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Remote 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's impression of gloss may be partial and nonuniform at image regions outside of a highlight. A rating scale and small probe points indicating image locations were used to investigate the differential perception of gloss within a single object. Gloss ratings given by observers were not uniform across a surface, but decreased as a function of distance from a highlight. When, by design, the distance from a highlight was uncoupled from the luminance value at corresponding probe points, the decrease in rated gloss correlated more with distance than with luminance change. Experiments also indicated that gloss ratings may change as a function of estimated surface distance, rather than as a function of image distance. Surface continuity affected gloss ratings, suggesting that surface and gloss processing are closely related.

1 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 in the perception of gloss (Beck and Prazdny 1981). The effects of highlights are especially dramatic when two images with and without highlights are placed side by side (figure 1).

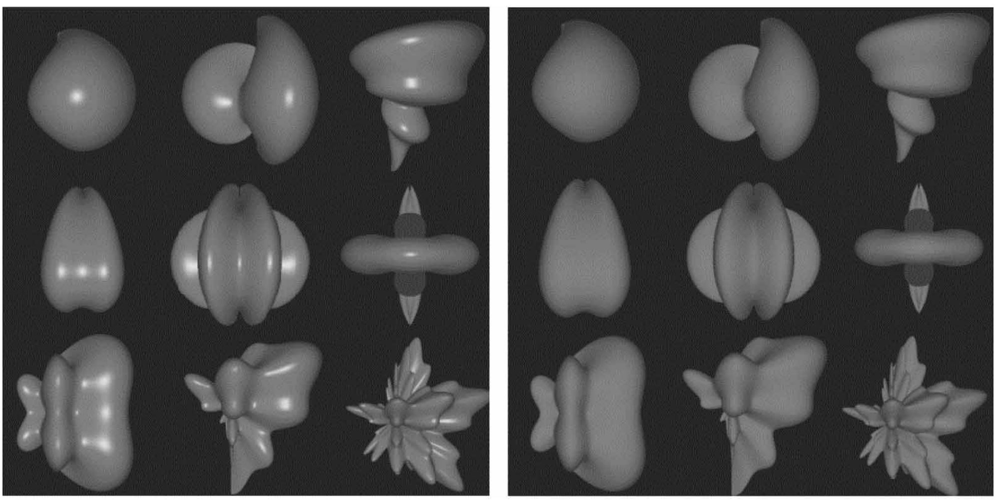

Figure 1. Glossy (left) and matte (right) objects. (Note that the perception of glossiness is likely to be diminished by the process of photographic reproduction, relative to what is visible on a computer monitor.)

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The patterns of luminance that lead to the perception of glossy highlights are based in part on the physical and chemical makeup 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 bidirectional-reflectance distribution 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.

For these two major components of rendering there are two corresponding aspects of perceptual judgment. On the one hand, an observer may seek to determine whether the surface of some whole object is a sample of a particular category, eg smooth plastic or polished metal. On the other hand, one may ask to what extent a particular portion of a given surface looks glossy at the present time, from a given viewpoint. The experiments reported in this paper, conducted with static achromatic images, arise from this second type of perceptual judgment.

Recent work by Ferwerda et al (2001) is an example of a *global* or 'whole object' approach to the psychophysics of gloss. In their work they seek 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, 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, page 402). Using a multi-dimensional scaling technique, Ferwerda et al (2001) found that the two most pertinent dimensions for human judgments are contrast gloss and distinctiveness-of-image, though a factor that seems to correspond to lightness in matte displays interacts with the two gloss dimensions. In Ferwerda et al's experiments, gloss was evaluated on equal-sized spheres and for whole objects, and no interaction between gloss perception and the three-dimensional (3-D) shape of the object was studied.

A different approach to gloss perception was taken in one of the earliest examples of computer manipulation of digitized gray-scale images for psychophysics, in which Beck and Prazdny (1981) demonstrated that perception of gloss depends on the presence of a specular highlight on an otherwise diffusely reflecting surface. (For the remainder of this paper, 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) asked how the highlight affected the judgment of gloss within different surface regions of a single object. Gloss was thus treated as a *local* quantity, which varies as a function of distance from highlights. They have shown 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 curvature of the surface (Beck and Prazdny 1981). Surface regions near a highlight which has an orientation that is inconsistent with the perceived surface curvature—ie 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 was to begin the process of quantitatively characterizing the parameters that affect the fall-off of the strength of the perception of gloss when an observer is asked to report gloss judgments for various locations closer or further away from a highlight. We further investigated which coordinates or units, whether of image distance or surface distance, are most pertinent to gloss propagation. In our last experiment we investigated how gloss propagation is affected by surface gaps or the presence of occluding objects interposed between highlights and other visible surface regions.

2 Methods

Observers were shown a series of images of tori with specular and diffuse lighting components. Images were rendered off-line by means of the OpenGL lighting model (Neider et al 1999). Despite the oversimplified treatment of the BRDF of the surface in the model, 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:

$$I = L_a M_d + L_{ga} M_d + (\boldsymbol{L} \cdot \boldsymbol{n}) L_d M_d + (\boldsymbol{s} \cdot \boldsymbol{n})^e L_s M_s \tag{1}$$

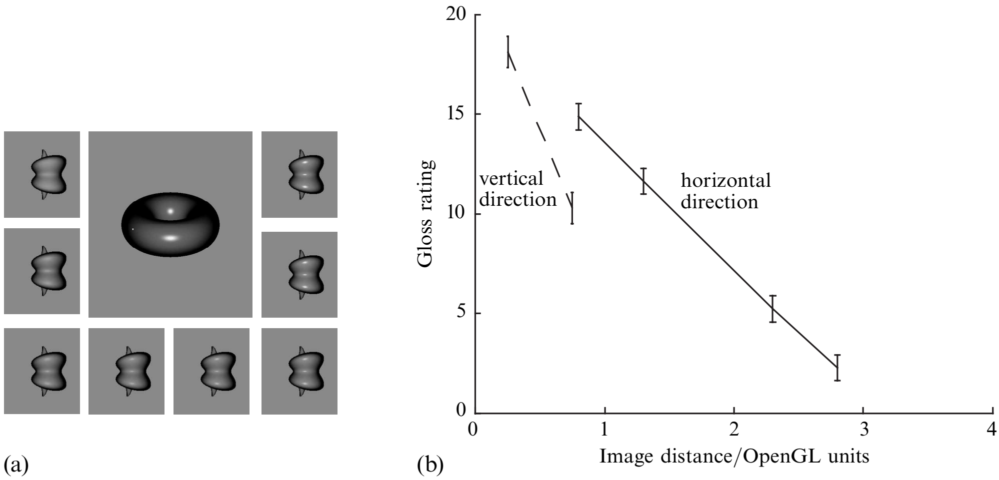
where I is the computed luminance of a surface patch; L_a and L_{ga} are the intensities of ambient illumination associated with the presence of a point source and of all other ambient illumination, respectively; L_d and L_s are the intensities of illumination that are diffusely and specularly reflected; 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; $\boldsymbol{L}$ is the direction vector of a point light source; $\boldsymbol{n}$ is the local surface normal vector; and $\boldsymbol{s}$ 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: $L_a = 0$, $L_{ga} = 0.06$, $L_d = 0.5$, $L_s = 0.5$, $M_d = 0.5$, $M_s = 0.85$, 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 environmental mapping and $L_a = 0$, $L_{ga} = 0.06$, $L_d = 0.8$, $L_s = 0.7$, $M_d = 0.5$, $M_s = 0.95$, 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 $\sim 30°$ from the main light source in experiments 2 and 3.

The radius of the torus was 1.75 and the radius of the ring forming the torus was 1 OpenGL units. The torus was tilted by 21.8° about the x (left–right) axis, to allow 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 in each trial, along with a test image (figure 2a). Observers responded by selecting the standard image that most closely corresponded to a specific region of the test image (indicated by a 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



(a) (b)

Figure 2. Experiment 1 sample display and results. (a) Snapshot of experimental screen. Test image (torus) is in the center, surrounded by gloss-scale samples. (b) Gloss rating as a function of image distance from the center of the highlight.

instructions that they were to compare the local glossiness near the probe point on the test image with the 'best' (ie highest degree of) glossiness that could be observed in each of the comparison images.

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

$$\rho = \sin^b(a\phi) + \cos^d(c\phi) + \sin^f(e\theta) + \cos^h(g\theta); \qquad (2)$$

here $x = r\sin\theta$, $y = \rho\sin\phi$, $r = \rho\cos\phi$, and $z = r\cos\theta$, for $0 \leqslant \theta \leqslant 2\pi$, and $-\pi/2 \leqslant \phi \leqslant \pi/2$. 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 1. Values of specular material parameter (M_s) and specular reflection exponent (e) for eight samples.

	Sample							
	1	2	3	4	5	6	7	8
M_s	0.05	0.10	0.15	0.20	0.30	0.40	0.65	0.75
e	1	32	64	100	130	150	190	240

In a preliminary experiment, observers were asked to assign values from 0 to 20 to eight gloss-scale samples. For subsequent experiments each observer's mean ratings were rescaled to the 0–20 range by using subject-specific coefficients determined in preliminary experiments. The same four observers participated in all of our experiments; three were naïve and one was an author. Conditions were presented in a random order in multiple trials for each condition.

To exclude possible differences in gloss ratings due to nonuniformity 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 four subjects. Error bars reflecting confidence intervals for a within-subjects design are based on subject × treatment interactions (Loftus and Masson 1994).

Statistical analysis was done by nonparametric techniques from MATLAB (MathWorks, Inc) and SAS (SAS Institute, Inc) packages, including the sign test and the Friedman ANOVA, which computes group effects after adjusting for subject variations. Statistics are reported as $\chi^2_{\mathrm{R},n,k}$ values for the number of conditions (n) and subjects (k) (Sachs 1982, page 550). Individual subjects' data were analyzed with Friedman ANOVAs for n conditions and t trials, or the sign test where appropriate.

Image distance was measured from the center of the highlight in the image plane. It is expressed in the arbitrary units used in the computer model of the torus (1 unit $\approx$ 60 pixels = 1.8 deg of visual angle, for a viewing distance of $\sim$60 cm). 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 4 pixels neighboring the probe point, on a scale from 0 to 1, where 0 corresponds to 0 and 1 corresponds to an intensity of 255 on an 8-bit monitor. We derived an estimate of the gamma of the monitor 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 m^{-2}.

Tori with a gap, with 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 1.0 and 1.5 units of distance (image distance) from the center of the highlight.

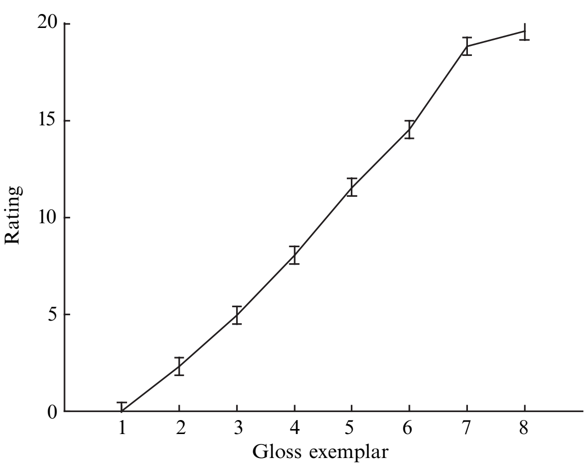


Figure 3. Mean gloss ratings for four observers of eight comparison exemplars.

3 Preliminary experiment: Rating of gloss-scale images

Our first objective was to construct and validate a series of comparison images the glossiness of which varied systematically ('gloss scale'). Eight exemplars of an object that varied from matte to highly glossy were prepared (see figure 2a), and parameters were initially selected on the basis of informal observations by the experimenters to yield approximately equal spacing among the exemplars in the dimension of glossiness.

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 randomized positions on the computer monitor, with an adjustable 0 – 20 slider next to each sample. 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, such that numeric differences between such ratings reflected as precisely as possible the differences in gloss of the corresponding samples. Each observer made six judgments of the eight gloss exemplars presented in a random order. Figure 3 shows the observers' mean ratings of the eight samples.

4 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 in the horizontal direction, and at two probe locations above and two below the highlight in 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—ie 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 four observers made six gloss judgments at the twelve probe positions, which were presented in a randomized order.

Mean gloss ratings are plotted as a function of image distance for all subjects (figure 2b). The solid line shows the perceived gloss in the horizontal direction and the dashed line the perceived gloss in 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 in both the horizontal and vertical directions (figure 2b). A nonparametric (Friedman) ANOVA of the change in gloss ratings with probe distance was significant for the horizontal direction ($\chi^2_{\mathrm{R},4,4} = 12$; $p < 0.01$) and for the vertical direction ($\chi^2_{\mathrm{R},2,4} = 4$; $p < 0.05$) for the combined data of the subjects. Friedman ANOVAs on data from individual subjects demonstrated the same result: a significant change of gloss rating with distance for each subject. Perceived gloss decreased more rapidly with probe distance in the vertical direction than in the horizontal direction (figure 2b). Possible factors causing the differences in decay rate might be the differences in curvature or the extent of the highlight.

5 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 luminance decrease. The aim of experiment 2 was to dissociate the distance between the probe and the highlight from changes in luminance.

An additional diffuse light with $L_\mathrm{d} = 0.5$, $L_\mathrm{ga} = 0.0$, and $L_\mathrm{a} = 0.0$ was added randomly to the left or right side of the torus on each trial. Setting $L_\mathrm{s} = 0.0$ 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

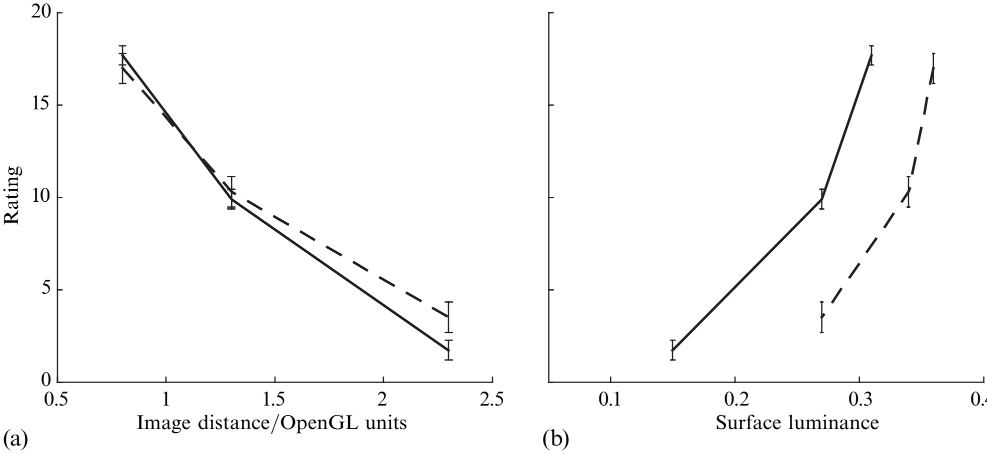


Figure 4. Results of experiment 2. (a) Gloss ratings as a function of image distance of probe point from highlight center. (b) The same gloss ratings as in (a) replotted as a function of luminance near probe point. Solid line: normal luminance distribution; dashed line: luminance augmented by a second illumination source. The divergence of the curves in (b) indicates that luminance is not the key determinant of gloss.

were located on the 'normal' side and three on the 'augmented' side of the specular highlight. Observers made sixteen gloss judgments for each probe point.

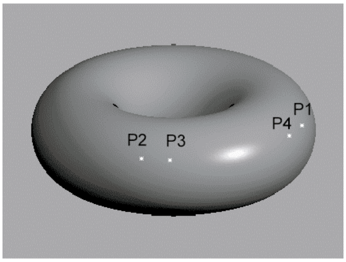
Mean gloss ratings are plotted as a function of distance and of surface luminance for all subjects (figure 4). The luminances are plotted on a scale from 0 to 1, where 1 represents the highest luminance achievable on our monitor. The solid line shows the gloss ratings for the normal side and the dashed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

6 Experiment 3: Dissociation of surface distance and image distance

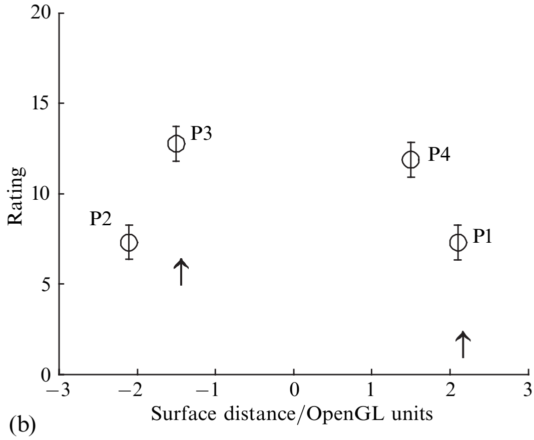
The aim of experiment 3 was to examine whether image distance or surface distance determines local gloss ratings. In our experimental model, two coordinate systems—image-based and surface-based—can be dissociated by either changing the curvature of the object or by using the foreshortening effect of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

The main light source was shifted by 30° to one side, as shown in the example in 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 an equal 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 and for the light shifted to the right was presented and results for symmetric conditions were pooled. Observers made twelve 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 owing 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.



(a)



(b)

Figure 5. Experiment 3: highlight shifted by 30°. (a) Positions of the probe points for a stimulus with the highlight shifted to the right. (b) Gloss rating for points P1 and P4 (high foreshortening area); P2 and P3 (low foreshortening area). P1 and P2, and P3 and P4 are at the same surface distances from the highlight center. P1 and P3 are the same image distance from the highlight center (marked with arrows).

The gloss ratings at the probe points P1 and P2 ($\chi^2_{\mathrm{R},2,4} = 0$; $p = 1$) and the probe points P3 and P4 ($\chi^2_{\mathrm{R},2,4} = 0$; $p = 1$) 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 ($\chi^2_{\mathrm{R},2,4} = 4$; $p < 0.045$). The results suggest that the perception of gloss varies as a function of surface distance rather than image distance. Individual data analysis (sign test) followed the same pattern as that of the group data, except that for one out of four subjects gloss ratings for P3 and P4 probe points were significantly different.

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

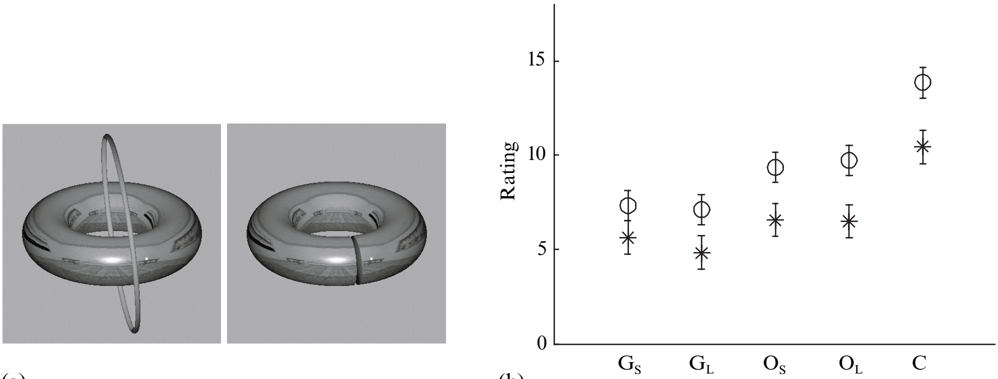
The aim of this experiment was to investigate how the impression of gloss spreads across a gap and an occluder. Tori with a gap, with an occluder, and without either were presented. Both probe points (near and far) were separated by either a gap or an occluder from the specular highlight. Two sizes of gaps and occluders were used corresponding to conditions $\mathrm{G_S}$ and $\mathrm{G_L}$ (small and large gap, respectively); and $\mathrm{O_S}$ and $\mathrm{O_L}$ (small and large occluder, respectively) (figure 6b).

Each of the four observers made five gloss judgments of the ten (probe positions) × ('obstruction type') combinations in a randomized order. The tori with a small gap and small occluder are shown in figure 6a.

Texture was mapped onto the torus with 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.

The mean ratings of gloss for the control condition (figure 6b) tend to be greater than for tori with gaps. A Friedman ANOVA was used to determine the significance of the type of obstruction effect. Based on experiments 1–3, where gloss rating depended on distance, two distance levels (near versus far probe point) were analyzed separately with five levels of surface continuity ($\mathrm{G_S}$, $\mathrm{G_L}$, $\mathrm{O_S}$, $\mathrm{O_L}$, and control) each.

Effect of the obstruction was significant for a near point only ($\chi^2_{\mathrm{R},5,4} = 10.1$; $p < 0.04$). Individual subjects differed with respect to the obstruction effect. A signed-rank test demonstrated a significant gap effect at $p < 0.05$ level for the near-point and the



(a) (b)

Figure 6. Experiment 4. (a) Two sample stimuli: (left) an occluding ring obscures a portion of the surface of the torus between the highlight and probe point; (right) a cut occurs in the torus at exactly those image positions occluded in the left image. Continuous torus not shown. (b) Gloss ratings at two distances: closer to the highlight (circles) and further from the highlight (asterisks). Conditions are small and large gap (G_S and G_L, respectively), small and large occluder (O_S and O_L), and control (C, no gap or occluder).

large-gap condition for two subjects. For the other two it was insignificant. Although gloss ratings with the occluder are on average larger than that with the gap (figure 6b), for most subjects and conditions there was no significant difference between the two when using nonparametric tests. Thus both Friedman ANOVA and pairwise comparisons support only the conclusion that the gap interfered with the perception of gloss.

8 Discussion

Gloss perception can be studied in either of two ways. One line of research investigates the global perception of gloss of entire objects. A significant amount of work has been done on determining the exact physical factors that give rise to a particular BRDF and to particular luminance profiles (Rong et al 1999), and to finding parameters of the BRDF (Ferwerda et al 2001) that affect global gloss perception. It was shown that the structure of the illumination environment (Fleming et al 2003) and consistency of reflections with a 3-D shape of reflecting surface (Beck and Prazdny 1981; Hartung and Kersten 2002) can greatly increase the glossiness of the whole object.

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. To make a clean distinction between variables that may affect mechanisms of gloss perception (distance, luminance), we avoided using mirror-like surfaces, or complex natural illumination environments. 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.

The decrease of gloss with distance has not been a focus of research until now, possibly because in natural environments with a dense light-source distribution, multiple highlights may 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.

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 3-D characteristics of surfaces and properties of glossy highlights (Beck and Prazdny 1981; Blake and Bülthoff 1990; Norman et al 1995; Todd et al 1997). 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. However, the degree of interaction between image features and surface characteristics in gloss perception remains to be determined.

A highlight occupies a small area on a surface; therefore, distant portions of two images of glossy and nonglossy objects have the same luminance distribution (figure 7). One is perceived as glossy and another is not. What visual mechanisms might lead to such different perceptions? One suggestion is that gloss propagates, by 'filling-in' from the 'source', the specular highlight. A brightness filling-in process in perception has been reported elsewhere (De Weerd et al 1998; Paradiso and Nakayama 1991). The dissipative nature of such a process might account for gloss decrease with distance.

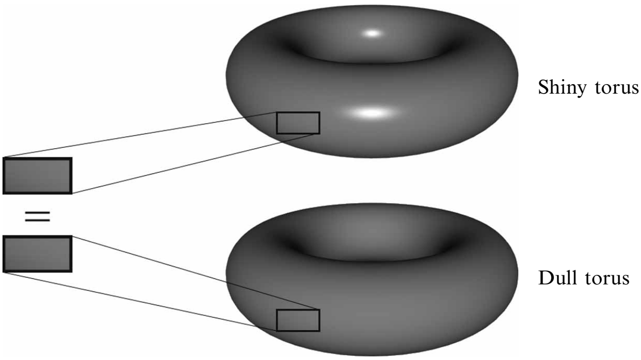


Figure 7. The shiny torus has the same luminance as the dull one everywhere except in those pixels that form the highlights. The perceived gloss in regions abutting the highlights is different from that derived from corresponding regions in the image of the dull torus. Points far from the highlight are similar in appearance to the corresponding points on the matte torus.

One way to gain theoretical understanding of the phenomena can be based on the Grossberg and Mingolla (1987) 'boundary web' idea. In this 3-D shape-from-shading model, they showed that the shading on a 3-D curved surface gives rise to boundary webs, which can be used to partially restrict the filling-in process. In a similar manner, a 3-D curved surface can reduce the flow of gloss with distance by means of boundary webs.

Alternatively, the effect of an apparent gloss decrease far from the highlight can be attributed to a change in the probability of the surface having the same characteristics as it does near the highlight. Both Bayesian and minimization-of-constraints theories have tools that can be developed for local-gloss estimates (Tappen et al 2003; Kersten et al 2004).

The present set of data 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 a nonlinear interaction exist between them? How would gloss decay be affected by the presence of reflections? Distinctiveness-of-image gloss was shown to be 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. 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 distinctiveness-of-image. Another possible research direction is to probe surface-based gloss propagation on objects with different curvatures.

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