The role of brightness and orientation congruence in the perception of surface gloss

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The perception of surface gloss depends on specular highlights but little is understood about how the visual system distinguishes specular highlights from other luminance maxima generated by variations in pigmentation or illumination. It has been argued that diffuse shading gradients provide information for identifying specular highlights. Specular highlights typically share the orientation of the diffuse shading locally. Specular highlights are typically proximal to the brightest region of the diffuse shading locally. We compared the contributions of these two relationships to perceived gloss. Highlight orientation relative to the diffuse shading was varied by rotating highlights. Highlight distance from the brightest region of the diffuse shading was varied by translating highlights in displays that preserved the orientations of highlights relative to their surrounds. Both manipulations reduced perceived gloss. Rotations reduced perceived gloss more than translations, even though translations displaced highlights into darker regions than rotations. The same reductions in perceived gloss occurred when highlights were matched in perceived contrast across conditions (Experiment 2b). The results provide evidence that the perception of gloss depends on highlight distance from the luminance maxima of the surrounding intensity gradient (brightness congruence) in addition to the shared orientation of highlights with their surrounds (orientation congruence).

Keywords: 3D surface and shape perception, shading, texture, gloss


Introduction

The luminance variations in images arise from complex interactions between surface optics, the illumination field, and intervening media. One of the fundamental goals of vision science is to explain how the visual system uses images to infer surface shape, albedo, and gloss. Recently, there has been a growing body of research that has tried to identify how the luminance variations in images determine the degree to which a surface appears glossy. Studies have approached this issue in three different ways: manipulating the surface and its illumination field, manipulating simple image statistics, or manipulating the locations of specular highlights.

One approach has evaluated how perceived gloss varies with parameters of the surface and the illumination field that can be simulated using ray tracing models. Using this approach, it has been shown that the degree to which a surface appears glossy depends on the observers’ viewing direction (Obein, Knoblauch, & Vienot, 2004), the shape of the surface (Ho, Landy, & Maloney, 2008; Nishida & Shinya, 1998; Wijntjes & Pont, 2010), and the illumination field (Doerschner, Boyaci, & Maloney, 2010; Fleming, Dror, & Adelson, 2003; Olkkonen & Brainard, 2010). It has also been found that perceived gloss increases if the surface occupies different positions in the image over time (Sakano & Ando, 2010; Wendt, Faul, Ekroll, & Mausfeld, 2010) or in the two eyes’ views (Wendt, Faul, & Mausfeld, 2008). However, it is not clear from these studies what information the visual system uses to infer surface gloss because each manipulation changed the image in a variety of complex ways.

A second approach has been to search for simple image statistics that are correlated with surface gloss (Motoyoshi, Nishida, Sharan, & Adelson, 2007; Nishida & Shinya, 1998). Motoyoshi et al. (2007) argued that specular reflections typically generate positively skewed luminance histograms. They proposed that the visual system computes subband skew (or something “similar”) to infer surface gloss. Consistent with this proposal, they modulated perceived gloss by manipulating the histogram skew of images of glossy surfaces. However, it has been argued that the correlation between gloss and skew is limited to a restricted set of surface geometries, surface reflectance properties, and illumination fields (Anderson & Kim, 2009; Kim & Anderson, 2010). Consequently, histogram or subband skew cannot distinguish gloss from other possible
sources of skew such as pigmentation, the illumination direction, and the surface geometry (see also Wijntjes & Pont, 2010).

A third approach has been to search for image cues that the visual system could use to distinguish specular highlights from other causes of luminance maxima (such as pigmentation or variations in surface geometry or illumination). The 3D shape of glossy surfaces strongly influences where specular highlights occur; therefore, specular highlights might be identified on the basis that they are “congruent” with shape information (Anderson & Kim, 2009; Beck & Prazdny, 1981; Blake & Bulthoff, 1990; Todd, Norman, & Mingolla, 2004). Several studies have manipulated the congruence of luminance maxima with shape information by repositioning specular highlights away from their rendered locations. Specular highlights were either rotated (Anderson & Kim, 2009; Beck & Prazdny, 1981), translated (Anderson & Kim, 2009), or their 3D depth was manipulated using binocular disparity (Blake & Bulthoff, 1990). Each of these manipulations diminished perceived gloss, which was attributed to an incompatibility of the relocated highlights with shape information.

Although the idea of using information about surface shape to identify specular highlights seems fruitful, more work is required to determine the image cues that the visual system uses to infer surface gloss. Below, we describe and test two image cues that the visual system might use to assess whether luminance maxima are congruent with diffuse shading gradients: orientation congruence and brightness congruence.

Orientation congruence

Several authors have observed that specular highlights typically share the same orientation as the diffuse shading that surrounds them (Anderson & Kim, 2009; Beck & Prazdny, 1981; Todd et al., 2004). The locations of specular highlights depend on the observer’s viewing direction, the illumination direction, and the surface normal. A large range of surface normals occur at regions of high surface curvature, so these regions are more likely to generate specular highlights (Koenderink & van Doorn, 1980). Specular highlights often run parallel to ridges and valleys in the surface’s geometry, since these structures preserve the surface normal along lines of minimum surface curvature. Diffuse shading gradients also run parallel to lines of minimum surface curvature, so highlights and diffuse shading tend to share the same orientation.

The correlation between the orientations of specular highlights and diffuse shading gradients can be appreciated in Figures 1a and 2a. Figure 1a shows three specular highlights in their rendered locations; note that the diffuse shading around each highlight is elongated in a similar direction to the highlight. The colors in Figure 2a indicate the orientation of a Gabor filter that responds maximally at each location in the image. Note that the vertically and horizontally elongated highlights in (a) are located within regions of diffuse shading that optimally stimulate filters with vertical and horizontal orientations, respectively. In contrast, (b) shows that the filters that respond maximally to the repositioned highlights in Figure 1b have a different orientation to those that respond maximally to the surrounding diffuse shading.

Figure 1. The luminance maxima in (a) are specular highlights. The specular highlights in (b) are displaced from their “correct position” and appear more like light paint than specular highlights. From Todd et al. (2004).

Figure 2. The orientation field for the images in Figure 1. The hue represents the orientation of the Gabor filter that responded maximally at each location in the image. Note that the vertically and horizontally elongated highlights in (a) are located within regions of diffuse shading that optimally stimulate filters with vertical and horizontal orientations, respectively. In contradistinction, (b) shows that the filters that respond maximally to the repositioned highlights in Figure 1b have a different orientation to those that respond maximally to the surrounding diffuse shading.
congruence can provide information that the luminance maxima are specular reflections. Moreover, if luminance maxima have a different orientation from their surrounds, this orientation incongruence could provide information that the luminance maxima are not specular reflections. For example, in Figure 1b, the specular highlights have been displaced from their rendered locations in a manner that generates orientation incongruence. Each of the relocated highlights has a different orientation than its surround; the relocated highlights cut across regions of similarly oriented image structure shown by the orientation field in Figure 2b. This orientation incongruence of the highlights in Figure 1b with their surrounds may explain why the surface appears matte and the repositioned highlights appear like overlaid pigment or smudges instead of specular reflections.

Brightness congruence

Several authors have observed that specular highlights occur near, but not precisely at, points where the diffuse shading gradient is brightest (Fleming, Torralba, & Adelson, 2009; Koenderink & van Doorn, 1980; Norman, Todd, & Orban, 2004). The diffuse shading gradient is brightest where the surface normal points at the illumination direction. In contradistinction, specular highlights occur where the surface normal bisects the illumination direction and the observer’s viewing direction. Therefore, although specular highlights occur near the brightest regions of the diffuse shading gradient, there is typically a small separation between them. It is often difficult to discern this separation, however, because the diffuse shading does not appear to be brightest at a single “point” but rather across an extended region that contains the highlight. Therefore, specular highlights often appear proximal to the brightest regions of the diffuse shading gradient (see Figure 1a).

The correlation between the positions of specular highlights and the maxima of the diffuse shading suggests that highlights might be identified by their positions relative to the brightest regions of diffuse shading. First, specular highlights are usually found within relatively bright regions of diffuse shading, even though they do not usually occur precisely where the luminance of the diffuse shading is maximal. Second, specular highlights are generically absent from relatively dark regions of the diffuse shading gradient. Therefore, if luminance maxima lie within dark regions of diffuse shading, this brightness incongruence could theoretically indicate that they are not specular reflections. In contradistinction, if luminance maxima lie within bright regions of diffuse shading, this brightness congruence provides information that they are potentially specular highlights.

Figure 3 demonstrates that the perception of gloss depends on the congruence of luminance maxima with bright regions of diffuse shading. Figure 3a shows highlights in their rendered locations; note that these highlights lie within bright regions of diffuse shading. In Figures 3b and 3c, the same highlights have been translated into dark regions of diffuse shading and appear as white pigment instead of specular highlights. Orientation congruence cannot explain the different appearance of the highlights in Figure 3, because they have a similar orientation to their surrounds in all of these images. This demonstration suggests that the visual system distinguishes specular highlights from other luminance maxima using their congruence with the brightest regions of the diffuse shading.

There is some evidence that the visual system uses orientation and brightness congruence to identify specular highlights. Beck and Prazdny (1981) rotated a specular highlight 90° in the image of a glossy vase and observed that the rotated highlight appeared as light paint on a matte vase. They argued that the rotated highlight ceased to appear as a specular reflection because its orientation was incongruent with the diffuse shading gradient. Anderson and Kim (2009) found perceived gloss diminished as highlights were rotated or translated relative to the surface’s diffuse shading. Although they were primarily

Figure 3. The specular highlights lie within the brightest regions of diffuse shading in (a) and the surface appears glossy. Brightness incongruence is generated in (b) and (c) by displacing the highlights into darker regions of diffuse shading. As a result of this manipulation, the highlights appear as white paint on a matte surface, not specular highlights on a glossy surface.
interested in assessing the influence of histogram skew on perceived gloss, they argued that orientation incongruence could explain why both rotations and translations reduced perceived gloss. Unlike the translations shown in Figure 3, the translations in Anderson and Kim’s study generated orientation incongruence by translating highlights into differently oriented regions of diffuse shading.

Although these data suggest that orientation incongruence reduces perceived gloss, the rotations and translations were confounded with changes in the brightness of the highlights’ surrounds. Specular highlights occur near the brightest regions of diffuse shading, so rotations and translations displace highlights into darker regions of diffuse shading. Even when highlights are rotated around their center, brightness incongruence is generated because the endpoints of the highlight are moved into darker regions. Therefore, there are three possible explanations for the reductions in perceived gloss that arose from rotating and translating the specular highlights in the studies of Anderson and Kim (2009) and Beck and Prazdny (1981). First, orientation incongruence may have reduced perceived gloss because the orientation of the highlights differed from their surrounds. Second, brightness incongruence may have reduced perceived gloss because the relocated highlights extended into darker surrounds. Third, both types of incongruence may have diminished perceived gloss. The goal of the experiments reported below was to test whether orientation congruence, brightness congruence, or both types of congruence are used to identify specular highlights and infer surface gloss.

Experiment 1

One of the goals of Experiment 1 was to assess whether brightness incongruence influences the perception of gloss. This required a stimulus where it was possible to displace a specular highlight from a bright region of diffuse shading without generating orientation incongruence. The smoothly curved surface with long straight ridges shown in Figure 4 satisfies this requirement; the target highlight and the diffuse shading are both horizontal within the region of interest, so vertical translations of the highlight manipulate brightness congruence but not orientation congruence.

The second goal of Experiment 1 was to investigate the reasons for the decline in perceived gloss that arises when specular highlights are rotated away from their rendered orientation. Rotations disrupt the congruence of the highlight’s orientation with the diffuse shading that surrounds it; however, they also shift the highlight into darker regions of diffuse shading. The relative contribution of orientation and brightness incongruence was investigated by comparing the effect of the rotation and translation manipulations on the perception of gloss. The translation conditions controlled for the brightness incongruence present in the rotation conditions because the highlight was further from bright regions of diffuse shading in the translation conditions than in the rotation conditions. Nevertheless, if orientation incongruence has a strong influence on the perception of gloss, then rotations will eliminate the appearance of gloss more effectively than translations.

Here, it is important to note that translations and rotations are fundamentally incommensurable dimensions. It is only valid to compare these two manipulations on the basis of the amount of brightness incongruence that they generate. Brightness incongruence was always larger for the translations than the corresponding rotations, so the translations control for the brightness incongruence in the rotation conditions.
Methods

Observers

Thirteen undergraduates from the University of Sydney participated. They were naive about the aims of the experiment and received a small amount of course credit for their participation.

Display

The stimuli were displayed on a 24-inch flat screen LCD monitor (DELL 2405FPW) with a resolution of 1920 × 1200. The PsychToolBox plugin SVN revision 703 (Brainard, 1997) for Matlab (R2007a) controlled the screen and ran on a MacPro Dual-Core Intel Xeon (Mac OSX 10.3.11). Pixel size was 1.28 arcmin. The monitor was viewed binocularly from a distance of 75 cm using a chin rest. The screen was the only source of illumination and the room was painted matte black.

Stimuli

Surface

The stimuli (Figure 4) were images of a gray surface seen against a black background (0.1 cd/m²). The surface was a frontal plane square (subtending 6.9°) that was deformed with a pseudorandom smooth curvature in depth. The surface curvature formed three ridges that were roughly horizontal and were separated vertically. Ray tracing software (Blender v2.49 Blender Foundation, www.blender.org) that ran on a PC (Intel Core2 Duo E6850, Windows XP SP3) rendered the image of the surface. A single directional light source illuminated the surface from above. The illumination direction formed an angle of 15° elevation at the surface with the viewing direction of the observer. The intensity of the shading of the surface was greatest at the peaks of the ridges and fell off more rapidly for the lower side than the upper side of each ridge. The diffuse shading was rendered with a Lambertian reflectance model and its luminance varied in the range of 0.1 to 31 cd/m². The specular highlights were rendered using the Phong model (hardness set to 400) and their peak luminance was 100 cd/m². The target highlight had a peak luminance of 142 cd/m².

Target highlight

The long straight ridge at the top of the image of the surface was rendered without a specular highlight. The target “highlight” was superimposed on this ridge by adding the luminance profile shown in Figure 5 to the diffuse shading. This luminance profile was selected because it appeared as a plausible specular highlight when it was superimposed along the top of the ridge (Figure 4a). To limit brightness incongruence, the target was sufficiently short (0.47° in length) so that small rotation angles produced small displacements of its endpoints. In the rotation conditions, the target highlight was centered on the top of the ridge as shown in Figure 4a but was rotated ±4°, 8°, 15°, 22°, 30°, 60°, and 90° (Figure 4b).

Although the target was rotated about its center, the rotations displaced its endpoints away from the brightest region of the diffuse shading locally. The bright region of the diffuse shading extended along the top of the ridge and was collinear with the target highlight’s original orientation (approximately horizontal; see Figure 4a). Relative to the brightest region of the diffuse shading, each rotation angle displaced the endpoints of the target ±1, 1.9, 2.9, 5.8, 7.7, 12.5, or 14.4 arcmin, respectively. The translation conditions (Figures 4c and 4d) controlled for this displacement, as explained below. In translation conditions, the target had its original orientation (Figure 4a) and was translated up or down perpendicular to the brightest region of the diffuse shading. The translations displaced the target into regions of diffuse shading that had the same orientation (approximately horizontal), so its orientation congruence with the diffuse shading was preserved. The magnitude of the translation was equal to 1, 1.9, 2.9, 5.8, 7.7, 12.5, or 14.4 arcmin. Consequently, the translated targets were the same distance from the brightest region of the diffuse shading as the endpoints of the rotated targets.

Procedure

The 14 rotations and 14 translations were each presented 6 times in a random order. Observers were instructed to first fixate the lower, middle, and upper ridges of the surface at the beginning of each trial. Then, observers rated the degree to which the target highlight on the upper ridge appeared as a specular reflection using a visual analog scale. Observers were instructed to raise a white bar in line with the words “surface gloss” if the target appeared to be a specular reflection from a glossy
surface. Observers were instructed to lower the bar in line with the word “paint” if the target appeared to be due to white paint on the surface or a region of intense illumination from something like a spotlight. The bar was 4.6° to the right of the right edge of the surface. It was 0.7° wide and had variable height in the range of 0° to 9°. Observers confirmed their rating with a mouse click and then a random dot surface (8.8° square) replaced the stimulus during the intertrial interval (2 s).

Prior to the experiment, observers were shown examples of bright regions due to paint or surface gloss from objects in the laboratory to clarify the nature of the discrimination. Observers also completed six practice trials before the main experiment. The practice stimuli were the images from Figure 4 of Todd et al. (2004), which are reproduced in Figure 1 of this paper. They were selected as practice stimuli because the highlights in Figure 1a appear as convincing specular reflections, whereas the same highlights appear more like surface pigment in Figure 1b where they are displaced from their rendered locations.

Statistical analysis

The results were analyzed using a multivariate analysis of variance with planned orthogonal contrasts. The Decision-Wise error rate (α = 0.05) was controlled for each of the contrasts (Bird, 2004). We tested for a main effect of rotation versus translation and for effects of rotation direction and translation direction. We tested for effects of the degree of rotation and for the degree of translation and weighted all conditions equally.

Results and discussion

Figure 6 shows the mean gloss ratings of all observers, which reflect the perceived gloss of the target highlight, not the surface globally. The results for clockwise and counterclockwise directions of rotation were not significantly different ($F_{(1,12)} = 0.2, p = 0.663$) and Figure 6 shows the results averaged across rotation direction. The target appeared less like a specular reflection as it was rotated so that its orientation differed from the diffuse shading ($F_{(1,12)} = 40.0, p < 0.001$). This decline was particularly rapid for the 4°–30° range of rotation angles. The translations also diminished gloss ratings ($F_{(1,12)} = 16.0, p = 0.002$) even though they preserved the congruence of the orientation of the target with its surround. Downward translations (Figure 4d) displaced the target into darker regions of diffuse shading than did upward translations (Figure 4c) and diminished gloss ratings more than upward translations ($F_{(1,12)} = 5.1, p = 0.043$). These results are consistent with the claim that perceived gloss depends on highlight proximity to the brightest region of the diffuse shading locally (brightness congruence).

Rotations and translations are fundamentally different dimensions; however, the present study can directly compare the rotations and translations on the basis of the amount of brightness incongruence that they generate. The top of Figure 6 shows the distance that each rotation angle shifted the endpoints of the target away from the brightest region of its surround. In translation conditions, the entire target was the same distance from the brightest region of its surround. Error bars are standard errors and are irrelevant for tests of statistical significance because the experiment is a within-subject design; $n = 13$.

Figure 6. The degree to which the target “highlight” appeared as a specular reflection (mean rating for all observers). The x-axis shows the orientation of the target relative to its surround for the rotation conditions (note that the translated target always had the same orientation as its surround). The top of the graph shows the distance that each rotation angle shifted the endpoints of the target away from the brightest region of its surround. In translation conditions, the entire target was the same distance from the brightest region of its surround. Error bars are standard errors and are irrelevant for tests of statistical significance because the experiment is a within-subject design; $n = 13$. 
gloss because they generated different image contrasts. As the degree of rotation or translation increased, the highlight was superimposed on progressively darker regions of diffuse shading. The target highlight was simply added to the diffuse shading profile, so its intensity and local contrast covaried with the rotations and translations. Changes in target contrast might explain the results of Experiment 1 because it is known that perceived gloss increases with highlight contrast (Beck & Prazdny, 1981; Nishida & Shinya, 1998; Pellacini, Ferwerda, & Greenberg, 2000; Wendt et al., 2008).

Experiments 2a and 2b were designed to test whether the variations in perceived gloss observed in Figure 6 can be attributed to variations in the target highlight’s contrast.

### Experiment 2a

In Experiment 1, perceived gloss declined progressively as the target highlight was rotated or translated. It was argued that these manipulations may have reduced gloss because they rendered the target incongruent with the diffuse shading or because they changed the target’s contrast. Since the appropriate measure of highlight contrast is unknown, we had observers equate the perceived contrast of the target across the different conditions from Experiment 1. Observers adjusted the target’s luminance so that it appeared to have equal contrast to a reference highlight on another surface.

#### Methods

**Observers**

Thirteen undergraduates from the University of Sydney participated. Observers were naive about the aims of the experiment and had not participated in Experiment 1. They received a small amount of course credit for their participation.

**Stimuli**

A “reference” surface and a “match” surface were presented side by side. The reference and match surfaces were both identical to that in Experiment 1 except for the luminance of the target highlight. The reference surface was presented 7.5° to the left of the center of the screen and the match surface was presented the same distance to the right. The target on the reference surface was in its original position and orientation as shown in Figure 4a. The target on the match surface was presented with each of the rotations or translations from Experiment 1. As in Experiment 1, the target was produced by adding the luminance profile shown in Figure 5 to the diffuse shading. Observers varied the amplitude of this luminance profile to adjust the contrast of the target on the match surface. Observers were able to vary the luminance of the target on the match surface through a large range; the peak luminance of the target could be set as low as 32 cd/m² or as high as 173 cd/m². The peak luminance of the target on the reference surface was fixed at 142 cd/m² as in Experiment 1.

**Procedure**

Observers were required to match the contrast of the target highlight on the two surfaces. They were instructed to equate the degree to which the brightness of the targets differed from their surrounds. Observers were instructed to “bracket” their matches by adjusting the target so that it appeared to have slightly higher contrast than the reference, then slightly lower contrast, and finally the same contrast. The rotations and translations tested in Experiment 1 were presented in a random order 3 times. At the beginning of each trial, the peak luminance of the target on the match surface was 32 or 173 cd/m² selected at random.

**Results and discussion**

Figure 7 shows the peak luminance of the target at PSE (mean of all observers). There was no significant difference in the target’s luminance at PSE between the rotations and the translations ($F_{(1,12)} = 0.2, p = 0.663$), or the directions of rotation ($F_{(1,12)} = 1.5, p = 0.224$), or...
the directions of translation ($F_{(1,12)} = 0.7, p = 0.419$). As the degree of rotation and translation increased, the luminance of the target at PSE decreased significantly ($F_{(1,12)} = 5.7, p = 0.035$). This suggests that the rotations and translations progressively increased the perceived contrast of the target in Experiment 1. Since perceived gloss increases with highlight contrast (Beck & Prazdny, 1981; Nishida & Shinya, 1998; Wendt et al., 2008), systematic increases in the perceived contrast of the target probably attenuated, rather than produced, the decline in gloss ratings found in Experiment 1.

### Experiment 2b

The rotations and translations were designed to generate orientation and brightness incongruence, but Experiment 2a indicates that they also increased highlight contrast. Although perceived gloss declined with orientation and brightness incongruence in Experiment 1, increasing highlight contrast may have diminished the magnitude of these effects. The goal of Experiment 2b was to assess the influence of the rotation and translation manipulations on perceived gloss when the perceived contrast of the target remains fixed. Observers viewed images with matching perceived contrast obtained from Experiment 2a. As in Experiment 1, observers rated the degree to which the target appeared to be due to a specular reflection. By preserving highlight contrast in Experiment 2a, we expect to observe larger effects of orientation and brightness incongruence.

### Methods

#### Observers

Twenty-five undergraduates from the University of Sydney participated. Observers were naive about the aims of the experiment and had not participated in Experiment 1 or 2a. They received a small amount of course credit for their participation.

#### Stimuli and procedure

Observers viewed the same surface as in Experiments 1 and 2a. As in those experiments, the target highlight was produced by adding the luminance profile shown in Figure 5 to the diffuse shading. To equate perceived contrast across conditions, the amplitude of this luminance profile decreased with the degree of rotation and translation. For each rotation and translation condition, the peak luminance of the target was the mean contrast setting of all observers for that condition obtained in Experiment 2a (Figure 7). The surface (Figure 4a) was presented to the right of the center of the screen in the same location as the “match” surface in Experiment 2a. Observers rated the degree to which the target appeared to be a specular highlight using the same visual analog scale used in Experiment 1. The visual analog scale was located on the left side of the monitor and was separated from the surface horizontally by a gap of 12°. The 14 rotations and 14 translations were presented three times in a random order. The procedure was the same as in Experiment 1.

A few additional conditions were included to assess the impact of any residual variations in the target’s perceived contrast on gloss ratings. In these additional conditions, the luminance of the target was either higher or lower than the contrast-matched stimuli. The target was presented with a 15° or a 30° rotation or with the corresponding translation. The decline in gloss ratings in Experiment 1 was particularly steep for the 15° and 30° conditions, so they should be particularly sensitive to any effect of small differences in perceived contrast. The peak luminance of the target differed from the mean of the PSE settings for these conditions in Experiment 2a by ±1 absolute deviation. These additional conditions were also presented 3 times and were randomly interleaved with the other conditions.

### Results and discussion

Figure 8 shows the mean gloss rating of all observers for highlights with equal perceived contrast. Note that gloss ratings refer to the perceived gloss of the target highlight, not the surface as a whole. The results are similar to Experiment 1; if anything, the differences between conditions are more pronounced with contrast-matched stimuli. The results for clockwise and counterclockwise directions of rotation were not significantly different ($F_{(1,24)} = 0.04, p = 0.843$), so Figure 8 shows the results averaged across rotation direction. As in Experiment 1, the translations diminished gloss ratings ($F_{(1,24)} = 19.8, p < 0.001$) even though they preserved the congruence of the orientation of the target with its surround. Downward translations displaced the target into darker regions of diffuse shading than upward translations and diminished gloss ratings more than upward translations ($F_{(1,24)} = 12.8, p = 0.002$). Since the orientation congruence and perceived contrast of the translated targets was preserved, these results provide evidence that brightness incongruence reduces perceived gloss.

Gloss ratings diminished progressively with the degree of rotation ($F_{(1,24)} = 43.4, p < 0.001$). Rotations reduced gloss ratings more than the translations ($F_{(1,24)} = 44.2, p < 0.001$) even though the brightness incongruence was larger for the translations. These data reveal that the brightness incongruence generated by highlight rotations cannot fully account for the decline in perceived gloss in...
these conditions. Rather, the results suggest that the rotations principally reduced perceived gloss because they rendered the target highlight incongruent with the orientation of its surrounds.

Experiment 2b also assessed the influence of small variations in highlight contrast on gloss ratings. Additional conditions were included where the luminance of the target was equal to ±1 absolute deviation of the contrast matches from Experiment 2a. Gloss ratings are expected to differ between these conditions if small differences in the perceived contrast of the target contributed to the decline in perceived gloss that arose from the rotations and translations. Figure 9 shows the mean gloss rating of all observers for the conditions with higher or lower perceived contrast. The degree to which the target appeared as a specular reflection was similar for the lower, higher, and matched contrast conditions. This similarity indicates that the results were not strongly influenced by any small differences in the perceived contrast of the target that may not have been eliminated in Experiment 2a.

At first glance, the failure of contrast to modulate gloss ratings in Experiment 2b may seem inconsistent with the prior finding that perceived gloss increases with highlight contrast (Beck & Prazdny, 1981; Nishida & Shinya, 1998; Wendt et al., 2008). However, highlight contrast was found to modulate perceived gloss in studies where observers rated differences between surfaces that all appeared glossy to varying degrees. In the present study, gloss ratings reflect a qualitative difference in the appearance of the target as either a specular reflection or overlaid pigment. Therefore, the failure to observe an effect of highlight contrast on perceived gloss in the present study might occur because gloss ratings were dominated by the large perceptual difference between specular reflections and pigmentation.

General discussion

The experiments reported here were designed to assess whether perceived gloss depends on the shared orientation of highlights with diffuse shading gradients (orientation congruence) and/or on the proximity of highlights to the brightest region of the diffuse shading (brightness congruence). Our data suggest that the visual system relies on both orientation congruence and brightness congruence to recover surface gloss. Experiment 1 translated a highlight from bright to dark regions of diffuse shading. The translated highlight appeared less like a specular reflection even though it always had the same orientation as the local diffuse shading gradient. To our knowledge, this is the first direct evidence that the perception of gloss depends on highlight proximity to the brightest regions of diffuse shading gradients.

The present study also provides evidence that the visual system infers gloss from the orientation congruence
between highlights and the gradients generated by diffuse shading. Previous studies found that perceived gloss diminished as specular highlights were rotated (Anderson & Kim, 2009; Beck & Prazdny, 1981) or translated (Anderson & Kim, 2009) in a manner that caused their orientation to differ from their surround. The present study controlled for the brightness incongruence that is generated when highlights are rotated by comparing rotated and translated highlights. Although brightness incongruence was greater for the translated highlights, the rotated highlights appeared less glossy. These results indicate that the rotated highlights appeared less glossy because their orientation was altered, not because they extended into darker surrounds. This is consistent with the view that the perception of gloss depends on the orientation congruence of highlights with their surrounds.

Experiments 2a and 2b assessed whether the rotations and translations of highlights reduced perceived gloss because they altered highlight contrast. One issue that arises when attempting to equate contrast between conditions is the selection of an appropriate metric of contrast that captures perceived contrast. There is currently no accepted measure of contrast that captures perceived contrast in the displays that were used in our experiments. We therefore determined perceived contrast experimentally (Experiment 2a) and used these values to assess the effects of perceived contrast on gloss (Experiment 2b). The results of the contrast matching experiment revealed that rotations and translations actually increased highlight contrast in Experiment 1. The results of Experiment 2b indicate that highlight contrast cannot explain the decline in perceived gloss that occurs when the highlights were rotated or translated because the same effects were observed for contrast-matched highlights. A similar procedure could be used to assess the contribution of highlight contrast to variations in perceived gloss that arise from manipulating histogram skew (Motoyoshi et al., 2007) or parameters of the visual scene such as the illumination field or the surface geometry (Fleming et al., 2003; Ho et al., 2008; Nishida & Shinya, 1998; Wijntjes & Pont, 2010).

The rotations and translations manipulated the congruence of the highlight with the surrounding luminance gradient, the surface shape, and the diffuse shading of the surface. Below, we argue that it is plausible that the perception of gloss depends on each of these relationships.

First, the visual system might discriminate plausible from implausible highlights using their local image context. Specular highlights are typically proximal to the brightest regions of diffuse shading gradients; however, textures can also generate luminance maxima that are proximal to bright surrounds. Therefore, the congruence of luminance maxima with bright surrounds is consistent with the possibility that they are specular highlights, but it is not diagnostic of specular highlights. Nevertheless, specular highlights are generally absent from dark regions of diffuse shading. Therefore, if luminance maxima are proximal to the dark region of the surrounding luminance gradient, this brightness incongruence provides information that they are not specular highlights. Likewise, it is possible to identify some implausible specular highlights on the basis that they are incongruent with the orientation of their local image context as shown in Figure 2b. Therefore, the orientation and brightness congruence of highlights with the surrounding luminance gradient provides information for discriminating plausible from implausible highlights. Consistent with this view, perceived gloss declined in the present study as the rotations and translations disrupted the orientation and brightness congruence of the highlight with its local image context.

A second way that the visual system might identify specular highlights is by evaluating the congruence of their locations with the recovered surface geometry. Todd et al. (2004) argued that there are strong interactions between the recovery of surface gloss and the recovery of shape from shading. Specifically, they argued that the perception of gloss may depend on the correlation of luminance maxima with lines of minimum surface curvature. Anderson and Kim (2009) also argued that the visual system assesses whether the positions of luminance maxima are compatible with the recovered 3D surface geometry. These arguments suggest that rotations reduced perceived gloss because they caused the highlights to be incongruent with lines of minimum surface curvature. Recently, the possibility that the perception of gloss depends on the congruence of highlights with the surface geometry was criticized on the basis that it requires that the “actual geometry of the surface should be known” (Wijntjes & Pont, 2010, p. 8). Although little is understood about how the visual system recovers surface shape, we know of no examples of perceived gloss in the absence of a vivid percept of 3D shape. The existing data are therefore consistent with the view that the visual system assesses whether the locations of potential highlights are compatible with the recovered surface geometry. An interesting question for future research is whether the visual system explicitly assesses the compatibility of highlights with 3D shape. This could be examined by manipulating the perceived shape of the surface while preserving the relationship of highlights with their local image context.

A third way that specular highlights might be identified is by evaluating their orientation and brightness congruence with diffuse shading. It is possible to synthesize images where the highlights are congruent with the shape of the surface (i.e., lie along lines of minimum surface curvature) but are incongruent with the orientation and luminance maxima of the diffuse shading. Recent work from our laboratory suggests that the perception of gloss depends on the compatibility of highlights with surface shading, not just the surface geometry (Kim, Marlow, & Anderson, 2011). The congruence of specular highlights with the diffuse shading was manipulated by rendering the specular and diffuse reflectance components of a surface using different illumination fields. This procedure
preserved the compatibility of the highlights with the surface geometry, yet perceived gloss declined with increases in the orientation and brightness incongruence of highlights with the diffuse shading. Therefore, it is plausible that one of the reasons why the rotations and translations reduced perceived gloss was because they rendered the highlight incompatible with the surface shading, not just the shape of the surface or its local image context.

The issue of how specular highlights are identified also bears on the proposal that specular highlights constrain the perception of 3D shape. Beck and Prazdny (1981) noted that specular highlights tend to have the same orientation as the minimum direction of surface curvature. Fleming, Torralba, and Adelson (2004) proposed that the orientation fields that specular highlights generate can provide useful constraints on 3D shape. Consistent with this claim, it has been found that specular reflections influence perceived shape (Fleming et al., 2004; Norman et al., 2004; Todd & Mingolla, 1983). However, these experiments do not indicate whether specular highlights contribute to the perception of shape before, after, or while they are (being) distinguished from other causes of luminance maxima. Luminance maxima generated by variations in pigmentation or illumination may not indicate the direction of minimum surface curvature, so it would be advantageous for shape computations to discriminate between plausible and implausible highlights. The brightness and orientation incongruence of luminance maxima with their surrounds provide two such methods for identifying implausible specular highlights.

The issue of how specular highlights are identified is also relevant to studies of how perceived gloss varies with changes in surface relief and other parameters of the visual scene. Fleming et al. (2003) varied the illumination field in which surfaces were embedded and observed that elongated highlights appeared glossier than isotropic highlights. One explanation for this finding is that the visual system can more readily identify that elongated specular highlights are in fact due to specular reflections because it can assess their orientation congruence with their surroundings. Likewise, changes in the anisotropy of highlights may explain why Nishida and Shinya (1998) found that perceived gloss increased with the degree of surface curvature. They used smoothly curved surfaces with elongated ridges and valleys, so the anisotropy of the highlights increased with the degree of surface curvature.

Our data provide evidence that orientation and brightness incongruency can identify luminance maxima that are not specular reflections; however, there are other sources of information for performing this discrimination, so perceived gloss does not depend solely on orientation and brightness congruency. For example, these congruencies will not cause luminance maxima to appear glossy if their binocular disparity (Blake & Bülthoff, 1990) or motion (Hartung & Kersten, 2002) is consistent with texture rather than specular reflection. We also observed that the perception of gloss depends on the luminance profile of potential highlights. Orientation and brightness congruency will not give rise to the perception of gloss if the smoothly varying luminance profile of the highlight in our studies (Figure 5) were simply replaced with a white line. More research is needed to identify how the luminance profile of potential highlights is also used to distinguish specular reflection from other causes of luminance maxima.

The results reported here and elsewhere support the view that the perception of gloss depends on the congruence of highlights with 3D shape information (Anderson & Kim, 2009; Beck & Prazdny, 1981; Blake & Bülthoff, 1990; Todd et al., 2004). We manipulated highlight orientation relative to diffuse shading gradients and manipulated highlight proximity to the brightest region of the diffuse shading locally. The results suggest that plausible specular highlights are identified using their congruence with both the orientation and the brightest region of the surrounding intensity gradient.

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Footnote

1A scale version of the image filter is shown in the key of Figure 2. The image filter was produced by combining a 1D difference of Gaussian profile with a 2D Gaussian envelope. The resulting profile was 9 pixels in length and the central lobe was 1 pixel wide. The positive and negative lobes summed to zero so the filter did not respond when presented with a uniform field.

References


