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Investigating Shape-from-shading Illusions Using Solid Objects

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Recent growth in the shape-from-shading psychophysics literature has been paralleled by an increasing availability of computer graphics hardware and software, to the extent that most psychophysical studies in this area now employ computer lighting algorithms. The most widely used of these algorithms in shape-from-shading psychophysics is the Phong lighting model. This model, and other shading models of its genre, produce readily interpretable images of three-dimensional scenes. However, such algorithms are only approximations of how light interacts with real objects in the natural environment. Nevertheless, the results from psychophysical experiments using these techniques have been used to infer the processes underlying the perception of shape-from-shading in natural environments. It is important to establish whether this substitution is ever valid. We report a series of experiments investigating whether two recently reported illusions seen in computer-generated, Phong shaded images occur for solid objects under real illuminants. The two illusions investigated are three-dimensional curvature contrast and the illuminant-position effect on perceived curvature. We show that both effects do occur for solid objects, and that the magnitude of these effects are equivalent regardless of whether subjects are presented with ray traced or solid objects. Copyright ©1996 Elsevier Science Ltd

Shape-from-shading Depth processing Three-dimensional curvature contrast Shading algorithms

INTRODUCTION

The past 20 years have been witness to a rapid growth in psychophysical investigations of shape-from-shading. The increased activity in this area of research is largely a consequence of the increasing availability of computer graphic systems. There are many obvious advantages to using such technology, such as the reduced time investment required for each experiment and the greater degree of experimental flexibility available to the experimenter. The primary advantage, of course, is the ease and precision with which shaded images can be manipulated. Thus it has become common practice for researchers to substitute computer-generated surfaces and shading algorithms for real objects and natural illumination in shape-from-shading experiments. The increasing work in this area has sought to address a number of important questions. One line of research has investigated which, if any, of the simplifying assumptions adopted by the machine vision community to overcome the problems of image analysis are employed by the human visual system (Berbaum *et al.*, 1983; Erens *et al.*, 1993a, b; Kleffner & Ramachandran, 1992; Mingolla & Todd, 1986; Ramachandran, 1988; Todd & Mingolla, 1983). Other lines of inquiry have investigated the processes underlying the integration of shading with other shape cues (Braunstein *et al.*, 1986; Bülthoff, 1991; Bülthoff & Mallot, 1990, 1988; Curran & Johnston, 1994b; Erens *et al.*, 1993b; Ramachandran, 1988), the effectiveness of shading as a cue to shape perception (Johnston & Passmore, 1994a; Koenderink *et al.*, 1994; Mingolla & Todd, 1986), and the level of the representation mediating shape from shading (Johnston & Passmore, 1994b, c; Todd & Reichel, 1989). Historically, research of the latter two issues have been closely related insofar as experiments investigating the effectiveness of shading typically employ perceptual judgement tasks that reflect the supposed geometric properties encoded by the visual system. Clearly it is important that the tasks given to subjects tap into the representational framework employed by the visual system.

Of those researchers who have investigated the effectiveness of shading, some have used local surface measurements as a means to probing subjects' impressions of solid shape. Mingolla and Todd (1986) report that subjects were poor at estimating the orientation of surface normals at various points on a computer-generated surface. Koenderink *et al.* (1994) found that subjects' judgements of relative depth are imprecise

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when compared to surface reconstructions derived from measures of surface orientation. Measures of surface orientation were made using a perceptual conformity task in which a probe stimulus was aligned with the surface normal and tangent plane at a number of points on photographs of shaded objects. Typically the reconstructed surfaces are smooth, depth scaled versions of the depicted surfaces (Koenderink *et al.*, 1995). Erens *et al.* (1993a, b) report that subjects are unable to distinguish elliptic and hyperbolic surfaces from shading for images in which illuminant direction is specified by the presence of a cast shadow on the surface. The results of other research suggest that shading is a poor cue to depth in comparison with binocular-disparity and kinetic cues (Bülthoff & Mallot, 1988; Cavanagh & Leclerc, 1989). These findings paint a rather bleak picture of the role of shading in shape perception; yet, chiaroscuro has been the prime vehicle for the depiction of surface shape in art, and shape is readily apparent in pictures of sculptures in which shading is the only cue available.

The apparent inconsistency between experimental results showing poor performance in shape-from-shading tasks and our perceptual experience suggest that some of the tasks used may not have favoured optimal performance. These tasks may have required subjects to make decisions about surface attributes that are not explicitly encoded by visual mechanisms (Johnston & Passmore, 1994a). This view is supported by the experimental results of Johnston *et al.* (1991) and Johnston and Passmore (1994a), who report Weber fractions of close to 0.1 for a curvature discrimination task in which shading provided the only information to shape. The value is close to that given for curvature discrimination on the basis of stereoscopic information (Johnston, 1991). It is possible that the recovery of curvature from shading depends upon the prior extraction of surface distance or surface orientation, the parameters of Marr and Nishihara's 2.5D sketch (Marr & Nishihara, 1978). However, Johnston & Passmore (1994a, b) showed that slant discrimination thresholds were a factor of 10 higher than the maximum change in the surface normal induced by a threshold change in surface curvature in a shape-from-shading task. In addition, it was demonstrated that, with a reduction in the elevation of the light source, curvature discrimination thresholds increased while slant discrimination thresholds decreased for the same surface patch. These findings generalized to stimuli defined by stereoscopic cues and texture cues. The evidence supports the view that surface curvature is recovered directly from the illuminance distribution in the retinal images rather than from a measure derived from the image, such as surface orientation. Thus, given the appropriate task, subjects are more likely to discriminate differences in surface geometry.

The ambiguity inherent in some shaded images, such as the well known "crater" illusion, has been used as a means of examining those processes underlying the extraction of shape-from-shading by the visual system. It appears that the visual system processes shape-from-shading in accordance with an assumption of a single, overhead light source (Benson & Yonas, 1973; Brewster, 1826; Gibson, 1950; Kleffner & Ramachandran, 1992; Ramachandran, 1988). This process has been shown to be based on a retinal, rather than a gravitational, frame of reference (Howard *et al.*, 1990; Ramachandran, 1988; Wenderoth & Hickey, 1993).

The ambiguity present in shaded images can be removed simply by including other, relevant, sources of three-dimensional form information; including boundaries (Ramachandran, 1988), stereo (Braunstein *et al.*, 1986), specular highlights (Blake & Bulthoff, 1990), surface texture (Curran & Johnston, 1994a), and cast shadows (Berbaum *et al.*, 1983; Erens *et al.*, 1993b). These studies have investigated factors affecting the tendency to see a curved surface as convex or concave. However, curvature varies in magnitude as well as in sign. Curran and Johnston (1996, 1994a) found that the perceived curvature of a convex spherical patch containing shading and texture cues was directly influenced by illuminant position. They report that the apparent curvature of the spherical patch was attenuated as the illuminant, initially positioned above the viewpoint, was rotated around the line of sight. This attenuation in perceived curvature became apparent when the light source tilt was extended beyond 90 deg. A similar effect was found when light source slant was varied; increasing slant resulted in an increase of apparent surface curvature. The effect of illuminant position on perceived curvature was reduced, but not eliminated, when a specularity was included in the surface's reflectance function. Similar enhancing effects of specularities on perceived curvature have been reported by other authors (Bülthoff & Mallot, 1990; Todd & Mingolla, 1983). The magnitude of the illuminant-position effect was also found to be mediated by the weight assigned to the texture cue, with the influence of the illuminant position being enhanced when a lower-weighted texture was substituted. As well as being influenced by illuminant position, Curran and Johnston (1994c) report that the apparent curvature of a convex surface is also influenced by the curvature of a surrounding surface. This effect, known as three-dimensional curvature contrast, is observed when two identical spherical patches defined by shading and/or texture cues are presented with one of the patches superimposed on a less-curved background sphere and the other superimposed on a more-curved background sphere. Under these conditions the former patch appears more curved than the latter. The existence of three-dimensional curvature contrast supports the view that the visual system encodes relative, rather than absolute, curvature (Johnston, 1992). Our investigations of three-dimensional curvature contrast suggest that it involves interactions at the level of representation of both brightness and surface curvature. Its persistence when the inducing surfaces are spatially separate from the test surfaces is taken as evidence that curvature perception involves non-local, as well as local, processes.

Many of the studies in the shape-from-shading

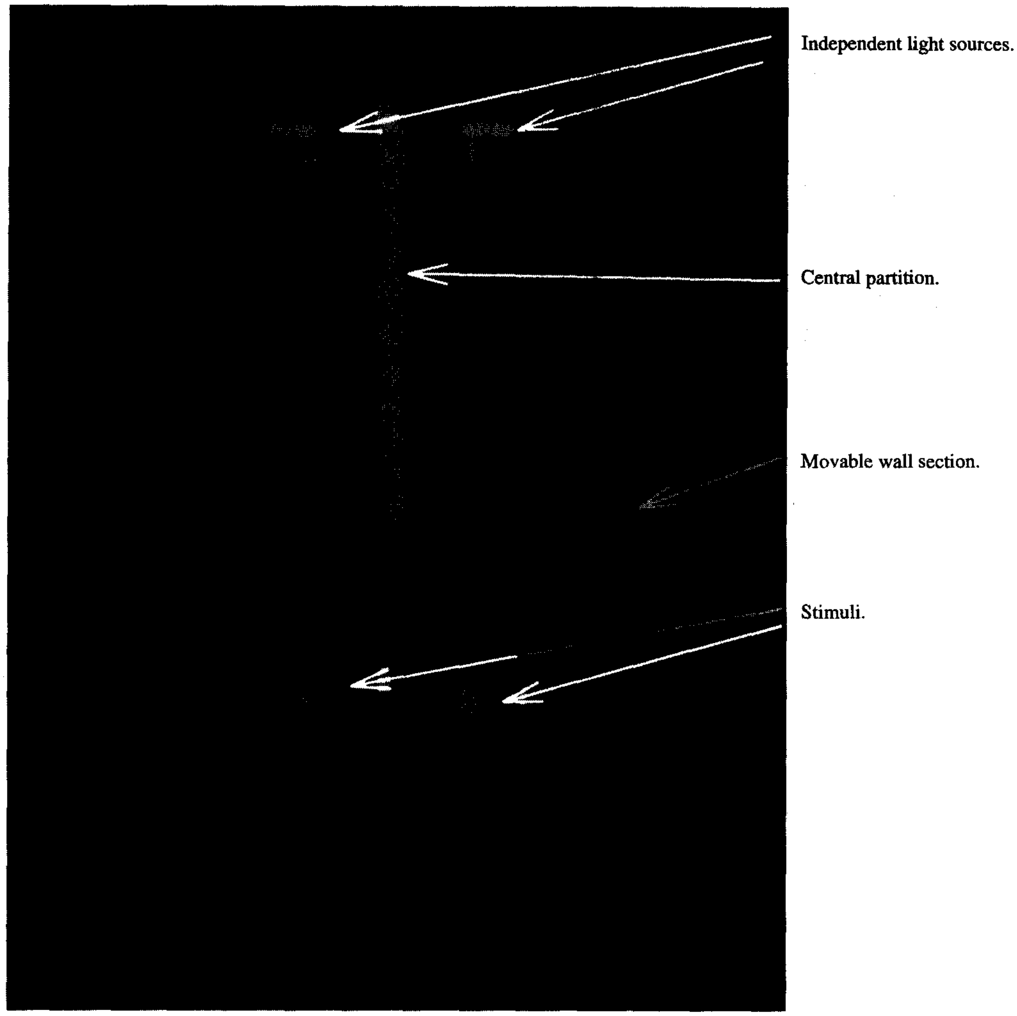

FIGURE 1. A schematic representation of the viewing box interior. Stimuli were presented through two apertures. The stimuli were illuminated independently and were separated by a central partition. Subjects observed the stimuli through a viewing aperture.

literature employ a widely used lighting model, the Phong illumination model (Phong, 1975). An implicit assumption of this type of research, in which computer lighting models are used to simulate natural lighting conditions, is that the experimental results would generalize to experiments using real objects and natural lighting conditions. Consequently, it is assumed that such experiments are addressing the question of how the human visual system processes shading information in the natural environment. However, the interactions of light in the real world are more complicated than in lighting models such as the Phong model. Mutual illumination, which describes how surfaces may act as secondary illumination sources by reflecting a proportion of their incident light onto each other, abounds in natural environments. This feature of naturally illuminated scenes is not satisfactorily modelled by the non-specific ambient illumination factor of the Phong lighting model (Parker *et al.*, 1992). Indeed, such concerns about the "physically unrealistic" stimuli generated by computer graphics have recently led to the use of real objects illuminated in a natural manner (Koenderink *et al.*, 1995). Given that there are important differences between natural lighting conditions and the Phong lighting model, and given that this particular lighting model is now commonly used in both shape-from-shading research and commercially available graphics software and hardware, the above assumption regarding the generality of experimental results to natural lighting conditions needs to be empirically tested. It is important to know whether the effects found in such experiments occur irrespective of the exact properties of the illumination, or whether they are peculiar to the illumination model used. The following experiments address this issue in two ways. Experiments 1 and 2 examine whether the two illusions described above, the effect of illuminant position on perceived curvature and three-dimensional curvature contrast, occur for real objects under natural illumination conditions. The results of these two experiments show that these effects do, in fact, generalize to real objects. In experiments 3 and 4 we investigate whether the magnitude of these effects using real objects is compar-

FIGURE 2. An example pair of stimuli used in experiment 1. Each stimulus is illuminated by a light source positioned at 0 deg tilt, 70 deg slant relative to the stimulus. The curvatures of the "surround" regions are $0.67\ \mathrm{cm}^{-1}$ and $0.29\ \mathrm{cm}^{-1}$ for the left and right stimuli, respectively, with curvature being defined as the reciprocal of the radius. The central patches of both stimuli have identical curvature. Yet the central patch embedded in the right stimulus appears more curved than the central patch embedded in the left stimulus.

able to their observed magnitude when using the Phong illumination model.

METHODS

Subjects

We tested 28 and 20 subjects in experiments 1 and 2, respectively. Nine subjects participated in experiment 3 and ten subjects were tested in experiment 4. All subjects had normal or corrected-to-normal vision.

Stimulus generation and display

Real objects were used in experiments 1 and 2, in which we tested whether subjects' perceived curvature of a spherical surface is influenced by either the curvature of a second surface in which the standard surface is embedded (three-dimensional curvature contrast) or the position of the light source illuminating the scene. Both real and ray traced objects were used in experiments 3 and 4, in which we compared the magnitudes of the above two effects for real and computer-generated surfaces.

The real objects were cast from pre-prepared moulds. Dental plaster, which was found to give the most acceptable white matte finish, was used as the casting material. A viewing box was constructed for presenting pairs of stimuli (see Fig. 1). The viewing box had a central partition such that a pair of stimuli were presented with one stimulus appearing on either side of the partition. Each half of the viewing box had its own internal light source emanating from a 12 V 20 W dichroic spot lamp with a light beam angle of 38 deg. Each light source was mounted on a vertical runner, thus allowing accurate adjustments of the light source position relative to the viewer and stimuli. The stimuli protruded from a sliding wall, which permitted the precise setting of a continuous range of viewing distances. The stimuli in experiment 1 consisted of four pairs of objects. Each object had a central spherical patch with a curvature of $0.48\ \mathrm{cm}^{-1}$, where curvature is defined as the reciprocal of the radius. Each central patch was embedded in a spherical surface whose curvature ranged from 0.29 to $0.67\ \mathrm{cm}^{-1}$ (see Fig. 2). For each stimulus pair the mean curvature of the central patches ($0.48\ \mathrm{cm}^{-1}$) was equal to the mean curvature of the two background surfaces. The stimuli in experiment 2 consisted of a single pair of objects. Unlike the stimuli in experiment 1, the stimuli used in experiment 2 were not embedded in a second curved surface. Both stimuli had a curvature value of $0.55\ \mathrm{cm}^{-1}$.

A set of stimuli pairs, of the same design as the stimuli in experiment 1, were moulded for experiment 3. Nine pairs of such stimuli were used. The surrounding surfaces had curvatures of 0.29 and $0.67\ \mathrm{cm}^{-1}$. The central patch embedded in the less curved surround ($0.29\ \mathrm{cm}^{-1}$) varied in curvature, in increments of 0.025 curvature units, from 0.28 to $0.48\ \mathrm{cm}^{-1}$; the central patch in the more curved surround ($0.67\ \mathrm{cm}^{-1}$) varied from 0.48 to $0.68\ \mathrm{cm}^{-1}$. The stimuli from the two "surround" sets were paired such that the mean curvature of the two central regions was equal to the mean curvature of the two backgrounds ($0.48\ \mathrm{cm}^{-1}$). The real-object stimuli used in experiment 4 were not embedded in a second curved surface. The standard stimulus had a curvature of $0.55\ \mathrm{cm}^{-1}$; the curvature of the comparison stimuli ranged from 0.28 to $0.505\ \mathrm{cm}^{-1}$, in steps of 0.025 curvature units.

The computer-generated analogues of the real-object stimuli used in experiments 3 and 4 were constructed by ray casting (Foley *et al.*, 1990). The stimulus generation software allowed control over the curvature of the stimuli, their location in the modelling space, the viewpoint and the location of a single point light source for each surface. The surfaces were rendered using the Phong illumination model,

$$P = sI_a + sI_p(\mathbf{N} \cdot \mathbf{L}) + gI_p(\mathbf{H} \cdot \mathbf{N})^n,$$

where P is the computed brightness, s is the albedo, I_a is the intensity of ambient illumination, I_p is the intensity of direct illumination, and g is the proportion of light reflected specularly. $\mathbf{N}$ and $\mathbf{L}$ are the surface normal and light source direction unit vectors and $\mathbf{H}$ is the unit vector which bisects $\mathbf{L}$ and the line of sight. The spread of specular reflection is controlled by the parameter n. The stimuli were modelled with Lambertian reflectance properties throughout the experiments. The product $\mathbf{N}\cdot\mathbf{L}$ was set to zero when negative. There were no surface inter-reflections.

In experiment 4 a grey level, random dot texture was added to the spherical surface stimuli using a texture mapping technique. This was to ensure that those stimuli illuminated from below did not become perceptually bi-stable in their curvature sign. The plane cannot be mapped onto a doubly curved surface without distortion. The nature of the distortion depends upon the mapping function. An equidistant azimuthal mapping, which preserves radial distances, was chosen. A detailed account of this mapping technique is described in earlier papers (Curran & Johnston, 1996, 1994b; Johnston & Passmore, 1994a).

The stimuli were displayed under polar projection on a 19" Sony Trinitron monitor screen under the control of a SUN Sparcstation 330. Rays were cast from a point 55 cm from the screen in experiment 3, and from a point 40 cm from the screen in experiment 4. The grey level display provided 8 bit resolution per pixel. In order to linearize the display a lookup table of luminance values was determined with a micro-photometer and used to control stimulus brightness. The position and direction of the light source are specified with reference to a coordinate frame centred on the patch. The z-axis extends out from the centre of the patch. Light source tilt is defined as the angle between the projection of the light source vector and the positive y-axis, and light source slant describes the angle of the light source vector relative to the z-axis (see Fig. 3).

The dimensions of the occluding apertures for the ray traced spherical patches were identical to those of the real objects. The three-dimensional curvature contrast stimuli (experiments 1 and 3) had inner and outer aperture diameters of 1.7 cm and 2.9 cm, respectively. Each stimulus used in experiments 2 and 4 had an occluding aperture of 1.7 cm diameter.

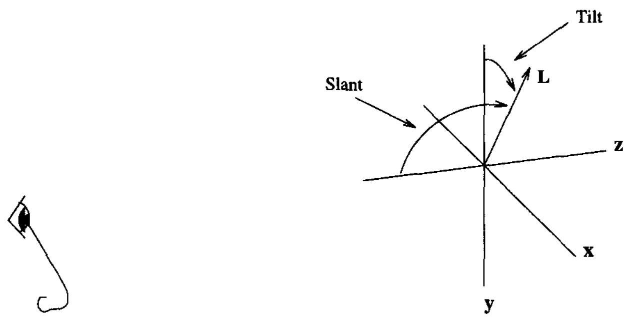

FIGURE 3. Light source slant and tilt as defined in the experiments. With the Cartesian coordinate system centred on the stimulus being viewed, tilt is defined as the angle between the positive y axis and the projection of the light source vector **L** on the x–y plane. Slant is defined as the angle between the light source vector and the positive z axis.

EXPERIMENT 1: THREE-DIMENSIONAL CURVATURE CONTRAST IN A REAL ENVIRONMENT

In this experiment subjects were presented with pairs of "real object" stimuli. The central spherical patches had identical curvatures (0.48 cm^{-1}). The curvature of the surrounding surfaces, in which the central patches were embedded, varied from 0.29 to 0.67 cm^{-1}. Four pairs of stimuli were presented to subjects in random order, with each stimuli pair being presented once. The mean curvature of the "surround" was always equal to the mean curvature of the central patches (0.48 cm^{-1}). Thus, for each presentation, one central patch was embedded in a surround whose curvature was less than or equal to the central patch, and the second central patch was surrounded by a surface of greater or equal curvature. The light sources were positioned at 0 deg tilt, 70 deg slant relative to the stimuli. The light sources were turned off between stimulus presentations. Subjects observed the stimuli pairs monocularly through a viewing aperture from a 55 cm distance. Head movements were restricted. The subjects' task was to decide which of the two central patches appeared the more curved.

Results

Table 1 lists the results for 28 subjects. If three-dimensional curvature contrast exists when real objects are substituted for ray cast stimuli, then one would expect subjects to report that a central patch embedded in a lower curved background appears more curved than an identical patch embedded in a more curved background. Column 2 records the number of subjects who reported that the central patch in the "low curvature" stimuli (i.e. those stimuli in which the background curvature was less than the central patch's curvature) appeared more curved than the central patch in the "high curvature" stimuli (those stimuli in which the background curvature was greater than that of the central patch). Column 3, on the other hand, lists the number of subjects who judged that the central patch in the "more curved" stimuli was more curved. When the two background surfaces were identical in their curvature, and, therefore, of the same curvature as the central stimuli, subjects performed at chance ($\chi^2 = 0.143$; d.f. = 1; NS). However, when subjects were presented with the three pairs of stimuli in which the background surfaces differed in curvature, there was a clear three-dimensional curvature contrast effect. When the backgrounds differed by 0.12 curvature

TABLE 1. The results of experiment 1, in which 28 subjects were tested

Background curvature	0.48 cm^{-1}	0.48 cm^{-1}	χ
No. of times central patch chosen as more curved	13	15	0.143 (NS)
Background curvature	0.42 cm^{-1}	0.54 cm^{-1}	
No. of times central patch chosen as more curved	26	2	20.57 ($P < 0.005$)
Background curvature	0.36 cm^{-1}	0.6 cm^{-1}	
No. of times central patch chosen as more curved	26	2	20.57 ($P < 0.005$)
Background curvature	0.29 cm^{-1}	0.67 cm^{-1}	
No. of times central patch chosen as more curved	25	3	17.29 ($P < 0.005$)

These results show a clear three-dimensional curvature contrast effect when solid objects are used. Thus a central patch with a curvature of 0.48 cm^{-1} appeared more curved when embedded in a less curved surround, and appeared less curved when embedded in a more curved surround.

units, 26 of the 28 subjects responded that the test patch embedded in the less curved background appeared more curved than the test patch embedded in the more curved background ($\chi^2 = 20.57$; d.f. = 1; $P < 0.005$). Table 1 shows similar results for the remaining two conditions, in which the background curvatures differed by 0.24 curvature units ($\chi^2 = 20.57$; d.f. = 1; $P < 0.005$) and by 0.38 curvature units ($\chi^2 = 17.29$; d.f. = 1; $P < 0.005$).

EXPERIMENT 2: THE EFFECT OF ILLUMINANT POSITION ON THE PERCEIVED CURVATURE OF REAL OBJECTS

In this experiment subjects were presented with a pair of spherical patches identical in their curvature. As in experiment 1, both stimuli were illuminated by independent light sources positioned at 0 deg tilt, 70 deg slant relative to the stimuli. The stimuli were viewed through two dove prisms from a 40 cm distance. Rotating the dove prism through which a shaded object is being viewed results in the apparent rotation of the scene, and is equivalent to rotating the light source illuminating the object. One of the dove prisms was fixed in its orientation, thus ensuring that a stimulus viewed through it appeared illuminated from above. The second dove prism was set to one of three orientations, thus simulating three light tilt conditions 0 deg, 90 deg and 180 deg. Subjects were shown the same pair of stimuli three times, once for each light tilt condition. However, they were unaware that the same pair was being presented. The prisms were positioned such that subjects could view both objects (one with each eye), and switch their gaze between stimuli in a natural way, without head movements. The viewing arrangement was such that when subjects fixated the left hand object the view from the right eye was occluded and when they fixated the right hand object the view from the left eye was occluded. The subjects' task was to indicate which of the two stimuli appeared most curved. Twenty subjects were tested.

Results

Table 2 shows the responses of subjects for the three presentation conditions, in which one stimulus illuminated from above was compared with a second stimulus illuminated either from above (0 deg tilt), from the side (90 deg tilt), or from below (180 deg tilt). In the 0 deg condition, in which both objects were illuminated from above, subjects' responses were evenly distributed between the two stimuli ($\chi^2 = 0.2$; d.f. = 1; NS). A similar result was obtained from the 90 deg condition, in which one of the objects was illuminated from the side ($\chi^2 = 0.8$; d.f. = 1; NS). However, in the 180 deg condition, 19 of the 20 subjects reported that the spherical patch illuminated from above appeared more curved than the patch illuminated from below ($\chi^2 = 16.2$; d.f. = 1; $P < 0.005$).

The results of the above experiments demonstrate that two previously reported curvature effects, which were observed for stimuli generated using the Phong illumination model (Curran & Johnston, 1996, 1994a, 1995), generalize to scenes illuminated by real lighting. However, it is important to know whether the magnitude of these two effects are comparable for ray traced and real objects. If, for instance, the effects are significantly stronger for those objects generated by Phong illumination it is possible that other measurable, but smaller, effects may be found with ray traced objects which are not found in real scenes. If this is the case researchers would necessarily have to exercise more caution when using experimental results of Phong illumination experiments to explain the visual system's processing of shape-from-shading. Conversely, if the above effects are stronger when viewing real scenes, there may be a number of "natural" shape-from-shading effects that would not be identified using the Phong illumination algorithm. This question is addressed in experiments 3 and 4, in which we compare the magnitude of the above effects for real and ray traced objects.

EXPERIMENT 3: THE MAGNITUDE OF THREE-DIMENSIONAL CURVATURE CONTRAST FOR REAL AND RAY TRACED STIMULI

In both the "real object" and "ray traced" conditions subjects were presented with pairs of stimuli similar to those depicted in Fig. 2. The curvatures of the two surround surfaces were fixed at 0.29 and 0.67 cm^{-1}. The curvature difference of the two central test patches was varied from trial to trial, with the constraint that their mean curvature was equal to the mean curvature of the surrounds (see Methods). Method of constants was used to measure subjects' psychometric functions in the real

TABLE 2. The results of experiment 2, in which 20 subjects were tested

Illuminant position (deg tilt)	0 deg	0 deg	χ
No. of times patch chosen as more curved	11	9	0.2 (NS)
Illuminant position (deg tilt)	0 deg	90 deg	
No. of times patch chosen as more curved	12	8	0.8 (NS)
Illuminant position (deg tilt)	0 deg	180 deg	
No. of times patch chosen as more curved	19	1	16.2 ($P < 0.005$)

Curvature perception is shown to be veridical when a spherical patch is illuminated from either above or from the side, but is underestimated when the stimulus is illuminated from below. These results concur with our earlier experiments involving ray traced stimuli (Curran & Johnston, 1994a, 1996) in which we found that curvature perception remains veridical for stimuli illuminated by a light source tilted up to 90 deg, but is increasingly underestimated as the light source tilt is increased beyond 90 deg.

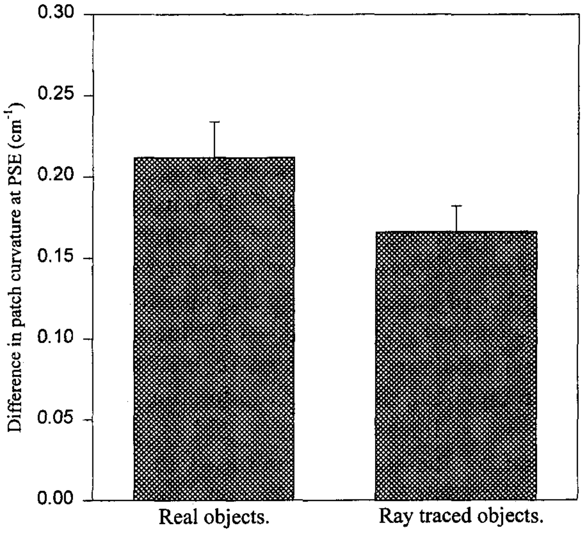

FIGURE 4. The magnitude of three-dimensional curvature contrast when viewing real objects (left) and ray traced objects (right). The results are averaged across nine subjects. Subjects produced three psychometric functions. Although the effect is slightly stronger when viewing real objects, the difference between the stimuli types was not significant ($t = 1.91$; d.f. = 8; $P > 0.05$).

object condition, based on eight presentations of each stimulus pair. The order of stimulus presentation, which was randomized, was computer controlled. The side of the central partition (left or right) that a stimulus appeared on was also randomly chosen. An adaptive method of constants, APE (Watt & Andrews, 1981), was used in the ray traced condition. The viewing distance and light source positions were identical to those used in experiment 1. Nine subjects were tested, with each subject generating three psychometric functions in each condition. Each psychometric function in the real-object and ray-traced-object conditions comprised 72 and 64 trials, respectively.

Results

Figure 4 plots the magnitude of three-dimensional curvature contrast as a function of the type of stimuli used. There was some subject variability. Most subjects (7) reported a larger effect for real stimuli than for ray traced stimuli, while the remaining subjects reported a stronger effect for ray traced stimuli. When averaged across subjects, the results show a slightly stronger effect for real objects than for ray traced stimuli. However, a two-tailed t-test shows that this difference between the two conditions is not statistically significant ($t = 1.91$; d.f. = 8; $P > 0.05$).

EXPERIMENT 4: THE MAGNITUDE OF THE ILLUMINANT-POSITION EFFECT FOR REAL AND RAY TRACED STIMULI

The stimuli used in this experiment were spherical patches with a bounding aperture of 1.7 cm diameter. The curvature of the standard stimulus remained fixed at 0.55 cm^{-1}, and the curvature of the comparison stimulus varied between 0.28 and 0.505 cm^{-1}. Stimuli in the real object condition were viewed through dove prisms, as in experiment 2. The standard stimuli were illuminated by a light source positioned at 70 deg slant, 135 deg tilt; the light source illuminating the comparison stimuli was positioned at 70 deg slant, 0 deg tilt. A light source tilt of 135 deg was used in this experiment to ensure that subjects' PSEs fell within the range of the available test stimuli. The viewing distance was 40 cm for both conditions. Subjects used a head and chin rest to prevent head movements. The head rest used in the ray traced condition had a central partition attached to ensure that only one stimulus surface was imaged on each eye. Here, as in experiment 3, method of constants was used in the real object condition and the APE adaptive method of constants was used in the ray traced condition. Ten subjects generated three psychometric functions in each condition. Each psychometric function in the real-object and ray-traced-object conditions comprised 70 and 64 trials, respectively.

Results

Figure 5 plots subjects' mean perceived curvature of real and ray traced objects for a light source tilt of 135 deg. The broken line in this figure indicates veridical perception. These data show a clear effect of light source position on perceived curvature for both types of stimuli, with subjects consistently underestimating surface curvature. Once again, there was some variability between subjects, with six subjects showing a greater effect for ray traced objects and four subjects demonstrating a greater effect for real objects. t-Test analysis failed to find a

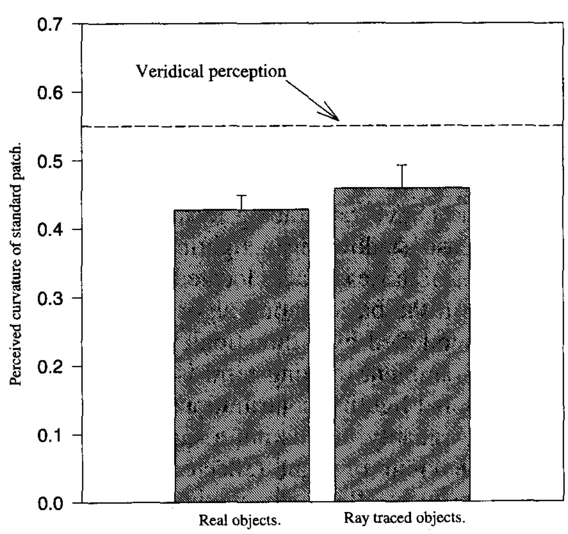

FIGURE 5. Perceived curvature of real objects (left) and ray traced objects (right) when the illuminant is positioned at 70 deg slant, 135 deg tilt. Results are averaged across ten subjects. Each subject produced three psychometric functions. The dashed line marks veridical curvature perception. The effect is slightly stronger for real objects, but this difference is not significant ($t = 1.36$; d.f. = 9; $P > 0.05$).

significant difference between subjects' perceived curvature of real and ray traced objects ($t = 1.36$; d.f. = 9; $P > 0.05$).

DISCUSSION

We employed the Phong illumination model in those experiments in which ray traced stimuli were used. The Phong lighting model is a widely used tool in shape-from-shading research. Despite its usefulness in producing readily interpretable images of three-dimensional scenes the algorithm is just an approximation of the ways in which real light interacts with objects. This is most apparent for scenes containing multiple objects, images of which contain a number of phenomena that the Phong model (in its most basic form) does not take into account; such as cast shadows and mutual illumination. An interesting characteristic of a cast shadow is its shape, which can act as a cue to both the object producing the shadow and the surface relief of the object receiving it (Cavanagh & Leclerc, 1989). A number of ray tracing techniques have been developed to handle cast shadows, such as shadow algorithms and recursive ray tracing (Foley *et al.*, 1990). Shadow algorithms, in contrast to the visible-surface algorithm used in the above experiments, determine which surfaces can be "seen" from the light source. The illumination calculation takes into account surface points that cannot be seen from the light source. The visible-surface algorithm determines which surfaces are visible from the viewpoint. By combining the results of these two algorithms, the ray tracer can construct convincing cast shadows. Images can also be constructed using recursive ray tracing techniques. This approach calculates cast shadows by firing an additional shadow ray from the point where the first ray intersects with the visible surface to the light source (or light sources). If this secondary ray strikes an object, then the surface point from which the ray originated will be in shadow and the contribution of the secondary ray's light source is ignored. Each of the shadow rays may, in turn, recursively spawn further shadow rays; such a recursive generation of shadow rays results in a ray tree.

Although the above ray tracing techniques allow the treatment of cast shadows in a lighting algorithm, the intensity values of those surfaces located within a shadow region are, as in the basic Phong algorithm used in our experiments, modelled by a directionless ambient-lighting term. This ambient-lighting term is used to account for all other global lighting contributions, such as mutual illumination. Arguably, this is not a satisfactory way to model the behaviour of light reflected from mutually illuminating surfaces. Radiosity methods (Foley *et al.*, 1990), which assume the conservation of light energy in a closed environment, make the ambient-lighting term redundant by more accurately modelling inter-object reflection.

Although techniques such as recursive ray tracing and radiosity methods handle cast shadows and mutual illumination effectively, they are more computationally intensive than shading algorithms of the kind that we have used in the experiments described above. Of course, it would be foolish to use a computationally simpler image-generation algorithm solely on the grounds of computational expense, particularly if it were to introduce artefacts into experimental results. Our experiments addressed this issue by investigating whether two previously reported illusions, found using ray traced stimuli incorporating the Phong illumination model, also occur for real objects under real lighting conditions.

A number of experiments in the literature report that the presence of cast shadows influences subjects' perception of a range of visual scenes. Kersten *et al.* (1994) found that the perceived motion of an object moving in a linear trajectory above a plane was influenced by the relative motion of the object's cast shadow. Berbaum *et al.* (1984) report that cast shadows resolve surface shading ambiguities. Similarly, Erens *et al.* (1993a) found that cast shadows disambiguate convex from concave surfaces, but not parabolic from hyperbolic surfaces; although there is also evidence that cast shadows do not affect performance on local surface slant and tilt judgement tasks (Mingolla & Todd, 1986). These effects of cast shadows on one's perception raised the possibility that the effect of illuminant position on perceived curvature (Curran & Johnston, 1996, 1994a) might be abolished when cast shadows are present. For example, in experiment 2, subjects could conceivably adopt a strategy of comparing the shapes of the two objects' cast shadows when deciding which of the two was more curved. Similarly, there was a possibility that the occurrence of cast shadows and mutual illumination in the real object stimuli of experiment 1 might have abolished the three-dimensional curvature contrast effect found with ray traced objects.

The results of experiments 1 and 2 provide a clear demonstration that both three-dimensional curvature contrast and the illuminant-position effect generalize from ray traced to real objects. Experiments 3 and 4 demonstrate that there is no significant difference in the magnitude of these effects, irrespective of whether they are produced using real objects and real lighting or ray traced objects and Phong lighting. It might be argued that the stimuli and illumination conditions in the real objects experiments were selected to give rise to images that would be similar to those used in the ray traced experiments and this maximized the likelihood of reproducing the two effects. However, there are some clear differences in addition to presence or absence of cast shadows and mutual illumination. Whereas the ray traced stimuli were modelled with a point light source, the light sources illuminating the real objects had substantial light beam angles (38 deg). Differential blurring was not present in the ray traced objects, but may occur when focusing on different points of real objects. Similarly, while information from accommodation cues would have conflicted with other geometric cues present in the ray traced objects (which are presented on a flat screen), it would be consistent with the geometric cues present in the real objects.

Our experimental results demonstrate that, when real objects are substituted for ray traced objects, any differences in the resulting retinal images do not contrive to abolish or change the magnitude of three-dimensional curvature contrast and the illuminant-position effect. This justifies to some degree the use of simple illumination models in psychophysical experiments. However, it should be noted that we have only demonstrated an equivalence between real and modelled objects for a limited set of very simple objects and illumination conditions. More complex scenes may well require more complex modelling techniques and ultimately any rendering technique needs to be calibrated against real scenes. Progress in understanding how the visual system recovers shape-from-shading will no doubt require the judicious use of a number of different approaches to stimulus generation.

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