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SHAPE PERCEPTION FROM SHADING
UNDER NATURAL LIGHTING CONDITIONS

DISSSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in
the Graduate School of The Ohio State University

By
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*****

The Ohio State University
2002

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ABSTRACT

Much of the recent research on the visual perception of shape from shading has employed computer generated images, which often do not include several basic components of shading that are common in natural scenes, such as cast shadows, indirect illuminations and specular highlights. In addition, the ambiguity in shaded images has been a puzzle for the studies on “shape perception from shading” since the 18th century.

The present research was designed to investigate the effects of the three components (i.e. cast shadows, indirect illuminations and specular highlights) on the shape perception and also the process of resolving the ambiguity in shaded images.

In the first three experiments, convex and concave half spheroids were used as stimuli. The presence of each of the three components could be turned on or off independently, the illumination direction could be from top or bottom, and the images were presented to observers in all possible combinations. Both the perception of the sign of curvature and the depth magnitude were tested. The results revealed clear biases in observers’ judgments of the sign of curvature (i.e.
convexity bias and overhead illumination bias). Different observers had different biases. Observers’ estimations of depth magnitude were affected by the sign of curvature, the presence or absence of cast shadows and the shininess of surfaces.

The forth and fifth experiments used images of randomly shaped objects as stimuli. Shape perception was very accurate comparing to the real shapes and it was also reliable across subjects and different illumination directions. The perception of complex shapes seemed to be more stable than convex and concave bumps. Even when the occluding contour of the complex shapes was masked off, shape perception was still very accurate and reliable across observers and illumination directions.

The estimations of illumination directions were also tested. The results showed close relationship between the estimated illumination direction and the judgment of the sign of curvature for convex and concave bumps. However, the illumination information may not be necessary for the perception of complex shapes.
Dedicated to my family
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1. What is “shape perception from shading”? Where does shading come from?

In a natural environment, objects are illuminated by various kinds of light sources such as the sun, the moon, lamps and light bulbs. These light sources make objects visible to human observers and the shading generated by them also provides information about three-dimensional shape.

Let’s take a look at an example in Figure 1. In the image, there are bright and dark areas, specular highlights on the surface and also the smooth occluding edge of the object. An observer is able to tell the shape of the object: it is a solid object with small hills and valleys on the surface. The primary information in the image is the two-dimensional distribution of bright and dark areas, which is called shading. Human observers are able to recover the 3D shape of an object from the shading appearance. The process underlying this phenomenon is the focus of the present thesis.
(1) **Shading is generated by the contact between a light and a surface.**

To better understand the basic concepts about shading, let’s follow the path of a light beam traveling in the air. When a light beam is emitted from a light source, it will often hit a surface. The amount of light that falls on a unit area of the surface is called *illuminance*. Its value varies with the angle between the light path and the surface (see Figure 2). When a surface faces directly to the light (i.e. perpendicular to the light source direction), it gets the maximum amount of illuminance (e.g. surface $\alpha$); otherwise, it gets less (e.g. surface $\beta$). In Figure 2, the same amount of light falls on both surfaces $\alpha$ and $\beta$, but since surface $\beta$ and the light source is not
perpendicular to each other as in the surface α case, the light falls on a larger area of surface β than on surface α. Therefore, the amount of light falling on a unit area (i.e. the illuminance) of surface β (i.e. the illuminance on surface β) is less than that on surface α.

Figure 2. When a surface is facing directly to the light (i.e. perpendicular to the light path), the amount of light falling on a unit area of the surface (i.e. illuminance) is more than any other surface orientations. The illuminance on surface α is more than that on surface β.

After light contacts a surface, part of the illuminance is absorbed and another part gets reflected. The amount of reflected light is called luminance. Shading refers to the gradation of luminance. Under the simplest lighting conditions, the amount of illuminance depends on the angle between light source and surface.
orientation, the luminance therefore varies with that angle too. An object is usually composed of small surface patches with different orientations. If the light source direction and intensity are constant for all the surfaces, the luminance of different surface patches will vary depending on the their relative orientations.

(2) The factors that affect a shading pattern include surface reflection, the presence of shadows and indirect illuminations

When light is reflected, its direction changes. Depending on the surface material, the reflection has different properties. In computer graphics, the reflection of incoming light is modeled as a combination of diffuse and specular components, which simulates the property of reflection in the real world. In one extreme case, light is scattered to all directions and this is called diffuse reflection. In another extreme case, light is reflected to only one particular direction, which is called specular reflection (see Figure 3). A perfect diffuse surface is often referred to as a Lambertian surface (see the left image in Figure 4). It was named after a German physicist J. H. Lambert who found that the luminance of a surface varies as the angle between the light source and the surface. The luminance on Lambertian surfaces does not change with an observer's viewing direction. On the other
extreme, a perfect specular surface (e.g. a perfect mirror surface) reflects incoming light to one single direction. If an observer’s eye is at that particular direction, a specular highlight will be seen and the place of specular highlight differs as the viewing direction changes. The reflection of most surfaces is a combination of the two components. The right surface in Figure 4 has a larger specular component than the left one which only has diffuse reflection. The specular component makes a surface appear shiny.

Figure 3. An illustration of the diffuse and specular reflection.
Lambertian surface

Surface with specular reflection

Figure 4. Two images showing a Lambertian surface and a surface with both diffuse and specular reflection.

In a natural environment, different surface areas are not illuminated equally. Shadows may appear on some surfaces due to the lack of illumination. Some shadows appear in areas that are facing away from a light source. In other words, the light cannot reach those areas because they are not facing the light source. This kind of shadow is called *attached shadow* since it is not separable from an object or a surface (see Figure 5). Sometimes, light is obstructed by other objects or surfaces on its way to a surface, the shadow generated by the obstruction of light is called *cast shadow* (see Figure 5). In the image of Figure 5, the dark area within the
boundary of the object is attached shadow area, the dark area outside the boundary is cast shadow area. The shadow in a scene is part of the shading pattern.

Figure 5. An illustration of attached shadow and cast shadow. Attached shadows appear in areas that are facing away from a light source but inseparable from a surface. Cast shadows are in the areas that light cannot reach because of the obstruction of light by other surfaces or objects.

There is usually more than one surface or object in a scene. If that is the case, light will be reflected many times among the surfaces. After light is reflected by a surface the first time, it may get reflected again by another surface and this process may repeat many times. The illumination on a surface therefore may come from two sources: directly from light sources or reflected by another surface. The first
kind of illumination is called direct illumination, the latter is called indirect illumination (see Figure 6). Both direct and indirect illumination on a surface affect its luminance.

![Diagram of direct and indirect illumination]

Figure 6. An illustration of direct and indirect illumination. The illumination on a surface may directly come from light source (i.e. direct illumination), or come from the reflected light by other surfaces (i.e. indirect illumination).
The images on the retina are two-dimensional, yet our perceptual experience is three-dimensional. How does this occur? Shading in an image is one potential cue for the perception of depth because shading appearance is partially determined by surface structure. However, a 2D shaded image can be inherently ambiguous because infinite number of shapes can generate the same image. Belhumeur, Kriegman, and Yuille (1999) demonstrated this ambiguity by doing computational analyses on Lambertian surfaces viewed in an orthogonal projection. They found that different combinations of shapes and light source positions could generate identical shaded images. Different shapes that are from a family of linear transformations can produce the same shaded image. This kind of transformation is called “generalized bas-relief” transformation.

There are many unanswered questions about the perception of shape from shading. How do human observers resolve the inherent ambiguity (i.e. how do they get unique shape perception when the information in an image is not enough)? Do the factors that affect shading appearance such as specular reflection, indirect illumination, cast shadow help to resolve the ambiguity? The following sections will discuss the prior research that is related to these.
2. The computational analyses of the “shape from shading”

The earliest investigations of shape perception from shading were performed by researchers in machine vision, and the algorithms they proposed provide a useful starting point for models of human perception.

The first attempt to use shading information for the computation of 3D shapes took place in the mid 1960s (Horn & Brooks, 1989). The task was to recover the shape of one part of the moon for human exploration. The special properties of the surface material of the moon and the knowledge of the light source – the sun, made the problem solvable. After that, many computational models were proposed to compute surface structure from shading (see Horn & Brooks, 1989 for a review). In a general case, as we have seen in the previous sections, shading patterns are affected by many factors and there is no simple relationship between shape and shading. How did the algorithms deal with the complexity in shading? The proposed algorithms got around the problem by focusing only on some factors and ignoring others. Most of the algorithms assume that the surface of an object is Lambertian that the surface scatters light equally in all directions and that there is only one light source with a known direction. Other factors are usually ignored. In
this way, the shading pattern is directly related to surface orientation.

To illustrate how the algorithms work, let’s go back to Figure 2. As shown in Figure 2, the relationship between the surface orientation and the illuminance is very simple: the illuminance is a function of the angle between the light source direction and the surface orientation. When light is perpendicular to the surface, the illuminance is at its maximum; as the angle deviates from 90 degrees, the amount of illuminance becomes smaller. If a surface is a Lambertian surface and there is no cast shadow or indirect illumination, the luminance on a surface is a proportion of the illuminance and therefore also varies with the angle between the light source and the surface orientation. The orientation of the surface can be computed from the luminance. The shape of an object can then be recovered from the orientations of small surface patches.

The algorithms described above can be used to compute shape in certain constrained lighting conditions. However, in the natural environment, cast shadow, specular reflection and indirect illumination also affect shading appearance and cannot simply be ignored. The algorithms that ignore those factors will lead to inaccurate results when analyzing images under natural lighting conditions.
Let's take a look at how the various factors discussed above violate the assumptions of the computational algorithms. Cast shadow is generated because of the obstruction of incoming light. The illuminance in cast shadow area is not the same as in other areas, which is not consistent with the simple light source assumption. Inaccurate shape will be generated if the algorithms treat the cast shadow area the same as other areas. Indirect illumination also varies the illumination on a surface and therefore makes shape computation less precise. The Lambertian surface assumption ignores specular highlights. For a surface with specular highlights, the relationship between the luminance and surface orientation is different from that of a Lambertian surface. The algorithms that assume Lambertian reflectance will not compute surface orientation accurately for shiny surfaces.

Another problem in “shape from shading” is the inherent ambiguity analyzed by Belhumeur et. al. (1999). Although computational models may avoid it by assuming that light source direction is known, human observers generally do not know light source position when looking at an image. How this ambiguity is resolved remains an open question.
3. How do human observers perceive shapes from shading?

In previous sections, two problems in "shape from shading" were raised (i.e. some factors that affect shading and the inherent ambiguity in shading). The principles of computational analyses were also discussed. Most of the algorithms get around these problems by ignoring specular highlights, cast shadow and indirect illumination, and also by assuming that the light source direction is known. Now let's examine how human observers deal with these problems.

(1) The effects of cast shadow, specular highlights and indirect illumination in the shape perception process

Empirical studies suggest that human observers can make use of cast shadow, indirect illumination and specular highlights. However, only a limited number of studies have investigated their effects and most of the tasks employed did not directly test shape perception.

The effects of cast shadow have been demonstrated in various visual tasks. The most frequently investigated aspect is its influence on perceiving the sign of surface curvature (i.e. whether a surface is convex, concave or flat). Convex surfaces are protuberances that come out of a background towards an observer, as in the left
image of Figure 7; concave surfaces are indentations that go into a background (see the right image in Figure 7). Cast shadows of a convex shape appear outside of the shape, on the opposite side of the light source. It is easy to determine light source position from the cast shadow position. Cast shadows for a concave shape are within the boundary of the shape, which is different from convex shapes and can be used as a cue to distinguish convexity and concavity.

Empirical studies have shown that observers are able to use cast shadows of convex shapes to figure out the light source position and then determine the convexity or concavity of other shapes in the same scene (Berbaum, Bever, and Chung, 1984; Erens, Kappers, & Koenderink, 1993a). Another study found that cast shadows were useful in estimating spatial position (i.e. the relative distance between block shaped objects in a 3D space) and the orientation of objects (Wanger, Ferwerda, & Greenberg, 1992). Moreover, cast shadows and indirect illuminations together were shown to be the dominant cues for observers to determine whether an object was lying on a plane or hovering above it (Madison, Thompson, Kersten, Shirley, & Smits, 2001).
Figure 7. An illustration of convex and concave shapes. The surface on the left comes out of a background toward an observer. This kind of shape is called convex shape. The surface on the right goes into a surface and is called a concave shape.

Not much research has investigated the effect of indirect illumination even though its effect has been known in the arts for a long time. Leonardo da Vinci (1452-1519) pointed out that the shading in different environments is not the same: the light falling through windows into a room and the light in an open field are different and a scene drawn in one environment cannot be mixed into another (see Richter, 1970). One reason for this is that the surfaces in a room are close together and a light beam has more chance to be reflected among surfaces than a light beam in an open field where there are not many surfaces. Therefore, indirect illumination is more common in a room-like environment than in an open field and the shading appearances are different.
Recent research has illustrated that human observers use the presence of indirect illumination for their judgments about whether a miniature room is white or black (Gilchrist & Jacobsen, 1984). White surfaces reflect more light than black surfaces and therefore there is more indirect illumination in a white room, which makes black and white room appear different. In addition, Madison, et. al.(2001) showed that indirect illumination helped observers to decide whether an object had contact with a surface.

The shininess of a surface (i.e. whether a surface has specular highlights) also affects shading. Does it affect shape perception? Todd, Norman, Koenderink, and Kappers (1997) found that local orientation estimations for shiny potato shaped surfaces were more accurate and reliable than matte surfaces. Blake and Bulthoff (1991) showed that stereoscopically viewed specular highlight was one cue for the perception of 3D local surface geometry (i.e. the convexity or concavity of a shape). It appears that specular highlights help shape perception.
(2) How do human observers resolve the inherent ambiguity of shaded images to perceive unique shapes?

Another issue in “shape from shading” involves the inherent ambiguity in shaded images. As mentioned before, Belhumeur et. al.(1999) analyzed mathematically the relationship between shaded images and the shapes that generated them. They found that the same shaded image could be the result of different combinations of illumination directions and shapes (i.e. the depth profile).

How do human observers resolve this kind of ambiguity?

Empirical research has provided evidence supporting the speculation that the observers resolve the ambiguity by preferring some shape interpretations over others. In the natural environment, not all the events occur with the same frequency; some are more common than others. A preference for more frequently occurring events may help to resolve the ambiguity. Such preferences are called priors or biases. Two priors (i.e. overhead illumination and convexity) were found and relevant studies will be discussed next.

A close relationship between shape perception and light source position was first discovered in the 18th century. In 1780, David Rittenhouse observed an
inversion of depth when looking through a tube without any lenses and the light was reflected opposite to its original direction by a mirror. When an observer did not notice the inversion of light direction, the object’s relief was reversed perceptually (i.e. convex shapes were seen as concave and concave shapes were seen as convex). The knowledge of the light source direction might have affected the perception of a shaded image.

In more recent studies, a bump shape such as a hemisphere or a muffin pan cusp has more commonly been used to investigate the relationship between shape perception and illuminant direction. The shading of those simple shapes is primarily due to the sign of curvature and the illumination direction. Under lighting conditions without cast shadows, specular highlights or indirect illuminations, a convex hemisphere under overhead illumination generates an image of a top bright, bottom dark shading pattern, which is the same as the image of a concave hemisphere under illumination from below (see Figure 8). If the illuminant direction is not known, the image can be perceived as either convex or concave. Many studies illustrate that this type of shaded image is usually perceived as a convex shape coming out of the background (Berbaum, Bever, & Chung, 1983; Berbaum, Bever, & Chung, 1984; Brewster, 1826; Ramachandran, 1988).
results suggested that human observers might have a preference to see the light source from above. An illustration is shown in Figure 8.

Figure 8. The top image in 8a shows that with the overhead illumination preference, a top bright bottom dark shading is perceived as a convex shape. The bottom image is a convex hemisphere illuminated from above. The top image in 8b illustrates that a top dark bottom bright shading is perceived as a concave shape with the overhead illumination prior. The image at the bottom of 8b is a convex shape illuminated from below, the shape can be perceived as concave with the prior of overhead illumination.
Previous findings have also shown that observers may rely on another prior in shape perception: they tend to see convexity rather than concavity. Hill and Bruce (1993) found that the hollow-face illusion (i.e. a concave face was perceived as convex) occurred when a hollow face was turned upside down, which indicated that convexity was preferred for a general shape: for unfamiliar shape (e.g. upside-down face). Hill and Bruce (1994) further investigated the convexity prior by using both hollow face and hollow potato as stimuli. They found stronger illusion for hollow face than for hollow potato, which indicated the effect of familiarity. In addition, the illusion of hollow face and potato did not differ when the stimuli were upside down. The results provided evidence for the hypothesis that the convexity was preferred for generic objects. Empirical evidence has also shown that the sensitivity in depth discrimination task under global convexity is higher than that under global concavity (Langer and Bulthoff, 2001).

The two priors discussed above (i.e. overhead illumination and convexity) can help to determine whether a shape is convex or concave. They may constrain the perceived shape to half of the possible shapes, but cannot help the perception of the
details of a shape such as the depth magnitude at different places. The inherent ambiguity in depth magnitude still exists according to the analysis of Belhumeur, et al. (1999).

Very few studies investigated shape perception by testing observers' estimation of depth magnitude. Konderink, van Doorn, Kappers, and Todd (2001) used four different tasks to test observers' shape perception. Observers looked at the photographs of sculptures. The perceived depth profiles were quite different for one observer in different tasks and among observers. However, when the perceived depth profiles were transformed using an affine transformation (a kind of Bas-relief transformation), they were virtually identical for different tasks and observers. The results are consistent with the analyses of Belhumeur et. al. (1999). They demonstrated that even though image information was not enough for the observers to determine a particular shape, they seemed to pick one shape from a group of possible shapes arbitrarily.

This first chapter introduced the basic concepts in shading and some factors that affect shading: the shininess of a surface, cast shadows and indirect illuminations. Previous studies found the effects of those factors in various tasks. However, their
effects on shape perception were hardly investigated. Moreover, no empirical studies have considered all of them in one experiment. It will be interesting to investigate their effects in one experiment by manipulating the presence of each factor and using a task that directly tests shape perception. In this way, the results under different manipulations can be compared to each other and the interactions among the experimental factors can also be analyzed.

With respect to the inherent ambiguity in shaded images, previous findings about the two priors showed that observers might rely on them to resolve ambiguity in perceiving the sign of curvature. Whether the process is influenced by various lighting conditions remains a question.

The first experiment used simple shapes' shaded images under different lighting conditions to investigate the basic effects of cast shadows, indirect illuminations, and specular highlights in shape perception. The presence of each factor was controlled independently in the experiment. Both the perceived sign of curvature and the depth magnitude were tested. The results will not only illustrate how observers make use of the various factors in their shape perception, but also how they resolve the inherent ambiguity in shaded images.
CHAPTER 2

The present set of experiments was designed to investigate the perception of simple shapes under various lighting conditions.

EXPERIMENT 1

In the first experiment, half spheroids were used as stimuli. A Spheroid is a spherelike shape. The difference between a spheroid and a sphere is that the radius along one axis of a spheroid is different from the other two identical radii while all the radii are the same for a sphere. In the present experiment, a spheroid's radius along the z-axis (i.e. the axis in depth) was varied to form different shapes. Subjects estimated both the sign of curvature and the depth magnitude of the depicted surfaces.
Methods

**Subjects.** Seven observers (4 males, 3 females) participated in the first experiment. They all had normal or corrected-to-normal visual acuity. Three of them received payment for the participation.

**Apparatus.** Experiments were run on a Dell Precision 420 PC with OpenGL graphics package for the production and the presentation of stimuli. Stimuli were presented within a 37.5 (horizontal) x 30.0 (vertical) cm rectangular region of the display screen with a spatial resolution of 1280 x 1024 pixels and refresh frequency of 85 Hz. The displays were viewed from a distance of 114 cm, such that the screen subtended 18.75° x 15.0° of visual angle and each pixel subtended 0.88‘ visual angle.

**Stimuli.** The stimuli were images of half spheroids on a planar surface. The shapes were similar to those used by Benson & Yonas (1973), Berbaum, Bever, & Chung (1984) and Morris (1996). The spheroid was either convex or concave. The radii of the spheroids in the horizontal and vertical axes were the same and had a fixed length. The radius along z-axis varied and the ratio between its length and the other radii was 1.3, 1.0 or 0.7.
The scene for the image rendering was constructed in 3Ds Max 4.2. A half spheroid shape was put at the center of a back wall in a room that was 120 by 120 by 120 inches (see Figure 9). The viewing point was at the center of the wall facing the shape and the viewing angle was 45 degrees. The scene was illuminated by a 20 by 20 inch area light in the center of the ceiling.

Figure 9. A demonstration of the layout of a scene for image rendering. The scales are not proportional to the original layout, only the relative positions are shown here. A spheroid was put at the center of one wall. A concave spheroid is shown in the figure. A light source was within a square region on the ceiling or on the floor. The viewing point was at the center of the wall facing the object.
The stimuli were rendered in Lightscape 3.2 using both radiosity and ray-tracing algorithms. The material of a spheroid and its background plane was either glossy or matte (i.e. Lambertian surface). The material of the other walls was all matte. The presence of specular highlights, indirect illumination or cast shadow was manipulated independently.

The images were rendered to be 512 by 512 pixels and they were presented in a 15 by 15 cm square on the left of the monitor screen. The spheroid at the center of the image was 3 cm in radius on the screen. The maximum intensity of the images was less than the maximum intensity of the display monitor and the mid point of the intensity range of the images was shifted to be at half of the maximum intensity for all the images. Figure 10 shows some example images.
Convex

without cast shadow
Light from above

without cast shadow
with cast shadow

Light from below

Concave

without cast shadow
Light source from above

without cast shadow
with cast shadow

Light from below

Figure 10. A sample of the stimuli in Experiment 1.
A probe was composed of two line segments and a curve in the middle. The curve indicated the depth profile of a half spheroid as if it were viewed from the side (see Figure 11). The gap between the line segments was fixed and was the same as the diameter of the shape in the image. Observers could adjust the curve to indicate both the sign and the magnitude of the curvature. A symbol of an eye was drawn at the right to the probe, which helped to indicate the direction of convexity or concavity. Curves to the right of the line segments indicated convex shapes, and curves to the left indicate concavity. The curve could also be stretched horizontally to match the perceived depth of the depicted surface in the image.
Figure 11. An example of the stimulus and the probe of Experiment 1. An image was presented on the left of the screen, the task probe was on the right. The solid curve in the figure is one possible setting and the dashed lines are some other possible settings with different depth magnitudes. Observers only saw one curve in the experiment. In the probe, the two line segments were fixed and the curve in the middle of the line segments could be adjusted by an observer. Both the perceived sign of curvature and depth magnitude of the surface in the image were indicated by the probe setting. The depth magnitude can be indicated by the curvature of the curve in the probe. The symbol at the right represents an eye. A curve on the right of the line segments indicates convexity and a curve on the left indicates concavity.

Design. The experiment was a six-factor within-subject factorial design. The images were generated under 96 conditions: 2 shapes (concave or convex) X 3 depth to radius ratios (0.7, 1.0, 1.3) X 2 shininess conditions (with or without specular highlights) X 2 illumination conditions (with or without indirect illuminations) X 2 shadow conditions (with or without cast shadows) X 2 illumination directions (light from top or from bottom). The images rendered under
the 96 conditions were presented randomly to the observers in one block of trials. Each subject did five blocks of trials.

**Procedure.** Images of the spheroids were presented on the left of the computer screen and a probe was presented on the right (see Figure 11). The curve in the probe was straight at the beginning of each trial. The observers covered one eye with an eye patch and viewed the displays monocularly. Their heads were stabilized by a chinrest at a viewing distance of 114cm.

Observers judged convexity or concavity of the shape in the image by setting the curve to the right or the left of the line segments in the probe. They could also stretch the curvature of the probe with the mouse so that it appeared to match the depicted spheroid. Both the sign of curvature and the depth magnitude were indicated in one response. When satisfied with the setting, observers pressed the space bar and a new image and probe appeared for the next trial. Observers received no feedback about their performance.

**Results and Discussion**

The results on the perceived sign of curvature and depth magnitude were analyzed separately.
1. Results on the perceived sign of curvature

The proportions of correct judgments under different conditions are shown in Figure 12.

![Correct responses of the sign of curvature](image)

Figure 12. The percentage of correct responses for the judgment of the sign of curvature under different lighting conditions. The error bars are 95% confidence intervals.
As shown in Figure 12, most of the convex shapes were correctly seen as convex while most of the concave shapes were incorrectly perceived as convex. It seems that observers had a bias to see surfaces as convex rather than concave. Similarly, observers' performance was better when the light source was from above than from below. The judgments of the sign of curvature were more accurate when the light source was from above. The difference in their judgments indicates that observers' perception is more consistent with the overhead illumination. Observers' biases will be analyzed in more detail in the discussion of Figure 13.

The perception of the sign of curvature was also affected by the presence of cast shadow. The shapes with cast shadow were perceived more accurately than those without cast shadow. This was true for both convex and concave shapes. This result provides new evidence about the effects of cast shadow in shape perception. Previous studies showed its effects in the perception of the relative spatial positions of objects (Madison, et. al., 2001; Wanger, et. al., 1992). Other experiments also showed that a reference object with obvious cast shadow helped the perception of another object's sign of curvature (Berbaum, et. al., 1984; Erens, et. al., 1993a). In the present experiment, the presence of cast shadow on the same shape was manipulated. For a convex shape, cast shadow appears outside of the shape and it is
obvious that its appearance helps to discriminate whether a shape is convex or not. However, for a concave shape, cast shadow appears within the region of the shape. Observers were still able to make use of the information. They saw concavity more accurately when cast shadow was present than when it was not.

The accuracy of perceiving the sign of curvature did not differ significantly between shiny and matte surfaces. This result is not consistent with the finding of Blake & Bulthoff (1991). They found that specular highlights helped the perception of the sign of curvature when an image was viewed binocularly. In the present experiment, observers viewed the images with only one eye, there was no binocular disparity. This may be the reason that specular highlights did not show any effects in the perception of the sign of curvature.

Indirect illuminations were not found to affect the perception of the sign of curvature.

Let’s go back to the priors that observers might use in resolving the ambiguity in shaded images. The results showed that observers tended to see the shapes as convex more often than concave; their responses were also more accurate when light was from above than when it was from below. The convexity prior appears stronger than the overhead illumination prior.
Large individual differences were also found in using the two kinds of priors. The percentage of the responses that were consistent with overhead illumination and convexity priors are plotted for each observer in Figure 13.

Figure 13. The percentage of correct responses that was consistent with overhead illumination or convexity for each observer. The error bars are 95% confidence intervals.

To better understand Figure 13, let’s first check what the chance level means. If observers perceived the sign of curvature correctly all the time, 50% of their
responses should be convexity and 50% of the responses would be consistent with overhead illumination because half of the stimuli were convex shapes and half of the images were rendered with overhead illumination. There was another possibility: if the observers just randomly picked one shape from the two options of convexity and concavity, they would also have about 50% chance of picking convexity over concavity and half of their responses would be consistent with overhead illumination.

The results in Figure 13 showed clearly that observers' responses were not perfect or random at all. Five out of the seven observers perceived significantly more convex shapes than concave ones. Three observers showed tendency to see light coming from above than from below.

The interesting phenomenon in this experiment is that the number of observers who demonstrated convexity preference was more than that showing overhead illumination preference. The effect of convexity prior also appeared stronger than overhead illumination. Observers had either one of the preferences and only one subject showed both.
2. The perception of the depth magnitude

All the observers’ depth magnitude settings were analyzed independently from the perceived sign of curvature. Only the magnitude was considered in the following analyses. The effects of all the factors and the interactions among them were tested by MANOVA. Since there were 96 conditions and 35 repeats for each condition, many effects were significant. Only the effects that could explain more than 5% of the total variance will be discussed here.

The analyses showed significant main effect of the sign of curvature (p<0.01). The differences in the sign of curvature explained 70.2% of the variance in perceived magnitude. Convex shapes were perceived to have more depth than concave shapes no matter what the perceived sign was (see Figure 14).

Since only absolute depth estimations were considered in the above analyses, it was not clear whether the perceived sign of curvature had an effect on the estimated depth magnitude. The results were then analyzed separately for correct and incorrect responses in the perception of the sign of curvature. Figure 15 shows that the estimated depth magnitudes for convex shapes were larger than concave shapes no matter whether the sign of curvature was perceived correctly or not. There was indeed a difference between the perceived depth magnitudes for concave shapes.
When concave shapes were seen as concave correctly, the perceived depth was more than when they were perceived incorrectly as convex.

The differences in the sign of curvature also had a significant interaction with the presence of cast shadows in the magnitude of the perceived depth (p<0.01), which explained 9.9% of the total variance of the responses (see Figure 14). The effect of cast shadow was in different directions for convex and concave shapes. For convex shapes, observers perceived more depth when the cast shadow was present than when it was not (see Figure 14). For concave shapes, the presence of case shadow reduced the perceived depth. In other words, the convex shapes with cast shadow appeared to have more depth than without cast shadow and the concave shapes with cast shadow looked flatter than those without cast shadow.
Convex shapes

- no cast shadow
- with cast shadow

Concave shapes

- no cast shadow
- with cast shadow

Figure 14. The main effect of the sign of curvature and the interaction between the sign of curvature and the presence of cast shadows are shown here. The main effect of the sign of curvature becomes obvious if the results in the two figures are compared. Convex shapes were perceived to have more depth than concave ones. Convex shapes appeared to have more depth when cast shadow was present in an image. The perceived depth of concave shapes was reduced when there was cast shadow.
Figure 15. The interaction between the perception of the sign of curvature and the depth magnitude for convex and concave shapes. In general, convex shapes were seen to have more depth than concave ones. There was little difference in the depth magnitude perception for convex shapes no matter what the judged sign of curvature was. For concave shapes, the perceived depth was more when they were correctly judged as concave than when they were seen as convex.

The shininess of a surface also influenced the estimated depth magnitude (p<0.01). The surfaces with specular highlights were perceived to have more depth than those that had a matte reflectance (see Figure 16). This effect explained 6.4% of the total variance in the responses. The specular highlights make the luminance variation larger on a shiny surface than a matte surface, which may cause larger
perceived depth on shiny surfaces.

The effect of shininess of surfaces

![Graph showing the effect of shininess of surfaces]

Figure 16. The main effect of specular highlights on perceived depth magnitude.

The results from the first experiment illustrate the basic effects of the experimental factors that were manipulated. Cast shadow had effects on both the perception of the sign of curvature and the depth magnitude. Specular highlights enhanced the perceived depth, while indirect illumination had no effect for either the perception of the sign of curvature or the depth magnitude.
The results also indicate that observers might use two priors to resolve the ambiguity in shaded images. The convexity prior appears stronger than overhead illumination prior. Individual observers had different priors.
EXPERIMENT 2

In Experiment 1, the boundary between a half spheroid and the background wall was abrupt and might be perceived as an occluding contour. An occluding contour appears at places that separate the parts of a surface that observers can see and those that they cannot see. It is the smooth edge of smooth solid shapes. At the occluding contour, the line of sight is perpendicular to the surface normal. Koenderink (1984) analyzed the relationship between convex or concave occluding contours and solid shapes. He proved that a convex occluding contour corresponded to an ovoid surface patch while a concave contour came from a saddle-shaped surface patch. In the first experiment, the boundary was a circle, which was convex everywhere. If the boundary between the shape and the background was perceived as an occluding contour, the solid shape can only be ovoid (i.e. convex in all directions) physically. Observers may have relied on this cue in the first experiment, which would have been responsible for the strong preference for convexity over concavity.
Empirical studies have shown that human observers use the information from smooth occluding contour in their shape perception. Howard (1983) showed that when the occluding edge of an object was at its bottom, the object was seen as a hollow. When the occluding edge was at the top of an object, the shape was perceived as a hill. So the position of a surface’s occluding edge helped to determine the perceived shape. Ramachandran (1988) demonstrated that the same shading pattern with different occluding edges could produce different shape perception. Other research also showed the effects of the occluding edges (Buckley, Frisby, & Freeman, 1994; Knill, & Kersten, 1991).

The occluding edges may constrain the explanation of the shading pattern and therefore play a role in resolving the ambiguity in shading. However, it is still not clear whether observers rely on it to determine the sign of curvature, or to detect the detailed shape of surfaces.

In Experiment 2, the shapes of the stimuli in Experiment 1 were changed by smoothing out the boundary between a bump and its ground plane (see Figure 17). The possibility of perceiving the boundary as smooth occluding contour was reduced. A comparison of the results of Experiment 1 and 2 will reveal the effects of the occluding contour.
Methods

The participants, the apparatus, the design and the procedure were the same as Experiment 1. The only difference was the shape of the stimuli. The sharp edge between a half spheroid and its background was smoothed out (see Figure 17 for some examples). An example of the stimulus and the probe is shown in Figure 18.
Convex:

without cast shadow  with cast shadow  
Light from top

without cast shadow  with cast shadow  
Light from below

Concave:

without cast shadow  with cast shadow  
Light from top

without cast shadow  with cast shadow  
Light from below

Figure 17. Some stimuli for Experiment 2.
Results and discussion

As in Experiment 1, the results of the perceived sign of curvature and the depth magnitude were analyzed separately.

1. The perceived sign of curvature

The effects of the various factors manipulated in the present experiment were similar to those in Experiment 1. Cast shadow helped the perception of the sign of curvature. Convex shapes were perceived more accurately when cast shadows were present than when they were not. In this experiment, cast shadow only helped the perception of convex shapes, not concave shapes. The accuracy in perceiving concavity was increased relative to the first experiment and the accuracy was the
same whether cast shadow was present or not. There was no effect of indirect illumination or specular highlights.

The sign of curvature and the illumination direction also affected the perception of the sign of curvature. The performance was better for convex bumps than concave ones. The perception of the sign of curvature was more accurate when light was from above than when light was from below. The biases for convexity and overhead illumination were similar to the findings of Experiment 1.

Individual observer’s responses are plotted in Figure 19. Four out of seven observers tended to see convexity over concavity. The number was one less than that in Experiment 1. Observer JT and JC reduced their convexity biases. With respect to the overhead illumination prior, there was also a difference. Observer JT showed slight overhead illumination bias, which was not obvious in Experiment 1. Either the convexity or the overhead illumination preference was dominant for 6 out of 7 observers. Only observer JT had both priors.
Biases for convexity and overhead illumination

Figure 19. The proportion of responses consistent with overhead illumination and with convexity. The error bars are 95% confidence intervals.

Experiment 2 changed the shape of the stimuli and the convexity bias was reduced for two observers. However, four observers still had strong biases to see the half spheroids as convex. The results indicated perceiving the boundary between a surface and its background as an occluding contour was not the only reason for the strong tendency to perceive convexity over concavity.
2. The perception of the depth magnitude

The effects of all the factors and their interactions on the perceived depth magnitude were analyzed using MANOVA. Only the effects that explained more than 5% of the total variance will be discussed.

![Graphs showing the effect of sign of curvature and shininess of surfaces on perceived depth magnitude.](image)

Figure 20. Some significant effects on the perceived depth magnitude. The sign of curvature, the shininess of a surface and the depth to radius ratio explained 64.4%, 16.1% and 7.2% of the total variance of the responses respectively. The error bars are 95% confidence intervals.
The sign of curvature had the largest effect as in Experiment 1 (p<0.01), accounting for 64.4% of the total variance. Convex shapes were perceived to have more depth than concave ones (see Figure 21).

The effect of the surface shininess explained 16.1% of the total variance. Surfaces with specular highlights appeared to have more depth than those without (see Figure 21).

The actual depth of the depicted surface also had a significant effect that accounted for 7.2% of the variance. This shows that as the simulated depth varied, the perceived depth changed accordingly.

The results of Experiment 2 were basically the same as Experiment 1. There are two differences. The first one is that the sign of concave shapes was perceived more accurately than in the first experiment. More of the concave shapes were seen correctly as concave. The second difference is the effect of cast shadow. The presence of cast shadow did not help the judgment of concave shapes’ sign of curvature compared to no cast shadow condition. With respect to the perceived depth magnitude, cast shadow did not affect it in the second experiment. The reason for this may be due to the smoothness between surface and background. When the boundary between surface and background disappeared, it was hard to distinguish
cast and attached shadow on a surface. The presence of cast shadow did not
significantly change the shading appearance compared to the no cast shadow case,
especially for concave shapes.
EXPERIMENT 3

In Experiment 1 and Experiment 2, observers perceived the sign of curvature more accurately when a half spheroid was illuminated from the above than when the light source was from below. Many researchers have also argued that the knowledge of the illumination direction is a key factor for the perceived shape (Berbaum, Bever, & Chung, 1983, 1984; Brewster, 1826). The third experiment used the same stimuli as in the first experiment to directly test observers' estimation of illumination direction under different lighting conditions. The results will be compared to the first experiment to reveal the relationship between shape perception and the illumination direction estimation.

Methods

The participants, the apparatus, the stimuli, and the experimental design were the same as the first experiment. Only the task was different.
**Task.** Observers adjusted the orientation of a gauge figure to make it pointing to the light source position. Gauge figures have been used in many studies to indicate an orientation (Koenderink, & van Doorn, 1995; Koenderink, van Doorn, Christou and Lappin, 1996; Koenderink, van Doorn, Kappers, & Todd, 2001). Some examples of gauge figures are shown in Figure 21. A gauge figure is composed of a circular base and a stick at its center. The stick is perpendicular to the base. The orientation of the gauge figure can be decomposed into two measures: slant and tilt. *Slant* refers to the angle between the line of sight and the orientation of the stick. *Tilt* is the angle between the projected orientation of the stick on the frontal parallel plane and the horizontal direction. In this experiment, only the slant was adjusted by the observers and the tilt was fixed at the vertical direction. Observers varied the slant of the gauge figure and adjusted its orientation to be pointing to the light source.
Results and discussion

The results of the illumination judgments were grouped into two categories. The estimated orientations that were above the line of sight were put into the “above” group. The responses that were below the line of sight were put into the “below” group.

Based on the results in the two categories, the percentage of the responses that were consistent with the overhead illumination prior and the convexity prior were calculated (see Figure 22). Results show that five out of seven observers had convexity bias and four observers had overhead illumination bias.
To compare the results of Experiment 1 and the present experiment, Figure 13 and 22 should be examined at the same time. The only difference was that subject BL showed overhead illumination direction prior, which was not obvious in Experiment 1. The other observers’ results were similar as in Experiment 1.

Figure 22. Individual subjects’ biases for convexity and overhead illumination.

In Experiment 1, individual observers’ priors for overhead illumination were calculated according to their judgments of the sign of curvature. Experiment 3
directly tested the perception of the illumination direction. The results on the overhead illumination priors were directly from the estimated illuminations. The similar results from the two experiments demonstrated the reliability of observers’ performance across different tasks. The results also indicated that there was a close relationship between shape perception and the perceived light source position.
CHAPTER 3

The stimuli in the first set of experiments are the typical kind of stimuli many previous studies have used to study shape perception from shading. However, the simple shapes are not representative of the shapes of the objects we see in our environment. Solid objects with complex surface structures are more often seen in the environment. In the second set of experiments, complex shapes were used to explore whether the perception of them was different from that of simple shapes.

One potential source of information for shape perception of complex solid shapes is the smooth occluding contour. As mentioned in the previous chapter, the shape of the occluding contour has a close relationship with the shape of 3D surfaces at the contour (Koenderink, 1984). A convex curvature at the contour corresponds to a positive Gaussian curvature (e.g. an ovoid shape) and a concave curvature corresponds to a negative Gaussian curvature (e.g. a saddle shape).

Todd & Reichel (1989) found that the existence of an occluding contour improved observers’ perception of the ordinal structure of a surface (i.e. the relative
depth of dots on a surface). When two dots were on a surface with its occluding contour present, their relative depth was estimated very accurately (more than 80% correct). When there was no occluding contour or the occluding contour did not belong to the surface that the dots were on, the accuracy decreased about 20 to 30%. The accuracy was also related to the size of the surface patch. Accuracy was higher for larger surface areas and the difference between with and without occluding contour conditions got smaller as the surface area increased.

In the present set of experiments, effects of smooth occluding contours were investigated. Occluding contours were masked off for half of the images. The perceived shapes from images with and without occluding contours will be compared. If smooth occluding boundary indeed helps shape perception, we would expect to see lower accuracy in the perception of images without occluding contours than those with them.

Another cue that may affect the shape perception of complex shapes is the illumination direction. Koenderink, van Doorn, Christou and Lappin (1996) found that observers perceived the same smooth solid objects to have different depth maps when the photographs of the objects were taken under different illumination directions. Surface areas with higher luminance were perceived to be closer. It was
important to note that the change in the depth map induced by different illumination directions was very small, only explained 4 to 6% of the variance in the responses. Chirstou, & Koenderink (1997) got similar results on the effects of illumination direction. Troje and Siebeck (1998) obtained a comparable result that the orientation of a human face shifted in a direction opposite to the shift of the light source position. In their experiments, when a light source was moved from left to right, the right region of a face became brighter and appeared closer than before, therefore the face was seen as rotated to the left. This result is consistent with the results from Koenderink et. al. (1996). In these studies, observers seem to perceive bright areas as closer than dark areas (see also Langer, & Bulthoff, 2000).

The present set of experiments investigated the perception of complex shapes. The smooth occluding contour was either present or absent in an image and four possible illumination directions were used. Two tasks that tested the perception of the sign of curvature and the depth magnitude were used.
EXPERIMENT 4

Methods

Subjects. Five observers participated in Experiment 4. They all had normal or corrected-to-normal visual acuity. One observer received payment for the participation.

Apparatus. Experiments were run on a Macintosh G4 with OpenGL graphics package for the production and presentation of the stimuli. The stimuli were presented within a 35.5 (horizontal) x 28.5 (vertical) cm rectangular region of the display screen with a spatial resolution of 1280 x 1024 pixels and refresh frequency of 75 Hz. The displays were viewed from a distance of 57 cm, such that the screen subtended 35.5° x 28.5° of visual angle and each pixel subtended 1.6°.

Stimuli. The stimuli included four randomly shaped objects, similar to the stimuli in Todd, et. al. (1997). Figure 23 shows an example image for each of these objects. The surfaces had only diffuse reflectance. Cast shadows and indirect illuminations were present in the images.
Figure 23. The four objects used in the experiment.

Figure 24. A demonstration of the scene for image rendering. The scales are not proportional to the real scene. Only the relative positions are demonstrated. An object was put at the center of Plane B (i.e. the plane on the right side). The light source was on Plane A that was facing the object. There were four possible positions of the light source as shown on Plane A: top, bottom, left and right. The light source was within a rectangle region.
The scene for image rendering was constructed in 3Ds Max 4.2. An object was in a room, which was 120 by 120 by 120 inches (see Figure 24). The object was about 4 feet in diameter and was put against the center of one wall with a distance of roughly 2 feet from its center to the wall. The viewing point was at the center of the wall facing the object with a viewing angle of 45 degrees. The light source was from the wall facing the object with four possible positions. It was either close to the top, bottom, left or right edge. The light source was 30 by 110 inches with the long edge parallel to the closest edge and its center was 20 inches from that edge.

The images were rendered in Finalrender. The effects of indirect illumination and cast shadow were generated by photon mapping algorithm (Birm, 2000).

The size of each image was 1024 by 1024 pixels. The maximum intensity of the images was less than that of the monitor screen and the mean intensity was in the range of 49% to 59% of the maximum intensity. For images without occluding contour, the occluding contour was cut off by a boundary that maximized the surface area while keeping its curvature convex everywhere (see Figure 26).
Figure 25. An example of the images under different illumination conditions in Experiment 4. The images of one object under different illumination directions are shown in the figure. Starting from the top left image, in clockwise direction, the illuminations are from: top, bottom, right, and left.
Figure 26. The images that correspond to those in Figure 25 with their occluding contours masked off. All the other properties are the same as in Figure 25.

**Tasks.** Two tasks were used to test the sign of curvature and depth magnitude. One was an extrema adjustment task and another one was a cross-section reproduction task.

The first task was called extrema adjustment and it was used to test the perceived sign of curvature of a surface. An image of an object was presented at the center of a screen facing directly to the observer. Three near points and three far points with different colors for each category (i.e. green for near points, yellow for
far points) were presented at the left and the right of the image respectively. All the
dots were at the same height and they could only be moved horizontally. Observers
put them at local maxima and local minima (see Figure 27). In other words,
wherever there was a point on a surface that was closer or farther in depth than the
dots around it, a near or far point should be put there. Observers could use any
number of near or far points on the surface depending on the number of near or far
extrema they perceived.

Figure 27. An example of the extrema adjustment task. Observers moved the near or
far points and put them at local extrema. The dots can only be moved horizontally.
The second task was a cross-section reproduction task for testing the perception of the depth magnitude. It was similar to that used by Koenderink, van Doorn, Kappers and Todd (2001). Subjects produced a depth profile of a cross section of an object (see Figure 28). During each trial, an image was presented at the center of a computer screen and there was a scan line at one of 4 possible heights. Several equally spaced dots appeared on the scan line. Images were shown on one monitor screen facing directly to the observer. A line of dots was shown on another monitor at the right of the first one. The dots on the right monitor corresponded to those on the object. Observers moved them up and down to form the depth profile of the shape they perceived from the image.
Figure 28. An illustration of the cross-section reproduction task. Observers moved the dots at the right vertically to make them form the depth profile of the corresponding dots in the image at the left. The arrows around one dot show the directions that the dots could be moved, they were not presented in the experiment.

**Design.** The design of the experiment was a 4 by 4 by 2 within-subject design. The conditions were 4 shapes $\times$ 4 illumination directions (up, down, left and right) $\times$ 2 contour conditions (with and without occluding contours). The images of one object under different conditions are shown in Figure 25 and 26. The images without occluding contours were presented to observers before those with occluding contours, which ensured that observers could not use their prior experience from the images with the occluding contours to perceive shapes in images without them. Images with and without occluding contours were presented
to observers in separate blocks of trials. Images under the combinations of other conditions were randomly shown to observers within one block of trials. Each observer did three blocks of trials for each task and each occluding contour condition.

**Procedures.** The observers covered one eye with an eye patch and viewed the displays monocularly with their heads stabilized by a chinrest at a viewing distance of 57cm. After each trial, observers pressed the space bar and a new display was presented. Observers received no feedback about their performance.

**Results and discussion**

The data set for this experiment was very large. Each of the five observers did 768 trials for the experiment. The trials were the combinations of all the following conditions: 4 objects, 4 scan lines for each object, 4 illumination directions, 2 occluding contour conditions, 2 tasks (extrema adjustment and cross-section reproduction), and 3 repeats for each condition.
1. Results of the extrema adjustment task.

To describe the results of the extrema adjustment task qualitatively, the responses were divided into three categories: hit, miss and false alarm. When a dot was put where there was a real extremum, the response was called a *hit* and it was a correct response. If an observer did not put dots at places where there were extrema, the responses were called *misses*. When a dot was put where there was no real extremum, the response was called a *false alarm*.

In this experiment, observers detected most of the real minima and maxima correctly. The percentage of hits among all the real extrema was 97.4%. The frequencies of the three categories were not significantly different between the results with occluding contour and those without occluding contour. Table 1 shows the frequency of the three kinds of responses for all the images and all the subjects.

<table>
<thead>
<tr>
<th>Response Types</th>
<th>Hits</th>
<th>Misses</th>
<th>False Alarms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>3681</td>
<td>99</td>
<td>785</td>
</tr>
</tbody>
</table>

Table 1. The frequencies of different types of responses for the extrema adjustment task.
Observers' errors in the extrema adjustment task were also analyzed. Figure 29 shows some examples of the responses. All the miss and false alarm responses occurred at reasonable places. The miss responses were usually at places where there was a shallow minimum or maximum that was hard to detect. All the false alarms occurred at inflection points. An *inflection point* is a point that connects a positive and a negative curvature. In Figure 29, the second and forth dots of the top three scan lines are all around inflection points.

Figure 29. The different types of responses for the extrema adjustment task. The depth profiles of the four scan lines are shown at the right of the image. The circles on the scan lines are the averaged positions of all the observers. The solid circles indicate hits, all the other circles are false alarms. The numbers above the circles are the frequencies that a dot was put there by the observers. The images were presented 60 times in total.
There was a special kind of false alarm responses that only happened for images without occluding contour. Some observers perceived a curvature with two bumps and a valley in between as three bumps and two valleys. The bright area within a concave region was perceived as a convex bump. An example is shown as the dashed line above the bottom scan line in Figure 29. The depth reversals did not happen all the time. They only occurred for two objects, within a small region of a surface, and only for certain trials of the responses of three observers. The reversals generally happened when there was a bright area in a valley. The results are consistent with results of Koenderink et al. (1996) and Troje & Siebeck (1998) and can be explained by the “dark means deep” hypothesis by Langer and Bulthoff (2000). In the present experiment, not all observers showed the reversals. For the observers who did show reversals, the reversals did not happen all the time. The results suggested that observers only used the “dark means deep” hypothesis on some occasions.

The existence of reversals showed that even in complex shapes, there was a tendency to see convexity. On the other hand, the small number of reversals revealed that there was much more information in complex shapes than simple shapes where the sign of curvature was often perceived incorrectly. Since reversals
only happened for images without smooth occluding contour, the occluding contour seemed to help resolving the ambiguity in shading at least for some images.

To analyze the accuracy of subjects' extrema adjustments quantitatively, the correlation between observers' extrema settings (only for the hit responses) and the positions of the real extrema was calculated. For each observer, the correlation was between the averaged settings across different illumination directions and real extrema positions. The correlation coefficients range from 0.96 to 0.99 with an average of 0.98.

The correlation between the responses under the four illumination directions and the ground truth (i.e. the real positions of the extrema) were also calculated and the values ranged from 0.98 to 0.99.

The correlation coefficients with the ground truth were almost perfect (higher than 0.96), which indicated that observers' perception of the sign of the surface curvature was very accurate. There was also no significant difference in the correlation coefficients between the images with and without smooth occluding contours (P>0.05).

To test the reliability among observers and whether there were any systematic effects of illumination directions, the correlations between all the possible pairs of
observers and between all the pairs of illumination directions were computed. The
computation included the results of the misses and false alarms. The correlation
coefficients were very high with values ranging from 0.93 to 0.99. The averaged
correlation between each pair of observers was 0.97 both with and without
occluding contours. The results suggested that observers basically agreed with each
other on the basic surface structure (i.e. where the hills and valleys were). The
averaged correlation between different illumination directions was 0.98 for images
both with and without occluding contours. Illumination directions did not seem to
affect the responses in a systematic way. The reliabilities among observers and
among illumination directions were not affected by the presence of the occluding
contours.

In the experiments of Koenderink et. al (1996) and Troje and Siebeck (1998),
different illumination directions led to a shift of perceived depth. To check whether
there were changes in perceived depth due to illumination direction in the present
experiment, the extrema positions under left and right illuminations were compared.
Since the scan lines were horizontal and the positions of extrema could only be
adjusted horizontally, only the left and right illuminations were possible to generate
changes in the extrema positions. To check the other directions, we also compared
the results under top and bottom illuminations. When the illumination moves from left to right, we expect to see the positions of the extrema to shift from left to right too. Only the signs of the position differences between pairs of extrema settings were considered in the comparison. The results of the analysis showed that the difference between left and right illumination directions was significant for both with occluding contours (z = -3.36, p<0.05) and without them (z = -2.51, p<0.05). The difference between top and down illuminations was not significant for images with (z = -0.18, p>0.05) and without occluding contours (z = -1.08, p>0.05). The significant difference in the extrema positions between left and right illumination directions suggests that the perceived depth magnitudes were changed when the light source position moved from the left to the right.

In summary, observers' perception of the sign of curvature (i.e. the locations of local extrema) was not only accurate relative to the ground truth, but also very reliable among different observers and different illumination directions. The presence of occluding contours did not improve performance in most of the analyses comparing to without occluding contour condition, it only helped to resolve the ambiguity in some shaded images.
2. Results of the cross-section reproduction task

The analyses of the results of the cross-section reproduction task were more straightforward than the extrema adjustment task. The relative depths of the dots on each scan line were calculated relative to the first dot (i.e. the leftmost dot) of the scan line. The correlations between the relative depths and the real depth differences were computed for each observer averaged across illumination directions and also for each illumination direction averaged across different observers. The results are listed in Table 2 and Table 3. The correlation coefficients were lower than those from the extrema adjustment task, but all the values were higher than 0.83, which showed that observers were very accurate in estimating the depth profile. Different occluding contour conditions did not have significant effects on the correlation coefficients (p>0.05).

<table>
<thead>
<tr>
<th>subjects</th>
<th>Correlation without occluding contour</th>
<th>DL</th>
<th>ET</th>
<th>BL</th>
<th>JT</th>
<th>BC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.83</td>
<td>0.87</td>
<td>0.88</td>
<td>0.88</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Correlation with occluding contour</td>
<td>0.89</td>
<td>0.82</td>
<td>0.87</td>
<td>0.92</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Table 2. The correlation coefficients between each observer's relative depth magnitude estimations and the true relative depths for the perception of images with and without occluding contour in the cross-section reproduction task.
Illumination directions
Top        Bottom        Left         right
Correlation without occluding contour  0.89  0.86  0.88  0.90
Correlation with occluding contour    0.93  0.92  0.92  0.93

Table 3. The correlation coefficients between the depth profile setting and the ground truth under different illumination directions.

To test the reliability among observers and among different illumination directions, the correlations between pairs of observers and pairs of illumination directions were computed and are listed in Table 4 and 5.

Without occluding contour

<table>
<thead>
<tr>
<th>Subjects</th>
<th>BC</th>
<th>BL</th>
<th>DL</th>
<th>ET</th>
<th>JT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>1.00</td>
<td>0.91</td>
<td>0.90</td>
<td>0.83</td>
<td>0.87</td>
</tr>
<tr>
<td>BL</td>
<td>0.91</td>
<td>1.00</td>
<td>0.91</td>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td>DL</td>
<td>0.90</td>
<td>0.91</td>
<td>1.00</td>
<td>0.82</td>
<td>0.85</td>
</tr>
<tr>
<td>ET</td>
<td>0.83</td>
<td>0.90</td>
<td>0.82</td>
<td>1.00</td>
<td>0.89</td>
</tr>
<tr>
<td>JT</td>
<td>0.87</td>
<td>0.91</td>
<td>0.85</td>
<td>0.89</td>
<td>1.00</td>
</tr>
</tbody>
</table>

With occluding contour

<table>
<thead>
<tr>
<th>Subjects</th>
<th>BC</th>
<th>BL</th>
<th>DL</th>
<th>ET</th>
<th>JT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>1.00</td>
<td>0.90</td>
<td>0.92</td>
<td>0.78</td>
<td>0.91</td>
</tr>
<tr>
<td>BL</td>
<td>0.90</td>
<td>1.00</td>
<td>0.89</td>
<td>0.83</td>
<td>0.91</td>
</tr>
<tr>
<td>DL</td>
<td>0.92</td>
<td>0.89</td>
<td>1.00</td>
<td>0.85</td>
<td>0.88</td>
</tr>
<tr>
<td>ET</td>
<td>0.78</td>
<td>0.83</td>
<td>0.85</td>
<td>1.00</td>
<td>0.85</td>
</tr>
<tr>
<td>JT</td>
<td>0.91</td>
<td>0.91</td>
<td>0.88</td>
<td>0.85</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 4. The correlation coefficients of the results between pairs of observers for images with and without occluding contour in the cross-section reproduction task.

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Table 5. The correlation coefficients for the cross-section reproduction task between pairs of illumination directions for images with and without occluding contour.

The averaged correlation coefficient between observers was 0.88 for the images without occluding contours and was 0.87 for those with occluding contours. The averaged correlation coefficient between pairs of illumination directions was 0.93 for images without occluding contours and 0.96 for images with occluding contours. The results indicated that observers were consistent in their estimations of the relative depth magnitude of the surfaces and different illumination directions did not make a difference.

All the correlation coefficients computed for the cross-section reproduction task were based on the results of the relative depth of a dot to the first dot on a scan line. To get a measure about the absolute depth estimation, the ratio of the averaged depth magnitude estimation relative to the real depth magnitude was computed.
The ratios for individual observers are shown in Table 6. Observers tended to underestimate the depth of the surfaces. The average ratio was 50%, which meant that the average perceived depth was only half of the real depth. This result is comparable to previous studies where depth was underestimated by more than 44% (Todd, & Reichel, 1989). The occluding contour did not have a reliable effect on the perceived depth for all the observers.

<table>
<thead>
<tr>
<th>Depth Ratio</th>
<th>Subjects</th>
<th>ET</th>
<th>BL</th>
<th>DL</th>
<th>BC</th>
<th>JT</th>
<th>Ave</th>
</tr>
</thead>
<tbody>
<tr>
<td>without occluding contour</td>
<td>0.36</td>
<td>0.37</td>
<td>0.40</td>
<td>0.60</td>
<td>0.71</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>with occluding contour</td>
<td>0.31</td>
<td>0.47</td>
<td>0.53</td>
<td>0.59</td>
<td>0.62</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. The ratio between the averaged depth magnitude estimation and the real depth magnitude.

To summarize the results of the two tasks, observers were accurate in perceiving both the sign of curvature and the detailed depth profile of complex shapes. The performance was very reliable among observers. The left and right illumination directions shifted the perceived extrema positions. However, illumination directions in general did not affect observers' shape perception. The
presence of occluding contours helped resolving ambiguity in shading, but in most cases did not improve performance comparing to no occluding contour conditions.

Let’s take a detailed look at the reliability among observers. According to Belhumeur et. al. (1999), shaded images are inherently ambiguous. Any given shaded image can be generated by different combinations of illumination direction and depth profile. If that is the case, it is almost impossible for observers to perceive identical shapes from the same shaded image. Contrary to the prediction, the correlations between observers were very high for the two tasks: the average was 0.88 for cross-section reproduction task and 0.97 for extrema adjustment task. Meanwhile, observers’ perception of both the sign of curvature and depth magnitude was very accurate relative to the ground truth (all the correlation coefficients were higher than 0.82).

In the present experiment, the illumination direction did not affect the accuracy in extrema adjustment and the perception of detailed depth profile. The results are not consistent with those for simple shapes. If observers have a preference of seeing overhead illumination as found in the first three experiments in the present study, their performance should be better for overhead illumination condition than light
from below case. The results did not show this. One reason for this might be that the mechanism for perceiving complex shapes from shading is different from that for simple shapes. The shading on complex surfaces is more complicated than simple shapes and simply assuming overhead illumination is not very useful in shape perception.

Let’s now compare the results under different illumination directions with previous studies. Previous studies have shown that different illumination directions generate different perceived depths even though the amount of change is small (Koenderink, et. al. 1996). Koenderink, et. al. used a powerful task (i.e. gauge figure adjustment) to get the depth map of a surface and analyzed the change in perceived depths under different illumination directions. The various illumination directions only explained 4 to 6% of the variance in their results. In the present experiment, there was indeed a shift of the extrema positions when illumination direction moved from the left to the right. This result is consistent with those of Koenderink, et. al. (1996). However, all the other analyses did not show difference between illumination directions. The reason for not finding the illumination effects may be that the effects are too small to detect using the current tasks, or that the
changes in shading are not big enough for observers to get different shape perception.

With respect to the effect of occluding contour, our results show that occluding contours may not be necessary for shape perception. The occluding contour did reduce the occurrence of depth reversals for some shaded images. However, the other analyses did not show significant effects. A possible reason is that there is still enough information in the images for observers to see the surface structure accurately. Todd, & Reichel (1989) found that ordinal shape perception improved as more area on a surface was shown to observers and the difference between images with and without occluding contour decreased as the size of an area increased. The largest surface area in the experiment was only 15% of the original image. They might have obtained similar results as this experiment if they had used more than 90% of the original image area. Future studies using various sizes of surface area will reveal more about the effect of occluding contours.
EXPERIMENT 5

According to the analyses of Belhumeur et. al. (1999), the combination of depth profile and illumination direction determines the appearance of a shaded image and different combinations can generate the same image. How well do observers perceive the light source direction during the shape perception process? If the illumination direction estimations are very accurate, it will explain why the shape perception is accurate for ambiguous images. Experiment 5 was designed to answer the question by directly testing the illumination direction estimation using the images from Experiment 4. The participants, apparatus, and the stimuli were the same as Experiment 4, only the task was different.

Methods

Design. The total number of conditions was 4 shapes X 2 contour conditions (with or without occluding contours) X 4 illumination directions (up, down, left or right)
=32. Observers did one block of trials for images without occluding contours and then another one for images with occluding contours. Images without occluding contours were presented before those with them. Each image was shown 4 times randomly within one block of trials.

**Task.** Subjects estimated illumination direction by adjusting the orientation of a gauge figure. An image was presented at the center of a screen with a gauge figure on it (see Figure 30). Subjects adjusted the orientation of the gauge figure to be pointing to the light source. The gauge figure's orientation could be changed in both slant and tilt at the same time by moving the mouse (see Figure 21 for an illustration of slant and tilt).

![Figure 30](image.png)

Figure 30. An example of the stimulus and probe in Experiment 5. A gauge figure was put at the center of an image and its orientation could be adjusted to be pointing to the light source.
Results and discussion

Since the results for the estimation of illumination direction were directions in 3D space, the angles between the mean estimated illumination directions and the real illumination directions under different illumination conditions and for different observers were calculated and the results are shown in Table 7.

<table>
<thead>
<tr>
<th>Error</th>
<th>Illumination Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects</td>
<td>Top</td>
</tr>
<tr>
<td>BC</td>
<td>41.28</td>
</tr>
<tr>
<td>BL</td>
<td>30.57</td>
</tr>
<tr>
<td>DL</td>
<td>23.42</td>
</tr>
<tr>
<td>ET</td>
<td>34.11</td>
</tr>
<tr>
<td>JT</td>
<td>11.22</td>
</tr>
<tr>
<td>Average</td>
<td>28.12</td>
</tr>
</tbody>
</table>

Table 7. The errors of averaged estimated directions compared to real illumination directions. The numbers are in degrees.

In general, observers' estimations of illumination directions were not accurate. The averaged absolute error between the mean estimation and the true illumination direction was 25 degrees. There were also large individual differences. When light was from below, the error was smaller than those under other illumination
directions. The results need to be considered together with the deviation results that will be shown afterwards.

The deviations from the mean response were calculated for each observer and the results are listed in Table 8.

<table>
<thead>
<tr>
<th>Deviations</th>
<th>Illumination Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects</td>
<td>Top</td>
</tr>
<tr>
<td>BC</td>
<td>29.05</td>
</tr>
<tr>
<td>BL</td>
<td>25.24</td>
</tr>
<tr>
<td>DL</td>
<td>24.77</td>
</tr>
<tr>
<td>ET</td>
<td>24.38</td>
</tr>
<tr>
<td>JT</td>
<td>9.65</td>
</tr>
<tr>
<td>Average</td>
<td>22.62</td>
</tr>
</tbody>
</table>

Table 8. The averaged deviations of individual responses from the averaged estimations under various illumination conditions. The numbers are in degrees.

The deviations of individual responses from the mean estimations under each illumination condition are very large. The average of the deviations is about 21 degrees. The results show that observers' responses under one illumination direction were not very concentrated. The deviations did not show a systematic trend for various illumination conditions. When light was from below, the deviation was the largest. This result shows that observers were not confident in estimating
light source position under this condition even though the estimation error was relatively small (see Table 7). No difference was found between the images with and without occluding contours.

To check whether illumination direction estimations were reliable across different repeats, the angles between the estimated directions of individual trials and the average estimations of the four repeats were computed for each object under different conditions and the averaged deviations of all the observers are shown in Table 9.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Deviations Over Repeats</th>
<th>Illumination Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top 15.08 15.82 13.44 12.07</td>
<td>Average 14.10</td>
</tr>
<tr>
<td>2</td>
<td>Top 18.86 22.54 10.37 9.54</td>
<td>Average 15.33</td>
</tr>
<tr>
<td>3</td>
<td>Top 12.83 13.93 15.27 13.86</td>
<td>Average 13.97</td>
</tr>
<tr>
<td>4</td>
<td>Top 10.87 13.80 13.31 16.16</td>
<td>Average 13.54</td>
</tr>
<tr>
<td>Average</td>
<td>Top 14.41 16.52 13.10 12.91</td>
<td>Average 14.23</td>
</tr>
</tbody>
</table>

Table 9. The deviations of the light source direction estimations at individual trials from the means of four repeats. The numbers are in degrees.
The deviations among different trials under the same condition were still large. The average was about 14 degrees. The results indicate that observers did not respond very reliably across repeats.

The third experiment in the previous chapter tested the illumination direction estimations and found that they were consistent with shape perception of simple shapes. The results of this experiment showed that observers could not accurately estimate the illumination directions for the perception of complex shapes. They were not reliable across different repeats and across different images under the same illumination condition.

The accurate shape perception in Experiment 4 and the poor performance in estimating illumination direction found in Experiment 5 suggest that the illumination estimation may not be necessary in the shape perception process. Other studies also showed similar results (Erens, Kappers, Koenderink, 1993b).
CHAPTER 4

CONCLUSIONS

The experiments presented in this dissertation have examined the ways in which the human visual system uses shading information to perceive the 3D structures of surfaces. The research focuses on two problems in the "shape perception from shading" process. One problem is how specular highlights, cast shadows and indirect illuminations influence shape perception. The other problem is how observers resolve the inherent ambiguity in shaded images.

In a natural environment, the shading on a surface is generated by the interaction between the light source direction and intensity, the material and structure of the surface and the structure of the scene. Observers are able to obtain the surface structure from shaded images. Research on this kind of phenomenon investigates the underlying process. Since the shading on a surface is affected by many factors and it is not easy to manipulate them independently, many studies used photographs as stimuli or investigated the effects of different lighting conditions indirectly. Some studies employed computer generated images, but
many factors that affect shading appearance (e.g. cast shadow, specular reflection and indirect illumination) were not considered. Moreover, the perception of the details of a shape (e.g. the perceived depth magnitude) has not been tested in most of the studies on “shape from shading”.

The present set of experiments used realistic pattern of shading in the stimuli by rendering images in a scene. The presence of cast shadow, specular highlights and indirect illumination was controlled independently. Both the perceived sign of curvature and the depth magnitude were tested. The results showed that observers used cast shadows to help them discriminating convex and concave shapes. The perceived depth magnitudes of the simple shapes were affected by the presence of cast shadows, specular highlights and the sign of curvature. It appears that human visual system does not just ignore the components in realistic shading pattern and follow the computational algorithms. The visual system uses almost all the information available in the shading for shape perception. The only factor that did not show an effect in the present research is the indirect illumination. In the images with indirect illuminations, the boundaries between surfaces are clearer than images without them. However, the boundary information may not be very useful for the tasks in the current research since they do not require observers to distinguish objects. It may be of more importance in other tasks such as object recognition task.
There is an interesting property of shaded images: they are inherently ambiguous. Observers somehow are able to resolve the ambiguity in their perception of shapes from shading. The process of resolving ambiguity is the second topic that the present set of experiments addresses.

Previous studies showed that observers used some priors in the perception process. Two commonly used ones are convexity and overhead illumination. The results from the present research showed that convexity prior was stronger than overhead illumination prior for simple shapes. Convexity prior was used more frequently and had stronger effects. Individual observers also had clear preferences for either one of the priors. For complex shapes, shape perception was very accurate and observers did not seem to use the two priors most of the time.

With respect to the origin of the priors, it may be related to the high frequency of their occurrences in our environment. There are more convex surfaces than concave ones and the light source is more often to be from above than from other directions. The visual system may obtain the knowledge either through observers’ experiences with the environment or through the evolution over generations.

The ambiguity in shaded images of complex shapes is harder to resolve than simple shapes since the detailed structure of a surface can not be determined by the two priors. Experiment 4 and 5 in the present study used complex shapes as stimuli and found very different results from simple shapes. The overhead illumination and convexity prior did not seem to affect the perception. Under
overhead illumination condition, the accuracy of shape perception was similar to other illumination directions. Concave surface patches were perceived correctly as concave most of the time. Shape perception was also very reliable for different subjects and various illumination directions. The results suggest that there may be different underlying processes for the perception of simple and complex shapes. However, this finding is only applicable to the stimuli, the scene structure, the light source positions and the tasks that were employed in the present research. Future studies that vary those manipulations may reveal more about the shape perception from the shading of complex shapes.

One potential source of information in solid objects that is not in simple convex or concave bumps is the smooth occluding contour. However, observers' performance did not change significantly even when the smooth occluding contours of the solid shapes were masked off. The occluding contour did not seem to affect the perception process. One possible reason for the result may be related to the way that we masked off the occluding contour. The area of the surfaces was kept as large as possible and the occluding contour was convex everywhere. The remaining surface areas may still have enough information for accurate shape perception. The convex contour might also provide some information about the surface structure. Future research that varies the size of the occluded region, or changes the convex occluding contour to randomly curved curvature may provide more insights about the perception process.
Illuminant direction has been found to be closely related to shape perception in both theoretical analyses and empirical studies of the “shape from shading” process. In two experiments of the present study, observers were asked to directly judge the illumination direction. One experiment used images of simple shapes and the results were consistent with the shape perception of those shapes. Another experiment used shaded images of randomly shaped objects. The results showed large errors from the true illumination direction and large deviations from the mean responses. The illumination direction estimations were not accurate or reliable. The results indicate that the illumination direction may not be necessary for the perception of complex shapes and there may be different processes for the perception of simple or complex shapes from shading.

In summary, the evidence from the current experiments demonstrates that human visual system obtains shape information from shading by considering various aspects that affect shading appearance: the shininess of a surface and the luminance in its surrounding areas (e.g. cast shadow). Human observers use two priors (convexity and overhead illumination) when dealing with the ambiguity in shaded images of simple shapes and there are large individual differences. There are some differences in observers' shape perception of simple and complex shapes. Whether there are different underlying processes for the shape perception of different structures needs further investigation.
BIBLIOGRAPHY


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APPENDIX

THE ALGORITHMS FOR THE GENERATION OF STIMULI

The following paragraphs will first introduce two kinds of illumination models for image rendering and then describe the techniques that were used for simulating the effects of direct and indirect illuminations, cast shadows and specular highlights in the presented experiments.

(1) An introduction of local and global illumination models.

There are two basic kinds of models that compute the reflected light from objects: local and global illumination models. The local models only consider the light directly from light sources or reflected once by objects. The global models take care of all kinds of light that comes from direct illuminations and also the light reflected among surfaces.
In a local illumination model, the intensity in an image is calculated by the direct light sources. The local illumination models simplify the light from other objects and assume that the light from the sky or other objects that falls on the object is uniformly projected onto an object from all directions. This component of light is called the ambient light. When a light is projected onto an object, the amount of light actually falling on the object is called illuminance.

For a shiny surface, the illuminance is reflected by the surface at primarily the same angle as the incidence angle. This part of reflected light is called the specular component and the reflected light depends on the incident angle of the light source and the viewing angle of the observer. For a matt (Lambertian) surface, it scatters incident light back into the air in all directions. This part of the reflected light is called diffused light. For the parts that are not facing the light source, there is no light and the surface is in the shadow (attached shadow). Many models were proposed to calculate the intensity of light at a certain position on a surface. Phong model is a popular one. Phong reflectance model considers the reflection from a surface composed of three parts that are linearly related to each other. For only one object, the intensity of light at a point is the sum of the ambient, specular and diffused light.
reflected light = ambient light + diffuse component + specular component.

To be more specific, the formula can be written as:

\[ I_p = I_a S + I_L S(L - N) + I_L g(H - N)^n \]

- \( I_p \) intensity of a picture element
- \( I_L \) is the intensity of light source
- \( I_a \) the intensity of ambient light.
- \( S \) is the shade or albedo of the surface (value ranges from 0-black to 1-white).
- \( g \) is the proportion of the specular reflection
- \( L \) unit vector in the direction of light source
- \( N \) unit vector of the surface normal (i.e. unit vector that perpendicular to the surface)
- \( H \) unit vector that bisect the angle formed by \( L \) and \( V \)
- \( n \) the sharpness of the highlight (\( n=\infty \), for a perfect mirror)
- \( \cdot \) denotes inner product of two vectors.

This formula is only for the calculation of the light intensity at one point on a surface. How about other points on the surfaces? Since the objects were usually drawn as a group of connected small polygons in computer graphics, the light intensity at the vertices can be calculated according to the formula discussed above.
The normal of other points on the surface except the vertices can be interpolated by the normal of the vertices and the light intensity at different places on a surface can be calculated by the interpolated normal using the formula mentioned above.

The local illumination models do not consider indirect illumination from other objects, therefore neglect the interreflection of lights from one object to another. Global illumination models include the lights falling on an object from direct light sources and also lights reflected from other objects or the background. Ray tracing and radiosity are the two major kinds of global illumination models.

Ray tracing starts from the position of the eye and propagates back to each pixel on the computer screen, then from the connected line between the eye and the pixels, the rays are traced back to the objects. When the rays hit an object or a surface, they generate reflected rays at the intersection and the spawned rays are then followed recursively. The light intensity at a point is computed by treating the points on the traces as light sources and the light sources are always point sources. The specular light at the different points directly due to the light sources is added to the intensity for each point. At each point, the diffused light from the light sources in the scene is calculated in the same way as the local reflection model. The ray tracing predominantly deals with specular interactions.
Radiosity mainly considers the diffused light. Light from light sources is shot into the scene and the surface patch with the most unshot energy then acts as the light source. The process iterates until a certain (high) percentage of the initial energy was shot. One surface may get shot many times. Every patch gets a constant radiosity after the process.

Both ray tracing and radiosity consider the interaction between an object and other objects or surfaces in the scene. For complex scenes, the globally rendered images appear more natural than the images generated by local illumination models.

(2) The techniques that simulate the effects of indirect illumination.

In the experiments presented in the dissertation, the effects of direct and indirect illumination were simulated by the radiosity technique in Lightscape. The radiosity technique assumes that all surfaces are pure Lambertian surface, so only diffuse reflection is considered in the computation.

Lightscape uses a process called progressive refinement radiosity to simulate the effects of indirect illumination. Surfaces are composed of small patches and the radiosity of each patch is updated over iterations. Radiosity here refers to the
amount of energy per unit area leaving a surface patch per unit time and is the sum of the emitted and the reflected energy.

At each iteration, the area with the largest radiosity or emitted energy (i.e. the brightest area) is considered as the light source and its contribution to other surfaces is computed. At the initial iteration, the radiosities are set either to zero or to their emission value (for light sources). For a particular patch (patch j), its radiosity is computed according to the following formula:

\[ B_j^{(k+1)} = B_j^{(k)} + R_j F_{ji} A B_i; \]

A single radiosity (patch i) shoots light into the environment and the radiosities of all other patches are updated. B refers to radiosity. R is the reflectivity of a patch. F is a constant, called a form factor, it parameterizes the relationship between patches j and i. \( \Delta B_i \) is the amount of unshot energy. The iteration process continues till all the interreflections are accounted for by the simulation.

(3) The techniques for simulating direct illumination, specular reflection and cast shadow.

Cast shadow and indirect illumination are simulated in Lightscape by Whitted Ray Tracing technique.
In the process of Whitted Ray Tracing, the light rays to the eye are traced back into the scene. When the rays hit a surface, they are spawned at the point of intersection, which is the opposite process of specular reflection. The spawned rays are then followed recursively. In our experiments, the ray tracing was specified to occur only once.

The luminance at an intersection point can be computed by considering the surface that a spawned ray hits as the light source. Only when the spawned ray can be traced back to the light source, the intersection point can get some luminance since the light is only traced back once. Therefore, only the specular reflection of a surface is simulated.

To simulate cast shadows, the direction of the spawned ray is compared to the light source direction at each interaction point. If they are the same and there is no surface in the way, there is no cast shadow. If the directions are the same, but the ray cannot be traced back to the light source, the intersection point is in cast shadow region. This test can be turned on or off to control the presence of the cast shadow.

The direct illumination was added to the rendering images in ray tracing algorithm.