sight has a small angle with the generating planes, and they will be more effective when the texture planes are more nearly orthogonal to the line of sight.

One result that we had not anticipated was the finding that the grid texture was substantially better than the others. However, this is in agreement with Kim et al.'s [9] finding that more than one texture orientation produces enhanced surface judgments.

Our finding that the X-axis rotation error was greater than the Z-axis rotation error suggests that efforts to improve surface orientation perception should focus on providing better cues in this direction.

It is interesting that the difference between X-axis and Z-axis rotation was most pronounced for the horizontal contour texture. Observation of Figure 8 suggests a reason. The horizontal contours, defined by planes orthogonal to the Z-axis, give excellent information about rotation about the Z-axis, but only give information about rotation about the X-axis in terms of compression which may be a less effective cue.

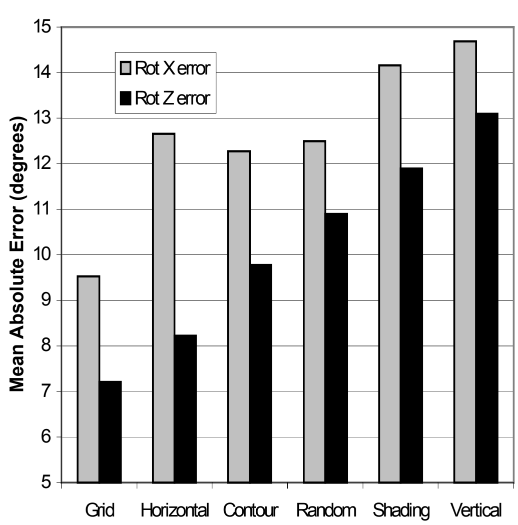

Figure 8: Error decomposed into errors of rotation about the x and z axes respectively.

4 Experiment 2

The goal of the second experiment was to understand in more general terms the influence of texture orientation and view direction on the accuracy of surface orientation. In order to do this we measured the effects of a greater variety of texture orientations as well as a number of view directions.

Three viewing directions were chosen. The first viewpoint was located directly above the surface, pointing down (also called *plan* view). Thus the view vector made an angle of 90 degrees with the x-z plane. The second view was the same as in the first experiment, a 45 degree angle with the x-z plane. The third viewpoint was a low 15 degree angle with the x-z plane.

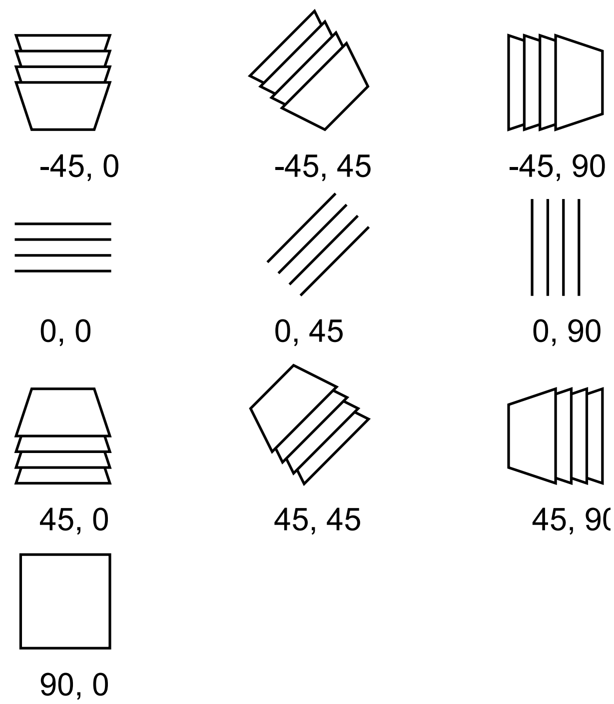

Figure 9: Ten orientations of texture planes were investigated. The view direction was either a plan view, as shown, or from the bottom of the figure. The first angle refers to the rotation of horizontal planes about the X axis (similar to slant), and the second number refers to the rotation about the Y axis (similar to tilt).

Ten different orientations of texture planes were chosen as illustrated in Figure 9. Note that some orientations were not evaluated because they were mirror reflections of other rotations. There was also a no-texture condition and in all cases the surface was shaded as well as textured. The 11 different textures are illustrated in the 90 degree view in Figure 10.

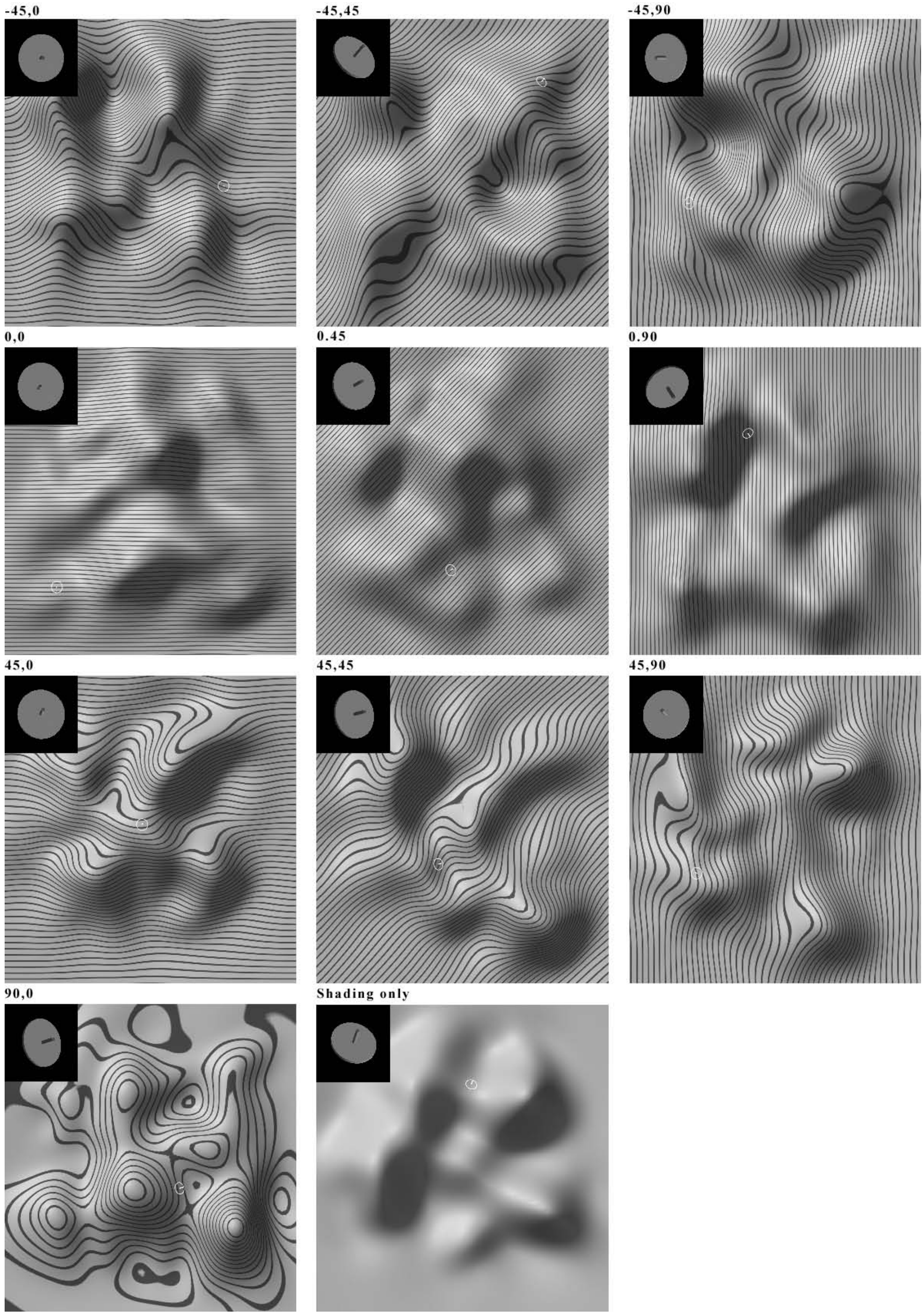

Figure 10: All of the textures used in Experiment 2. The 90 degree view (plan view) is shown.

4.1 Procedure

The 11 different texture types viewed from 3 different viewpoints resulted in 33 total conditions. As in the first experiment a different random surface was generated for each of the 33 conditions and the conditions were presented in a different random order to each subject.

Again, a participant was asked to set an orientation at five different test points for each texture orientation combination. The entire set of 33 conditions was then repeated yielding a total of 10 test points per subject for each combination of texture and view direction.

4.2 Subjects

There were 14 subjects, mostly undergraduate and graduate students who were paid for participating.

4.3 Results from Experiment 2

Figure 11 summarizes the mean absolute error for all combinations of textures and view directions. An ANOVA revealed a significant effect of viewing angle ($F(2,26) = 16.7$; $p < 0.0001$). Overall, the largest errors occurred with the plan view condition (28 degrees on average) and the smallest errors overall occurred with the 45 degree viewing angle (20.2 degrees on average). However, the mean error with the 15 degree viewing angle was not significantly worse (20.84 degrees) according to Tukey's HSD test. There was also a main effect of texture condition ($F(10,130) = 6.38$; $p < 0.0001$) and a significant interaction between view angle and texture $F(20,260) = 7.53$; $p < 0.001$) indicating that the effect of texture varied depending on the view angle.

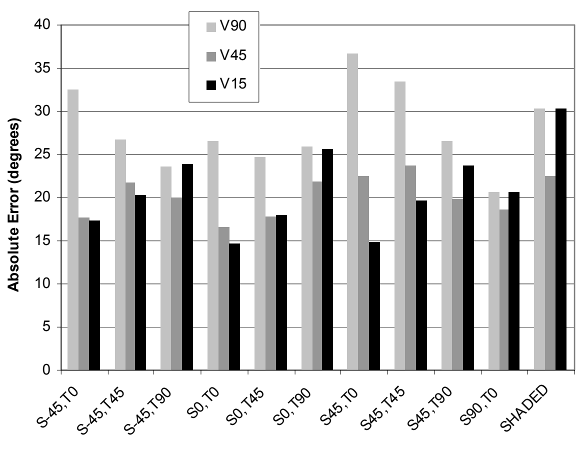

Figure 11: Mean absolute error for all 11 textures at each of the 3 view directions.

Examining the angular error about the X-axis, revealed a systematic bias in the overall judged orientation of the surface as a function of view direction. (Note in this case we are looking at the mean error, not the mean absolute error as we did for Experiment 1). These data are summarized in Figure 12. The effect was largest for the 90 degree view, and was such that the top of the display apparently appeared tilted away from the viewer (by -13.4 degrees on average). For the 45 degree view the overall bias was minimal (1.2 degrees on average). Whereas for the 15 degree view the bias was in the opposite direction (by 8.7 degrees on average). Overall, this orientation effect can be described as a bias towards a 45 degree tilt of the surface with respect to the view direction such that the perceived tilt is reduced relative to 45 degrees by about 30%; more data points would be needed to determine the precise shape of the function.

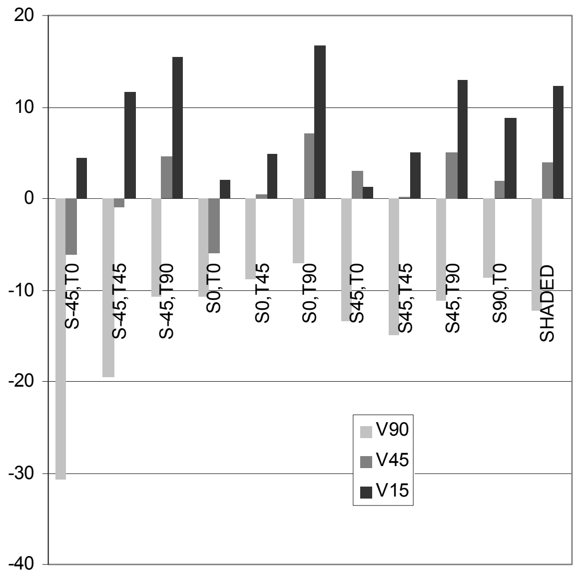

Figure 12: Mean angular error about the X-axis for all textures and all view directions.

Once we had removed the 13.4 degree systematic tilt about the X-axis the 90 degree view data revealed in interesting effect. The parallel plane textures that were 45 degrees oblique to the line of site with this view direction (S-45T0, S-45T45, S-45T90, S45T0, S45T45, S45T90) cause an additional bias of perceived tilt of the surface towards the normal of the parallel plane textures. On average this was 6.22 degrees.

Concerning the question of the interaction between view direction and parallel plane texture orientation, in general the results support our hypothesis. For each of the viewpoints the parallel plane texture that resulted in the lowest error was the one that was exactly or most nearly orthogonal to the view direction (S90T0 for the 90 degree view, S45T45 for the 45 degree view and

S0T0 for the 15 degree view). Also, in each of the cases where line of sight was nearly coplanar with the texture planes, the judged orientation was worse than that for the simple shaded surface. There were however, cases that produced even worse judgments. Specifically the S45T0 and S45T45 textures resulted in very poor judgments from the 90 degree and 45 degree viewing directions. We suspect that this was due to some kind of interaction with lighting resulting in inverted depths. However, we have only anecdotal evidence to support this.

5 Discussion

Overall we found that parallel plane textures nearly orthogonal to the line of sight were best in supporting shape estimates. When the line of sight had a small angle with the texture planes, surface orientation judgments were poor. This suggests that viewpoint should be taken into account when adding textures to surfaces to enhance shape perception. One way of applying this result would be to modify algorithms for generating principal curvature direction textures to bias the orientation of the texture contours so that they become more nearly orthogonal to the line of sight.

The biasing of texture depending on the view direction may be most applicable for static illustrations. In environments where it is possible to interactively navigate to an arbitrary view, textures that work well independent of viewpoint are likely to be more useful. In this case one possible solution is to use one of the techniques that use textures aligned with the principal curvature direction [7]. Our results from the first experiment also suggest that draped grids may provide an effective and simple solution for arbitrary oblique views. These are especially interesting when we consider the magnitude of the errors. Error magnitudes for non-stereoscopic views have been typically reported to be in the 20 degree range [8, 9, 15]. Most of our parallel plane textures also resulted in mean absolute errors of between 15 and 25 degrees. Yet the simple grid, with an oblique 45 degree view produced mean errors of only 12 degrees on average suggesting that this rather mundane solution may be a good one. A grid can also act as a measuring device, if it is made with standard squares. We have found it useful to lay graph paper-like grids that have both small squares and large squares on digital terrain models. However, a grid is not likely to be useful if the surface is to be displayed in plan view – although we did not specifically measure this condition.

We made an innovation in the method of measuring orientation, adding a large shaded version of the orientation glyph to the upper part of the screen as illustrated in Figure 6. The subjects said that they found this to be useful and we believe that it may have reduced some errors due to ambiguity in perception of the smaller glyph. Nevertheless, there would appear to be scope for further development in this area. In these types of experiments there are two sources of error. The first is due to misperception of the orientation of the test surface. The second is due to misperception or inaccuracy in subject's ability to precisely judge the orientation of the test glyph. The glyph that has become standard for these kinds of experiments relies mainly on the shape of a small ellipse as a cue to orientation, with the line merely disambiguating two alternatives 180 degrees apart. It seems likely that there are other devices that would allow for more precise specification of orientation.

Finally, it is still common for surfaces to be displayed in plan view with artificial illumination to reveal surface shape. Our results strongly suggest that an oblique viewpoint will allow for better judgments of surface orientation, and this generally supports the use of interactive 3D graphics for surface visualization.

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