Research Article

Lightness Constancy in the Presence of Specular Highlights

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ABSTRACT—***Visible surfaces in a natural environment often have multiple components of reflectance, including a diffuse component, by which light is scattered isotropically in all possible directions, and a specular component, by which light is reflected anisotropically within a limited range of directions. The research described in the present article was designed to investigate how these different components of reflectance influence the perception of lightness. Human observers were presented with shaded images of smoothly curved surfaces and asked to compare the relative lightness of different surface regions whose diffuse and specular components of luminance were independently manipulated. The results revealed that observers are able to discount the presence of specular highlights so that the relative lightness among different regions is determined almost entirely by the diffuse component of surface reflectance.***

One of the most remarkable aspects of human perception is the ability of observers to determine the reflectance properties of surfaces under variable conditions of illumination—a phenomenon that is referred to as lightness constancy. The reflectance, or albedo, of a surface is a measure of how it reflects light. For example, a typical white paper reflects 85% of its incident illumination, whereas black felt reflects only about 10%. The intensity of reflected light is called luminance (L), and it is affected by both the surface reflectance (R) and the intensity of the incident illumination (I), as is sometimes described by the following equation: $L = RI$. The term lightness refers to an observer's perception of surface reflectance. The theoretical problem that is posed by this phenomenon is that there is no obvious correlate of reflectance in the pattern of luminance that stimulates the retina. Thus, a white surface under low illumination and a black surface under high illumination could produce exactly the same luminance.

The earliest attempts to explain lightness constancy were based on the idea that the perception of surface reflectance must somehow involve an estimate of the illumination intensity (Katz, 1935; Koffka, 1935). Although there have been numerous experiments to test this hypothesis (e.g., Beck, 1961; Kozaki & Noguchi, 1976; Logvinenko & Menshikova, 1994; Noguchi & Kozaki, 1985; Rutherford & Brainard, 2002), the results have often been inconsistent. One important problem for this approach is that the patterns of illumination in natural scenes are seldom homogeneous, so the intensity of illumination can vary dramatically across different regions. The empirical evidence suggests that the visual system solves this problem by grouping a scene into regions that have approximately uniform patterns of illumination, and that lightness is determined from the relative luminances within each region (e.g., see Adelson, 1993; Gilchrist, 1977; Gilchrist et al., 1999; Knill & Kersten, 1991).

Most research on lightness perception has been restricted to flat, opaque, matte surfaces, for which luminance is governed by just two physical parameters (i.e., the surface reflectance and the incident illumination), as described by the equation given earlier. However, there are many situations encountered in natural vision for which the behavior of light is considerably more complex. Consider, for example, some of the common optical phenomena that are depicted in Figure 1. One of the effects that is shown in this image is the diffuse reflection of light on a matte, *Lambertian* surface—that is, the light colored bands on the torus. When a beam of light strikes a matte surface, the reflected rays are diffusely scattered in all possible directions. The surface area over which the beam is spread varies as a cosine with the angle of incidence. Thus, if a matte surface is perpendicular to the direction of illumination, the light energy will be concentrated within a relatively small area, and the luminance will be greater than in other surface regions at more oblique angles, where the illumination is distributed over a larger area. This relation between incidence angle and luminance for matte surfaces was first discovered in the 18th century by the German scientist Johan Lambert, and is now referred to as Lambert's law. This is what produces the gradients of luminance on matte surfaces, which are an important source of information for the perception of three-dimensional (3D) shape from shading (e.g., see Mingolla & Todd, 1986; Todd & Reichel, 1989).

Another common optical phenomenon that is depicted in Figure 1 is the specular reflection of light on shiny surfaces. When a beam of light strikes a shiny surface, it is reflected much like a billiard ball caroms, with little or no scattering. Examples of specular reflections in this image include the bright highlights on the dark bands of the torus and the glass bowl, and the reflections of these objects on the polished tile floor. Whereas the luminance of a matte surface is invariant over viewing directions, the luminance of shiny surfaces is anisotropic. That is to say, the specular reflections at any given surface location are visible only from a limited set of possible vantage points.

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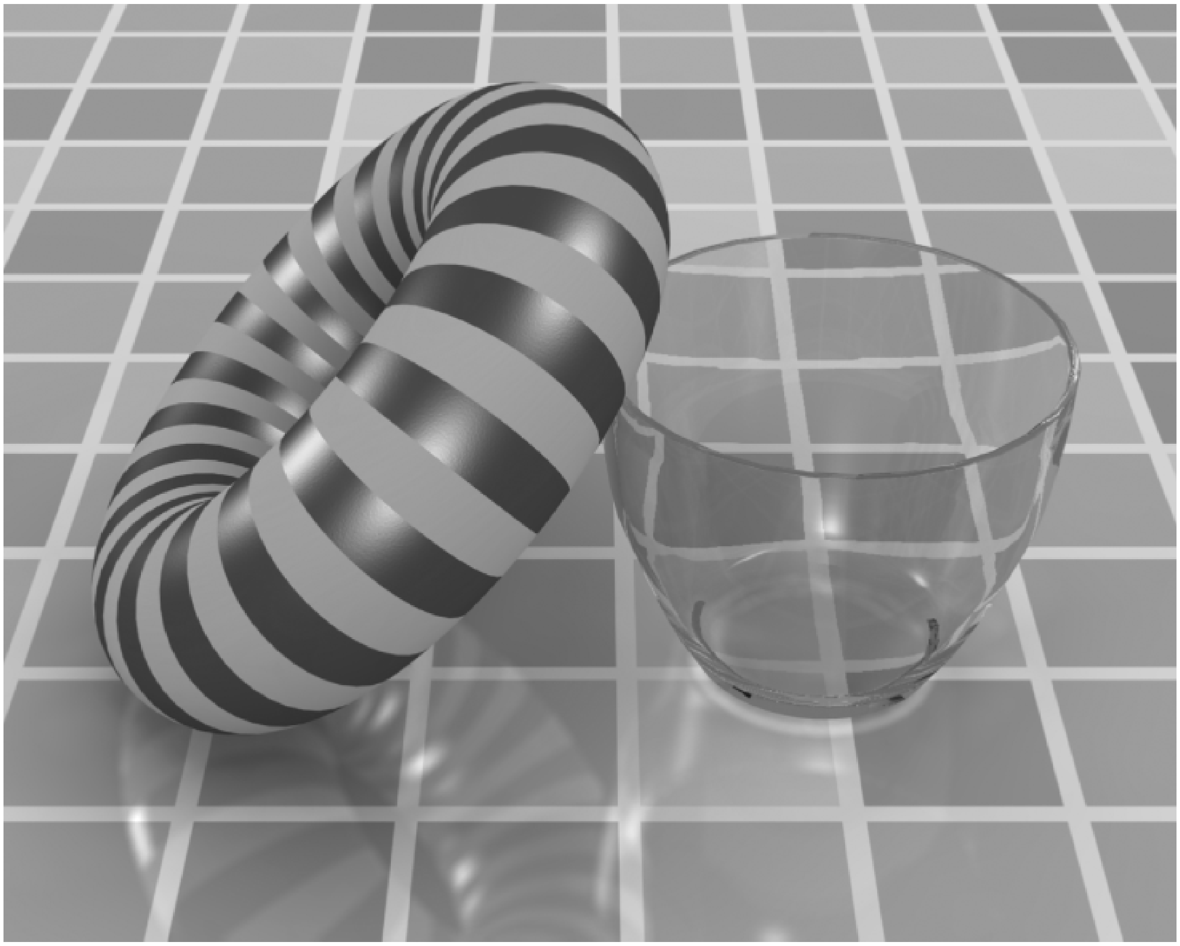

Fig. 1. Image depicting several possible sources of luminance change in natural vision, including the effects of transparency, gradients of shading due to surface curvature, variations in diffuse reflectance, and specular highlights. Note in particular how the dark bands on the torus contain regions with noticeably higher luminance than is evident on the light bands. These regions are interpreted as specular highlights rather than surface color, thus suggesting that the specular components of surface reflectance may somehow be discounted in the perceptual analysis of lightness.

A third type of optical phenomenon depicted in Figure 1 is the appearance of transparency in the glass bowl (cf. Metelli, 1974; Singh & Anderson, 2002). When a beam of light strikes a transparent material, it is transmitted through it, though the direction of the beam may be altered because of the effects of refraction. Refraction is what causes the apparent distortion of the tile floor when viewed through the curved glass. A related effect that is not shown in Figure 1 is the appearance of translucency. Translucent surfaces also transmit light, but the transmitted light is scattered randomly in different directions. Examples of translucent surfaces include frosted glass and human skin.

Given all these different optical phenomena that can influence the luminance of any given surface patch, it is remarkable that the visual system can tease them all apart in order to achieve the perception of lightness, shininess, transparency, translucency, and many other surface properties. One interesting aspect of observers' perceptions suggested by Figure 1 is that the appearance of lightness may be based only on the diffuse component of surface reflectance. Note that the dark bands on the torus contain regions with noticeably higher luminance than is evident on the light bands, but these regions of high luminance are interpreted as specular highlights rather than surface color. This suggests that the specular components of surface reflectance may somehow be discounted in the perceptual analysis of lightness.

The research described in the present article was designed to investigate the precision of this discounting process under a variety of different conditions. Observers were presented with images of smoothly shaded curved surfaces and asked to compare the relative lightness of different surface regions whose diffuse and specular components of luminance were independently manipulated.

METHOD

Stimuli

The stimuli were created on a Silicon Graphics Crimson VGX workstation, and were viewed on a 19-in. color monitor with a spatial resolution of 1280×1024 pixels. On each trial, observers were presented with a shaded image of a smoothly curved ellipsoid surface whose relative semiaxes in height, width, and depth were 1.0, 1.3, and 2.0, respectively (see Fig. 2). The perspective projection of this object in the image had a height of 13.4 cm and a width of 17.8 cm (i.e., 12.7° and 16.9° of visual angle).

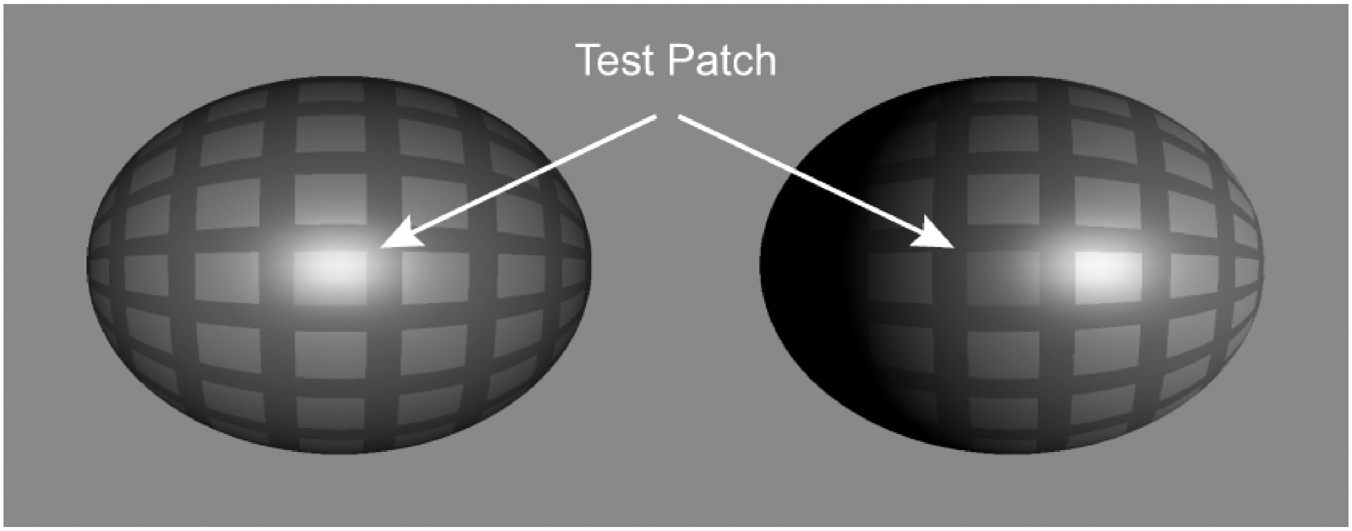

Fig. 2. Two example stimulus configurations from the present experiment. The object on the left is from the centered-highlight condition. It has a standard diffuse reflectance of .5 and a test-patch reflectance of .425 (−15%). The object on the right has the same reflectance parameters but is from the outside-highlight condition. The test patches on both objects are indicated by arrows.

The shading at each point on the ellipsoid was computed as an additive combination of two different types of reflected light: diffuse reflections (L_d) that were visible from all possible directions and specular reflections (L_s) that were visible only from a limited range of directions. For purposes of the present discussion, the intensities of the diffuse and specular reflections at the point of observation are defined as proportions of the maximum possible pixel intensity (i.e., $L_d + L_s \leq 1$). The diffuse reflection for each surface location was computed from the following equation: $L_d = d(\mathbf{I} \cdot \mathbf{N})$, where d is the diffuse component of reflectance, $\mathbf{I}$ is a unit vector toward the light source, and $\mathbf{N}$ is a unit vector that is normal to the surface. The specular reflection was computed as follows: $L_s = s(\mathbf{H} \cdot \mathbf{N})^{20}$, where s is the specular component of reflectance, and $\mathbf{H}$ is a unit vector that bisects the angle between the viewing direction and the direction of illumination at the surface location. The exponent in this equation controls the range of directions over which highlights are visible.

The surface of the ellipsoid was textured with a grid of approximately square patches against a light gray background (see Fig. 2). One of the squares in the center of the elliptical projection was designated as the test patch, and all of the remaining squares were identified as standard patches. The diffuse reflectance of the standard patches had four possible values—.2, .3, .4, and .5—which varied randomly across trials. The diffuse component of the test patch varied relative to the standard by 5, 10, 15, or 20% in both positive and negative directions. Thus, for each standard diffuse reflectance, there were eight possible test-patch reflectances. The diffuse reflectance of the background always had a constant value of .35. In addition, the background, standard, and test regions all had a uniform specular reflectance of .5.

These surfaces were illuminated by a single point light source at an infinite distance in the horizontal plane. The direction of illumination varied across trials, with possible orientations of 0.0°, 18.4°, and 66.8° relative to the observer's line of sight. In the 0.0° (centered-highlight) condition, the specular highlight was approximately centered within the test patch; in the 18.4° (edge-highlight) condition, it was centered on the edge of the test patch; and in the 66.8° (outside-highlight) condition, it was located primarily outside the test patch (see Fig. 2).

To briefly summarize the experimental design, there were 96 possible displays that could be presented on any given trial. These were defined by the various combinations of three highlight locations, four standard diffuse reflectances, and eight test diffuse reflectances.

Procedure

Three naive observers participated in the experiment. All had normal or corrected-to-normal visual acuity. On each trial, observers were required to judge whether the apparent surface color of the test patch was lighter or darker than the surface colors of the surrounding standard patches. Responses were made by pressing the appropriate button on a handheld mouse. Observers made 20 judgments for each possible stimulus over a series of 10 experimental sessions.

RESULTS

The combined results for all 3 observers for each combination of highlight location and standard diffuse reflectance are presented in Figure 3; a similar pattern was exhibited by each individual observer. The solid curves in this figure are the best-fitting psychometric functions obtained using probit analysis (Foster & Bischof, 1991). On each curve, the position where the test patch is equally likely to appear lighter or darker than the standard patches defines the point of subjective equality (PSE), and significant deviations of that point relative to the standard diffuse reflectance reveal systematic biases in observers' judgments. The precision of these judgments is revealed by the slopes of the psychometric functions, which are typically defined as Weber fractions (i.e., the magnitude of the difference threshold relative to the magnitude of the standard).

It is clear from Figure 3 that subjects had difficulties with this task at the lowest level of diffuse reflectance of the standard when the test patch was covered with a specular highlight, and we were unable to

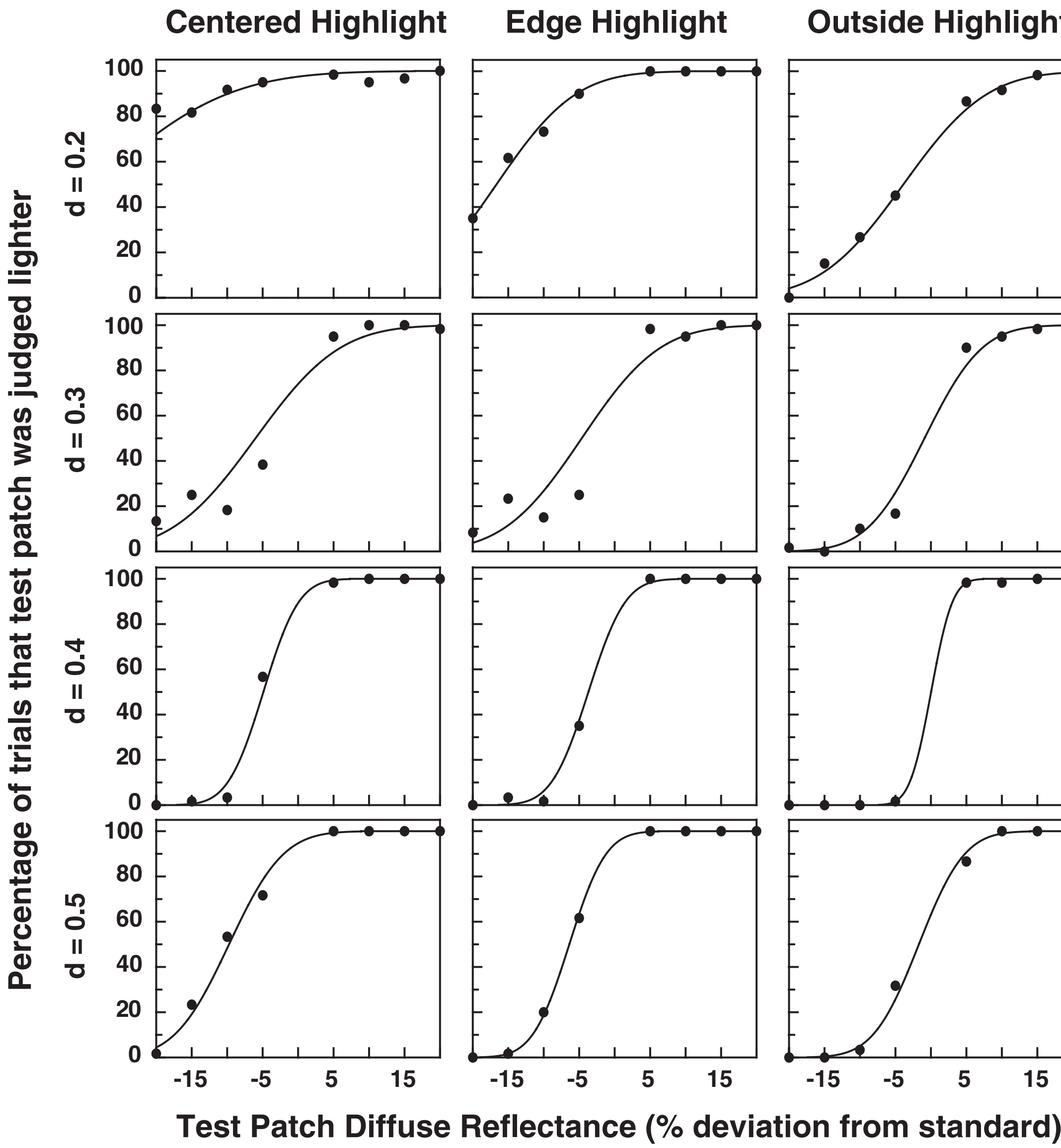

Fig. 3. Combined results for all 3 observers for each combination of highlight location and standard diffuse reflectance. The solid curves in this figure are the best-fitting psychometric functions obtained using probit analysis.

obtain reliable estimates of the difference thresholds or PSEs in those conditions. Observers' performance in the remaining conditions, however, was remarkably good. The average Weber fractions for the centered, edge, and outside highlights were 4.34%, 3.78%, and 3.11%, respectively, and the average PSEs for these different highlight placements were −6.88%, −4.91%, and −0.86%, respectively. These findings indicate that when the test patch contained a specular highlight, the observers were biased to judge it as slightly lighter than would otherwise be the case when no highlight was present.

In evaluating the nature of these biases, it is important to recognize that the presence of a specular highlight in the test patch increased the image intensity in that patch by 150 to 300%, depending on the value of diffuse reflectance. Indeed, if observers' lightness judgments had been based on the total proportion of light reflected among the different surface regions, then they would have judged the test patch to be lighter than the standard on every trial, except perhaps in the outside-highlight conditions. Clearly, that did not occur. These findings suggest, therefore, that the highlights were somehow perceptually discounted so that the relative lightness among different regions was determined primarily by the diffuse component of surface reflectance.

Many previous experiments on lightness perception have found that the apparent color of a surface patch is often defined by the ratio of its luminance relative to the luminances of neighboring patches within the same local framework (e.g., see Jacobsen & Gilchrist, 1988). Luminance ratios are particularly informative in this regard because they are invariant over changes in the amount of illumination—provided that the illumination is the same over all of the different surface regions to be compared. That is why grouping processes are also of critical importance in lightness perception (Gilchrist et al., 1999).

Smoothly curved objects, such as those used in the present study, pose problems for traditional accounts of lightness constancy because illumination varies continuously as a function of surface orientation relative to the direction of illumination and the observer's line of sight. One possible way of dealing with this issue would be to employ some sort of edge integration (e.g., see Land & McCann, 1971). For example, with the objects used in the present experiment, observers could potentially base their judgments on the ratio of image intensity between the test patch and its adjacent background relative to the ratio of image intensity between the standard patches and their adjacent background regions. In the absence of any specular highlights, this strategy would correctly compensate for variations in image shading due to changes in surface orientation, and might therefore make it possible to achieve accurate lightness comparisons among spatially separated regions with large differences in illumination.

When the test patch contains a specular highlight, however, this strategy would produce a systematic pattern of errors. It is important to keep in mind that the background, test, and standard regions all had a uniform specular reflectance, so that adding specular reflections to the diffuse reflections in regions with highlights dramatically reduced the ratio of image intensity between the test patch and its adjacent background (see also Gilchrist & Jacobsen, 1983). Thus, if observers had based their responses on edge integration, then they should have responded that the test patch appeared darker than the standard on every trial. It is clear from Figure 3, however, that the vast majority of errors were in the opposite direction.

DISCUSSION

The term lightness is typically defined in vision textbooks as the perception of surface reflectance. Surfaces that reflect a relatively high proportion of the incident light are generally perceived as light gray or white, whereas those that reflect a relatively small proportion are generally perceived as dark gray or black. The research described in the present article suggests, however, that this classical definition of lightness may be overly simplistic, in that it is applicable only to matte surfaces. Many of the materials observed in a natural environment have multiple components of reflectance, including a diffuse component, by which light is scattered isotropically in all possible directions, and a specular component, by which light is reflected anisotropically within a limited range of directions. The results of the present experiment provide clear evidence that the perceptual mechanisms for determining the apparent color of a surface are somehow able to discount the specular components of reflectance so that the perception of lightness is based primarily on the light that has been reflected diffusely.

The discounting of specular reflections in the determination of surface lightness is similar in many respects to other previously reported phenomena in which the luminance within a given neighborhood is perceptually partitioned into multiple components. The most well known example is the scissioning of luminances in the perception of transparency as arising from multiple surfaces in the same location (see Fig. 1; Metelli, 1974; Singh & Anderson, 2002). Another example is the perception of lightness in the presence of a veiling luminance, as typically occurs when viewing a scene through a window. In that case, the light reflecting from the window provides an additive veil that alters the luminance ratios for all other surface patches within the scene. Gilchrist and Jacobsen (1983) have shown that human observers are able to discount the veil when making lightness judgments, but only if the scene depicts a complex arrangement of 3D surfaces in multiple orientations. Lightness constancy is not obtained, in contrast, when a veiling luminance is added to a 2D Mondrian pattern.

In order to correctly interpret the images employed in the present study, an observer must perceptually attribute the variations in luminance to several distinct causes (cf. Adelson & Pentland, 1996; Bergstrom, 1977; Knill & Kersten, 1991). These include (a) variations in surface orientation relative to the observer and the direction of illumination, which are perceived as surface curvature; (b) variations in the diffuse component of reflectance, which are perceived as differences in lightness; and (c) variations in the specular component of reflectance, which are perceived as differences in shininess. How might this partitioning of luminance into multiple components be accomplished? For the displays employed in the present study, there are a few basic image characteristics by which the different causes of luminance variation could potentially be distinguished. Note in Figure 2, for example, that the curvature of the depicted object produces a smooth gradient of luminance change over the entire surface. The variations in diffuse reflectance, in contrast, produce abrupt changes in luminance at the boundaries of each square check in the surface texture. Finally, the specular highlights in these displays could potentially be identified by regions of unusually high contrast.

Although there is some validity to these simple rules of thumb for identifying the causes of luminance change, they are clearly not sufficient for the perceptual interpretation of more complex scenes. Smooth gradients of luminance can be due to a variety of factors other than surface curvature, including the attenuation of illumination as a function of distance from the light source, the interreflections of light among multiple objects in a scene (e.g., see Gilchrist & Jacobsen, 1984; Madison, Thompson, Kersten, Shirley, & Smits, 2001), or the penumbras of cast shadows. Similarly, abrupt changes in luminance can be due to changes in diffuse reflectance or to changes in 3D orientation at the edges of a polyhedral surface (e.g., see Adelson, 1993; Gilchrist, 1977).

Identifying the specular components of reflected light is an especially interesting problem. Although the specular reflections of luminous objects often produce regions of high luminance contrast, similar high contrasts can also occur when a local surface region is self-luminous (Bonato & Gilchrist, 1994) or is illuminated by a spotlight. This ambiguity is compounded still further by the fact that the specular reflections of nonluminous objects can produce luminance contrasts that are quite small (e.g., the reflections on the tiled surface in Fig. 1).

It is interesting to note that the identification of specular highlights is particularly difficult for desaturated, gray surfaces like those used in the present experiment. For many natural objects, the diffuse and specular components of reflectance could potentially be distinguished by variations in their chromatic structure. For example, if a red apple is illuminated by a white light, the diffuse components of reflectance will appear red, whereas the specular highlights will appear white. D'Zmura and Lennie (1986) and Lee (1986) have developed computational models that can exploit these chromatic variations for computing the spectral composition of the illuminant in order to achieve color constancy, though there is some empirical evidence that human observers may be insensitive to this information (Yang & Maloney, 2001). An important limitation of these models is that they are applicable only for scenes that contain multiple chromatic colors (e.g., a basket of green and yellow peppers), and they would therefore be incapable of computing the reflectances of achromatic surfaces, such as the ones depicted in Figures 1 and 2.

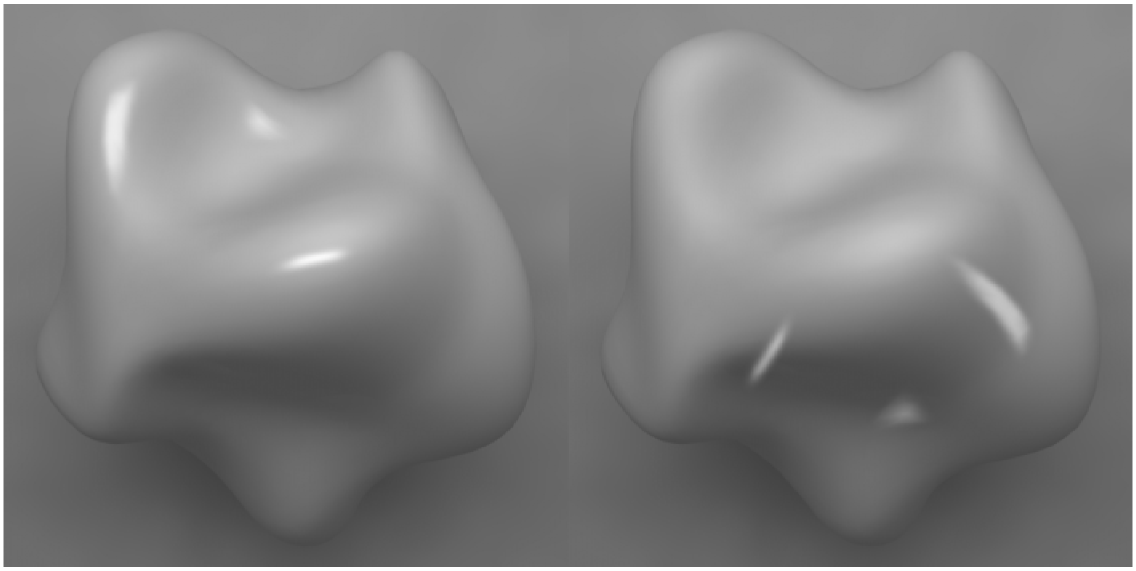

Fig. 4. Illustration of possible and impossible highlight patterns. Note how the localized highlights in the image on the left provide an overall appearance of surface gloss. The image on the right shows an identical pattern of shading, except that the highlights have been transformed so that they are no longer consistent with the diffuse shading or aligned in directions of minimum surface curvature. The highlights in that case are perceptually interpreted as stray beams of light or patches of white paint, and the depicted surface appears much less glossy.

There is some anecdotal evidence to suggest that the identification of specular highlights may involve strong interactions with the perceptual analysis of 3D shape from shading. Consider, for example, the pair of images presented in Figure 4, which are adapted from an earlier demonstration by Beck and Prazdny (1981). Note how the locally defined highlights in the object on the left give the surface a glossy appearance. An important property of highlights that is evident in this figure is that they are generally elongated along lines of minimum curvature. If this property is altered through photo editing, as in the image on the right, then the depicted surface appears much less glossy. The highlights in that case are perceptually interpreted as stray beams of light or patches of white paint.

Existing computational models for determining shape from shading or achromatic surface reflectance have not been designed to deal with specular highlights, and would most likely produce erroneous results in regions where they are present. Moreover, because highlights behave differently than other optical structures over changes in viewpoint or the direction of illumination, they also pose problems for current theoretical models of the perception of 3D shape from motion or binocular disparity. The available evidence suggests, however, that the presence of highlights in a scene may sometimes actually facilitate the perceptual judgments of real human observers (e.g., see Blake & Bülthoff, 1991; Norman, Todd, & Phillips, 1995; Todd, Norman, Koenderink, & Kappers, 1997). Understanding the mechanisms by which this is accomplished is a fascinating problem for future research.

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