Effects of Image Dynamic Range on Apparent Surface Gloss

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Abstract

In this paper we present results from an experiment designed to investigate the effects of image dynamic range on apparent surface gloss. Using a high dynamic range display, we present high dynamic range (HDR) and standard dynamic range (tone mapped, SDR) renderings of glossy objects in pairs and ask subjects to choose the glossier object. We analyze the results of the experiments using Thurstonian scaling, and derive common scales of perceived gloss for the objects depicted in both the HDR and SDR images. To investigate the effects of geometric complexity, we use both simple and complex objects. To investigate the effects of environmental illumination, we use both a simple area light source and a captured, real-world illumination map. Our findings are 1) that limiting image dynamic range does change the apparent gloss of surfaces depicted in the images, and that objects shown in SDR images are perceived to have lower gloss than objects shown in HDR images; 2) that gloss differences are less discriminable in SDR images than in HDR images; and 3) that surface geometry and environmental illumination modulate these effects.

Introduction

One of the defining characteristics of glossy surfaces is that they reflect images of their surroundings. High gloss surfaces produce sharp detailed reflection images that clearly show all the features of the surround, while low gloss surfaces produce blurry images that only show bright "highlight" features. Due to the presence of light sources and shadows, the illumination field incident on glossy surfaces can have high luminance dynamic range. This means that the reflections from glossy surfaces can also be high dynamic range. However in conventional images of glossy objects, these high dynamic range reflections must be clipped or compressed through tone mapping so the images fit within the output range of the display medium (see Figure 1). While the utility of conventional display systems demonstrates that the general characteristics of glossy surfaces are still conveyed by these tone-mapped images, an open question is whether the tone mapping process distorts apparent gloss of the imaged surfaces.

In this paper we present results from an experiment designed to investigate the effects of image dynamic range on apparent surface gloss using a high dynamic range display. In the experiments we present high dynamic range (HDR) and standard dynamic range (tone mapped, SDR) renderings of glossy objects in pairs and ask subjects to choose the glossier object. We analyze the results of the experiments using Thurstonian scaling, and derive common scales of perceived gloss for the objects depicted in both the HDR and SDR images. To investigate the effects of geometric complexity, we use both simple and complex objects. To investigate the effects of environmental illumination, we use both a simple area light source and a captured, real-world illumination map. Our findings are 1) that limiting image dynamic range does change the apparent gloss of surfaces depicted in the images, and that objects shown in SDR images are perceived to have lower gloss than objects shown in HDR images; 2) that objects differing slightly in gloss are less discriminable in SDR images than in HDR images, and 3) that surface geometry and environmental illumination modulate these effects. The following sections describe our methods and results.

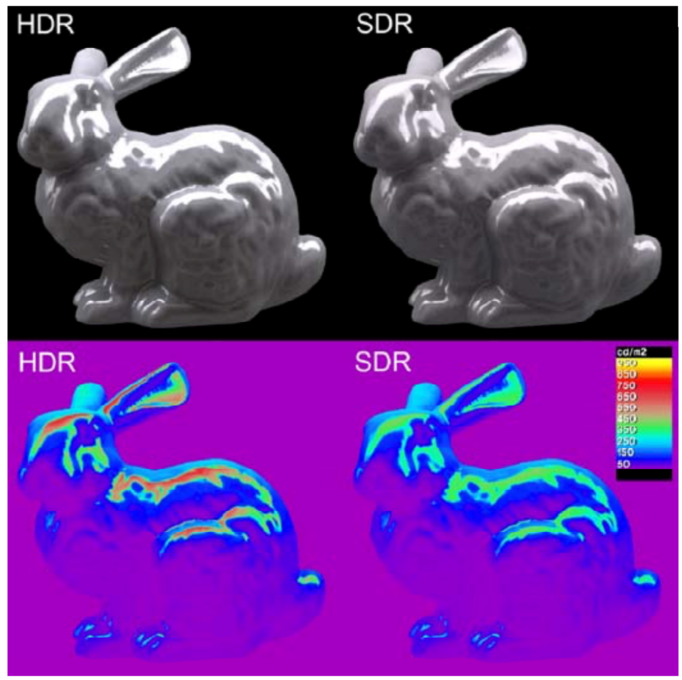

Figure 1. *High dynamic range (HDR) and standard dynamic range (SDR) images of a bunny object. The image pair on the top looks similar in limited dynamic range prints, but would appear different on a high dynamic range display that could reproduce the full luminance range in the HDR image (see the false color image pair on the bottom).*

Related Work

The earliest modern studies of gloss perception have been attributed to Ingersoll [1] who examined the appearance of glossy papers. In 1937, Hunter [2] observed at least six different visual attributes related to apparent gloss. He defined these as:

<u>specular gloss</u>: perceived brightness associated with the specular reflection from a surface
<u>contrast gloss</u>: perceived relative brightness of specularly and diffusely reflecting areas

distinctness-of-image (DOI) gloss: perceived sharpness of images reflected in a surface
haze: perceived cloudiness in reflections near the specular direction
sheen: perceived shininess at grazing angles in otherwise matte surfaces
absence-of-texture gloss: perceived surface smoothness and uniformity

In 1937, Judd [3] formalized Hunter's observations by writing expressions that related them to the physical features of surface bi-directional reflectance distribution functions (BRDFs). Hunter and Judd's research established a conceptual framework that has dominated work in gloss perception to the present day.

In 1987, Billmeyer and O'Donnell [4] published an important paper that investigated the multidimensional nature of gloss perception. They collected ratings of the differences in apparent gloss between pairs of acrylic-painted panels with varying gloss levels viewed under a fluorescent desk lamp outfitted with a chicken-wire screen, then used multidimensional scaling techniques to discover the dimensionality of perceived gloss. For their experimental conditions, they found that gloss could be described by a single dimension. However, this work was significant because it was the first to study the multidimensional nature of gloss perception without preconceptions about how many or what the dimensions might be. In a 1986 report to the CIE, Christie [5] summarized the research findings on gloss perception up to that date. Since that time, McCamy [6,7] has published a pair of review papers on the gloss attributes of metallic surfaces and Sève [8] and Lozano [9] have outlined frameworks for describing gloss that seek to improve on Hunter's classifications. In the Imaging Science literature, there has been considerable interest in the effects of gloss on printed image quality with efforts to characterize artifacts like differential gloss, bronzing, and gloss mottle [10,11,12,13,14,15].

One of the challenges in conducting gloss perception research is producing and controlling the stimuli used in the experiments. Generating consistent physical samples is very difficult. Therefore, the development of physically-based computer graphics techniques that can produce and present radiometrically accurate images of complex scenes has been a boon to the psychophysical study of gloss perception. One of the earliest computer graphics studies was done by Nishida and Shinya [16] who rendered bumpy glossy surfaces using direct point lighting. They found that observers made consistent errors in matching gloss properties across different surface geometries and suggested that the results of their experiments could be explained with a simple image histogram matching strategy. Pellacini et al. [17] conducted a set of experiments inspired by Billmeyer and O'Donnell's multidimensional scaling studies, but with images of a glossy ball inside a checkerboard box with a ceiling-mounted area light source. For this stimulus set, they found that observers used two dimensions to judge gloss, "c" a measure related to the contrast of the image reflected by the surface, and "d" a measure related to the sharpness of the reflected image. Ferwerda et al. [18] extended this work to characterize multidimensional gloss differences. More recent work has examined the role of natural illumination patterns [19] and complex object geometry [20] on surface gloss perception.

Although computer graphics has greatly facilitated the study of gloss perception, one of the caveats of all of these studies is that they use images of glossy surfaces as stimuli rather than the physical surfaces themselves. Because the potentially high dynamic range reflections from glossy surfaces are compressed for display, there is the potential that the gloss properties of the displayed surfaces are distorted. In our experiment, we employ an HDR display to enable more accurate presentation of physically-based glossy stimuli.

Experiments

We conducted a scaling experiment to investigate the effects of image dynamic range on apparent surface gloss. The stimuli and procedure are described in the following sections.

Stimuli

The stimuli for the experiments consisted of computer graphics images of glossy objects with different material properties rendered in different lighting environments. The attributes for each dimension are described below.

Materials: Gloss is an attribute of many surfaces, including metals, plastics, papers, and paints. Eventually we would like to study all these materials. However, in these experiments we used measured data on the reflectance properties (BRDFs) of achromatic latex paints. The BRDFs were modeled using the Ward [21] light reflection model. The three reflectance parameters of the Ward model are ρ_d (the diffuse reflectance), ρ_s (the energy of the specular lobe), and α (the spread of the specular lobe). We fixed ρ_d at 0.19 (mid-gray) and set α at 0.04 (small spread) to optimize visible gloss differences. To change surface gloss, we varied ρ_s across the ranges indicated in Table I. The ranges were selected to produce significant visible differences in apparent gloss from end to end. The endpoint images for each range are shown in Figure 2 (note that the visible differences are significantly compressed in the printed images). The step sizes were selected to be small enough to produce confusion between adjacent steps, which is necessary for the Thurstonian scaling analysis we used.

Table I. The ρ_s values for the HDR (H) and SDR (S) experimental images. Identification used in the paper is noted.

Specular energy (ρ_s)					
H1/S1	H2/S2	H3/S3	H4/S4	H5/S5	H6/S6
0.019	0.026	0.033	0.041	0.048	0.056
H7/S7	H8/S8	H9/S9	H10/S10	H11/S11	
0.065	0.073	0.082	0.091	0.101	

Geometry: Recent studies point to the importance of mesoscale surface texture in the perception of material properties [20]. To investigate this issue we studied two object geometries, a smooth sphere (ball) and a 3D laser scan of a ceramic rabbit (bunny) [22].

Illumination: Recent studies have also demonstrated the importance of real-world illumination for the accurate perception of material properties [23,19]. To investigate this issue, we rendered images of scenes using two illumination environments, a simple square area source and Debevec's "Uffizi" HDR illumination map that captures the illumination field outside the Uffizi Museum in Florence, Italy [24].

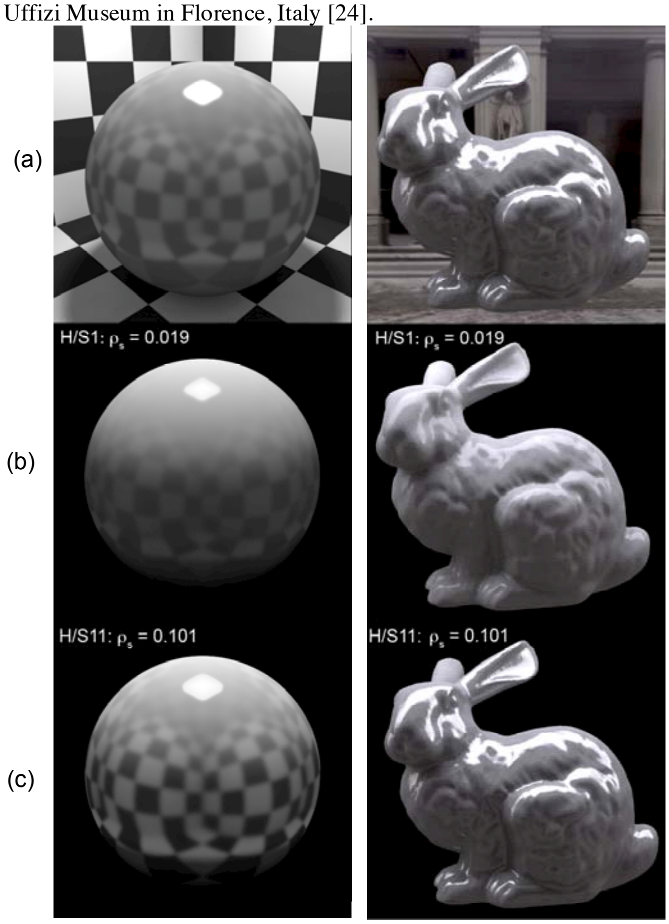

Figure 2. *(a) ball/box and bunny/Uffizi environments used in the experiments. The backgrounds and foregrounds were clipped in the stimulus images. (b,c) Range of stimuli used in the experiments for (left) least/most glossy balls and (right) least/most glossy bunnies. Note that the gloss differences are significantly compressed in the printed versions.*

Rendering: The combinations of geometry and illumination yielded the two scenes, ball/box and bunny/Uffizi shown in Figure 2. The scenes were rendered using the Radiance rendering system [25]. Fore and aft planes of the viewing camera were set to clip the surrounding environment. Thus, the illuminated objects appeared solely against a black background. Image size was 600x600 pixels and the images were saved as linear floating point high dynamic range HDR images. Eleven images of each scene were rendered using the parameters listed in Table I. The HDR images were scaled so the maximum luminance in each image set was 760 cd/m^2 (based on the maximum capability of our HDR display).

Display: The images were shown on a custom-made high dynamic range display (see Figure 3 and [26]) built from components of a 30-inch Apple Cinema HD Display with 2560 x 1600 addressable pixels and a pair of Planar PR5022 DLP projectors. The backlight was removed from the LCD and substituted with backlighting from two projectors which were rotated ±90° and tiled behind the LCD. The rotated, tiled projectors provided a backlight resolution of approximately 1500 x 935 addressable pixels. Images from projectors and on the LCD display were aligned geometrically and corrected colorimetrically using custom camera-based calibration software [27]. The maximum luminance of the display was 760 cd/m^2 with minimum luminance of 0.018 cd/m^2 for a small black center region surrounded by a completely white field. This translates to a contrast ratio of 41,500:1 for the case of an image with maximum flare, but would increase for less-extreme cases. The display was driven by an Apple Mac Pro 3 computer with dual Quad-Core Intel Xeon processors and dual NVIDIA GeForce 8800 GT graphics cards.

Figure 3. *High dynamic range display: (top) front view showing LCD panel, (bottom) rear view showing tiled DLP projectors.*

Tone mapping: To evaluate the effects of image dynamic range on apparent surface gloss, the HDR image sets were duplicated and a sigmoidal tone mapping operator [28] was applied to create SDR image sets. The parameters of the sigmoid were chosen to leave the midtone relationships in the images linear while progressively compressing highlight and shadows. Though it would have been possible to use other tone mapping operators, for the purposes of this study we felt that this approach did the least harm to the luminance relationships in the images and corresponded to methods we had used in related work [17]. The dynamic range of the operator was set to make the SDR images fit within the 160:1 measured dynamic range [29] of a 30-inch Apple Cinema HD Display. Thus, when presented on the HDR display, the SDR images simulated how the images would look on a conventional LCD monitor.

Procedure

Method: The HDR and SDR image sets of the ball/box and bunny/Uffizi scenes were presented in to observers using a paired-comparison method. On each trial, two of the glossy objects listed in Table I were randomly paired and the observer was asked to identify which object looked glossier (shinier or more reflective). For each scene, 253 image pairs were presented which represents a full factorial of the image set, including self-pairs. Thus, over the course of the experiment, each HDR image in the set was compared to every other HDR and SDR image and each SDR image was compared to every other HDR and SDR image.

Subjects: Twenty-three subjects participated in the experiments (11 female, 12 male). The group included both expert and non-expert observers. Subjects ranged in age from 17 to 47 and had normal color vision and acuity. Viewing distance was fixed at 25 inches with use of a headrest.

Results

Thurstonian scaling methods [30] were used to derive scales of apparent gloss for the objects represented by the HDR and SDR images. In Thurstonian scaling, the variance in the paired comparison judgments is used to calculate response distributions for each object. Overlaps in the distributions are then used as a measure of perceived distances in gloss between the objects.

The derived scales are summarized in Figures 4 and 5. Each graph shows the perceived gloss scale as a function of specular energy, ρ_s. The least glossy object has been normalized to have a value of 1. In each figure, the blue diamond glyphs represent the objects depicted by SDR images and the red square glyphs represent objects depicted by HDR images.

Figure 4 shows the gloss scales derived for the ball/box scene. There are several trends to notice. First, note that the HDR images were all seen as glossier than their corresponding objects in the SDR images. This suggests that under these conditions (simple geometry, simple high contrast illumination), the brightness of the single specular highlight is an important cue to gloss. Next, observe that the overall range of the HDR object scale is larger (Δ7.1) than the corresponding SDR object scale (Δ6.3). This suggests that presentation in an HDR image makes the gloss differences between the objects more salient. Note that the perceived gloss response for the SDR images follows a linear fit ($R^2 = 0.98$). However, the response for the HDR images appears to be compressive in nature (natural log, $R^2 = 0.96$). The compressive behavior of the HDR gloss scale at the high end suggests that there may be limits to the effectiveness of specular intensity as a gloss cue. One possible explanation could be Weber's Law constraints on luminance JNDs. The rendered luminance differences between the highlights of the lowest gloss H1 and H2 objects is 24% (239 vs. 296 cd/m^2), but the difference for the highest gloss H10 and H11 objects is only 7.3% (708 vs. 760 cd/m^2). Thus, the brightest highlights are possibly less discriminable, which could lead to compression of the scale range.

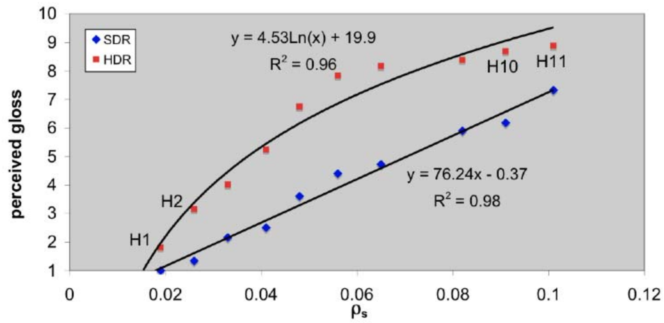

Figure 4. *Scaling results for ball/box scene. Note that samples with ρ_s of 0.073 were removed from the analysis because rendering errors were found in their images post experiment.*

Figure 5 shows the gloss scales derived for the bunny/Uffizi scene. Our intent in testing this scene was to investigate how complex geometry and illumination interact with image dynamic range to affect the apparent gloss of depicted objects. There are several trends to notice in the graph. First, note that as with the ball/box scene, the objects shown in the HDR images are each judged to be glossier than the corresponding objects shown in the SDR images. Similarly, the overall range of the HDR objects is greater (Δ6.7) than the range of the SDR objects (Δ5.9), indicating better discrimination among the HDR set. Note that the perceived gloss responses to both the HDR and SDR image sets follow a linear fit ($R^2 = 0.96$ and 0.99, respectively). Therefore, unlike the ball/box scene, the response for the HDR images for the bunny/Uffizi set is not compressive. This suggests that while specular brightness is still an important cue to gloss, real-world scene factors such as geometric and/or illumination complexity may make it harder to judge specular brightness, which in turn may increase the relative importance of other cues such as reflection contrast.

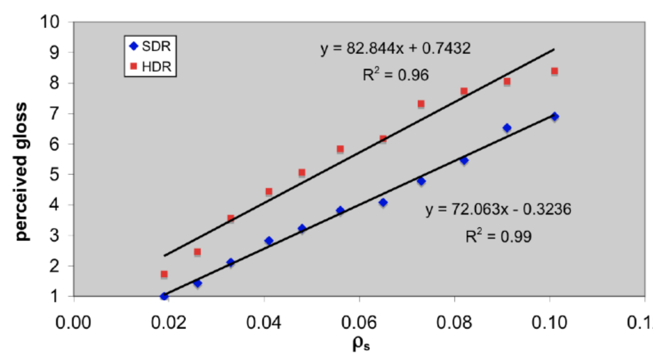

Figure 5. *Scaling results for bunny/Uffizi scene.*

Conclusion

This paper has presented results of an experiment designed to investigate the effects of image dynamic range on the apparent gloss of rendered objects. We found that image dynamic range does impact apparent surface gloss; HDR images were perceived as glossier than their SDR counterparts. We also found that differences in gloss were generally more discernible in HDR images than in SDR images, however the effectiveness of absolute specular intensity as a gloss cue may in some cases follow a compressive function. Finally, surface geometry and illumination patterns were also found to affect the relative effectiveness of different gloss cues. For future work, we plan to conduct more extensive and systematic studies of these effects, looking at a wider range of material properties, geometries, and illumination fields. We also intend to study the multidimensional nature of perceived gloss and use HDR and SDR images to investigate the interactions between specular intensity and other cues such as reflection contrast and sharpness, which have been shown to be important sources of information for surface gloss. Our overall goal is to understand how, and how well, images serve as visual representations of object properties both to advance basic scientific understanding and to enable applications such as computer-aided material appearance design.

Acknowledgments

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References

[1] Ingersoll, L.R., "A means to measure the glare of paper," Electr. World, 63, 645-647 (1914).
[2] Hunter, R.S., "Methods of Determining Gloss," NBS Research paper RP 958, J. Res. NBS, 18, 77, 281 (1937).
[3] Judd, D.B., "Gloss and glossiness," Am. Dyest. Rep. 26, 234-235 (1937).
[4] Billmeyer, F.W. and O'Donnell, F.X.D., "Visual gloss scaling and multidimensional scaling analysis of painted specimens," Color Res. App. 12(6), 315-326 (1987).
[5] Christie, J.S., "Evaluation of the attribute of appearance called gloss," CIE Journal 5 (2) 41–56 (1986).
[6] McCamy, C.S., Observation and measurement of the appearance of metallic materials. Part I. Macro appearance," COLOR research and application, 21, 292–304 (1996).
[7] McCamy, C.S., "Observation and measurement of the appearance of metallic materials. Part II. Micro appearance," COLOR research and application, 23, 362–373 (1998).
[8] Sève, R., "Problems connected with the concept of gloss," Color Res. Appl. 18, 241–252 (1993).
[9] Lozano, R.D., "A new approach to appearance characterization," COLOR Res. & Appl. 31, 164-167 (2006).
[10] Arney, J. S., Smith, C., MacDonald, C., A Gonio-photometric Analysis of Ink Jet Bronzing, NIP24, 24, 432-434(2008).
[11] Farnand, S., Wilosek, D., Measurement of Differential Gloss Using a Micro-goniophotometer, NIP23, 23, 368-372 (2007).
[12] Gatt, A., Westland, S., Bala, R., Increasing the Dimensionality of Soft Proofing: Gloss and Material, CIC06, 14, 78-83 (2006).
[13] Kam-Ng, M., Reed, P., Diagnosis for Differential Gloss in Color Hard Copy Outputs, NIP20, 20, 450-453 (2004).
[14] Mehta, P., Johnson, K., Wolin, D., A New Method of Measuring Gloss Mottle and Micro-Gloss using a Line Scan CCD-Camera Based Imaging System, NIP17, 17, 714-717 (2001).
[15] Ng, Y. S., Wang, J., Gloss Uniformity Attributes for Reflection Images, NIP17, 17, 718-722 (2001).
[16] Nishida, S. and Shinya, M., "Use of image-based information in judgments of surface reflectance properties," J. Opt. Soc. Am., 15(12), 2951-2965 (1998).
[17] Pellacini, F., Ferwerda, J. A., Greenberg, D. P., Toward a psychophysically-based light reflection model for image synthesis, SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques, 55–64 (2000).
[18] Ferwerda, J. A., Pellacini, F., Greenberg, D. P., A psychophysically-based model of surface gloss perception, Proceedings of the SPIE: Human Vision and Electronic Imaging VI, vol. 4299, 291–301 (2001).
[19] Fleming, R. W., Dror, R. O., Adelson, E. H., "Real-world illumination and the perception of surface reflectance properties," Journal of Vision 3, 5, 347–368 (2003).
[20] Te Pas, S. F., Pont, S. C., A comparison of material and illumination discrimination performance for real rough, real smooth and computer generated smooth spheres, APGV'05: Proceedings of the 2nd symposium on Applied perception in graphics and visualization, 75–81 (2005).
[21] Ward, G. J., Measuring and modeling anisotropic reflection, SIGGRAPH '92: Proceedings of the 19th annual conference on Computer graphics and interactive techniques, vol. 26, 265–272 (1992).
[22] Turk, G., Levoy, M., Zippered Polygon Meshes from Range Images, SIGGRAPH 94, 311-318 (1994).
[23] Fleming, R. W., Torralba, A., Adelson, E. H., "Specular reflections and the perception of shape," Journal of Vision 4, 9, 798–820 (2004).
[24] Debevec, P.E., Malik, J., Recovering High Dynamic Range Radiance Maps from Photographs, SIGGRAPH 97, (1997).
[25] Ward, G., The RADIANCE lighting simulation and rendering system, International Conference on Computer Graphics and Interactive Techniques, Proceedings of the 21st annual conference on Computer graphics and interactive techniques, 459 – 472 (1994).
[26] Ferwerda, J.A. and Luka, S., A high resolution, high dynamic range display for vision research (abstract), 8th Annual Meeting, Vision Sciences Society, Journal of Vision, 9(8), 346a (2009).
[27] Luka, S. and Ferwerda, J. A., Colorimetric Image Splitting for High-Dynamic-Range Displays, In Process, SID International Symposium Digest of Technical Papers (2009).
[28] Tumblin, J., Hodgins, J. K., Guenter, B. K., Two Methods for Display of High Contrast Images, ACM Transactions on Graphics, 18(1) 56-94 (1999).
[29] Video Electronics Standards Association (VESA) display measurement standard, Flat Panel Display Measurements (FPDM) Standard, Version 2.0, (2001).
[30] Torgerson, W.S., Theory and Methods of Scaling (Wiley, New York, 1958).

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