Highlights, disparity, and perceived gloss with convex and concave surfaces

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Glossy and matte objects can be differentiated using specular highlights: bright patches in the retinal image produced when light rays are reflected regularly from smooth surfaces. However, bright patches also occur on matte objects, due to local illumination or reflectance changes. Binocular vision provides information that could distinguish specular highlights from other luminance discontinuities; unlike surface markings, specular highlights lie not at the surface depth, but "float" in front of concave surfaces and behind convex ones. We ask whether observers implicitly understand and exploit the peculiarities of specular geometry for gloss and shape perception. Our participants judged the glossiness and shape of curved surfaces that included specular highlights at various depths. Observers demonstrated substantial deviations from a full geometric model of specular reflection. Concave surfaces appeared glossy both when highlights lay in front of and (incorrectly) behind the surface. Failings in the interpretation of monocular highlights were also apparent. Highlight disparity had no effect on shape perception. However, the perceived gloss of convex surfaces did follow geometric constraints: only highlights at appropriate depths produced high gloss ratings. We suggest, in contrast with previous work, that the visual system invokes simple heuristics as gloss indicators to accommodate complex reflections and inter-reflections that occur particularly inside concavities.

Keywords: material perception, 3D surface and shape perception, crossmodal perception, gloss and specular highlights, binocular vision

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Introduction

The objects and surfaces that we encounter daily are made of a wide variety of materials (e.g., stone, metal, plastic, or fabric). Each of these materials reflect, refract, and transmit light differently, enabling us to distinguish between them. In this paper we consider the perception of surface gloss under binocular viewing. While matte surfaces scatter reflected light in all directions, glossy surfaces reflect some (or all) light regularly, creating specular highlights. Both monocular and binocular cues can help observers to identify bright areas in the image that correspond to specular highlights. The "orientation fields" of highlights provide one monocular cue: when a glossy object reflects its surroundings, these reflections are distorted according to the object's curvature. Unlike texture, highlights tend to "cling" to areas of high curvature (Longuet-Higgins, 1960), such that they are aligned with long curvature axes (Fleming, Torralba, & Adelson, 2004). In addition, it has been suggested that images of glossy objects have a characteristic skew in their luminance distribution that contributes directly to perceived gloss (Fleming, Dror, & Adelson, 2003; Motoyoshi, Nishida, Sharan, & Adelson, 2007). However, skew alone is insufficient to promote percepts of gloss; spatial structure is also important (Fleming et al., 2003). The location and orientation of specular reflections must be consistent with the object's shape, as defined, for example, by diffuse shading patterns (Anderson & Kim, 2009; Beck & Prazdny, 1981; Bouzit, Adams, & Graf, 2007; Kerrigan, Adams, & Graf, 2010; Kim, Marlow, & Anderson, 2011; Marlow, Kim, & Anderson, 2011).

Object or observer motion causes specular highlights to glide across the surface of a glossy object, rather than moving with it, like texture (e.g., Doerschner et al., 2011; Hartung & Kersten, 2002; Hartung & Kersten, 2003). As binocular observers, we have access to analogous information under static viewing, via images from the separate vantage points of our two eyes. Highlight location depends on both the shape of the object and viewer position; a single light source is reflected from different surface points to reach the two eyes. Consequently, specular highlights do not lie at the stereoscopically defined depth of the reflecting surface.

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For simple curved surfaces, as shown in Figure 1, highlights lie behind convex surfaces, but in front of concave surfaces. (For specific, unusual viewing conditions, such as a light source lying between the surface and its focus point, these rules can be broken, such that highlights appear behind concave surfaces.) With more complex surfaces and lighting, specular reflections generate disparity fields that may contain a wide variety of both horizontal and vertical disparities, whose corresponding depth field may contain discontinuities or be ill-defined (Muryy, Fleming, & Welchman 2012).

Previous work, exploiting simple curved surfaces and clearly defined highlight disparity, suggests that observers use an accurate internal representation of highlight geometry when estimating gloss and shape (Blake & Bülthoff, 1990, 1991). More recent studies also suggest that gloss perception is enhanced when highlight disparity (depth) is veridical (Wendt, Faul, Ekroll, & Mausfeld, 2010; Wendt, Faul, & Mausfeld, 2008). However, Blake and Bülthoff (1990, 1991) reported anomalous results for highlights on concave objects, not predicted by an accurate model of highlight geometry. They attributed these anomalies to rendering limitations that produced conflicts between stereoscopic and monocular shape cues, such that shape was not reliably defined for concave objects. They concluded that humans "employ a physical model of the interaction of light with curved surfaces...firmly based on ray optics and differential geometry." We tested an alternative hypothesis: observers interpret highlights incorrectly on concave objects due to an incomplete model of highlight geometry. Our observers reported both shape and gloss for surfaces with various highlight locations and shape cues of varying reliability (Figure 2). The results are clear: observers fail to make full use of highlight disparity when judging the glossiness of concave surfaces, even when shape is accurately perceived.

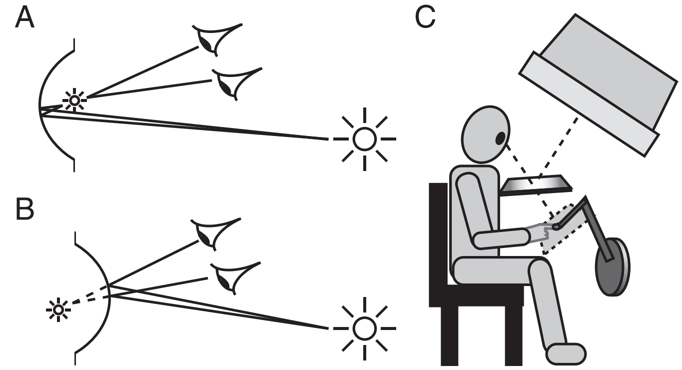

Figure 1. Concave and convex highlight disparity and visual-haptic set-up. (A, B) The image of a specular highlight appears in front of a concave surface (positive relative disparity) and behind a convex surface (negative relative disparity), adapted with permission from Blake and Bülthoff (1990, 1991). C) Visual haptic setup: Observers wore stereo shutter goggles (CrystalEyes, RealD, Beverly Hills, CA) to enable stereoscopic presentation of stimuli; head position was maintained using a headrest. Haptic feedback was provided via a PHANToM force feedback device attached to the observer's right index finger.

Methods

Subjects

Ten observers, including both authors, had normal or corrected-to-normal acuity, good stereovision (< 40 seconds of arc, Stereo Fly test, Stereo Optical Company, Inc., Chicago, IL) and no history of amblyopia or strabismus. Participants gave informed consent and the local ethics committee approved the study.

Experimental setup

Visual stimuli were generated using the Phong lighting model (Phong, 1975) implemented in OpenGL and displayed on a CRT monitor (iiayama, Oude Meer, The Netherlands), viewed via a mirror as shown in Figure 1C. Haptic stimuli were generated using OpenHaptics and presented using a PHANToM force feedback device (SensAble Technologies, Wilmington, MA). This setup allows observers to view and touch simulated objects that are spatially aligned.

The study was conducted in a darkened room. Visual stimuli were consistent with one convex bump and one concave dimple on a plane (see Figure 2), illuminated by a single distant light source. The inclusion of both a convex and concave stimulus strengthens the shape percept for the concave object due to the single light source assumption (Kleffner & Ramachandran, 1992) counteracting the effect of the convexity prior (Langer & Bülthoff, 2001). The resultant shaded discs each subtended 6.6° at the viewing distance of 57 cm, and were displaced ±4.2° horizontally from the screen's center. Bumps and dimples were spherical sections, whose centers protruded or recessed 1.1, 1.6 or 2.4 cm from the plane of the screen (Figure 3 shows cross-sections of these shallow, medium, and tall objects). The lighting direction had a slant of 64° (the angle between the lighting vector and the screen normal) and a tilt of 135° (the angle between a horizontal axis in the screen's plane and the projection of the lighting vector). One of the objects had a specular highlight, whose position in depth relative to the surface (defined by its relative horizontal disparity) varied across trials, in the range −20 to +30 arcmin. The highlight disparity values presented for each shape included the correct disparity, zero relative disparity, the opposite absolute disparity

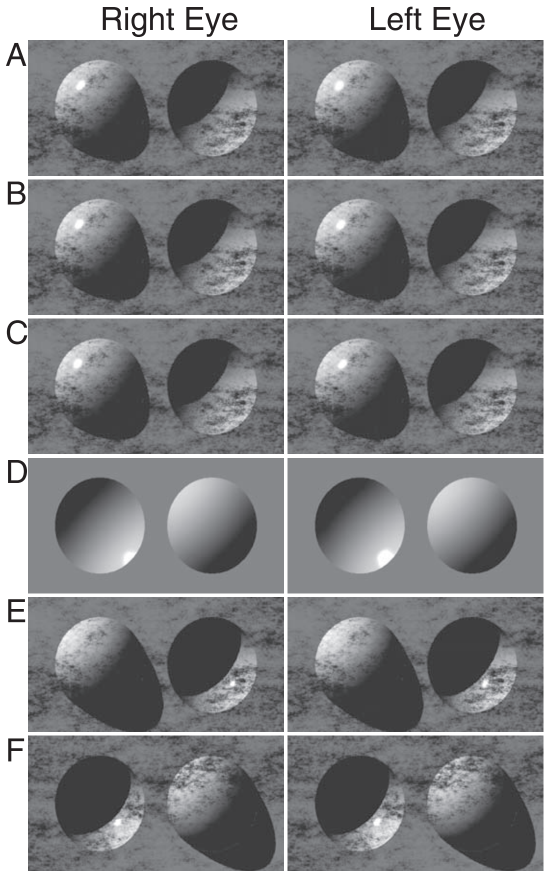

Figure 2. Example stimuli stereo pairs for cross fusion. For demonstration purposes, example stimuli are presented here as stereo pairs for cross-fusion but were presented stereoscopically via shutter glasses during the experiment. (A–C) Visual stimuli for medium and high reliability conditions, 1.6 cm height convex target object. Disparity of highlight is: correct; zero (on the surface); and reversed (i.e., in front of the surface), for A–C, respectively. D) Low reliability condition, 1.1 cm height concave target, disparity of highlight is reversed (i.e., incorrect, as far behind the surface as a veridical highlight would have been in front). For this shallowest concave object (and not for any other) the highlight is at the edge of the object and only partially visible at all disparities and thus has a different shape in the left and right eyes' images. E) Medium and high reliability conditions, 2.4 cm height concave target object. Disparity of highlight is −20 min arc (i.e., incorrect, at the furthest point behind the surface that was presented). F) Medium and high reliability conditions, 2.4 cm height concave target object. Disparity of highlight is correct.

and the opposite relative disparity. The vertical disparity of the highlight was invariant, and geometrically correct. The horizontal disparity of the highlight was manipulated by changing the simulated eye positions used to generate the specular component of the stimulus. This allowed horizontal and vertical highlight disparity to be manipulated independently, while keeping highlight shape and size consistent with the rendered surface. Our combination of a simple surface shape and a single light source enabled us to systematically measure the effect of horizontal highlight disparity on gloss perception. More complex illumination fields can enhance the perception of gloss (Fleming et al., 2003). However, despite a single point light source, when our stimuli were viewed stereoscopically with the correct highlight disparity, authors and naïve observers perceived glossy surfaces that, in the medium and high reliability conditions, resembled polished marble. In addition to the stimuli described above, we also interleaved a stimulus with a bump and dimple of height ±0.8 cm. Under our illumination, this surface had no visible highlight and thus provided a matte reference.

On *low reliability* trials, shape was defined primarily by shading, with a very weak binocular cue from the interocular differences in the shading pattern (Figure 2D). In addition to shading, stimuli in the *medium reliability* trials were wrapped with a 1/f noise texture pattern and cast shadows were also rendered, providing more reliable depth information (see Figure 2A–C and E-F). *High reliability* trials were visually identical to the medium reliability trials, but included simultaneous and consistent haptic (touch) shape information; it is well known that observers are able to combine haptic and visual cues to reduce noise in perceptual estimates and disambiguate shape (e.g., Adams, Graf, & Ernst, 2004; Ernst & Banks, 2002; Helbig & Ernst, 2007; Wijntjes, Volcic, Pont, Koenderink, & Kappers, 2009). The scene was only visible while observers made haptic contact with it, ensuring that observers relied on the visual-haptic stimulus for their judgments, rather than on any initial, visual-only information. The haptic surface was defined by low coefficients of static and dynamic friction, and compliance, such that the objects felt hard and smooth (implemented via OpenHaptics parameters: stiffness = 0.68; damping = 0.12; static friction = 0.28; and dynamic friction = 0.38).

Procedure

On each trial, an arrow indicated which of two shaded discs should be judged. Observers adjusted a visual-haptic pointer on a sliding scale to indicate how shiny the object looked from "not shiny" (0) to "very shiny" (10). Via another sliding pointer, observers adjusted a 2D contour until it matched the cross-section of the judged shape. Observers were given unlimited time to view the stimuli and adjust their settings before proceeding to the next trial. Each observer completed two blocks of 133 trials for the medium and high reliability conditions and four blocks for the low reliability condition. Each block included every combination of target object position (left/right),

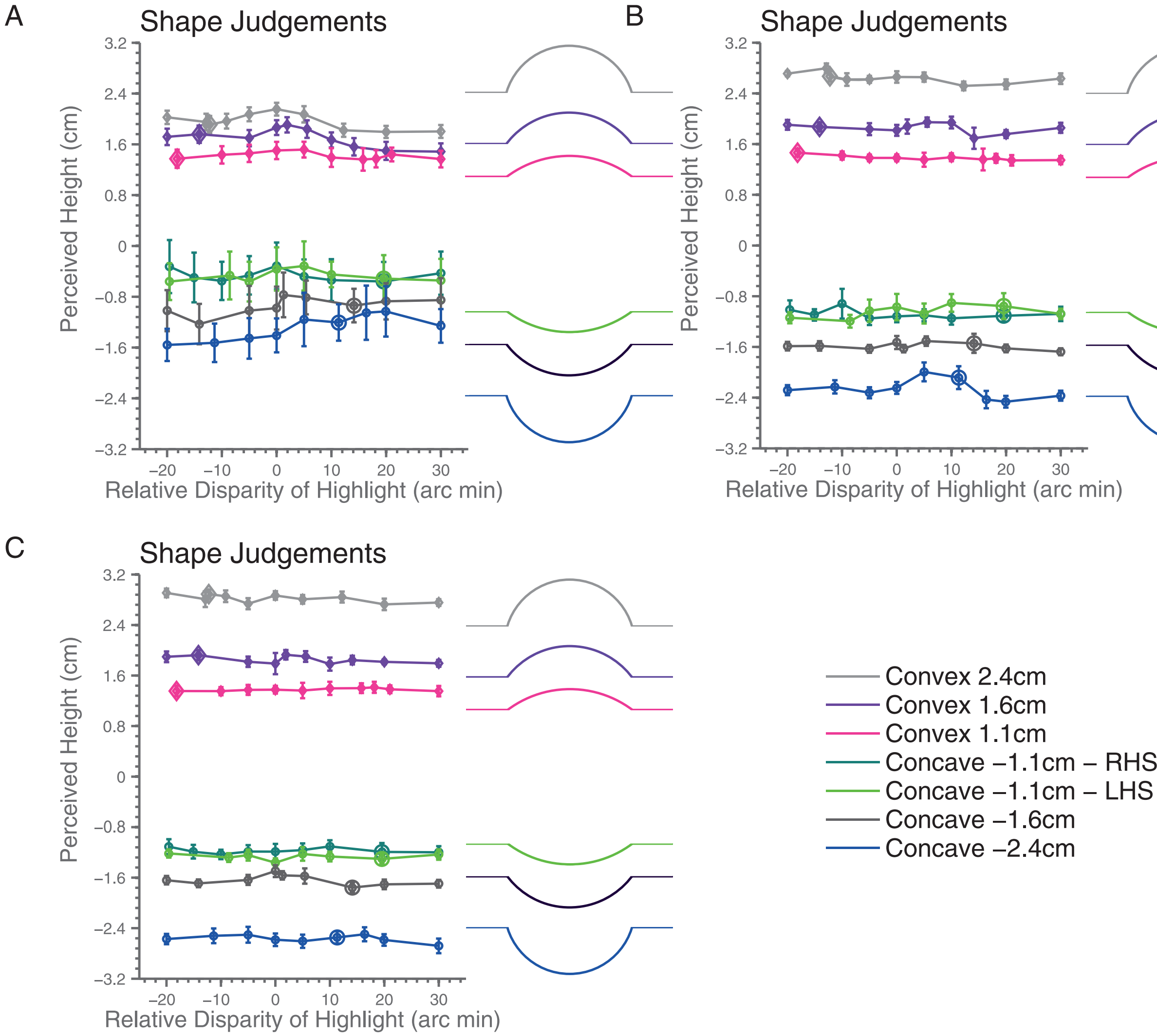

Figure 3. Shape responses for low, medium and high reliability conditions. (A–C) show shape responses for the low, medium and high reliability conditions respectively. Each shape is indicated by a different color—see legend—error bars show ±1*SEM*. Adjacent contours show the true stimulus heights, each contour is aligned with the correct height response on the *y*-axis. Larger symbols show the geometrically correct highlight disparity. For the shallowest concave surfaces, data are plotted separately for objects presented to the left and right of fixation (RHS and LHS). This is because the size of the visible highlight was different in these two configurations—see Figure 4 legend.

bump/dimple height (six possible values) and highlight disparity (10 or 11 values, including monocular highlights and highlight absent condition). Trial order within blocks and block order were randomized across participants. The study took approximately 2 hours, including breaks.

Results

The manipulation of shape reliability was effective in modulating observers' curvature perception. With minimal shape cues (low shape reliability condition), the *sign* of surface curvature was accurately reported, but curvature magnitude was underestimated and responses were variable, particularly for concave surfaces (see Figure 3A). When reliable cues were available, observers' convex and concave shape perception was very accurate (medium and high reliability conditions, Figure 3B and 3C). Perceived shape was very similar in the medium and high reliability conditions, with no significant differences between the two except for the deepest objects (±2.4 cm), where slightly more depth was reported in the high reliability condition [convex objects: $F(1, 7) = 5.70$, $p = 0.048$ ($\mu_{high} = 2.6$ cm, $\mu_{medium} = 2.3$ cm), concave objects: $F(1, 7) = 27.97$, $p = 0.001$ ($\mu_{high} = -2.8$ cm, $\mu_{medium} = -2.6$ cm)]. In other words, the addition of haptic shape information had little effect on shape perception, suggesting that shape information provided by the visual cues in these conditions (shading, cast shadows, texture, and disparity) was very reliable.

Gloss ratings were also very similar across the medium and high reliability conditions (Figure 4B and 4C), with a statistically significant difference found only for the shallowest concave surface, which was rated as slightly glossier in the medium reliability condition [shallow objects on the left (LHS) and right (RHS) of fixation have visible highlights of different sizes, and have thus been analyzed separately: LHS: $F(1, 7) = 6.62$, $p = 0.037$, $\mu_{\text{high}} = 7.0$, $\mu_{\text{medium}} = 7.6$; RHS: $F(1, 7) = 9.49$, $p = 0.018$, $\mu_{\text{high}} = 4.0$, $\mu_{\text{medium}} = 4.9$]. Observers utilized a wide range of response values; surfaces with correct highlight disparity were given high gloss ratings (large symbols, Figure 4), whereas those surfaces without highlights were given low gloss values (gloss rating for concave and convex objects: $\mu_{concave} = 2.41$, $SEM = 0.57$, $\mu_{convex} = 2.10$, $SEM = 0.55$).

Comparing the left and right columns in Figure 4, our most striking finding is that observers are insensitive to highlight disparity sign when judging the glossiness of concave objects. In contrast, disparity sign has a substantial effect on perceived gloss with convex objects. Thus, despite excellent shape recovery in the medium and high reliability conditions, observers showed perceptual failures, relative to a full geometric model, when judging the gloss of *concave* surfaces (Figure 4B and 4C). Larger symbols show the geometrically correct highlight depth for each surface shape. If an accurate model of highlight geometry were implemented, perceived gloss ratings would peak at these points. When highlights were located correctly in front of the surface, concave objects were (correctly) perceived as quite glossy (average gloss rating for correct highlights across medium and high reliability conditions: 6.48). Also, as expected, gloss ratings were lowest when the highlight lay on the surface (zero relative disparity, average rating: 4.20); the straightforward interpretation of this stimulus is a bright patch on a matte object caused by a light paint spot or local spotlight (Figure 2B). The dip in gloss ratings at zero disparity is clear across surface curvature sign and magnitude. Interestingly, however, when the highlight was moved further away from its correct position, to sit behind the concave surface, that surface was again perceived as glossy, just as glossy as a surface with a correctly positioned highlight. In the "behind" position, the highlight is far from correct, but observers appear to disregard highlight disparity *sign* for concave objects: both near and far bright spots are interpreted as highlights (average gloss rating with incorrect sign, but correct magnitude: 6.90).

We tested sensitivity to highlight disparity sign by comparing asymmetric and symmetric curve fits to the gloss rating data; data following a symmetric pattern would suggest that observers are insensitive to highlight disparity sign. The asymmetric fit was defined by an inverted Gaussian with five free parameters (the mean—corresponding to the low point of the function and separate spread and scaling parameters on each side of the mean). For the symmetric curve fit, a single pair of spread and scaling parameters defined the curve on both sides of the mean. Gloss perception of medium and high reliability concave stimuli was well fit by the symmetric model, with the asymmetric model producing only a modest improvement (reduction in sum of squared residuals: $\mu_{\text{medium}} = 26\%$, $\mu_{\text{high}} = 21\%$, averaged across object depths). Cross-validation revealed that the asymmetric model did not provide a significantly better fit than the symmetric model ($p > 0.05$ for all concave objects, medium and high reliability conditions, from *t*-tests on residuals calculated by excluding each data point in turn). This suggests that observers disregard the sign of highlight disparity, despite being sensitive to its magnitude. In fact, some observers appear to lack even a basic model of highlight geometry, despite good stereoscopic vision: two observers (excluded from all analyses) were completely insensitive to highlight disparity, perceiving any surface with a highlight as very glossy, irrespective of highlight depth.

In contrast with concave objects, a more sophisticated model of highlight geometry predicts our observers' gloss perception of convex objects. Across all observers, convex objects appeared highly glossy when the highlight disparity was correct or close to correct (see Figure 4D-F, average gloss rating for correct highlight across medium and high reliability shape conditions: 8.44). The lowest gloss ratings were reported when the highlight had zero relative disparity (average gloss rating across medium and high reliability conditions: 4.86), and ratings were significantly higher for correct than incorrectly signed highlight disparity (mean rating for reversed highlight disparity: 5.58). We again tested sensitivity to highlight disparity sign using symmetric or asymmetric data fits. In the medium and high reliability conditions, where gloss was strongly modulated by highlight disparity, responses to convex objects were poorly fit by the symmetric model, with considerably better asymmetric fits (reduction in sum of squared residuals: $\mu_{\text{medium}} = 53\%$, $\mu_{\text{high}} = 50\%$). Cross validation confirmed that the asymmetric model provided a better fit for convex objects (all $p < 0.05$, except 1.6 cm and 2.4 cm objects in medium condition: $p = 0.06$ and $p = 0.08$). However, note the larger error bars for the right hand side of plots 4E and 4F—some observers were more sensitive than others to disparity sign; a small subgroup of observers had a tendency to perceive convex surfaces with a near (incorrect) highlight as glossy. This was rather surprising given the alternative, viable stimulus interpretation: in the

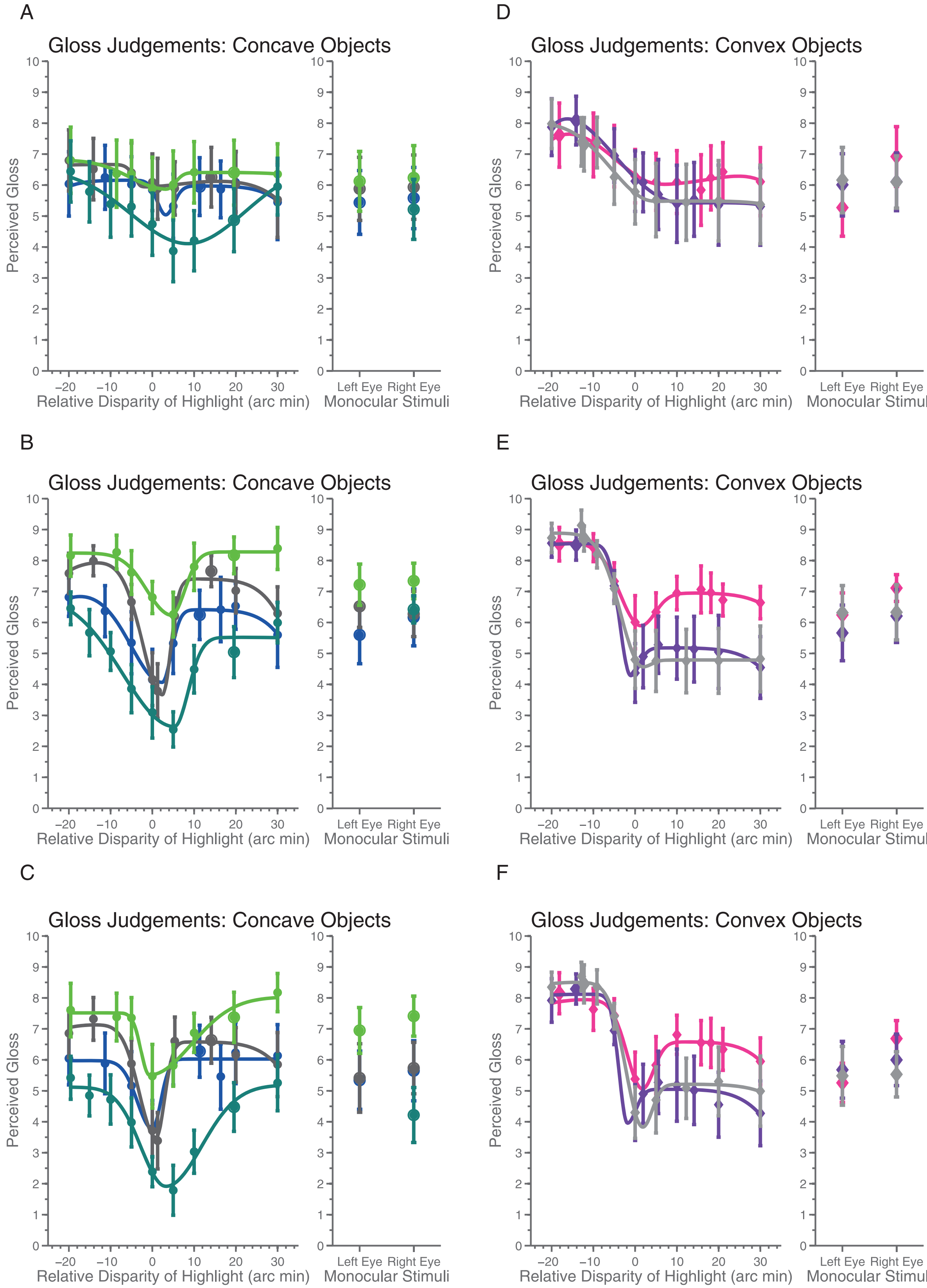

Figure 4. Perceived gloss for low, medium and high reliability conditions. (A–C) show perceived gloss for concave shapes in the three reliability conditions, respectively, while (D–F) show perceived gloss for convex shapes. Legend as in Figure 3, error bars show ±1*SEM* and larger symbols again show the correct highlight disparity. Gloss ratings for the shallowest concave surfaces have been plotted separately for left and right presentations (light and dark green); when this object was to the right of fixation the highlight was only partially visible to one eye due to the geometry of the scene, whereas when it was presented on the left, a large highlight was visible to both eyes.

case of convex objects, a highlight with positive (incorrect) disparity can be perceived as a separate white object, like a small cloud, floating in front of a matte surface (see Figure 2C). This description fits both informal observations of our convex stimuli and the majority of our observers' data. Further analyses confirm that observers are more sensitive to highlight disparity sign for convex, than for concave objects: convex objects with incorrect (near) highlights are perceived as significantly less glossy than concave objects with incorrect (far) highlights ($t_7 = 2.5$, $p < 0.05$; $\mu_{\text{convex}} = 4.9$, $\mu_{\text{concave}} = 6.5$, averaged across medium and high reliability and all convex or concave shapes, excluding the shallowest surfaces, where gloss is complicated by partially occluded highlights—see below). Furthermore, gloss ratings depend on disparity sign for convex, but not concave objects [main effect of disparity sign for convex objects: $F(1, 7) = 8.1$, $p = 0.025$; $\mu_{\text{correct}} = 8.0$, $\mu_{\text{incorrect}} = 5.4$; but not concave objects: $F(1, 7) = 4.2$, $p > 0.05$; $\mu_{\text{correct}} = 5.9$, $\mu_{\text{incorrect}} = 6.4$].

Across both convex and concave surfaces, highlight disparity had a smaller modulatory effect on gloss perception in the "low" reliability condition, where the depth of the surface, and thus the relative depth of the highlight, was not reliably defined (Figure 4A and 4D).

For all highlight depths, gloss perception of concave surfaces was modulated by the magnitude of surface curvature: somewhat surprisingly, highly curved surfaces produced lower gloss ratings. The exception is the shallowest concave surface on the right of fixation (Figure 4A through 4C lowest line)—in this configuration only a sliver of a highlight was visible on the edge of the surface, and observers rated this surface as least glossy. We implemented the Phong model (Phong, 1975) to produce highlights whose spread is modulated by surface curvature (compare Figure 2A and 2D). The shape-gloss relationship in our data suggests that observers perceive surfaces with larger highlights as glossier, consistent with other evidence (Beck & Prazdny, 1981; Marlow, Kim & Anderson, 2012). This was true for gloss judgments of both concave and convex surfaces [main effect of highlight size, as indexed by object shape: concave surfaces $F(3, 21) = 7.5$, $p = 0.018$, G-G correction, $\varepsilon = 0.44$; convex surfaces $F(2, 14) = 7.5$, $p = 0.051$, G-G correction, $\varepsilon = 0.56$]. Post-hoc, Bonferroni-corrected comparisons revealed that the shallowest concave shape (1.1 cm), presented on the right of fixation (small highlight) was perceived as less glossy than the same shape presented on the left (large highlight, $p = 0.002$); and also less glossy than the 1.6 cm concave surface ($p = 0.011$). The shallowest convex surface (large highlight) appeared glossier than deeper surfaces (1.1 cm vs. 1.6 cm, $p = 0.051$). The effect of highlight size for convex surfaces was more pronounced with incorrectly positioned highlights (interaction between highlight sign and shape magnitude $F(2, 14) = 7.3$, $p = 0.029$, G-G correction, $\varepsilon = 0.52$); it appears that the "larger highlights = more glossy" heuristic has a larger effect when there is uncertainty in the interpretation of a potential highlight (concave objects, convex objects with misplaced highlights).

Why might the visual system use highlight size as a gloss cue? Smoother surfaces actually create smaller, more focused highlights, given a single distant light source. However, in the more complex light fields that typically illuminate natural scenes, very glossy or mirrored objects reflect the surrounding scene more sharply than matte objects (Pellacini, Ferwerda, & Greenberg, 2000) and so may produce multiple large, bright areas.

Further limitations to the observers' model of highlight geometry were revealed when they viewed monocular highlights (within otherwise binocular scenes). Monocular highlights occur in normal viewing of glossy surfaces such as our stimuli, either when the surface does not extend far enough to "capture" one eye's highlight, or when the light's path is occluded by the surface (the potential reflection point lies within a shadow). For a given scene it is geometrically plausible to have a monocular highlight visible to one eye, but not to the other eye. However, observers do not display this sensitivity, making equal, moderately glossy judgments for a monocular highlight presented to either the correct or incorrect eye (right hand component of each plot in Figure 4).

Discussion

Observers' interpretation of specular highlights reveals a limited geometric model. Although the glossiness of convex surfaces is perceived broadly in line with an accurate geometric model, this is not the case across all stimuli: bigger highlights signal more gloss and monocular highlights viewed with either eye suggest moderate gloss. Surprisingly, for concave surfaces, highlights in entirely the wrong depth location—behind the surface—signal high gloss.

When the visual system is presented with a highlight at the wrong depth location (e.g., behind a concave surface rather than in front of it) it must find some "explanation" of the retinal input. One interpretation, given a misplaced highlight, would be to amend the estimate of surface shape to accommodate it, e.g., a concave surface with a far (incorrect) highlight could be perceived as glossy and convex. Although convex/concave reversals driven by highlight disparity have been reported elsewhere (Blake & Bülthoff, 1990, 1991), highlight disparity had little effect on perceived shape in the current study. It may be that a prior for overhead lighting (e.g., Adams et al., 2004; Kleffner & Ramachandran, 1992) and weak disparity cues remained strong enough to veto a reversed curvature interpretation even in our "low reliability" condition. In a supplementary experiment we explored this possibility further by manipulating the simulated illumination and stereoscopic depth cues to increase uncertainty of object curvature. However, perceived curvature sign continued to be unaffected by highlight disparity—see Appendix for details. Rather than changing their shape estimate, our observers perceived concave surfaces to be glossy, even when the binocular highlights were inconsistent with that interpretation. This failure to reject an interpretation of gloss was not due to uncertainty in shape as suggested by Blake and Bülthoff (1990, 1991): even when shape information was reliable and shape estimates were accurate, observers perceived concave surfaces with incorrect highlights as glossy.

A potential interpretation of an errant bright spot positioned behind a concave surface is of a light source viewed through a transparent surface. Is it possible that our observers perceived not gloss, but transparency? Gloss and transparency are somewhat related: the separation of image components at different depths, that correspond to reflections and surface texture, is similar to that necessary to perceive transparency (Anderson, 2011) and gloss has even been conceptualized as a form of transparency (Mulligan, 1993). Furthermore, transparent objects are often glossy (Fleming & Bülthoff, 2005); the surface structure required to transmit light regularly will also result in mirror-like reflection of any reflected light. However, we think it is unlikely that observers perceived transparency from our experimental stimuli: casual inspection of Figure 2E reveals a percept of gloss rather than transparency; other transparency cues are absent—the surface in front of the light source is not visible with reduced contrast, and nothing else can be seen through the surface. Instead, it seems that the visual system determines that the bright spot in the image is a specular highlight on a glossy, concave object. Why might the visual system accept this interpretation? Firstly, if a light source is very close to a concave surface (between the surface and its focal point) a virtual, far image is produced. For our stimuli, such a light source would need to be less than 1.7 cm or 2.7 cm from the deepest or shallowest concavities respectively, and closer still to produce highlights at the actual disparity-defined depths presented to our observers. Such light sources (unlike the simulated distant one) would be clearly visible in the image. Alternatively, light sources at low elevation (close to the image plane), could in theory produce inter-reflections leading to spurious binocular matches. While these interpretations are inconsistent with our stimulus images, the visual system appears to have learned that the relationship between highlight disparity and gloss is more complex for concave objects, and thus regards a highlight on a glossy surface as the most plausible explanation for the errant bright region. Observers thus perceived highlights either in front of, or behind concave surfaces as indicative of gloss. Only highlights lying at the surface depth result in a perception of a matte surface.

Observers did implement the constraints of highlight geometry when assessing the glossiness of convex surfaces. This could be because highlight geometry is simpler for the convex than for the concave case: for simple convex surfaces, highlight images will always be virtual, located behind the surface, and not subject to surface inter-reflections. In contrast, given particular viewing and lighting conditions, highlights can appear either in front of or behind a concave surface, or can be partially or completely occluded from view by the surface itself. It appears that observers invoke a simplified model of highlight geometry that is robust to the complexities of reflections and inter-reflections inside concave objects: any potential highlight that lies off the surface (i.e., with nonzero relative disparity) provides evidence of gloss. Additionally, due to the statistics of objects in our natural environment, observers may have had more experience with convex objects than concave, and may thus have more reliable representations of their highlight geometry.

Despite a simplified model of gloss, we rarely make errors in our estimates of object material. No doubt other cues to surface shape and gloss are exploited, such as the alignment of specularities and diffuse shading (Anderson & Kim, 2009; Beck & Prazdny, 1981), the relationship between highlight color and surface color (Nishida et al., 2008), flow fields of local image orientations in richer light fields (Fleming et al., 2004) and highlight motion (Doerschner et al., 2011; Hartung & Kersten, 2002, 2003; Sakano & Ando, 2010; Wendt, Faul, Ekroll, & Mausfeld, 2010). However, it remains surprising that the binocular disparity of specular highlights, which could be such a valuable cue to surface gloss and shape, constrains perception in an incomplete manner.

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Appendix

In a supplementary experiment, we investigated whether highlight disparity would have an effect on perceived curvature sign when shape was more ambiguous. To this end, simulated illumination was from the left or right (lighting tilt = 0° or 180°), rather than from above-left (consistent with a light-from-above prior). In addition, shading and texture were consistent with an object height of ±1.1 cm, but the disparity of this shading and texture was consistent with a flat surface (as in Blake & Bülthoff, 1990, 1991). Observers estimated surface shape (via a sliding pointer, as in our main experiment) on trials with a "concave highlight" (positive highlight disparity consistent with a concave interpretation), "convex highlight" (negative highlight disparity, consistent with a convex object) or no highlight.

In contrast to previous findings (Blake & Bülthoff, 1990, 1991), highlight disparity had only a small effect on the *sign* of curvature; all objects were perceived as convex on the majority of trials (proportion perceived as convex: 70.7%, 86.9%, and 73.2% for "concave," "convex," and no highlight conditions, respectively). An ANOVA revealed a significant effect of highlight condition, $F(2, 26) = 4.73$, $p = 0.032$, G-G correction, $\varepsilon = 0.70$, but this was driven by a significant difference between the "no highlight" and "convex highlight" conditions (Bonferroni pairwise comparisons, $p = 0.028$, other comparisons not significant [n.s.]). Thus, we failed to replicate Blake and Bülthoff's finding that highlight disparity sign *determined* perceived curvature. Disparity sign did affect quantitative depth: the magnitude of depth estimates varied significantly according to highlight condition [concave highlight: 1.12 cm, convex highlight: 1.35 cm, no highlight: 1.06 cm, $F(2, 26) = 12.21$, $p = 0.001$], with significant differences between positive ("concave") and negative ("convex") highlight disparity ($p = 0.006$) and between the "convex" and "no highlight" conditions ($p = 0.007$, Bonferroni pairwise comparisons).

In summary, therefore, our supplementary experiment found that highlight disparity has little effect on perceived curvature sign, and a small but significant effect on curvature magnitude. There was an effect of highlight presence, with the "convex" highlight producing more convex responses than no highlight. This finding is in agreement with a bias reported elsewhere (Bouzit, Adams, & Graf, 2007); the presence of a highlight acts as a cue to convexity because highlights are more likely to be occluded on concave objects. Why did we fail to find the large effects of highlight disparity on perceived curvature sign, as reported previously? In contrast with previous studies (Blake & Bülthoff, 1990, 1991), our observers estimated quantitative depth, rather than making a 2AFC on convexity sign. This methodological difference, alongside stimulus differences may account for the somewhat disparate findings (our lack of a significant or substantial effect on curvature sign). Their stimuli included convex and concave regions within the same object, so a convexity prior (e.g., Langer & Bülthoff, 2001) would have little effect on perceived curvature sign. In contrast, our stimuli were separated spatially which could have increased the influence of the convexity prior on the attended object (van Doorn, Koenderink, & Wagemans, 2011). Together, these results suggest that while highlight disparity sign can be used as a cue to object shape, it is a very weak cue and will normally be dominated by other cues or biases, such as the convexity prior.