Perceptual Gloss Across Real and Virtual Samples with Diverse Backgrounds and Dynamic Ranges

Yuan Tian, Elena Fedorovskaya, and Mekides Assefa Abebe

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Abstract

Gloss perception is influenced by the illumination field, background, scene dynamic range, object shapes, and material surface optical properties. Additionally, there is a discrepancy in gloss perception between real-world and virtual scenarios. To understand gloss perception in both contexts, especially considering the varied backgrounds against which materials are encountered, a thorough measurement and mathematical modeling of the physical and perceptual properties of the samples is necessary. Accordingly, we have designed an overall framework for perceptual gloss measurement and cross-media reproduction, for studies to be conducted on a component-by-component basis. The first component focuses on understanding and measuring gloss perception for real and colored samples. However, current state-of-the-art studies on perceptual gloss, in both real and virtual viewing modalities, measure perceptual gloss using only achromatic stimuli. There is an established assumption that a perceptual gloss model based on the achromatic characteristics of materials can accurately represent gloss perception for all types of materials. The influence of color on the glossiness of colored materials has not been well investigated. In this study, we investigate and present the results of our initial exploration into the influence of color on gloss perception. The study was conducted using flat painted stimuli with various levels of glossiness, along with the standard NCS gray gloss scale samples. The color and gloss characteristics of the stimuli were measured both physically and perceptually. Perceptual gloss assessments were performed in a controlled laboratory setup under standard D65 illumination. The CIELCh and glossmeter measurement results demonstrate that color significantly influences gloss perception. With increasing gloss units, we observed a decrease in luminance and increase in chroma, along with a hue shift towards yellow. Variations in the dependency of these color attributes among the NCS gray gloss stimuli, painted chromatic stimuli, and paper backings were

Munsell Color Science Laboratory, Rochester Institute of Technology

also noted. It is also shown that perceived gloss measurements can be effectively modeled as a quadratic function of gloss units. In general, the study provides useful insights into how the chromatic characteristics of materials influence perceptual gloss. It suggests that perceptual gloss models and reproductions should include a broader range of chromatic materials and types. Our future research will build on these findings and the general framework to model perceived gloss in both virtual and physical environments, enhancing cross-media reproduction.

Introduction

Gloss perception, strongly linked to the characteristics of specular reflection, is a pivotal aspect of visual material perception. Previous studies have explored the influence of natural illumination and complex real-world scenes on gloss perception, revealing the fundamental role of natural illumination in accurate surface perception (Fleming et al., 2003; Hartung & Kersten, 2002). These works explained the significance of complex real-world lighting, which promotes more consistent gloss perception and enhances the perceived glossiness of objects compared to simpler lighting conditions, underscoring the human visual system's reliance on the interplay of natural illumination.

Recent advances in the field of gloss perception have expanded its scope to encompass the effects of backgrounds and scene dynamic range. For example, it was observed that spheres against a black background appeared significantly glossier than those against a white background (Doerschner et al., 2010). Additionally, Phillips et al. investigated how surface geometry, scene illumination, and eye movements impact perceived gloss (Phillips et al., 2010), while Adams et al. emphasized the role of tone mapping in high dynamic range images for achieving gloss constancy (Adams et al., 2018). These findings contribute to a holistic understanding of the factors influencing gloss perception, with implications for real and virtual applications, particularly in the field of printing.

In the broader context of gloss perception, Hunter and Harold in 1987 classified it into six distinct types: specular gloss, sheen, contrast gloss, absence-of-bloom gloss, distinctness-of-reflected-image gloss, and absence-of-surface-texture gloss. Furthermore, research efforts have aimed to bridge the gap between material properties and perceptual gloss. Studies by Ferwerda et al. in 2001, Toscani et al. in 2020, and Faul in 2019 have explored connections between physical parameters and gloss perception, while Tanaka et al. in 2023 established an exponential relationship between objective measures like gloss unit, haze, image distinctness, and high dynamic range luminance and perceived gloss (Faul, 2019; Ferwerda et al., 2001; Richard S. Hunter, 1987; Tanaka et al., 2023; Toscani et al., 2020).

Moreover, there has been a determined effort to bridge the gap between gloss perception in the real world and virtual environments. For instance, Xiao et al.

in 2023 developed psychometric gloss scales for both real and virtual settings, converting material smoothness parameters into gloss units during rendering. Chen et al. in 2022 collected perceived gloss data from 3D printed samples and corresponding photos, using this information to predict material parameters in rendering systems, ultimately achieving a better match for perceived gloss (Chen et al., 2022; Xiao et al., 2023).

In summary, previous research has investigated into various aspects of gloss perception, encompassing the influence of illumination field, background, scene dynamic range, and the relationships between reflection model parameters and perceived gloss, both objective and subjective. Nevertheless, the current state of the art in gloss perception studies presents limitations. The scope of these studies often excludes diverse real-world environments, focuses on scenes with limited dynamic range illumination, and predominantly uses achromatic and virtual samples. These limitations constrain the practical applicability of the findings in diverse industries and applications.

To address these limitations, we intend to investigate perceptual gloss across a broad spectrum of diverse backgrounds and surroundings, sample colors, material types, and extended dynamic range conditions. Our goal is to enhance our understanding and measurement of gloss perception in both real-world and virtual scenarios, considering the varied backgrounds against which materials are encountered. To accurately represent perceptual gloss for rendering and cross media reproduction applications, a thorough measurement and mathematical modeling of both the physical and perceptual properties of the samples need to be performed. The general workflow for such a study should at least include the main components outlined in Figure 1.

As illustrated in Figure 1, the perceived gloss of stimuli changes depending on whether real physical or rendered virtual viewing modalities are utilized. Characteristics such as material type, surface color, shape, luminance level, and illumination type will also affect perceived glossiness. To understand the perceptual and physical factors influencing gloss perception, we begin by investigating the influence of color first, as this factor has been largely overlooked in related state-of-the-art studies.

Therefore, in this study, we present the results of our initial investigation into the influence of color on gloss perception. The study was conducted on flat painted samples with various levels of glossiness, along with NCS gray gloss scale samples. Perceptual assessments of the painted samples were performed in a controlled laboratory setup under standard D65 illumination. The overall experimental methodology and results are detailed in the following sections.

Color and Gloss

As mentioned in the introduction, most of the existing perceptual gloss studies have been conducted on achromatic samples. Standard organizations such as NCS also only provide achromatic perceptual gloss scales. There seems to be a consensus that gloss can be measured and represented irrespective of the chromatic characteristics of the stimuli. However, with the complex characteristics of material appearance and human perceptual processing, such a general conclusion may not be accurate. Therefore, understanding and quantifying the influence of color on the perception of gloss is particularly important. Accordingly, a perceptual experiment and gloss unit measurements are performed to compare and analyze the perceived glossiness of chromatic and achromatic paints.

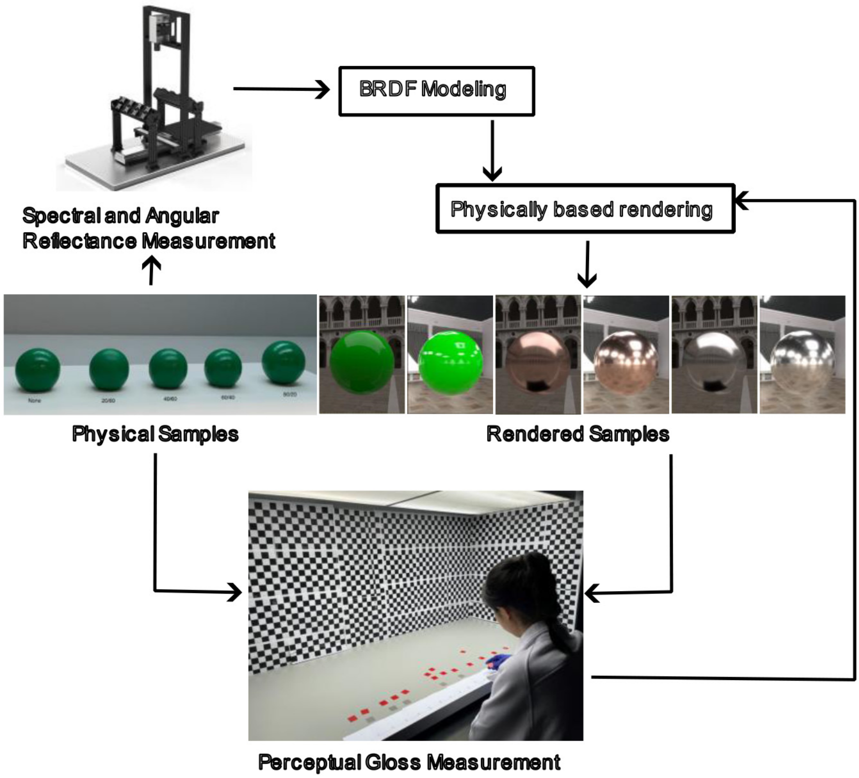

Figure 1: *Proposed workflow for general and complete perceptual gloss modeling across physical and virtual cross media reproduction.*

Experimental Methodology Description

The psychophysical experiment to measure perceived gloss is conducted following graphical ruler method. In the experiment, we used a light booth with a D65 illumination, measured to have (193.94, 203.90, 232.65) in absolute CIEXYZ. As shown in the values, the luminance (Y) of the perfect diffuser is 203.9 cd/m2. The close-up experimental setup is shown in Figure 2. The papers with checkerboard patterns on the walls of light booth are used so that observers can judge the gloss by looking at the reflection of checkerboard patterns from sample surfaces. The distinctness of reflected images is shown to be one of the major perceptual cues for glossiness assessments. A linear length scale, numbered from 0 to 100, is placed in front of observers to represent perceived gloss values. Observers position samples on this scale based on their assessment of glossiness and the relative position between samples. The two reference anchors at the ends of the scale (0 and 100) represent a perfect diffuse matt surface and a mirror-like glossy surface, respectively. The experiment had 12 participants (with normal vision acuity and normal color vision). Observers are instructed to imagine these surfaces when placing samples. The placement of samples should be linear in relation to the perceived gloss (Figure 2).

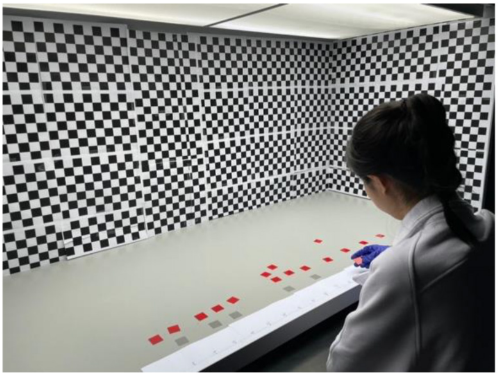

Figure 2: *Psychophysical experiment setup. An observer is assessing the gloss of a red sample and putting it along the length scale.*

Experimental Stimuli

For the experiment, a total of 39 painted stimuli were prepared. Among these, 32 samples were red (16 on black backings and 16 on white backings), and the remaining 7 were taken from the NCS standard gray gloss scale book. The NCS gloss scale used was NCS S 5000N, with the gloss levels of the 7 samples measured according to ISO 2813 at a 60° angle, corresponding to 2, 6, 12, 30, 50, 75, and 95 gloss units (Figure 3). To create the red samples, we used a glossy red paint, applying it on contrast papers with white and black backings as substrates. The CIELCh values of the red paint are provided in Table 1. The paint was applied using a drawdown machine with a 10-mil bar, resulting in a paint thickness of 254 μm. To achieve 16 different glossiness levels, various mixtures of glossy and matte Liquitex acrylic varnishes were applied on top of the dried red paint. The varnish was also applied using the drawdown method with a 10-mil bar, but with a layer of tape under the two ends of the bar to control the varnish thickness to the thickness of the tape. The 16 varnish mixtures had different glossy and matte varnish proportions: 0/100%, 10/90%, 20/80%, 30/70%, 40/60%, 50/50%, 55/45%, 60/40%, 65/35%, 70/30%, 75/25%, 80/20%, 85/15%, 90/10%, 95/5%, and 100/0%. Finally, we cut 2.5 cm × 2.5 cm squares from the painted and varnished papers, both from white and black backings. The complete set of final experimental stimuli is shown in Figure 3.

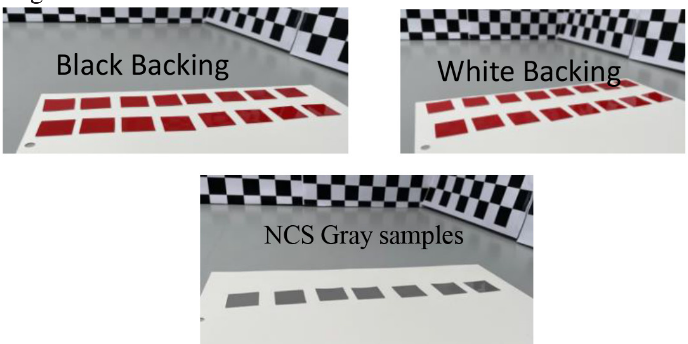

Figure 3: *Red samples with white and black backings as well as NCS gray gloss scale samples.*

Measurement

In addition to perceptual gloss measurement, we also physically measured the experimental stimuli. The glossiness of the samples, in gloss units, and their spectral reflectance were measured using a BYK handheld gloss meter and a ColorEye 7000 spectrophotometer, respectively. The reflectance measurements were taken in both specular-included and specular-excluded modes. Gloss units were recorded at 20°, 60°, and 85° angles. Finally, the reflectance data were used to compute the CIELAB and CIELCh values according to the 2° standard observer and D65 illumination. The measurement results are provided in Figure 4.

	White B. (spe)	**Black B. (spe)**	**White B. (spi)**	**Black B. (spi)**
L*	38.66	37.46	43.18	42.70
C*	71.82	71.27	57.00	56.75
h*	38.20	39.22	31.67	32.05

Table 1: *CIELCh values of unvarnished red samples with white and black backings. The values are computed from the specular excluded (spe) and specular included (spi) spectrophotometer mode measurements.*

Experimental procedure

During the experiment, participants were first asked to arrange the NCS gray samples on the scales according to their perceived gloss. This provided additional references beyond the imagined perfect diffuser and mirror-like surfaces at scale values of zero and 100. Participants then arranged the red samples, with either white or black backings, using the positions of the gray samples as references. The red samples with white and black backings were arranged separately. After participants finished arranging the red samples, the experimenter recorded their positions. Participants were not allowed to change the positions of the gray samples once they were arranged, ensuring that the same gray gloss scale locations were used for both the black and white backing red samples.

Results

Spectral reflectance measurements of all experimental stimuli were performed in specular included and excluded modes by adjusting the spectrophotometer's specular port (Berns, 2019; X-Rite, 2013). These measurements were converted to CIELCh using the 2-degree standard observer and D65 illumination, as shown in Figure 4.

CIELCh lightness (L^*) slightly decreases for samples with higher gloss units in the specular excluded mode compared to the specular included mode. Chroma (C^*) shows a slight increase in high-gloss samples, while hue (h^*) shifts towards yellow for high-gloss red and varnish samples in the specular excluded mode.

Common practice in color measurement involves using specular excluded measurements for reflective glossy samples to avoid specular reflections. Accordingly, a statistical analysis using linear mixed-effect regression is performed on specular excluded measurement results. The results revealed significant relationships between lightness (L^*) and gloss units ($F(1,11) = 11192.64$, $p<0.001$), and sample types ($F(2,10) = 31186.47$, $p<0.001$), although no significant difference was observed between red samples with different backings($t(253) = 1.61$, $p = 0.109$). However, a significant difference was found between red and NCS gray samples ($t(145) = 24.91$, $p<0.001$). Gloss units also significantly affected Chroma (C^*) ($F(2,10) = 44262.5$, $p<0.001$), with increases observed in higher gloss units for red samples on different backings and NCS samples. A significant difference was noted between red samples on different backings ($t(457) = -3.79$, $p = 0.0002$) and between red and NCS samples ($t(426) = -64.69$, $p<0.001$) regarding C^*. Hue (h^*) was not significantly affected by gloss units ($F(1,11) = 1.86$, $p = 0.2$), but sample types ($F(2,10) = 113.55$, $p<0.001$) and their interaction with gloss units ($F(2,10) = 6.72$, $p = 0.014$) showed significant effects. Deviations in hue were observed with increasing gloss units for red samples, but not for NCS samples, with significant differences between red and NCS samples ($t(423) = -3.50$, $p<0.001$).

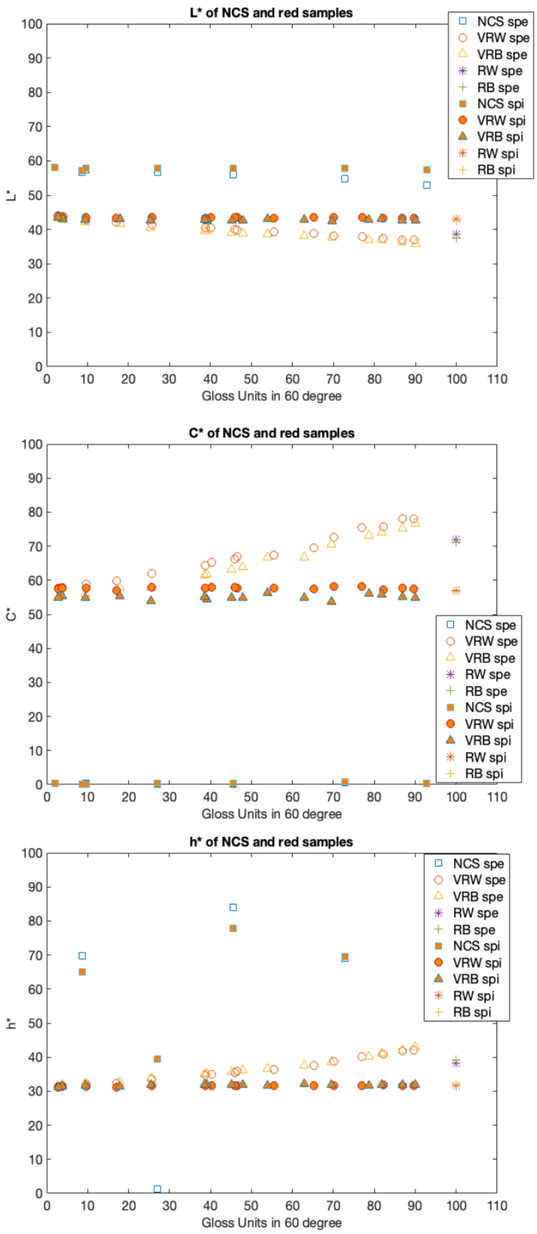

Figure 4: *CIELCh and gloss units of red and gray samples measured by spectrophotometer. Measurements include black and white backings with varnish-only paintings, red ink-only paintings, combined varnish and red ink paintings, as well as the NCS samples. Abbreviations used in the legends are: 'V' – varnished, 'R' – red samples, 'W' – white backing, and 'B' – black backing.*

In addition to analyzing physical measurements, we examined the effect of gloss units and sample types on perceptual gloss scales. Gloss meter measurements at 60° are shown in Figure 5, while observers' scaling results of perceptual gloss for the experimental stimuli is presented in Figure 6. The colored lines in Figure 5 represent linear regression predictions of gloss units based on varnish concentration levels for different sample types: red samples with white and black backings, and NCS gray samples. For NCS samples, the x-axis represents their NCS gloss levels, given with the NCS chart. If the NCS gloss levels and gloss meter units were identical, the fitted line for NCS samples would have a slope of 45°, but our results show they are not the same units.

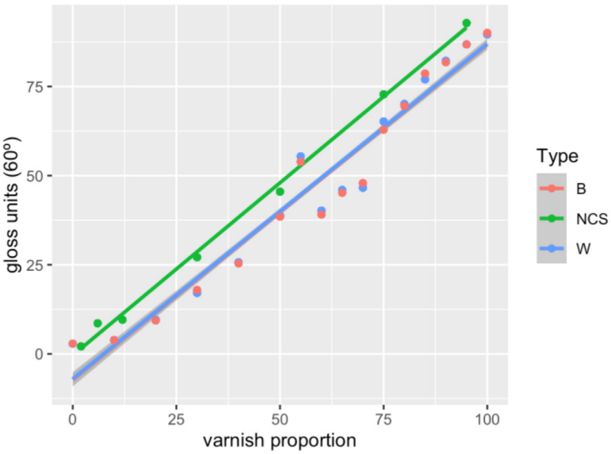

Figure 5: *Varnish proportion vs. gloss units measured by gloss meter. B = red samples with black backing, NCS = NCS gray samples, W = red samples with white backing. Fitted lines are linear regression estimates, with the gray area representing standard error. Red samples have 16 data points; NCS samples have 7.*

Whereas Figure 6 demonstrates the expected correlation between measured gloss units and perceptual gloss scales. Perceptual gloss increases with gloss units, but the rate of increase diminishes as the samples become glossier, indicating a non-linear relationship. This observation agrees with the findings of Ji et al in 2004 and 2006. (Ji et al., 2006) (Ji et al., 2004). Linear regression modeling was performed to determine if the relationship between gloss scales and gloss units follows a linear, quadratic, or cubic function. As shown in Figure 7, and supported by ANOVA analysis, the relationship is best modeled with a quadratic function. There is a significant difference between linear and quadratic functions ($F(1) = 32.85$, $p<0.001$), no significant difference between quadratic and cubic functions ($F(1) = 2.62$, $p=0.11$), and a significant difference between linear and cubic functions ($F(2) = 17.79$, $p<0.001$), indicating that a quadratic function is sufficient to fit the data.

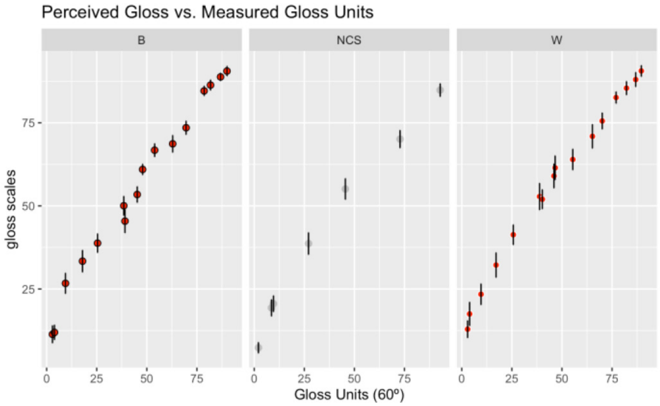

Figure 6: *Relationship between perceived gloss and gloss units for red samples with black backing, NCS gray samples, and red samples with white backing (left to right). Circles represent mean values; black bars represent standard error.*

Further statistical analysis confirmed the significance of gloss units on perceptual gloss scales ($F(1,11) = 989.1$, $p<0.001$), with gloss scales increasing as gloss units increase ($B = 0.88$, $SE = 0.03$). However, no significant effect was found due to sample types ($F(2,10) = 1.12$, $p = 0.36$), indicating that sample types do not affect perceptual gloss scales. Additionally, there was no significant interaction effect between gloss units and sample types ($F(2,10) = 1.19$, $p = 0.34$), suggesting that the effect of gloss units on perceptual gloss scales is consistent across all sample types.

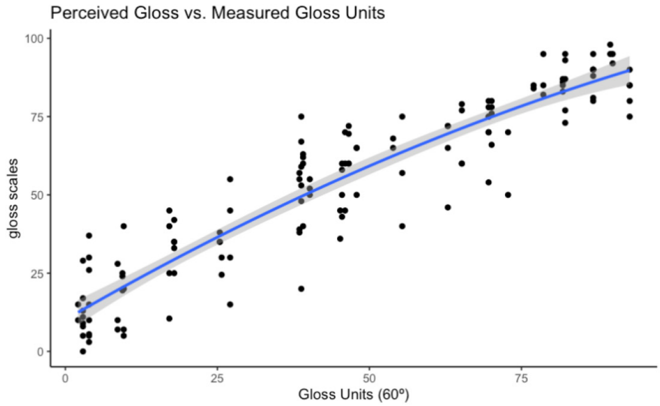

Figure 7: *Relationship between gloss units and perceptual gloss scales for red and gray samples. The blue line represents the quadratic function fit, with the gray area indicating standard error.*

Discussion and Future Research Directions

In the analysis of gloss perception using the CIELCh color space, it is important to recognize that perceptual lightness and chroma are interdependent. This interdependence means that changes in one attribute are likely to affect the other. However, the CIELCh color space was not specifically designed for glossy samples, which limits its accuracy in predicting perceptual attributes of such samples.

Previous studies, such as Fairchild (2013), indicate that glossier samples with lower brightness tend to exhibit higher chroma, assuming colorfulness remains constant, while hue generally remains unchanged. The slight shift towards yellow in h* measurements observed in our study might be attributed to the inherent slight yellow tint of the glossy varnish used.

Our analysis highlights notable differences between red samples and NCS gray samples in their CIELCh perceptual attributes, leading us to expect different perceptual gloss judgments between these samples. However, the effect of gloss units on perceptual gloss levels does not show significant differences between gray and colored samples. This discrepancy between the CIELCh trends and our observers' gloss judgments could be due to the independence of color perceptual attributes, such as lightness, chroma, and hue, from gloss perceptual attributes. Additionally, discrepancies in experimental stimuli design may have contributed to the differences observed. The red samples were prepared within the gloss levels achievable with available glossy red paint and varnish, whereas the NCS samples were standardized. This suggests that more rigorous alignment based on physical measurements might be necessary for more accurate comparisons.

In varnished painted samples, reflections can be influenced by three layers: the substrate, paint, and varnish. Properly modeling the perceptual attributes of such glossy paints requires considering both diffuse and specular reflections from each layer. Previous studies (Dalal & Natale-Hoffman, 1999), used the Logistic Dose Response function to model CIELCh attributes, focusing on front surface reflection only. However, the suitability of CIELCh and related color spaces for such applications remains questionable since they were primarily designed based on matte and a few glossy samples. Furthermore, factors such as object shapes, illumination, viewing angles, and modalities should be included in modeling the perceptual attributes of glossy samples.

Our findings on perceptual gloss measurements indicate that gloss scales increase more rapidly at lower gloss units before becoming linear, consistent with Ji et al. (2004, 2006). However, unlike Ji et al., our gloss scales do not show a rapid increase at high gloss units, possibly because our most glossy sample did not reach the gloss level where this trend change occurs. Additionally, the small area of our samples may have made it difficult for observers to accurately judge and compare gloss based on reflected image sharpness. Another difference is that Ji et al. (2006) used magnitude estimation, which yields ratio scales, while our experiment used interval scales.

Generally, a limitation of our study includes the discrepancy between experimental red samples and standardized NCS gray samples, which may affect comparability. The use of CIELCh space, designed mainly for matte samples, might not fully capture the perceptual attributes of gloss. Additionally, the small sample area and interval scales for perceptual gloss assessments could influence observer judgments. The study also focused on a limited range of colors and gloss levels, necessitating broader sampling. Finally, factors like viewing angles, illumination conditions, and object shapes were not extensively explored, impacting the generalizability of the findings.

Therefore, as explained in the introduction section, future studies should explore the relationship between color perceptual attributes, gloss units, and perceptual gloss scales using a broader range of colors, sizes, and shapes of stimuli with more evenly spaced gloss levels. Addressing the limitations of our current study, we need to incorporate a wider variety of materials and ensure standardized gloss levels for all samples. As shown in Figure 1, the next step should involve conducting spectral reflectance measurements of samples with different materials and shapes at multiple incident and reflecting angles to establish a bidirectional reflectance distribution function (BRDF). Using the measured BRDF, we can develop reflection models for object appearance rendering under various illumination fields, luminance levels, and shapes, leveraging the established surface optical properties. This approach will enable us to model perceived gloss accurately in both virtual and physical environments, bridging the gap between these settings. By achieving a comprehensive understanding and modeling of gloss perception, we can enhance cross-media reproduction and ensure more accurate and consistent visual experiences across different platforms. Furthermore, incorporating factors such as viewing angles and illumination conditions will provide a more holistic view, ensuring that the perceptual gloss models are robust and applicable to real-world and virtual scenarios. This will ultimately contribute to better design and evaluation of materials in diverse applications, from industrial design to digital content creation.

Conclusion

In conclusion, our study highlights the complex interplay between gloss units, color perceptual attributes, and perceptual gloss scales, revealing notable differences in CIELCh attributes between red and NCS gray samples. Despite these differences, the effect of gloss units on perceptual gloss levels remained consistent across sample types, underscoring the independence of color and gloss perceptual attributes. Addressing the limitations identified, future research should encompass a broader range of colors, sizes, shapes, and more evenly spaced gloss levels to develop a comprehensive understanding of gloss perception. Establishing a bidirectional reflectance distribution function (BRDF) through detailed spectral reflectance measurements will enable more accurate modeling of perceived gloss in both virtual and physical environments. This approach promises to bridge the gap between these environments, enhancing cross-media reproduction and ensuring more accurate and consistent visual experiences across various platforms.

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