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The Role of Shape in Modeling Gloss

Davit Gigilashvili and Akib Jayed Islam
Department of Computer Science, Norwegian University of Science and Technology; Gjøvik, Norway

Abstract

Gloss is an important appearance attribute, and its exact perceptual mechanisms are yet to be fully understood. Previous works attempted to model the relationship between optical and perceptual gloss. The state-of-the-art studies demonstrate that the human visual system has a poor ability to recover surface reflectance and perceived gloss rather depends on image cues that are generated by a complex interaction among optical material properties, illumination, object shape and its surface geometry. Therefore, perceptual models defined on a particular shape, such as a sphere, may not generalize to other objects. To investigate shape-specific differences, we conducted a psychophysical experiment with a simple sphere and complex Lucy shapes. We scaled the magnitude of apparent gloss to study how the shape affects perceived gloss, and how the role of optical material properties varies between the shapes. We observed significant cross-shape differences, which we argue can be explained by the analysis of the image cues.

Introduction and Background

Gloss is an important appearance attribute. For instance, saying that an object is red would not be enough to fully convey its look, because matte and highly glossy objects significantly differ in appearance. The ASTM Standard Terminology of Appearance [1] defines gloss as *"angular selectivity of reflectance, involving surface-reflected light, responsible for the degree to which reflected highlights or images of objects may be seen as superimposed on a surface."* The magnitude of gloss plays an important role in our lives. Glossiness not only affects how precious and attractive objects appear to potential customers [2, 3, 4, 5], but also defines how we interact with them due to perceived fragility [5, 6]. Unlike color vision, considerably less is known about gloss perception [7]: neither standard observer is defined for gloss [8], nor a robust and sophisticated perceptually uniform gloss space has been established to date that makes manipulation of gloss appearance subject to costly trial-and-error process [9].

The fundamental problem in gloss perception research has been bridging the gaps between optical material properties, such as surface reflectance, and the magnitude of gloss perceived by the human visual system (HVS). The state-of-the-art on gloss perception is well summarized in the following reviews [7, 8]. Hunter's classic work [10] was the first one to point out the multidimensional nature of apparent gloss, mentioning at least six different types of it: *Specular gloss* ("brilliance of specularly reflected light, shininess"); *Sheen* ("shininess at grazing angles"); *Contrast gloss* ("contrast between specularly reflecting areas and other areas"); *Absence-of-bloom gloss* ("absence of smear or excess semi-specular reflection adjacent to reflected highlights and images"); *Distinctness-of-reflected-image gloss* ("distinctness and sharpness of reflected images"); *Absence-of-surface-texture gloss* ("surface evenness, absence of texture, indicated by difficulty of recognizing presence of surface"). These dimensions may vary across the shapes. Gigilashvili *et al.* [11] noticed striking differences in the responses when observers were asked to rank objects by glossiness. For a spherical shape, some observers prioritized DOI – i.e. how clearly they could see the mirror reflection of the environment, while others put more weight on overall shininess of the object and brightness of the highlights. When spheres were replaced with complex bust figurines, the vast majority of the observers relied on the latter criterion only, as the DOI factor was absent, because the complex shape of the object did not permit seeing the environment reflectance image.

Figure 1: Although both objects are made of an identical material, the sphere permits observing a mirror reflection of the environment, while Lucy does not. This difference in shape and surface complexity affects perceived gloss.

The seminal work by Pellacini *et al.* [12] proposed the first psychophysically-based light reflection model that enabled gloss manipulation in a perceptually meaningful way for computer graphics applications. The authors varied the reflectance parameters of Ward's [13] heuristic model to generate synthetic images of different materials. They quantified perceptual distances among these materials and conducted MDS to identify contrast and DOI as two essential perceptual dimensions. Afterward, they used magnitude estimation techniques to scale each of these dimensions and proposed a psychophysically-based model, which related steps in Ward's reflectance parameters with intuitive and perceptually uniform steps in gloss. Although this work was a great breakthrough and remains influential to this date, the whole model is defined on spherical objects only, which is identified as a limitation by the authors themselves.

When discussing shape, it is important to specify what scale of geometric variation is meant. *Micro-scale roughness* of the surface is inversely correlated with perceived gloss [12, 14, 15] – rougher objects appearing less glossy. *Meso-scale pertubations*, such as adding bumps also effects perceived gloss, but in more non-monotonic and complex way. While small pertubations decrease DOI and hence gloss, the bumps with very high amplitude change the local curvature of the surface and make more specular reflections visible, which can increase perceived gloss [16, 17]. *Macro-scale differences in shape* may also change apparent gloss [11, 18, 19, 20].

To understand why shape impacts the magnitude of apparent gloss, we need to look deeper into the perceptual mechanisms of the HVS. The HVS proposedly relies on image cues, i.e. statistical and spatio-geometric regularities in the image intensities, such as brightness of the specular highlights and the contrast between specular and non-specular ares [12, 14, 21, 22, 23], sharpness of the highlights [12, 22, 23], and total area covered by specular reflections [21, 22, 23]. While these cues are indeed affected by surface reflectance, the image structure is generated by a complex interaction among illumination, 3D object shape, and optical properties of a material [19, 23].

Nevertheless, the attempts to bridge a gap between physics and perception, and to construct gloss space or a perceptual embedding, are limited to variations in BRDF properties, and at most, surface roughness [12, 14, 24]. While the micro-level surface roughness indeed affects DOI or the ability to reflect surrounding scene, as well as contrast, sharpness, coverage area of the highlights, and other image cues proposedly used by the HVS, the same is true for macro-level shape variations (for instance, see Fig. 1). Models defined on one shape may not generalize to others [20], and proposedly, we may even need to refer to the problem as *object appearance* rather than *material appearance* [25].

In order to demonstrate the importance of shape in modeling perceptual gloss, in this study we revisit the classic work by Pellacini *et al.* [12]. We use the same set of materials but in addition to a sphere, we also study a Lucy shape. We conducted psychophysical experiment to scale perceived gloss for both shapes, to investigate how the magnitude of perceived gloss changes between them, and to explore to what extent the perceptual model [12] can be generalized from spheres to more complex Lucy. Finally, we discuss how image cues explain observed cross-shape discrepancies and formulate directions for future work.

Methodology

We conducted a psychophysical experiment to scale the magnitude of perceived gloss in individual synthetic images.

Stimuli

We used a path tracer of the Mitsuba Physically-based Renderer [26] to generate the synthetic images that varied in three parameters of the original Ward model [13] used to describe the BRDF: diffuse reflectance, ρ_d; strength of the specular component, ρ_s; and the spread of the specular lobe α, which is phenomenologically similar to surface roughness found in microfacet-based models. We used the same 27 materials used by Pellacini *et al.* [12] that according to the authors correspond to the measured properties of real paints ranging from white to shades of gray and black, and rendered them in two different shapes: sphere and Stanford Lucy [27]. Three levels of each parameter (α, ρ_s, and ρ_d) were used, totaling to 27 images per shape, and 54 in total (examples in Fig. 1). The parameters are summarized in Table 1[1]. Apart from this, we included 30 additional materials (60 images). They were selected in a way to simplify correlating gloss rating with *distinctness* and *contrast* dimensions from the previous work [12]. Similarly to that work, we fixed α to 0.04 and varied ρ_d and ρ_s, to scale the *contrast* axis. ρ_d and ρ_s values from the original 27 materials were supplemented with values sampled between them (summarized in Table 2); and fixed ρ_d and ρ_s, and varied α from 0.01 to 0.19, to scale *distinctness* axis (summarized in Table 3). Two materials with α, ρ_d and ρ_s equal to 0.07, 0.099, 0.03 and 0.10, 0.099, 0.03, respectively, were shown twice for each shape to check the intra-observer consistency. For sphere, observers turned out highly consistent, and the scores between the two trials differed on average by 2 (by 8 for Lucy). In the final analysis, the mean of the two trials is reported.

As DOI is essential for perceiving gloss, it is important the images to be shown in a realistic, complex scene, which will be reflected if the material is reflective enough. For this purpose, we used Bernhard Vogl's museum environment map [28]. Similarly to the previous study, the objects were placed on a diffusely reflecting checkerboard texture. The width and height of each rendered image was 512×512 pixels, rendered with 16384 samples per pixel. Mitsuba default tonemapper was used to tone map high-dynamic range result to 8-bit PNG images.

Experimental Procedure and Observation Conditions

The objective of the experiment was to assess how overall magnitude of perceived gloss varies across the shapes. The images were shown one-by-one in a random order, and the task of the observer was to use a scale slider to assess the glossiness of the depicted object on the scale of 0-100, where 0 corresponds to minimal gloss. The experiment was performed using QuickEval tool [29] in a controlled environment on a calibrated sRGB EIZO CG246 ColorEdge display, with a gamma of 2.2, a whitepoint color temperature of 6500K, and a max. luminance of 80 cd/m^2. Distance between the display and the observer was 65 cm. The display resolution was 1920x1080. The image size was 13.55cm (both horizontally and vertically) occupying approximately 12° of the field of view (FoV). The experiment took approximately 20-25 minutes per observer.

Instructions

Before the experiment, the definition of gloss from the ASTM Standard Terminology of Appearance [1], as well as the real life examples of glossy and matte objects were given to ensure that the observers understood the task correctly. They also went though a quick pilot experiment to clear up any uncertainties regarding the task. The following instruction was given to the observers: *"Judge the apparent glossiness of the object in the image on a scale from 0 (least glossy) to 100 (most glossy) by adjusting the scale slider"*.

Observers

15 observers with normal or corrected-to-normal vision participated in the experiment, including the two authors of this article. Except of the authors, the observers were naïve to the purpose of the study. 14 observers were first- and second-year computer science graduate-level students. The standard deviation among observers' scores for each stimulus was on average 15, which points out the existing cross-observer differences. However, no difference was found between the authors and the naïve observers.

[1] The dataset of the images is available at: `https://github.com/davitgigilashvili/TheRoleOfShapeinModelingGloss`

Table 1: Parameters for the original 27 materials from [12].

Name	Value
Alpha, α	0.04, 0.07, 0.10
Specular Reflectance, ρ_s	0.033, 0.066, 0.099
Diffuse Reflectance, ρ_d	0.03, 0.193, 0.767

Table 2: Parameters for additional images for contrast gloss scaling. Alpha was fixed to 0.04. Additional points were sampled between original ρ_d and ρ_s values (cf. Table 1).

Name	Value
Alpha, α (fixed)	0.04
Specular, ρ_s	0.017, 0.033, 0.050, 0.066, 0.083, 0.099
Diffuse, ρ_d	0.030, 0.087, 0.193, 0.420, 0.767

Table 3: Parameters for additional images for DOI gloss scaling. Similarly to the original work [12], ρ_d and ρ_s were fixed to 0.03 and 0.099, respectively. 11 levels of $alpha$ were used, sampled from 0.01 to 0.19 with steps of 0.02, supplemented with 0.10.

Name	Value
Alpha, α	0.10, 0.01 to 0.19 (with 0.02 interval)
Specular, ρ_s (Fixed)	0.099
Diffuse, ρ_d (Fixed)	0.03

Results

First of all, we investigate how the magnitude of perceived gloss changes between the shapes when the material remains identical. Fig. 2 shows gloss rating for spherical objects as a function of gloss rating for Lucy made of the same material. If the null hypothesis were true and the shape had no impact on perceived gloss, then the values for both shapes should have been nearly identical (assuming some degree of noise) and the correlation should have been nearly perfectly linear. However, we observe from the plot that this is not the case. Not only the absolute magnitudes of the two are not similar, but also simple linear regression fails to adequately explain all variation in the data, manifesting a gloss constancy failure. The boxplots in Fig. 3 show that mean and median gloss rating is higher for spheres when α=0.04, and higher for Lucy when α=0.07 and α=0.10. We studied how the gloss rating changed for all 57 materials. Fig. 4 illustrates that for low α, sphere is perceived glossier than Lucy made of the same material, while for high α, Lucy is perceived glossier. For more moderate α values, the two become roughly equivalent. The boxplots also show that spherical objects depend on all those three parameters: perceived gloss being positively correlated with ρ_s, and negatively correlated with α and ρ_d, while for Lucy's gloss rating is weakly affected by changes in ρ_d and especially, in α; while, on the other hand, it rapidly increases with the increase of specular component ρ_s.

Afterward, we analyze the stimuli with fixed alpha and varying ρ_s and ρ_d, and with fixed ρ_s and ρ_d, and varying alpha, to study how contrast and distinctness (as defined by Pellacini *et al.* [12]) relate with the gloss rating of our stimuli, respectively. The results for distinctness are shown in Fig. 5. It turned our that $d = 1-\alpha$ definition of distinctness is robust enough for our data too, which describes approximately 94% of the variation in gloss rating for this subset of stimuli ($R^2 = 0.94$ both for sphere and Lucy). Root Mean Square Error (RSME) is also reasonably low and equals to 5.20 and 2.86, for sphere and Lucy, respectively. There is another important point worth highlighting: the slope of the fitted curve is considerably steeper for sphere than it is for Lucy, meaning that change in distinctness has larger impact on apparent gloss of spherical shapes than it is for Lucy.

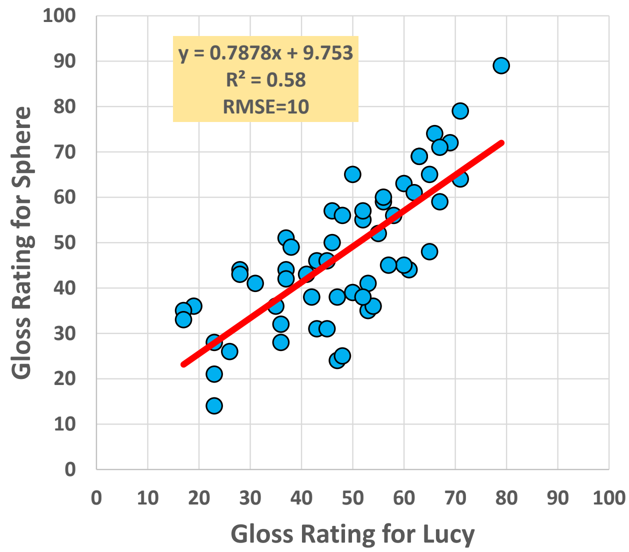

Figure 2: Gloss rating for spheres as a function of gloss rating for Lucies made of the same material, for all 57 materials. As we can observe, the magnitudes are not only far from being similar, but also the relationship cannot even be adequately described by a simple linear model. R^2, RMSE, and the fitted curve equation are shown in the top left corner.

As for contrast (Fig. 6), whose optimal definition was found in [12] to be $c = \sqrt[3]{\rho_s + \rho_d/2} - \sqrt[3]{\rho_d/2}$, our fitting did not turn out as good as it was reported in the previous work [12]. R^2 is 0.77 for sphere, and 0.62 for Lucy, with RMSE equal to 10.39 for the latter. More accurate embedding was obtained with a more straightforward linear regression with two independent variables ρ_s and ρ_d, that increased R^2 to 0.89 for both shapes. Moreover, the strength of specular component alone (ρ_s) describes the variation in Lucy gloss rating better than the sophisticated contrast parameter (R^2=0.69).

Analysis and Discussion

The results in the previous section have shown that apparent gloss constancy fails across shapes, and Lucy and Sphere made of the same material oftentimes differ in perceived gloss.

The results from Pellacini *et al.* [12] have been partially reproduced for a spherical shape, but the model did not generalize to Lucy. For low α materials, spheres are glossier than Lucy objects made of the same material; for high α the opposite is true. While all of Ward's parameters have considerable impact on gloss appearance of a sphere, Lucy remains less affected by α, and primarily co-varies with the strength of the specular component. The model by Pellacini *et al.* [12] varied DOI with Ward's heuristic spread of specular lobe parameter (α), which is phenomenologically similar to surface roughness found in microfacet-based models. As mentioned in the introduction, DOI can be blurred and become less distinct not only by micro-level variations of shape, but also macro-level complexities of surface geometry and varying curvature. As observed by Gigilashvili *et al.* [11], observers rely on DOI for spherical shapes, but it is not the factor when more complex shapes are used. This can be attributed to the fact

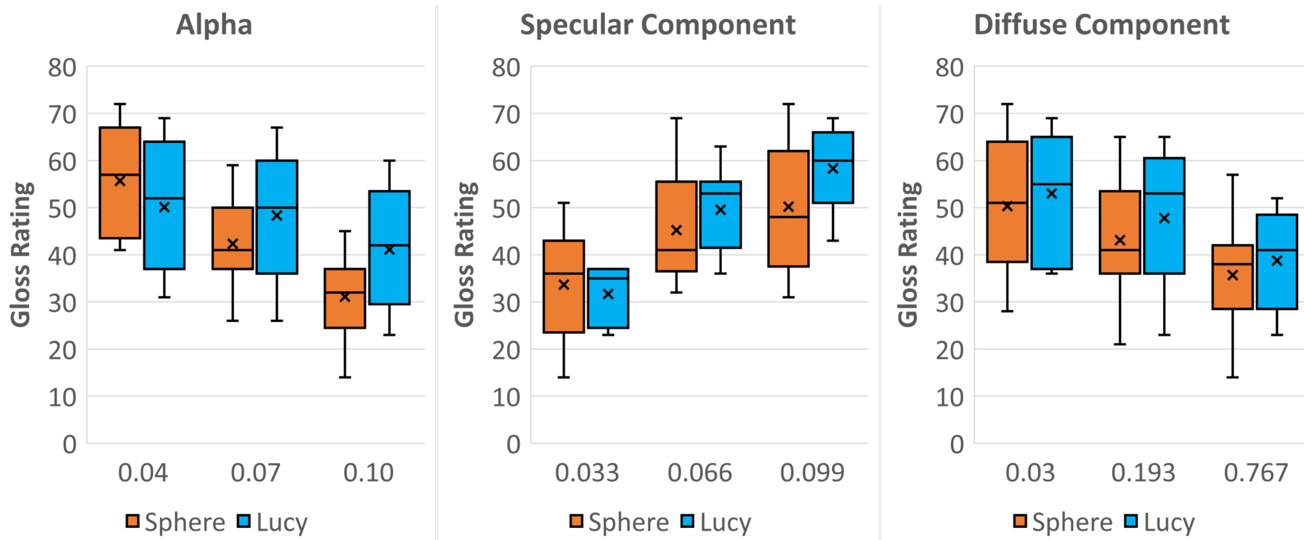

Figure 3: Boxplots for original 27 materials show how gloss ratings change by optical properties: α, ρ_s, and ρ_d. The boxes correspond to the interquartile range, the horizontal line inside the box is median, while X symbol corresponds to mean. The top and bottom whiskers extend to the maximum and minimum values, respectively. While all three parameters seem important for sphere, Lucy seems to be strongly variant to specular component only.

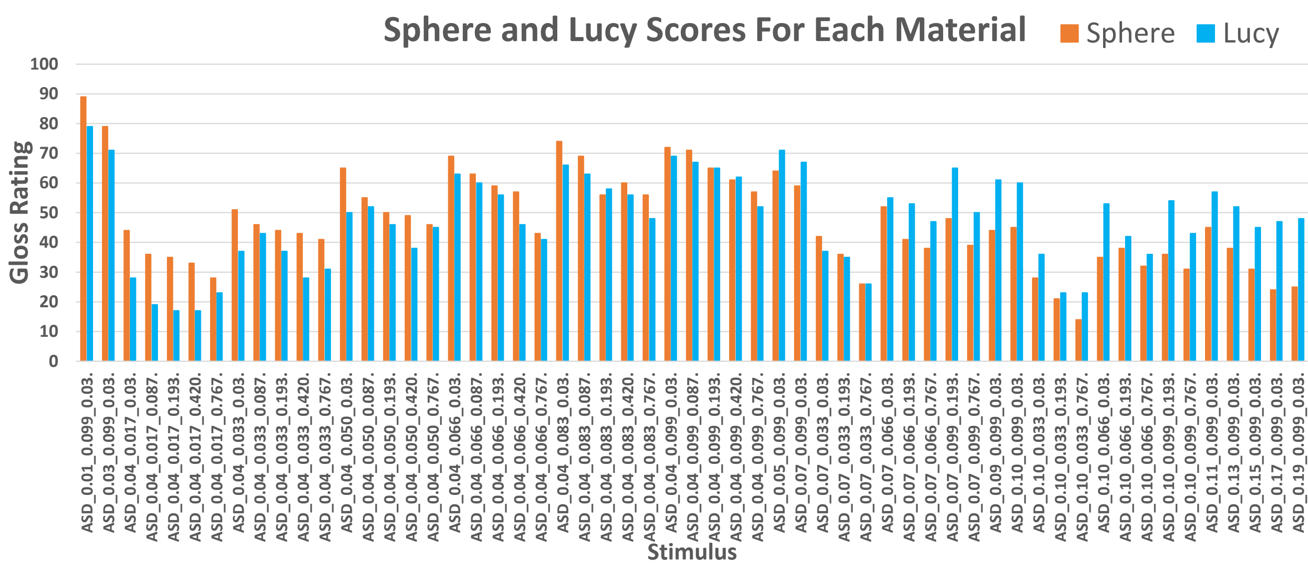

Figure 4: The bar plots show how the average Sphere and Lucy gloss ratings vary for all 57 materials. Material properties are written below, where numbers correspond to α, ρ_s, and ρ_d, respectively. The materials are ranked by α from left to right. It is apparent that for low alphas, sphere is usually glossier than Lucy made of the same material, while for high alphas the opposite is true.

that simple shape, such as a sphere, permits to observe the mirror reflection of the environment, while Lucy does not (see Fig. 1). This is also consistent with another study [20], which showed that subsurface scattering albedo is negatively correlated with gloss for spherical objects, but not for Lucy, because higher absorption in the subsurface increases the contrast, and better contrast increases the visibility of the mirror reflections. These observations once again highlight a need to include shape in modeling gloss, or to tailor existing models to each shape [25].

As mentioned above, Hunter [10] identified at least six different dimensions of gloss. However, in this study we have primarily discussed just two of them: DOI and contrast gloss. Pellacini *et al.* [12] argue that these two dimensions are sufficient to model gloss specifically for their stimuli, however, they leave possibility that for other stimuli other gloss dimensions may be more important. Our findings indicate that gloss dimensions are not universal and they can be specific to an object. While *distinctness-of-image gloss* and *contrast gloss* are primary gloss dimensions for a simple spherical object, *specular gloss* comes into play instead of DOI for more complex shapes, such as Lucy in this study and the bust figurine in the previous one [11].

Observed differences in the magnitudes of apparent gloss between the shapes once again illustrate that we have poor ability to recover surface reflectance. These discrepancies could potentially be explained by differences in image cues (coverage area, contrast and sharpness of the highlights [9, 23]). Let's refer to

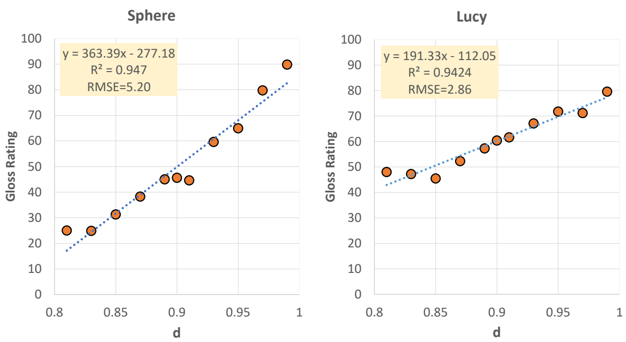

Figure 5: Gloss rating as a function of distinctness parameter, which is defined in [12] as: $d = 1 - \alpha$. The fitted line is shown in blue. The equation R^2 and RMSE are given in the top left corner of the plot. We can observe that both fitting are good, and the slope of a sphere is larger.

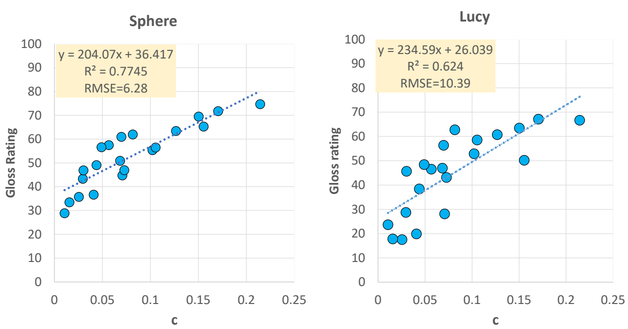

Figure 6: Gloss rating as a function of distinctness parameter, which is defined in [12] as: $c = \sqrt[3]{\rho_s + \rho_d/2} - \sqrt[3]{\rho_d/2}$. Neither shape provided as good fitting as in the previous work, and the fit looks less accurate for Lucy.

Fig. 7, which shows a sphere and a Lucy with identical parameters. Both of them have low α, which is associated with high DOI. As we can observe, the visible surface of a sphere is entirely covered with specular reflections, the object appearing like a mirror. On the other hand, Lucy has a more diverse distribution of surface normals, and within a small region, different parts of the surface are facing to completely different directions. Because of this, only small part of Lucy is covered with specular reflections, which is not enough for getting the impression of the surrounding world. This explains why sphere appears glossier when α is low.

On the other hand, when α is high, Lucy appears glossier. In this case, DOI is very low, and a sphere cannot be used as a mirror anymore. This difference can be rooted in other gloss cues: sharpness of the specular highlights, and contrast between specular and non-specular areas that are higher for Lucy, because color of a rough sphere is rather homogeneous, while Lucy has more diverse distribution of light and dark regions, which it owes to its high surface curvature. The complex surface of Lucy creates larger contrast in the areas occluded from the direct illumination (e.g. below the wings, in the armpit etc.). Furthermore, Lucy produces smaller yet higher number of specular regions (Fig. 7), which has been demonstrated to be also playing a role [16]. Finally, within a given dataset, observers get used to the fact that a sphere can be a mirror. When α increases and this is not possible anymore, the loss of mirror-effect is more noticeable than blurring small highlights of the Lucy that was not mirror-like anyway.

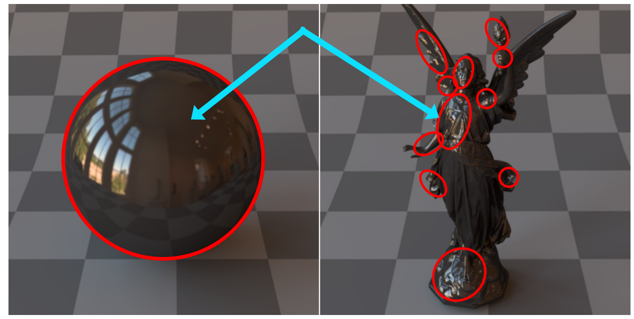

Figure 7: Coverage area is an important gloss cue (marked with red ellipses). While the entire surface of a sphere is covered with specular reflections, only small part of Lucy's surface is positioned in a way to reflect specularly toward the camera (compare areas a cyan arrow is pointing to). This makes Lucy less mirror-like, even though both objects are made of an identical material with α=0.01, ρ_s=0.03, and ρ_d=0.099.

This study comes with multiple limitations: first of all, we used the Ward's heuristic model to make our study comparable with that of Pellacini *et al.* [12], while real-life optical counterparts of its heuristic parameters cannot be varied independently. Future study should use more realistic microfacet-based model, which enables investigation on materials with subsurface light transport that also affects apparent gloss [20]. More robust definition of the perceptual dimensions than in the discussed model [12] is also needed (e.g., it neglects the effect of α on contrast gloss). Besides, low dynamic range images are subject to limitations of the tone mapping. High intensity specular highlights, which might be clipped, contain crucial gloss cues. Thus, future works should be conducted on HDR displays, or with physical objects.

We understand that the link between the computer graphics model and perception is not straightforward and the explanation of underlying perceptual mechanisms most probably lies in analysis of image cues. However, Pellacini *et al.* [12] demonstrated that exploring the link between the rendering parameters and perception can enable more perceptually-aware rendering in practical applications. The objective of this work is to demonstrate why this kind of models should also incorporate the shape parameters, while the exact reason for cross-shape discrepancies needs to be brought to light with further studies. There are indications that dimensionality of gloss may differ between Lucy and sphere. The shape-specific dimensionality of gloss can be revealed with MDS in future studies. Besides, the exact mathematical definition of candidate image cues and quantitative modeling of perceived gloss by them definitely merits a rigorous study in the future.

Conclusion

We conducted a psychophysical experiment to identify whether the overall magnitude of perceived gloss varies between the shapes. We found that gloss constancy fails across the shapes, and a sphere and a Lucy made of an identical material do not necessarily appear equally glossy. If the spread of the specular lobe is low and the reflected image is sharp, sphere appears glossier; if it is high and reflected image is blurry, conversely, Lucy appears glossier than a sphere. The distinctness-of-image is a strong glossiness cue for spherical objects that permit observing mirror-reflections. Its importance decreases considerably for Lucy, as

Lucy's complex surface geometry does not permit observing clear reflectance image of the environment. We also illustrated that the model defined on spherical objects [12] does not generalize well to Lucy. Therefore, we advocate for incorporating shape features into future gloss models, which requires rigorous investigation in the years coming. We hypothesize that this can be achieved by analysis of the image cues. While we propose area covered by the specular highlights, their sharpness, and contrast between specular and non-specular parts as potential candidate cues, future work is needed for exact mathematical formulation of these metrics and bridging the gap between image statistics and perception.

References

[1] "ASTM E284-17 Standard Terminology of Appearance," ASTM International, West Conshohocken, PA, 2017.

[2] Jiří Filip, Martina Kolafová, Michal Havlíček, Radomír Vávra, Michal Haindl, and Holly Rushmeier, "Evaluating physical and rendered material appearance," *The Visual Computer*, vol. 34, no. 6-8, pp. 805–816, 2018.

[3] Midori Tanaka and Takahiko Horiuchi, "Investigating perceptual qualities of static surface appearance using real materials and displayed images," *Vision Research*, vol. 115, pp. 246–258, 2015.

[4] Waka Fujisaki, Midori Tokita, and Kenji Kariya, "Perception of the material properties of wood based on vision, audition, and touch," *Vision Research*, vol. 109, pp. 185–200, 2015.

[5] Davit Gigilashvili, Jean-Baptiste Thomas, Marius Pedersen, and Jon Yngve Hardeberg, "On the appearance of objects and materials: Qualitative analysis of experimental observations," *Journal of the International Colour Association (JAIC)*, vol. 27, pp. 26–55, 2021.

[6] Roland W Fleming, Christiane Wiebel, and Karl Gegenfurtner, "Perceptual qualities and material classes," *Journal of Vision*, vol. 13, no. 8:9, pp. 1–20, 2013.

[7] Alice C Chadwick and RW Kentridge, "The perception of gloss: A review," *Vision Research*, vol. 109, pp. 221–235, 2015.

[8] Frédéric B Leloup, Gael Obein, Michael R Pointer, and Peter Hanselaer, "Toward the soft metrology of surface gloss: A review," *Color Research & Application*, vol. 39, no. 6, pp. 559–570, 2014.

[9] Davit Gigilashvili and Jean-Baptiste Thomas, "Appearance beyond colour: Gloss and translucency perception," in *Colour Engineering: Fundamentals and Applications*, Phil Green, Ed., chapter 16. Wiley, In Press.

[10] Richard S Hunter, "Methods of determining gloss," *NBS Research paper RP*, vol. 958, pp. 19–39, 1937.

[11] Davit Gigilashvili, Jean-Baptiste Thomas, Marius Pedersen, and Jon Yngve Hardeberg, "Perceived glossiness: Beyond surface properties," in *Proceedings of the 27th Color and Imaging Conference (CIC27)*. Society for Imaging Science and Technology, 2019, pp. 37–42.

[12] Fabio Pellacini, James A Ferwerda, and Donald P Greenberg, "Toward a psychophysically-based light reflection model for image synthesis," in *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*, 2000, pp. 55–64.

[13] Gregory J Ward, "Measuring and modeling anisotropic reflection," in *Proceedings of the 19th Annual Conference on Computer Graphics and Interactive Techniques*, 1992, pp. 265–272.

[14] Jean-Baptiste Thomas, Jon Yngve Hardeberg, and Gabriele Simone, "Image contrast measure as a gloss material descriptor," in *Proceedings of the 6th International Workshop on Computational Color Imaging (CCIW2017)*. Springer, Cham, 2017, pp. 233–245.

[15] Lin Qi, Mike J Chantler, J Paul Siebert, and Junyu Dong, "The joint effect of mesoscale and microscale roughness on perceived gloss," *Vision Research*, vol. 115, pp. 209–217, 2015.

[16] Lin Qi, Mike J Chantler, J Paul Siebert, and Junyu Dong, "Why do rough surfaces appear glossy?," *JOSA A*, vol. 31, no. 5, pp. 935–943, 2014.

[17] Yun-Xian Ho, Michael S Landy, and Laurence T Maloney, "Conjoint measurement of gloss and surface texture," *Psychological Science*, vol. 19, no. 2, pp. 196–204, 2008.

[18] Peter Vangorp, Jurgen Laurijssen, and Philip Dutré, "The influence of shape on the perception of material reflectance," in *ACM Transactions on Graphics*, 2007, vol. 26, pp. 77:1–77:10.

[19] Maria Olkkonen and David H Brainard, "Joint effects of illumination geometry and object shape in the perception of surface reflectance," *i-Perception*, vol. 2, no. 9, pp. 1014–1034, 2011.

[20] Davit Gigilashvili, Weiqi Shi, Zeyu Wang, Marius Pedersen, Jon Yngve Hardeberg, and Holly Rushmeier, "The Role of Subsurface Scattering in Glossiness Perception," *ACM Transactions on Applied Perception*, vol. 18, no. 3, pp. 10:1–10:26, 2021.

[21] Jacob Beck and Slava Prazdny, "Highlights and the perception of glossiness.," *Perception & Psychophysics*, vol. 30, no. 4, pp. 407–410, 1981.

[22] Phillip J Marlow, Juno Kim, and Barton L Anderson, "The perception and misperception of specular surface reflectance," *Current Biology*, vol. 22, no. 20, pp. 1909–1913, 2012.

[23] Phillip J Marlow and Barton L Anderson, "Generative constraints on image cues for perceived gloss," *Journal of Vision*, vol. 13, no. 14, pp. 1–23, 2013.

[24] Josh Wills, Sameer Agarwal, David Kriegman, and Serge Belongie, "Toward a perceptual space for gloss," *ACM Transactions on Graphics*, vol. 28, no. 4, pp. 1–15, 2009.

[25] Davit Gigilashvili, *On the Appearance of Translucent Objects: Perception and Assessment by Human Observers*, PhD thesis, Norwegian University of Science & Technology, June 2021.

[26] Wenzel Jakob, "Mitsuba Renderer," 2010, http://www.mitsuba-renderer.org.

[27] "The Stanford 3D Scanning Repository," 1994, http://graphics.stanford.edu/data/3Dscanrep/.

[28] "Bernhard Vogl's Light Probes," `https://www.dativ.at/lightprobes/`, Accessed: 2022-14-07.

[29] Khai Van Ngo, Jehans Jr. Storvik, Christopher André Dokkeberg, Ivar Farup, and Marius Pedersen, "Quickeval: a web application for psychometric scaling experiments," in *Image Quality and System Performance XII*. International Society for Optics & Photonics, 2015, vol. 9396, pp. 1–13.