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Perception of surfaces from line drawings

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Abstract

We test the perception of 3D surfaces that have been rendered by a set of lines drawn on the surface. Each surface is rendered as a family of curves which are in the simplest case the intersections with a family of parallel planes. On each trial, a surface or its "distorted" version is shown in this way, in an arbitrary orientation on an LCD screen or in a volumetric 3D display. The distortion is produced by stretching the surface in the *z*-direction by 30%. The subject's task is to decide whether two sequentially presented surfaces are identical or not. The subject's performance is measured by the discriminability d', which is a conventional dependent variable in signal detection experiments. The work investigates the question whether a surface rendered with planar and geodesic curves is easier to recognize than one where the curves are not planar or not geodesic.

Keywords: Psychophysical experiment; Shape perception; Line drawing; Volumetric display; 3D image

1. Introduction

This paper addresses a question of perceptual reconstruction of 3D surfaces. The reconstruction problem is computationally difficult because the 3D percept has to be produced from 2D image(s). It is known that this inverse problem can be solved (at least in principle) if the visual system can impose constraints on the family of possible solutions (see [11] for a review). To shed more light on the underlying perceptual mechanisms we study the effect of constraints that can be applied to surface contours: planarity and geodesic constraints. We also test the role of binocular disparity as a depth cue. Binocular viewing is tested by using Perspecta, a volumetric display.

The paper is organized as follows: Section 2 reviews prior work, Section 3 describes the psychophysical experiment conducted, Section 4 presents results, Section 5 provides discussion, and Section 6 sketches possible directions for future work.

2. Prior work

The systematic study of the role of surface contours in perception of 3D surfaces started with the work of Stevens [15,16]. He discussed the role of planarity and geodesic constraints, especially in the case of developable surfaces. The effect of geodesic constraint was further studied by Knill [7,8]. The interaction of *a priori* constraints imposed on surface contours and binocular disparity was tested by Stevens and Brookes [17], by Mitchison [10] and by Pizlo et al. [13]. Finally, the role of symmetry of an object and its contours was studied by Hochberg and Mcalister [5], Attneave and Frost [3], and Pizlo et al. [12]. All these studies demonstrated that contours constraints are critical not only in monocular, but also in binocular vision.

3. Psychophysical experiment

3.1. Subjects

Five subjects were tested including one author (SP). SP was familiar with the stimuli and with the research

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hypotheses being tested. The other four subject were naïve as to the design of stimuli and the hypotheses. SP received substantially more practice than the other four subjects.

3.2. Stimuli

The surfaces to be rendered are a family of single Gaussian functions with different aspect ratios. Given a Gaussian function F that is restricted to a standard domain, the intersection with a family of intersecting surfaces is computed. In the simplest case, the intersecting surfaces are a family of parallel planes, but in more complex cases other surface families are used. The number of intersecting surfaces was constant, but their position relative to the Gaussian surface, as well as orientation relative to the square base was randomized, in order to avoid comparing local cues, rather than the shapes of the whole surfaces. The intersection with a particular plane is computed using a simplicial continuation method; see, e.g., Allgower and Gnutzmann [2]. The method is related to the well-known "marching cubes" method from computer graphics, e.g., Bloomenthal [6], but by subdividing into simplices the ambiguous cases are avoided.

The implementation of the continuation method assumes only that the manifold of simplices is topologically a disk. This is easily accomplished in the case of planar sections. We extended it to nonplanar surfaces by simplicial subdivisions of annular regions which were cut to be topologically a disk. The seam along which the annulus was cut requires no special treatment as long as the discretization along the seam is compatible. That is, the fact that an intersection curve crossing the seam is connected can be ignored by the rendering algorithm and the result is indistinguishable by the observer.

Five families of intersecting surfaces were considered:

1. Parallel vertical planes that are parallel to the axis of symmetry of the Gaussian F.
2. Parallel oblique planes intersecting the symmetry axis of the Gaussian at an angle of 45 degrees.
3. Radial vertical planes that are parallel to the axis of symmetry of the Gaussian F.
4. Radial oblique planes intersecting the symmetry axis of the Gaussian at an angle of 45 degrees.
5. A family of spheres.

The family of spheres consists of spheres of equal radius whose centers are along a line and are evenly spaced. The center line lies in the plane $z = 0$ and intersects the axis of symmetry of the Gaussian. Examples for each family of curves are shown in Fig. 1.

Contours produced by intersecting surfaces 1–4, but not 5, were planar. All contours in case 3 were geodesic lines. None of the contours in case 2, or 5 were geodesic. One contour in 1 and 4 (the one approximately intersecting the symmetry axis of the Gaussian surface) was approximately a geodesic line.

3.3. Procedure

On each trial the subject was shown two stimuli and the task was to decide whether their aspect ratios were the same. Each stimulus was shown for one second, and they were separated by a one second pause (blank display). The 3D orientation of each stimulus was random subject to some constraints in order to eliminate views that provide zero, or close to zero information about the 3D shape (see Section 3.3.1). The size of each stimulus was also randomized. As a result, the subject had to pay attention to the aspect ratio of the 3D surface, rather than to its height.

Signal detection method was used [9]. On "same" trials, the two stimuli had identical aspect ratio, and on "different" trials the aspect ratios were different by 30%. The order of trials was randomized. Each session consisted of 200 trials: 100 same and 100 different. Hits and false alarm rates were used to estimate the discriminability d'. Viewing was either monoscopic (binocular viewing of an image displayed on an LCD monitor, see Section 3.4), or stereoscopic (binocular viewing of an image displayed in a volumetric 3D display, see Section 3.5). The order of the 10 sessions (five types of contours and two modes of viewing) was random and different for each of the five subjects.

3.3.1. View selection

The random views at which an observer sees the rendered Gaussians exclude the case where the planar curves are seen edge-on, with a view direction that lies within a degrees of the cutting planes. Such a view would not give any spatial information on account of the intersection curves being a collection of straight-line segments. We also exclude a view that is within b degrees of the axis of symmetry, i.e., seeing the Gaussian from above, a view within c degrees of being perpendicular to the axis of symmetry, and a view that sees the back face of the Gaussian base plane, since such views again would yield little or no spatial information (Fig. 2). In practice, we choose the angle limits a, b, and c to be 30, 30, and 5 degrees, respectively.

3.4. Display on conventional LCD

In half of the sessions the images were displayed on a conventional LCD. Viewing was monoscopic, with a binocular stimulus disparity of zero. The viewing distance was approximately 50 cm.

Only the visible lines were displayed. The hidden line removal is accomplished by rendering the curves as lines and then rendering the surface itself, using flat shading, in the color of the background, in our case white. The depth ordering and occlusion computations of the graphics hardware then shows the intersection curves only on the visible parts of the surface, irrespective of the point of view. That is, the rendered complex of curves and surface can be freely rotated in real time on standard PC graphics hardware. To resolve numerical issues, the intersections are offset from the underlying Gaussian by a slight dilation.