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EFFECTS OF HIGHLIGHTS ON GLOSS PERCEPTION

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Abstract

The perception of a glossy surface in a static monochromatic image can occur when a bright highlight is embedded in a compatible context of shading and a bounding contour. Some images naturally give rise to the impression that a surface has a uniform reflectance, characteristic of a shiny object, even though the highlight may only cover a small portion of the surface. Nonetheless, an observer may adopt an attitude of scrutiny in viewing a glossy surface, whereby the impression of gloss is partial and nonuniform at image regions outside of a highlight. Using a rating scale and small probe points to indicate image locations, differential perception of gloss within a single object is investigated in the present study. Observers’ gloss ratings are not uniform across a surface, but decrease as a function of distance from a highlight. When, by design, the distance from a highlight is uncoupled from the luminance value at corresponding probe points, the decrease in rated gloss correlates more with distance than with luminance change. Experiments also indicate that gloss ratings change as a function of estimated surface distance, rather than as a function of image distance. Surface continuity affects gloss ratings, suggesting that apprehension of 3D surface structure is crucial for gloss perception.
Introduction: Local and global perspectives on gloss

Humans are readily able to evaluate the glossiness of objects. However, the mechanisms of gloss perception are not understood, and psychophysics in this area is sparse. The presence of bright specular highlights is the most important factor. The effects of highlights are especially dramatic when two images with and without them are placed side by side (figure 1).

The patterns of luminance that lead to the perception of glossy highlights are based in part on the physical and chemical make-up of material surfaces, and the tendency of a surface composed of a given type of material to scatter light in a particular way is characterized by a bi-directional reflectance function (BRDF; Torrance and Sparrow 1967). The surface of an object, such as a vase, may be homogeneously covered by a certain material, such as a glaze. Notwithstanding the homogeneity of a material surface, however, the location and the size of highlights on a surface depend also on the momentary position of illumination sources, the eye, and the surface geometry. Computer algorithms for rendering a glossy object therefore require both the selection of an approximation to some particular BRDF and the specification of the viewing geometry to be simulated, including the position of the eye, the object surface, and the illuminant sources.

To these two major components of rendering there correspond two aspects of perceptual judgment. On the one hand, an observer may seek to determine whether some whole object's surface is a sample of a particular category, i.e., smooth plastic or polished metal. On the other hand, one may take the perspective of a still-life painter, and ask to what extent a particular portion of a given surface looks glossy at the present time from a given viewpoint. The presently reported experiments, conducted with static achromatic images, arise from this second type of perceptual judgment.
Recent work by Ferwerda, Pellacini and Greenberg (2001) is an example of a *global* or "whole object" approach to the psychophysics of gloss. Their work seeks to identify those aspects of a computational surface reflectance model that have noticeable effects on human judgments of degree or quality of gloss. Candidate dimensions include the six described by Hunter (1987): specular gloss, distinctiveness-of-image (DOI), haze, sheen, the absence-of-texture gloss, and contrast gloss or luster, defined as "gloss associated with contrasts of bright and less bright adjacent areas of the surface of an object." Luster increases with increased ratio between light reflected in the specular direction and that reflected in diffuse directions which are adjacent to the specular direction" (Hunter 1987 p. 402). Using a multi-dimensional scaling technique, Ferwerda et al. (2001) find that the two most pertinent dimensions for human ratings are contrast gloss and DOI, though a factor that seems to correspond to lightness in matte displays interacts with the two gloss dimensions. In their experiments, gloss is evaluated on equal sized spheres and for whole objects, and no interaction between gloss perception and 3D shape of the object is studied.

A different approach to gloss perception is taken in one of the earliest examples of computer manipulation of digitized gray scale images for psychophysics, in which Beck and Prazdny (1981) demonstrate that perception of gloss depends on the presence of a specular highlight on an otherwise diffusely reflecting surface. (For the remainder of this article, we often use the term "highlight" to refer to a specular highlight.) See figure 1 for a demonstration of this effect. Beck and Prazdny (1981) ask how the specular highlight affects the judgment of gloss within different surface regions of a single object. Gloss is thus treated as a *local* quantity, which varies as a function of distance from highlights. They show that a highlight produces a compelling impression of gloss only at limited distances. Increasing the size or brightness of a specular highlight increases the size of the area where gloss is perceived. One can describe the effect as a type of limited "gloss propagation."

Mechanisms of gloss perception involve more than just local operations on image data. Highlight orientation has to be consistent with the surface's curvature (Beck and Prazdny 1981). Surface regions near a highlight whose orientation is inconsistent with the perceived surface curvature -- i.e., the longer axis of the highlight is in the direction of maximum curvature -- are seen as matte or less glossy than regions near highlights that "fit" the local surface geometry. The perception of gloss is also influenced by gradients of shading. Surface curvature that is indicated by contours without shading, however, fails to give rise to the perception of gloss, even in the presence of highlights that would be efficacious in the presence of shading.

The goal of our experiments is to begin the process of quantitatively characterizing the parameters that affect the fall-off of the strength of the perception of gloss as an observer is asked to report judgments for various locations closer or further from a highlight. We further investigate which coordinates or units, whether of image distance or surface distance, are most pertinent to gloss propagation. Our last experiment investigates how gloss propagation is affected by surface gaps or the presence of occluding objects interposed between highlights and other visible surface regions.
Methods

Observers were shown a series of images of tori with specular and diffuse lighting components. Images were rendered off-line using the OpenGL lighting model (Neider et al., 1999). Despite the model’s oversimplified treatment of the surface’s BRDF, subjects easily perceived gloss and were able to rate it reliably. The illumination model is described by four parameters and the material surface by three:

\[
I = I_a M_d + I_{ga} M_d + (L \cdot n) L_d M_d + (s \cdot n) L_s M_s, \tag{1}
\]

where \(I\) is the computed luminance of a surface patch; \(I_a\) and \(I_{ga}\) are the intensities of ambient illumination associated with the presence of a point source and of all other ambient illumination, respectively; \(L_d\) and \(L_s\) are intensities of illumination that are diffusely and specularly reflected; \(M_d\) and \(M_s\) are the proportions of light that are diffusely and specularly reflected from the modeled surface; \(e\) is an exponent that governs the degree of spread or scatter of specular reflection; \(L\) is the direction vector of a point light source; \(n\) is the local surface normal vector; and \(s\) is a normalized sum of two unit vectors, the first pointing from the surface to the light position, and the second from the surface to the viewpoint.

In Experiments 1-3 the following parameters were used: \(I_a = 0, I_{ga} = 0.06, I_d = 0.5, L_s = 0.5, M_d = 0.5, M_s = 0.85,\) and \(e = 150.\) Experiments 2 and 3 had an additional diffuse light with \(L_d = 0.5.\) (In Experiment 2, \(L_d = 0.2\) for the first light.) Experiment 4 used an environmental mapping and \(I_a = 0, I_{ga} = 0.06, I_d = 0.8, L_s = 0.7, M_d = 0.5, M_s = 0.95,\) and \(e = 150.\)

In all the experiments the light source was modeled as behind the eye (positive \(z\) values) with respect to the object and had no distance-dependent fall-off of intensity. Image projections were orthographic. Coordinates of the light source, viewpoint, and the torus were \((0, 0, 10), (0, 0, 5)\) and \((0, 0, -13),\) respectively (OpenGL units). The viewpoint coordinates and the material properties remained constant in all experiments. A second light source affecting only the diffuse component was positioned at \(-30\) degrees from the main one in Experiments 2 and 3.

The radius of the torus was 1.75 and the radius of the ring forming the torus was 1 in open GL units. The torus was tilted by 21.8° about the \(x\) (left-right) axis, in order for the observer to see the full torus.

Experiments involved a rating procedure in which the same series of standard images (the “gloss scale”) was presented to an observer on each trial, along with a test image (figure 3a). Observers responded by selecting the standard image that most closely corresponded to a specific region of the test image (indicated by small red “probe dot”) with respect to judged gloss. Since we asked observers to compare a small region of the test stimulus with exemplars of entire objects, we made clear in our instructions that they were to compare the local glossiness near the probe point on the test image with the “best” (i.e., highest degree of) glossiness that could be observed in each of the comparison images.

Images for the gloss scale were generated using spherical harmonic functions. The objective was to generate an image that is sufficiently different from the torus (or any known object) and also has a good measure of gloss, with proper parameters. The geometry of the sample objects was specified by the following equation:

\[
\rho = \sin^6(a \phi) + \cos^6(c \phi) + \sin^4(e \psi) + \cos^4(g \phi) \tag{2}
\]
where \( x = r \sin(\theta) \), \( y = \rho \sin(\phi) \), \( r = \rho \cos(\phi) \), and \( z = r \cos(\theta) \), for \( 0 \leq \theta \leq 2\pi \) and \( -\pi/2 \leq \phi \leq \pi/2 \). Our comparison objects were constructed by setting \( a = 3 \), \( b = 2 \), \( c = 1 \), \( d = 1 \), \( e = 1 \), \( f = 1 \), \( g = 1 \), and \( h = 1 \).

Certain parameters of Equation 1 were fixed for all exemplars: \( L_a = 0 \), \( L_d = 0.5 \), \( L_s = 0.5 \), \( L_{ga} = 0.06 \), and \( M_d = 0.6 \). The light position was at \((0, 0, 15)\) and the object was at \((0, 0, 0)\). Parameters for the proportion of specular reflectance, \( M_s \), and the scatter of specular reflectance, \( e \), varied across the eight samples, as listed in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tbody>
<tr>
<td>( M_s )</td>
<td>.05</td>
<td>.10</td>
<td>.15</td>
<td>.20</td>
<td>.30</td>
<td>.40</td>
<td>.65</td>
<td>.75</td>
</tr>
<tr>
<td>( e )</td>
<td>1</td>
<td>32</td>
<td>64</td>
<td>100</td>
<td>130</td>
<td>150</td>
<td>190</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 1. Values of specular material parameter \((M_s)\) and specular reflection exponent \((e)\) for eight samples.

Linearity of our “gloss scale” in perceptual space was validated in a preliminary experiment, where gloss scale samples were assigned values from 0 to 20. The same four observers participated in all of the experiments; three were naïve and one was an author. Conditions were presented in a random order for multiple trials each. Mean ratings were rescaled to the 0-20 range using subject-specific coefficients determined in preliminary experiments.

To exclude possible differences in gloss ratings due to non-uniformity of the surface of our computer monitor, Experiments 1-3 were presented in symmetric (bilateral) configurations. That is, for each trial with a given probe/highlight location relative to the central axis of an image, a trial with a configuration symmetric relative to this axis was presented. Gloss ratings were not different for such points (for each subject) and were pooled for analysis. Data are plotted as a mean over 4 subjects. Error bars reflecting confidence intervals for within subject design are based on subject-X-treatment interaction (Loftus and Masson, 1994).

Image distance was measured from the center of the highlight in the image plane. It is expressed in arbitrary units used in the computer model of the torus (1 unit = 60 pixels = 1.8° of visual angle, for a viewing distance of ~60 centimeters). Surface distance is the distance of the probe from the center of the highlight along the represented surface. Surface distance was calculated from the known angular position of the probe and the torus geometry. Luminance at a given probe point for Experiment 2 was defined as an average of calculated intensity values for four pixels neighboring the probe point on a scale from 0 to 1, where 0 corresponds to 0 and 1 corresponds to 255 on an eight-bit monitor. We derived an estimate of the monitor gamma of 1.275 by comparing increasing digital intensity values on a 0 to 255 scale for a region to the measured luminance from the monitor to a maximum of 39.1 cd/m².

Tori with a gap, an occluder, and without either were presented in Experiment 4. Two sizes of gaps and occluders were used, 0.16 and 0.25 units (in OpenGL units). Two probe points were positioned at approximately 1 and 1.5 units of distance (image distance) from the center of the highlight.
Preliminary experiment: Rating of gloss scale images

Our first objective was to construct and validate a series of comparison images whose glossiness varied systematically ("gloss scale"). Eight exemplars of an object that varied from matte to highly glossy were prepared (see figure 3a), and parameters were initially selected based on informal observations by the experimenters to yield approximately equal spacing among the exemplars on the dimension of glossiness.

Figure 2. Mean gloss ratings for four observers of eight comparison exemplars.

To validate our subjective choice of parameters for the samples, four observers with normal or corrected-to-normal vision rated the eight gloss samples. All samples were presented simultaneously in a randomized position on the computer monitor. The observers were instructed to assign the value of 20 to the sample that appeared glossiest and a zero to the one that appeared least glossy. They could then freely assign intermediate values to the remaining samples. Each observer made six judgments of the eight gloss exemplars presented in a random order. Figure 2 shows the mean ratings of the observers, which are approximately equally spaced.

Experiment 1: Gloss perception as a function of distance

The aim of Experiment 1 was to determine whether the perception of gloss changes with distance from the highlight. Gloss was measured at four probe locations to the right and (symmetrically) to the left of the highlight along the horizontal direction and at two probe locations above and two below the highlight along the vertical direction. Horizontal probe points were positioned along geodesic curves at a constant "top to bottom" distance with respect to the cardinal axes of the torus — i.e., at the same height, if the torus were lying flat on a plane parallel to the ground. Vertical probe points were positioned along the central meridian. Each of the 4 observers made 6 gloss judgments at the 12 probe positions presented in a randomized order.
Mean gloss ratings are plotted as a function of image distance for all subjects (figure 3b). The solid line shows the perceived gloss along the horizontal direction and the dashed line along the vertical direction. Statistical tests confirmed that the data for the left and right, and for the above and below conditions, respectively, were not significantly different, so the data were pooled for subsequent analysis, giving six probe displacements: four horizontal and two vertical. Perceived gloss decreased with the distance of the probe from the highlight along both the horizontal and vertical directions (figure 3b). An ANOVA analysis of the change in gloss ratings with probe distance was significant for the horizontal direction ($F(3,9) = 69.36; p < .001$) and for the vertical direction ($F(1,3) = 40.16; p < .01$). Perceived gloss decreased more rapidly with probe distance along the vertical direction than along the horizontal direction. Possible factors causing the differences in decay rate might be the differences in curvature or in the extent of the highlight.

**Experiment 2: Dissociation of luminance and image distance**

In Experiment 1 increasing distances from the highlight are confounded with decreases in the luminance of the torus. Thus, it is possible that observers perceive the surface as less glossy simply as a function of the intensity decrease. The aim of Experiment 2 was to dissociate the distance between probe and highlight from changes in luminance.

An additional diffuse light with $L_d = 0.5$, $L_{gg} = 0.0$, and $L_g = 0.0$ was added randomly to the left or right side of the torus on each trial. Setting $L_g = 0.0$ means that the second light source did not produce a specular highlight on the surface of the torus. The second light source thus had the effect of raising the luminance near all probe points on one side of the torus, compared to the luminance at corresponding locations on the other
side of the highlight. We therefore refer to the sides of the torus as having “augmented” and “normal” luminance distributions (figure 4). Three probe points were located on the “normal” side and three on the “augmented” side of the specular highlight. Observers made 16 gloss judgments for each probe point.

Mean gloss ratings are plotted as function of distance and of intensity for all subjects (figure 4). The intensities are plotted on a scale from 0 to 1, where 1 represents the highest luminance achievable on our monitor. The solid line shows the gloss ratings for the normal side and the dashed line shows the gloss ratings for the augmented side. Gloss changes as a function of probe distance from the highlight rather than as a function of surface luminance.

**Experiment 3: Dissociation of surface distance and image distance**

The aim of Experiment 3 was to examine whether image distance or surface distance determines local gloss ratings. In our experimental model two coordinate systems, image-based and surface-based, can be dissociated by either changing the curvature of the object or by using the foreshortening effect of image projection. The latter was exploited in Experiment 3.

The main light source was shifted by 30 degrees to one side. Following is an example of light position shifted to the right side (figure 5a). There were two probe points to the right (P1 and P4) and two probe points to the left (P2 and P3) of the highlight. Probe points P1 and P4 were in the area of high foreshortening, P2 and P3 in the area of low foreshortening. The probe points P1 and P2 were at the same surface distance from the highlight, and so were P3 and P4. Two probe points P1 and P3 were located at different surface distances from the highlight but, because of foreshortening of the image,
they were at the same image distance. An equal number of trials for the light shifted to the left was presented and results for symmetric conditions were pooled. Observers made 12 gloss judgments at each of the probe points.

During initial attempts at stimulus generation, shifting the main light source to the side caused significant parts of the surface to appear dark. This could potentially cause an imbalance for gloss ratings on either side of the specular highlight due to different amounts of contrast gloss to the left or right. Therefore, an additional diffuse light source was added to approximately equalize the torus luminance on either side of the highlight.

The gloss ratings at the probe points P1 and P2 (F(1,3)=0.0; p<.987) and the probe points P3 and P4 (F(1,3)=.53; p<.51) that were at equal surface distance from the highlight did not differ significantly (figure 5b). In contrast, the probe points that were equidistant from the highlight in image distance but differed in surface distance, P1 and P3, differed significantly (F(1,3)=10.16; p<.049). The results suggest that the perception of gloss varies as a function of surface distance rather than image distance.

**Experiment 4: Spread of gloss across a gap and an occluder**

The aim of this experiment was to investigate how the impression of gloss spreads across a gap and an occluder. Tori with a gap, an occluder, and without either were presented. Both probe points (Near and Far) were separated by either a gap or an occluder from the specular highlight. Two sizes of gaps and occluders were used corresponding to conditions G_s, G_L, O_s, O_L (figure 6b).

Each of the 4 observers made 5 gloss judgments of the 20 probe positions-X-obstruction type "combinations in a randomized order. The tori with a small gap and a small occluder are shown in figure 6a.
Texture was mapped onto the torus using the environmental mapping function in OpenGL to help increase the global perception of gloss. This operation might have changed the perception of the torus to one of a shiny silvery object. According to subjects’ reports, this was not the case.

Figure 6. Experiment 5. (a) Two sample stimuli. Left: an occluding ring obscures a portion of the torus’s surface between the highlight and probe point. Right: a cut occurs in the torus at exactly those image positions occluded in Left. Continuous torus not shown. (b) Gloss ratings at two distances: closer to the highlight (circles) and further from the highlight (stars). Conditions are small and large gap (Gs and G1), small and large occluder (Os and Ol) and control (no gap or occluder).

The mean ratings of gloss for tori with occluders (figure 6b) tend to be greater than for tori with gaps. A Dunnett statistical test compared the effects of a gap and of an occluder on the perception of gloss. Table 2 shows the t-values when the gap and occluder tori are compared to the control stimulus in which neither were present. For the near probe point, both the gap and the occluder decreased the perception of gloss from that of the control for both the small and large gap and the small and large occluder (p < .05). For the far probe point, only the gap reduces the perception of gloss significantly (p < .05).

<table>
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<th>Gs</th>
<th>Gl</th>
<th>Os</th>
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<tr>
<td>NEAR</td>
<td>3.43</td>
<td>3.66</td>
<td>2.63</td>
<td>2.68</td>
</tr>
<tr>
<td>FAR</td>
<td>2.75</td>
<td>3.02</td>
<td>2.18</td>
<td>2.33</td>
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Table 2: t-values for the Dunnett test comparing the perceived gloss of tori with a gap and an occluder with that of the control (no gap or occluder). A one-tailed test was used since the presence of a gap and occluder always decreased the perceived gloss [t (12)=2.41, p<.05].
The perceived gloss with the occluder is not significantly different from that of the control, suggesting that an occluder reduces the perception of gloss less than that of a gap.

A within-subjects ANOVA compared the factors of Type of Obstruction (gap versus occluder), Size (large versus small gap or occluder), and Distance (near versus far probe point). Only the decrease in gloss ratings with probe distance from the highlight was significant (F(1, 3)=16.31; p<.02). However, one observer differed in the pattern of the results from the other three. An ANOVA was performed in which this observer was excluded. The difference between the gap and the occluder was now significant (F(1,2)=236.65; p<0.01) as was the probe distance (F(1,2)=13.7; p<0.03, one-sided). The ANOVA also supports the conclusion that the gap interfered more strongly with the perception of gloss than did the occluder.

**Discussion**

Gloss perception can be studied in either of two ways. One line of research investigates the global perception of gloss of entire objects. With this approach gloss is considered as a categorical quality; whole objects can be compared as being more or less glossy. A significant amount of work has been done on determining the exact physical factors that give rise to a particular BRDF and luminance profiles (Rong et al. 1999) and to finding parameters of the BRDF (Ferwerda et al. 2001) and aspects of structure of the illumination environment (Fleming et al. 2001) that affect global gloss perception.

Alternatively, one can ask whether gloss varies along a surface. In this approach gloss is treated as a local quantity. It is obvious that gloss can be different between different areas of a multi-part object, such as a teapot, whose handle and spout might be made of different materials. We believe that a deeper look into mechanisms of gloss processing is reached by testing the uniformity of gloss perception for a one-part object such as a torus. Our experiments confirm observations (Beck and Prazdny 1981) that specular highlights are important for a surface to be perceived as glossy, and demonstrate that gloss ratings decrease as the distance from a highlight increases.

Our findings that gloss ratings are better described as a function of surface distance from the highlight, and that surface continuity promotes gloss perception at a distance from the highlight, suggest that surface representation and gloss perception are closely related. This is in agreement with results on the interaction of perceived 3D characteristics of surfaces and properties of glossy highlights (Beck and Prazdny 1981, Blake and Bulthoff 1990, Norman et al. 1995, Todd et al. 1997). Furthermore, a poor fit of gloss function in image coordinates (figure 5), and relative insensitivity of gloss ratings to moderate biases of image luminance profile as in Experiment 2, suggest that mechanisms of gloss perception operate at levels higher than the stage of retinal image processing. One can hypothesize that perception of gloss depends on and occurs after a representation of a surface has been formed. If this were true, manipulations that change the perception of surface curvature would affect gloss fall-off with distance.

Interactions between glossy highlights and surface perception can be bi-directional. Stereo disparity of a highlight, for example, affects estimates of whether an otherwise ambiguous surface is convex or concave (Blake and Bulthoff 1990). This suggests that features of the highlight, along with shading profile and bounding contour, serve as
Figure 7. The shiny torus has the same luminance as the dull everywhere except in those pixels that form the highlights. The perceived gloss in regions abutting the highlights is different from that derived from corresponding regions in the image of the dull torus. Points far from the highlight are similar in appearance to the corresponding points on the matte torus.

with distance has not been a focus of research until now: in natural environments with a dense light source distribution, multiple highlights exist on a single object. Even though each highlight is effective over a limited area, these areas can merge, giving a seemingly uniform perception of gloss.

Another aspect of many glossy objects is a reflection of the environment, and DOI gloss is one of the important dimensions of gloss space (Ferwerda et al. 2001). In Experiments 1-3 we excluded texture from environmental reflections in order to prevent subjects from making simple “ordinal decisions” across probe points. The gloss space of the stimuli of these experiments is therefore one-dimensional, with only contrast gloss being present. The next step is to study whether adding a DOI dimension would eliminate gloss differences between probe points.

How can the phenomenon of gloss decrease be explained? One possibility is that the visual system estimates the probability of a surface being less or more reflective. Direct evidence exists only in the immediate vicinity of a highlight. Surface properties can change with distance, or with the transition to a different part of an object (usually accompanied by a curvature change). Both Bayesian and minimization of constraints theories have tools that can be employed to develop estimates of the probability of a surface being less glossy at a given point. The presence of texture or environmental
reflection can be taken into account as additional evidence for glossiness at a given point. However, the relation between gloss perception and surface properties might not be as direct. Our subjects claimed that they "knew" that surface properties are the same for the whole object, and yet their perception of gloss changed with distance.

A second hypothesis is that the perception of gloss depends on a spatially local filling-in process that is triggered by distinctive highlight and surface features. A filling-in process in perception has been reported for brightness (De Weerd et al. 1998, Paradiso and Nakayama 1991), hue (Krauskopf 1963), and texture (De Weerd et al., 1995). There are three differences between cases involving the spread of gloss and the filling-in of brightness, hue and texture. First, the filling-in process in the case of brightness, hue and texture is initiated by sharp contours whereas in the case of gloss it is initiated by graded contours. Sharp contours would generally give rise to the perception of a stain or a spot and not to the perception of gloss. Second, the filling in of brightness, hue, and texture is interpolated between the edges of a demarcated area. In contrast, the spread of gloss is extrapolated to neighboring surface areas. The spread of gloss differs from the cases cited in an important respect. The perception of gloss decreases with surface distance from the highlight. This suggests a local process that dissipates. In contrast, the filling-in of brightness hue and texture is uniform throughout the bounded region defined by the edges and does not decrease with distance from the edges. In this respect the spread of gloss is more similar to simultaneous contrast that also falls off with distance. Third, our experiments indicate that the visual system constructs a surface in three dimensions and that filling-in occurs in terms of the 3-D surface properties and not the properties of the retinal projection. The filling in for brightness, hue, and texture has been investigated for two-dimensional surfaces.

Grossberg and Mingolla (1987) presented a model for 3D shape-from-shading where they showed that the shading on a 3D curved surface gives rise to "boundary webs," which can be used to contain the filling-in of brightness. These boundary webs partially restrict the filling-in, thereby giving rise to a perception of a shaded surface. In a similar manner a 3D curved surface can reduce the flow of gloss with distance by means of boundary webs. The contrast between brightness of a specular highlight and of surrounding areas (contrast gloss) and the spatial profile of a specular highlight could be two features determining overall gloss perception. An object's bounding contour and shading profile are determining characteristics of 3D surface shape. One attractive feature of boundary webs is that they take into account not only the internal shading profile of regions but also their bounding contours, and therefore can explain the independence of gloss decrease on slight variations in local luminance. Cases of inconsistency of highlight orientation with shading profile, which result in a failure to perceive glossiness, would greatly change the boundary web configuration and can thus be addressed by the theory.

The present study also suggests future directions for the experimental study of mechanisms of gloss perception. Our graphical rendering model was intentionally simplified to keep possible variables under control. A few steps would bring displays closer to real-life glossy objects. The first one is to study gloss propagation when multiple highlights are present. Would the effect on gloss ratings be additive, or would there exist a non-linear interaction between them? How would gloss decay be affected by the presence of reflections? One prediction is that reflections would reduce or eliminate gloss decay with distance from the highlight. However, studies show that static
reflections by themselves are not enough (Hartung and Kersten 2002), perhaps because in the absence of specular highlights they can be perceived as paint on the surface. Therefore we would predict that a reflective surface would look somewhat less glossy at a distance from the highlight, but the gloss decay would be a function of the degree of reflectivity or DOI. Another possible research direction is to probe surface-based gloss propagation on objects with different curvatures.
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