Gloss perception under low vision: Effects of illuminance and surface color*

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Abstract

Individuals with low vision experience reduced spatial resolution, and illuminance levels influence their visual acuity. However, the effects of these factors on gloss perception have not been fully clarified. Previous studies have also reported a relationship between color saturation and gloss perception in individuals with normal vision. Since people with low vision tend to perceive colors as less saturated than those with normal vision, this may influence their perception of gloss. This study investigated the effects of illuminance and object surface color on perceived gloss. Experiments were conducted under normal and simulated low vision conditions using low vision simulation glasses. Semi-cylindrical physical stimuli in four hues (red, green, yellow, and blue) and gray were prepared, each in high and low saturation levels. Each stimulus was overlaid with a transparent cover exhibiting one of five levels of glossiness. Participants rated the perceived gloss of each stimulus relative to a gray reference stimulus with moderate gloss. Results showed that the simulated low vision condition led to an overall reduction in perceived gloss. However, neither the hue nor the saturation of the stimuli significantly affected gloss evaluation. The line spread function of the stimuli was also calculated, and we conducted a quantitative analysis of the specular reflection area. This analysis indicated that changes in image characteristics—such as maximum luminance, haze, contrast, and highlight width—contributed to reduced gloss perception. These findings suggest that changes in image features, rather than color saturation, play a more critical role in the decline of gloss perception associated with reduced visual acuity.

Keywords

gloss perception, low vision, illuminance, color

1. Introduction

In recent years, increasing attention has been directed toward the mechanisms underlying visual impressions of surface qualities, particularly gloss perception. Numerous studies have demonstrated that lighting conditions play a critical role in shaping the appearance of materials. For example, It was shown that the interaction between lighting and surface reflectance significantly influences subjective impressions of gloss [1, 2]. Building on this, previous studies have shown that directional lighting enhances the perception of gloss and roughness, whereas diffuse lighting tends to soften those appearances of objects [3, 4].

In addition to lighting, surface color—particularly chroma—has been identified as a contributing factor in gloss perception. He et al. (2018) demonstrated that reducing chroma, while keeping hue and lightness constant, led to a significant decrease in perceived gloss, suggesting that chroma directly contributes to the impression of gloss [5].

However, these findings are based exclusively on observers with normal vision. In individuals with low vision—often resulting from age-related conditions such as cataracts—visual functions such

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as retinal resolution, contrast sensitivity, and color perception are typically degraded. Cataracts, in particular, increase scattering in the lens and reduce retinal exposure to short-wavelength light, leading to diminished perceived saturation [6, 7]. This reduction in chroma sensitivity may impair gloss perception; however, this relationship remains largely unexplored. Moreover, gloss impressions are known to vary with illuminance [8], and Leat et al. (1999) emphasized that visibility in individuals with low vision is especially sensitive to lighting conditions [9]. Therefore, investigating changes in gloss perception under varying lighting environments is essential for designing realistic and supportive visual environments for people with low vision.

The present study investigates how surface color—including chroma—and ambient illuminance influence gloss perception under simulated low vision conditions, compared to normal vision. Specifically, we employed a subjective rating method to examine how lighting and surface color attributes affect perceived gloss. The stimuli consisted of 25 semi-cylindrical physical objects, generated by combining five gloss levels (15, 25, 35, 60, and 110 GU) with five surface colors—four chromatic (red, yellow, blue, and green) and one achromatic (gray). Three levels of ambient illuminance (30 lx, 300 lx, and 1000 lx) were tested. Gloss ratings were collected under both normal and simulated low vision conditions.

2. Experiment 1: Evaluation of gloss perception under different illuminance and surface color conditions

2.1. Stimuli

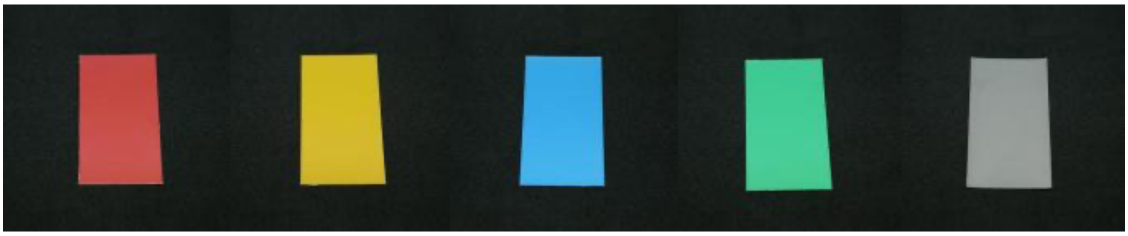
In this experiment, we used semi-cylindrical physical stimuli that varied in both hue and glossiness levels. Because highlight visibility strongly depends on surface curvature, using curved surfaces helps ensure that highlights remain perceptible even at lower gloss levels. This allows participants to focus on gloss perception rather than overall surface reflectance. A total of 25 physical stimuli were created by combining five different hues—four chromatic colors (red, yellow, green, and blue) and one achromatic color (gray)—with five levels of glossiness. To independently manipulate surface color and glossiness, we employed a layered construction method, in which a colored sheet and a transparent gloss layer were fabricated separately and then combined.

The color sheets used in the experiment were selected from standard color samples based on the Natural Color System (NCS). The chromatic colors included S 2060-R (red), S 2060-Y (yellow), S 2060-G (green), and S 2060-B (blue). An achromatic gray sample, NCS S 5000-N—defined by equal blackness and whiteness (s = w = 50%)—was also selected to ensure consistency between the chromatic and achromatic conditions. The CIE 1976 $L^*a^*b^*$ values for each sample, calculated based on spectral reflectance measurements obtained using a spectrophotometer (Konica Minolta, CM-700d), are shown in Table 1.

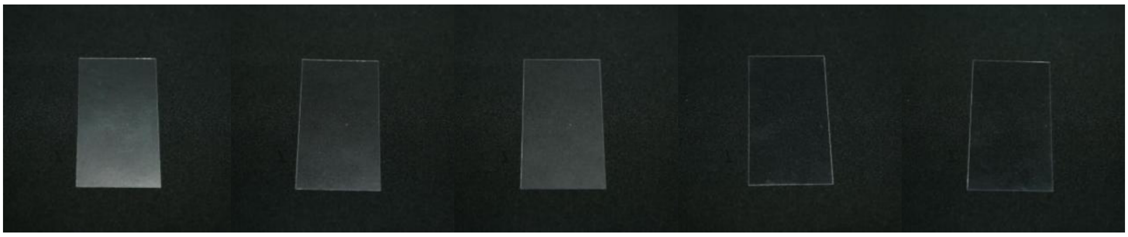
Table 1
CIE 1976 $L^*a^*b^*$ values of the NCS standard color sheets used in Experiment 1, relative to the instrument's standard white under illuminant D65, a 10° standard observer.

Hue	NCS code	L^*	a^*	b^*	C^*
Red	S 2060-R	49.0	39.3	14.0	41.72
Yellow	S 2060-Y	67.2	6.5	55.7	56.08
Green	S 2060-G	55.9	-20.2	-31.9	37.76
Blue	S 2060-B	59.5	-44.0	16.8	47.10
Gray	S 5000-N	57.1	0.1	0.0	0.1

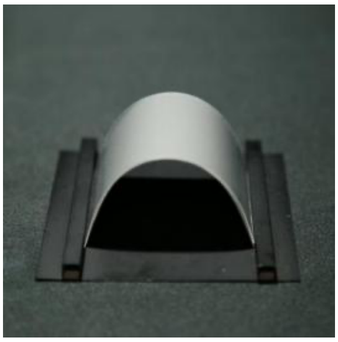
The gloss layers consisted of transparent rectangular plastic sheets, matching the size of the color samples, as shown in Figure 1(b). Glossiness level was controlled by applying either gloss or matte coatings to the surface. Five glossiness levels were prepared: 15, 25, 35, 60, and 110 gloss units (GU), as measured using an appearance analyzer (Rhopoint, IQ FLEX 20-S). Each gloss layer was placed over the gray sample during measurement to simulate the actual viewing conditions. Accordingly, the reported glossiness values represent the combined appearance of the color sample and the gloss layer. The measured color differences (ΔE^*_{ab}) after applying the gloss coatings, relative to the uncoated condition, ranged from 0.36 to 2.04 across all colors. Most values were below 1.5, indicating that the magnitude of color change was generally small and unlikely to influence participants' visual judgments



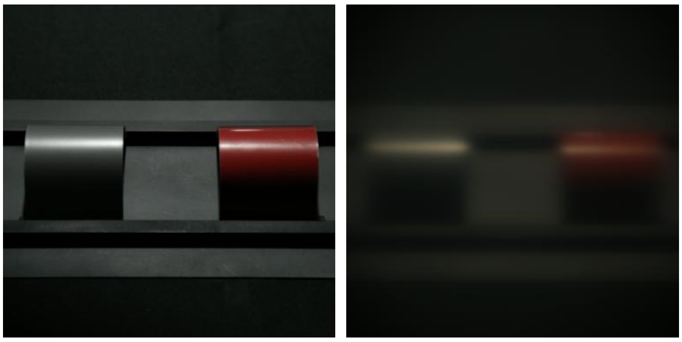
(a) Colored sheets.



(b) Gloss layers (from left to right, glossiness levels are 15, 25, 35, 60, and 110).



(c) Side view of a stimulus.



(d) Reference and test stimuli.
(left, normal; right, with simulation goggle).

Figure 1: Stimuli in Experiment 1.

As shown in Figure 1(c), each stimulus was created by overlaying one of the five colored sheets with one of the five gloss layers. The combined sheet was gently curved and mounted on a black base to produce natural light reflections, with its center slightly elevated. The width of the base was set to 6 cm, and the horizontal length of each stimulus was also 6 cm. At a viewing angle of 45°, the highlight region on the curved surface had an approximate curvature of 0.292 cm^{-1}.

The stimuli were presented in pairs on a single base, as Figure 1(d) shows. The left side consistently displayed a reference stimulus, consisting of the gray colored sheet (NCS S 5000-N) with a glossiness level 35. In contrast, the right side displayed one of the 25 test stimuli (5 colors × 5 glossiness levels). The horizontal distance between the two stimuli was fixed at 5 cm to ensure a visually comparable layout. At a viewing distance of 50 cm and a viewing angle of 45°, each 6 cm-wide stimulus subtended a visual angle of approximately 6.86°, and the entire span—including both stimuli and the inter-stimulus gap—subtended approximately 18.92°.

2.2. Low vision simulation goggles

We used cataract simulation goggles manufactured by Forks in the Road Vision Rehabilitation Services LLC to simulate low vision conditions for comparison with normal vision. These goggles are designed to mimic a visual acuity of 20/200 (or 0.1), corresponding to the legal definition of blindness in the United States under the ICD-9CM criteria for severe visual impairment. The goggles reproduce visual characteristics typically associated with cataracts, such as reduced contrast and blurred vision across the visual field. While such simulation devices cannot fully replicate the complex experiences of individuals with visual impairments, they are widely used in research and educational settings as a safe and consistent method for approximating low vision conditions [10]. Figure 2 shows the stimulus view with and without the simulation goggles.

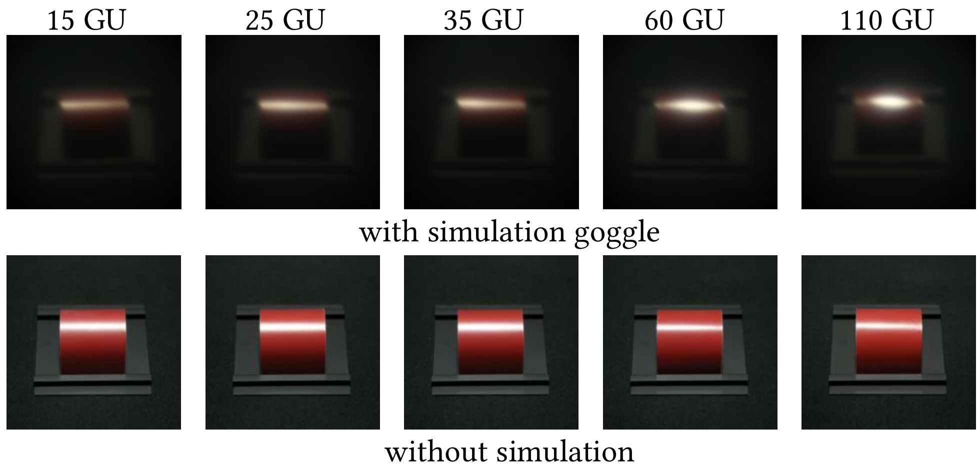


Figure 2: Example of the stimulus view with and without simulation goggles.

2.3. Experimental environment

The experiment was conducted in a darkroom. The viewing angle was set to approximately 45°, and the viewing distance was fixed at 50 cm. The stimuli were illuminated by a high-CRI (R_a = 92) LED light source positioned 1 meter directly above them. Three levels of illuminance (30 lx, 300 lx, and 1000 lx) were tested. The room was lined with black fabric to eliminate stray light and minimize visual interference.

2.4. Procedure

Participants first adapted to 30 lx lighting in a darkroom for one minute. They were then presented with a reference stimulus (gray and glossiness level 35), along with two examples illustrating low (15 GU) and high (110 GU) glossiness levels. Gloss score values were not disclosed; participants were simply informed which stimuli represented weak and strong gloss.

Next, the 25 experimental stimuli were presented randomly under the same lighting condition. Participants rated perceived gloss using a 10-point scale, with a score of 5 corresponding to the reference stimulus. This procedure was then repeated under 300 lx and 1000 lx lighting. After completing these tasks under normal vision, participants wore low vision simulation goggles and repeated the entire procedure under simulated low vision, following the same lighting sequence. One session consisted of the entire procedure. Accordingly, each session involved evaluating all stimulus combinations once under both vision conditions and all three lighting levels (six blocks in total). Each session lasted approximately 60 minutes. Each participant completed four sessions.

Six participants (three male and three female), all in their twenties, took part in the study. Baseline visual acuity was measured at 50 cm using a near- and intermediate-distance Landolt C chart (TMI Co., Ltd.). Two male participants had uncorrected visual acuity of 1.2, one female had 1.2 with contact lenses, and the remaining three had 1.0 with spectacles. The goggles allowed for over-the-glasses wear, so the three participants kept their spectacles on during use. With the goggles, one participant's acuity dropped from 1.0 to 0.2, while the others' dropped to 0.3. This variation is likely due to individual differences in visual function, ocular anatomy, and the potential influence of fogging in the goggles. All reduced acuity values met this study's low vision criterion (≤ 0.3).

2.5. Results and discussion

Figure 3 visualizes the relationship between the mean subjective gloss ratings and the physical glossiness values (GU) of the stimuli, with the horizontal axis representing glossiness units and the vertical axis indicating the average subjective gloss score on a 10-point scale (1 to 10). Error bars indicate standard errors (SE). The fitted curves represent logarithmic functions that approximate the relationship between perceived gloss and physical glossiness. A separate fitting curve was calculated for each color. The coefficients of determination (R^2) ranged from 0.86 to 0.99, indicating a high degree of fit and suggesting that the logarithmic model is appropriate for this dataset.

To quantitatively compare gloss sensitivity, we focused on the logarithmic fit coefficient (analogous to the slope in linear regression). This coefficient reflects how sharply participants differentiated between glossiness levels and serves as an index of gloss discriminability. A larger coefficient (i.e., a steeper curve) indicates higher discriminability, meaning participants clearly distinguished among glossiness levels. In contrast, a smaller coefficient (i.e., a flatter curve) indicates reduced differentiation, suggesting difficulty in gloss discrimination. Comparative analysis revealed that the fitted curves tended to be flatter under simulated low vision conditions than those under normal vision, suggesting a decline in gloss discrimination ability under impaired visual conditions.

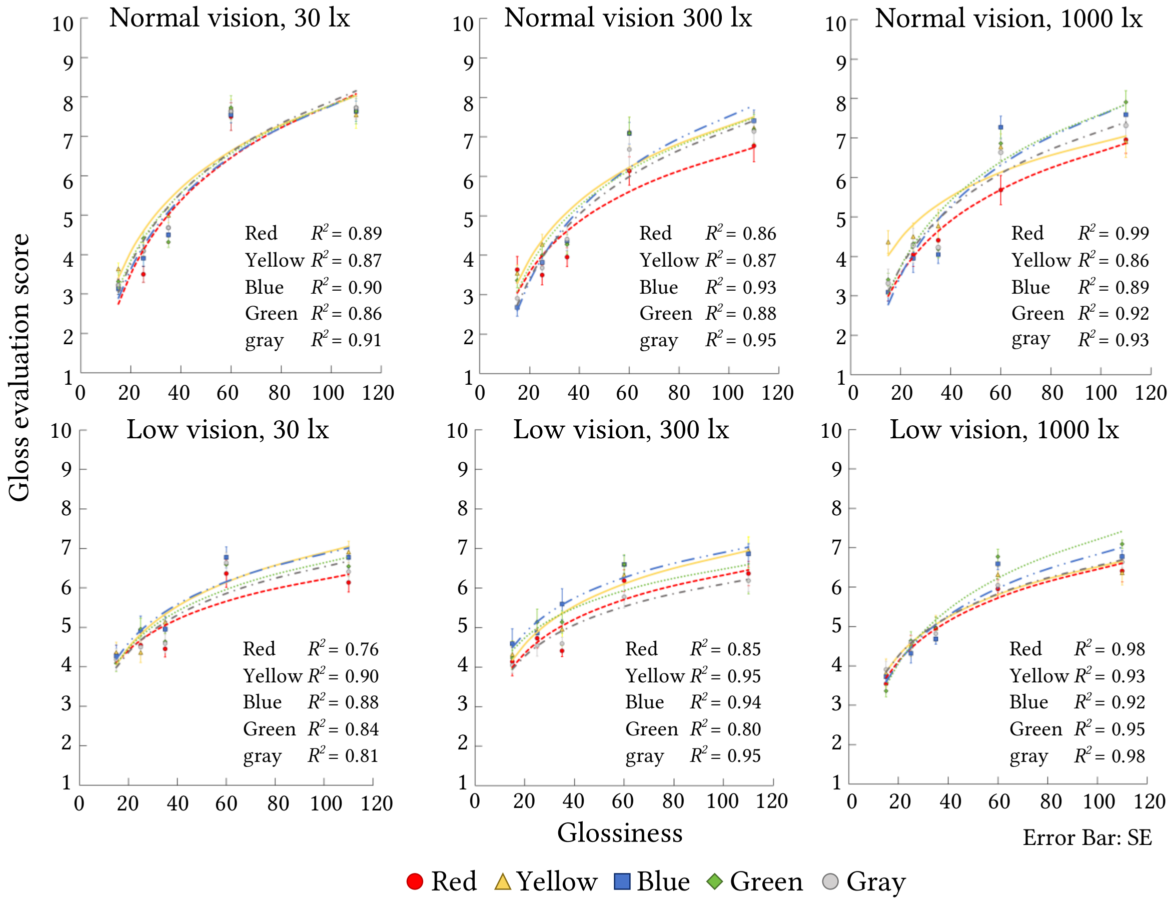


Figure 3: Gross evaluation results under normal and simulated low vision conditions.

The stimuli with 60 GU in Figure 3 exhibit unusually high gloss evaluation scores. This may be attributed to the nonlinearity between gloss unit (GU) values and perceived visual differences or to the method used to prepare the gloss layers in this study, which involves applying a gloss coating over a matte base. Although the measured gloss difference between the 60 GU and 110 GU stimuli is 50 GU, the actual perceived difference may have been smaller due to potential inaccuracies introduced by the handmade coating process.

Figure 4 presents the extracted logarithmic fit coefficients used to compare gloss discrimination ability between normal vision and simulated low vision across different illuminance levels (30 lx, 300 lx, and 1000 lx), as well as the overall average. The vertical axis represents the logarithmic fit coefficient, and the horizontal axis shows the visual condition (normal vs. simulated low vision). Results are displayed as color-coded bar graphs by hue, with error bars indicating SE. A larger coefficient corresponds to a taller bar, reflecting greater gloss discrimination ability.

Within each illuminance condition and for the overall average, statistical comparisons were conducted to examine differences across hues under both visual states. Although some significant differences were observed in specific cases ($p < .05$), the overall influence of hue on gloss discrimination was limited, with no consistent trends observed across most conditions.

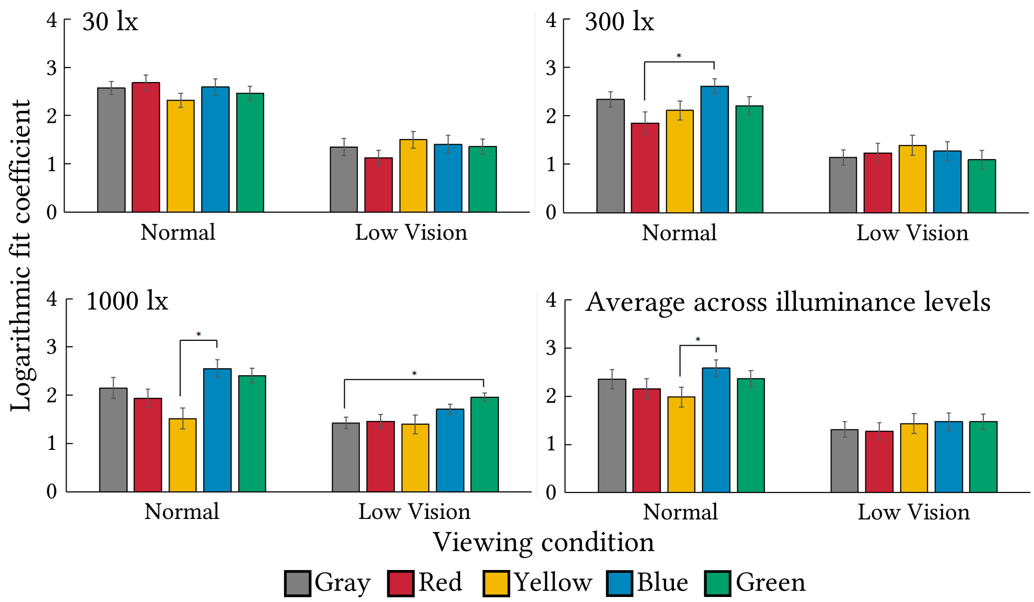


Figure 4: Comparison of logarithmic fit coefficients across normal and simulated low vision conditions, by hue and illuminance. Asterisks (*) indicate statistically significant differences ($p < .05$).

Figure 5 compares average gloss discrimination, represented by logarithmic fit coefficients, between normal and simulated low vision conditions, without separating by hue. Significant differences were observed across all illuminance levels, indicating reduced discrimination under the simulated low vision condition. Under normal vision, gloss discrimination slightly decreased with increasing illuminance, whereas it showed a slight increase under low vision.

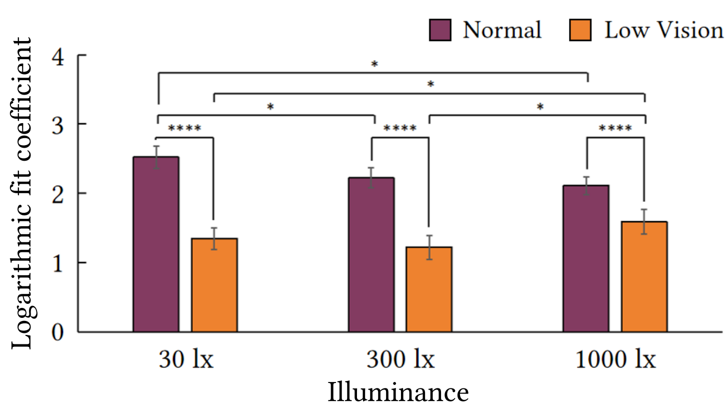


Figure 5: Overall gloss discrimination by visual condition: normal vs. simulated low vision (averaged across hues). $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$, $^{****}p < .0001$.

3. Experiment 2: Influence of chroma on gloss perception

In Experiment 1, we did not observe apparent differences among stimulus hues. However, since NCS color samples were used, lightness and chroma were not strictly controlled, making it difficult to isolate the effect of chroma. To further investigate the influence of chroma on gloss perception under low vision conditions, we used Munsell color samples with constant value (lightness) across all samples. Two chroma levels (high and low) were selected for each of four hues.

3.1. Experiment

Munsell color samples with the same value (lightness) and two chroma levels (high and low) were selected for each of four hues, resulting in a total of eight color samples. The average values are presented in Table 2.

To ensure consistent surface curvature across stimuli, a semi-cylindrical mold was attached to the hollow side of each stimulus, with a side radius of 3 cm and a front width of 5 cm. This construction ensured that all stimuli maintained a constant surface curvature radius of 3 cm.

The gloss layers were prepared like in Experiment 1, with five glossiness levels: 15, 25, 35, 60, and 110 gloss units (GU). Gloss measurements were conducted with each gloss layer placed over a Munsell color sheet to replicate the viewing condition.

The procedures and participants were the same as those in Experiment 1; however, Experiment 2 included additional color groups and was conducted exclusively under the 300 lx.

Table 2
CIE 1976 $L^*a^*b^*$ values of Munsell color samples used in Experiment 2, relative to the instrument's standard white under illuminant D65, 10° standard observer.

Munsell code	L^*	a^*	b^*	C^*
5R 6/8	59.53	32.31	15.56	35.86
5Y 6/8	60.32	6.24	52.23	52.60
5G 6/8	61.72	-36.73	14.25	39.40
5B 6/8	62.61	-27.50	-20.61	34.37
5R 6/2	60.92	7.62	3.36	8.33
5Y 6/2	60.30	0.96	13.66	13.69
5G 6/2	60.95	-9.39	3.99	10.20
5B 6/2	61.61	-6.72	-4.83	8.28

3.2. Results and discussion

Since the logarithmic fit coefficients showed a similar pattern to those in Experiment 1, the present analysis focuses on chroma variation as the primary factor of interest. Figure 6 displays the logarithmic fit coefficients comparing gloss discrimination between high- and low-chroma surfaces under both normal and simulated low vision conditions.

Under normal vision, a slight decrease in discrimination was observed for low-chroma surfaces, with a significant difference found only for the blue group ($t = 2.477$, $p = 0.017$). Under simulated low vision, no significant differences were observed across hues, and in some cases, low-chroma surfaces exhibited equal or even better performance than their high-chroma counterparts.

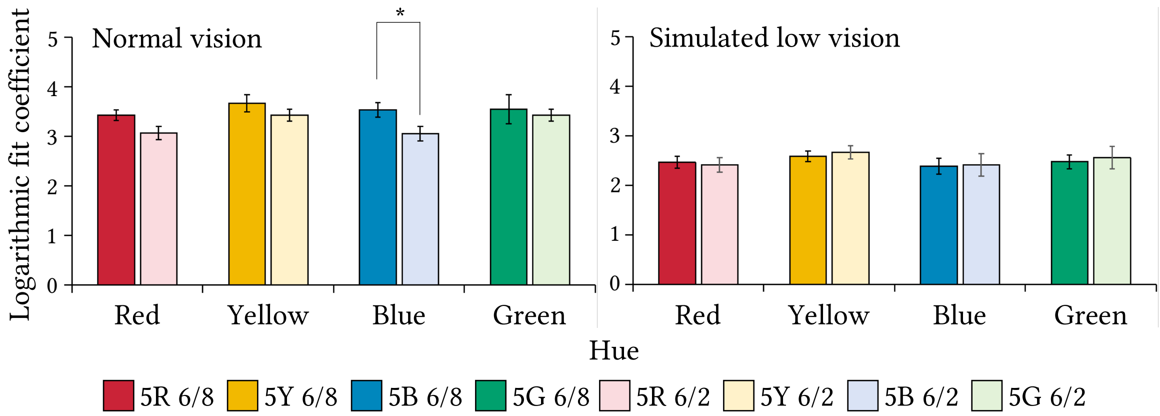


Figure 6: Relationship between chroma and gloss discrimination ability. $^{*}p < .05$.

4. Discussion

To visualize the luminance distribution, images of each stimulus from Experiments 1 and 2 were captured under a uniform illuminance condition using a 2D colorimeter (CA-2000, KONICA MINOLTA). The camera was positioned 50 cm from the stimulus surface at a 45° angle, with the light source placed directly overhead to replicate the participant's viewing conditions. Additional images were taken with the low vision simulation goggles placed directly over the camera lens to simulate the low vision condition.

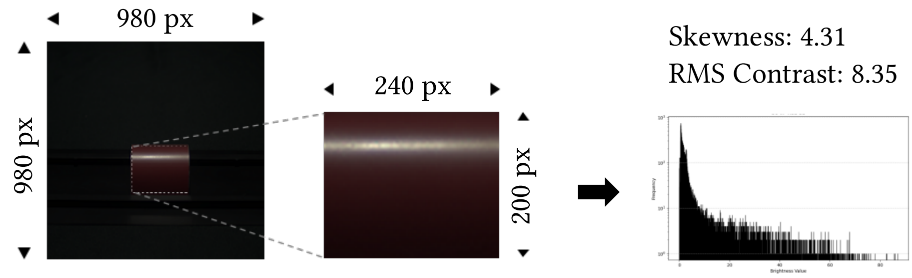


Figure 7: Example of stimulus image crop and luminance histogram.

Images captured by the CA-2000 had a resolution of 980 × 980 pixels, with each stimulus centered in the frame. A margin of approximately 5–10 pixels was left from the stimulus boundary, and a central region of 240 × 200 pixels was selected for analysis. Using Python, luminance histograms were generated from each image, and skewness and root-mean-square (RMS) contrast were calculated based on these histograms.

4.1. RMS contrast

RMS contrast is an index that indicates how much pixel luminance deviates from the mean luminance, calculated as the standard deviation of image luminance. In this study, RMS contrast was computed from the luminance histogram of each stimulus to examine whether it varied depending on illumination conditions and surface color. Figure 8 shows the relationship between glossiness and RMS contrast for the blue surface color under each illumination condition. This pattern was consistently observed across both experiments.

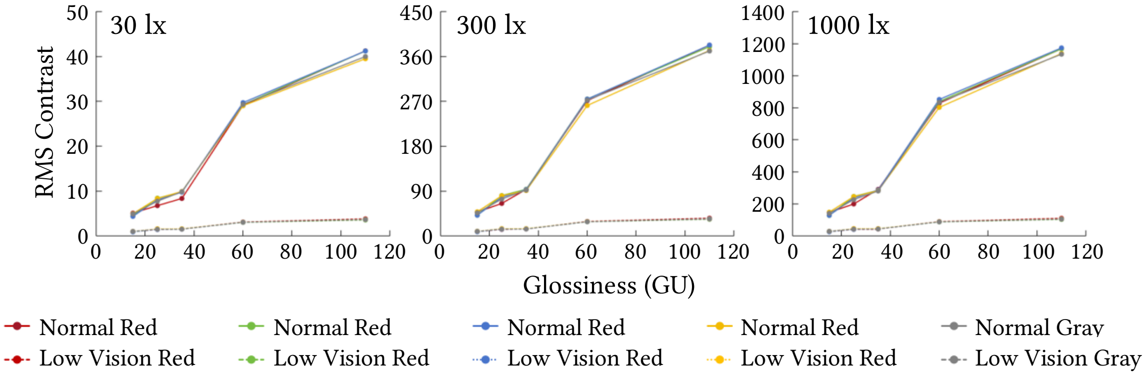


Figure 8: Relationship of RMS contrast and gloss score in Experiment 1.

Since absolute RMS contrast varies with illumination, we normalized the log-transformed RMS contrast values within each color group at each illuminance level in Experiments 1 and 2 by setting the highest value to 100% and scaling the remaining four stimuli accordingly. Figure 9 shows the relationship between normalized RMS contrast and average gloss scores for both experiments. The horizontal axis represents the relative RMS contrast, and the vertical axis indicates the corresponding average gloss scores. The results demonstrated a strong linear fit ($R^2 > 0.9$) and statistically significant differences between normal and low vision conditions in both experiments (Experiment 1: $t(146) = 5.58$, $p < .001$; Experiment 2: $t(76) = 5.73$, $p < .001$). These findings suggest that sensitivity to contrast variation is reduced under low vision conditions.

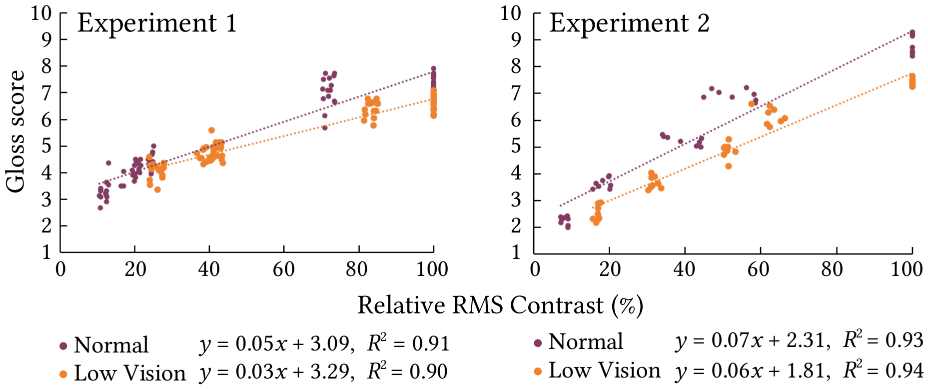


Figure 9: Relationship between normalized RMS contrast and average gloss score in Experiments 1 and 2.

4.2. Skewness

As Motoyoshi et al. (2007) [11] demonstrated, skewness is a critical image statistic influencing gloss perception. In our stimuli, skewness generally increased with increasing glossiness level, regardless of illuminance level or hue. However, a clear difference was observed between the normal and simulated low vision conditions: skewness values were consistently lower under the simulated low vision condition. This suggests that reduced skewness may be one of the factors contributing to diminished gloss perception under low vision conditions.

Figure 10 shows the relationship between skewness and average subjective gloss scores in Experiments 1 and 2. The horizontal axis represents skewness, while the vertical axis indicates the mean subjective gloss rating. Logarithmic fitting curves were applied to all data. Although the range of skewness values was narrower under the simulated low vision condition, the slope of the fitted curve was steeper. This suggests a higher sensitivity to slight differences in skewness under low vision simulation. These findings imply that skewness remains a relevant cue for gloss perception even under simulated low vision. However, skewness alone could not fully account for the changes in perceived gloss, indicating that other visual features may also contribute to gloss perception.

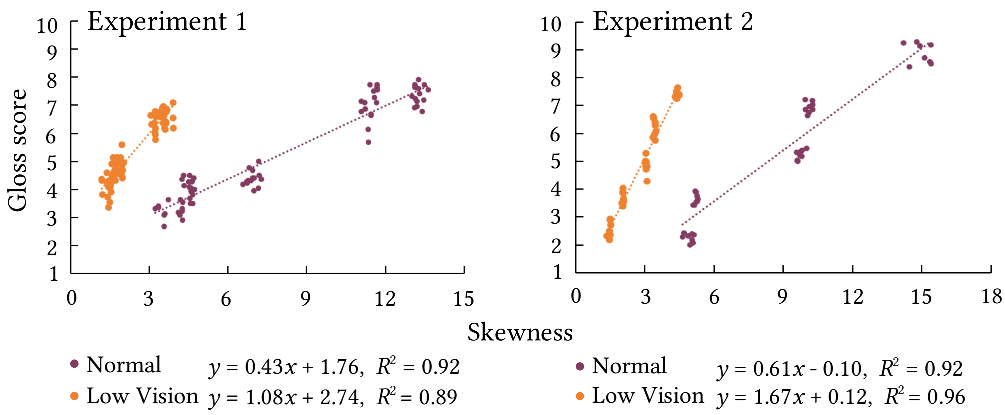


Figure 10: Relationship between skewness and average gloss score in Experiments 1 and 2.

4.3. Line spread function of specular reflection (SR-LSF)

To evaluate the visual impression of gloss unevenness on material surfaces, Inoue et al. (2020) proposed a measurement method using a line light source [12]. This method captures the specular reflection region as a visually reproducible image from the participant's viewpoint. First, a line light image of specular reflection (SR-LLI) is obtained, followed by calculating the line spread function of specular reflection (SR-LSF) based on this image.

In the present study, the stimuli inherently produced linear highlights, making them well-suited for this method. Therefore, following the approach of Inoue et al., we measured the SR-LLI and SR-LSF for the five types of stimuli used in Experiment 2 under both vision conditions, as shown in Figure 11 [13, 14, 15]. In the measurement setup, both the observation and illumination angles were set to 20 degrees, and the viewing distance was fixed at 500 mm—the same as in the psychophysical experiment. The point light source was also positioned 500 mm above the stimulus.

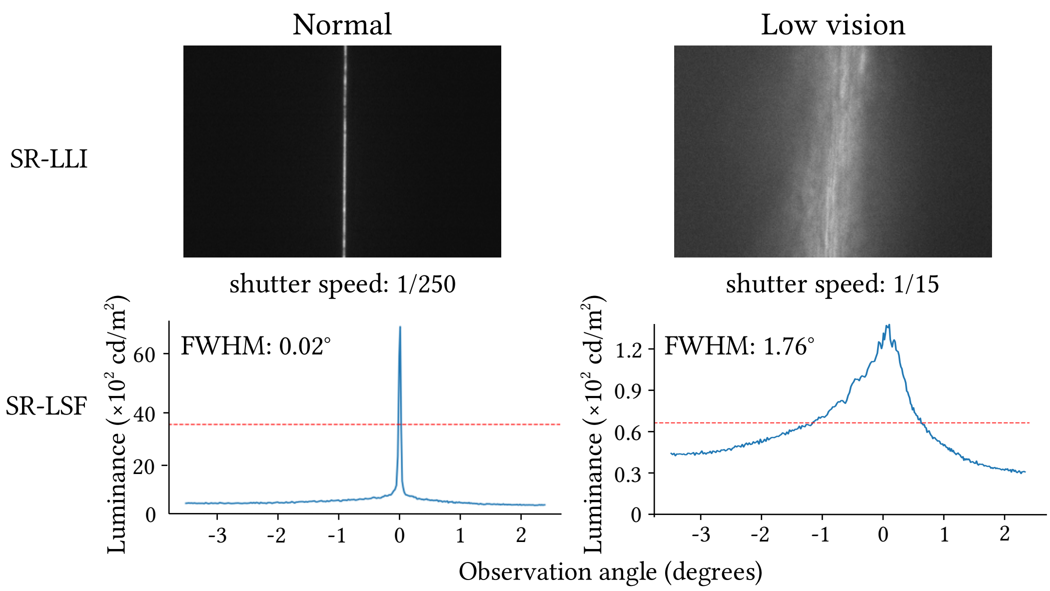


Figure 11: Example of SR-LLI images and SR-LSF graphs obtained from a glossiness level 110 stimulus in Experiment 1, under normal vision (left) and low vision simulated conditions (right).

The dashed lines in the graphs indicate the vertical axis position corresponding to the full width at half maximum (FWHM) of each curve. The horizontal axis represents the angular deviation from the highlight position, with negative values indicating the camera side and positive values indicating the light source side. The vertical axis shows the average luminance at each angular position. The shutter speed used during image acquisition is also noted. To allow direct comparison, the shutter speed was standardized across all measurements, enabling the SR-LSFs for different glossiness levels to be overlaid and compared within the same graph, as shown in Figure 12. The luminance values were converted from the digital camera outputs based on their relationship with the luminance measured by the 2D colorimeter CA-2000.

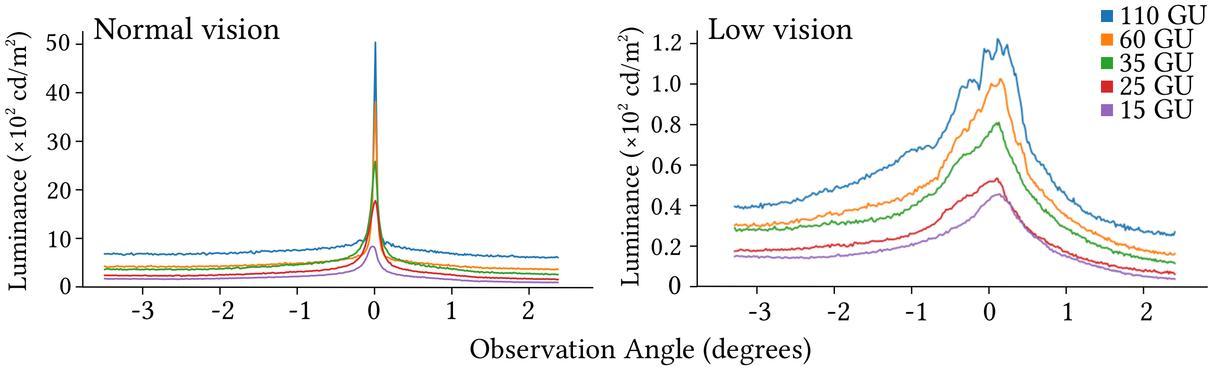


Figure 12: SR-LSFs for different glossiness levels.

Comparison between normal vision and simulated low vision conditions suggests that a reduction in peak luminance may contribute to decreased gloss perception. Specifically, as the peak luminance of a stimulus decreased, the average subjective gloss rating also declined. This finding supports previous research [8], emphasizing that highlight intensity is an important visual cue for gloss perception.

Analysis of the SR-LSF graphs revealed that the full width at half maximum (FWHM) generally decreased with increasing glossiness level. However, under normal vision, the differences in FWHM between glossiness levels were relatively small—particularly between levels 60 and 110—suggesting that highlight spread may not be a primary visual cue under this condition. In contrast, under the simulated low vision condition, highlights appeared more diffused, and FWHM varied more noticeably across glossiness levels. This indicates that highlight spread may serve as a helpful cue for gloss perception under reduced visual acuity. As noted earlier, participants' sensitivity to changes in skewness also increased under the low vision condition, possibly due to the emergence of this additional cue.

Changes in the shape of the SR-LSF curves were also observed. High-gloss stimuli produced steep, sharp-edged curves with high luminance contrast, whereas low-gloss stimuli resulted in smoother, more gradual curves, indicating blurred highlight boundaries. This pattern corresponds to an increase in *haze*, one of the perceptual attributes of gloss defined by Hunter et al. (1937) [15]. Furthermore, the SR-LSF curves appeared to be generally blurred and rounded under low vision conditions. This may reflect the effect of the simulated cataract lens, which incorporates a diffusion filter that reduces luminance contrast. As a result, the SR-LSF curves across different stimuli became more similar, making it more challenging to distinguish gloss levels and thereby reducing gloss discrimination ability.

Our analyses indicate that changes in image characteristics—such as maximum luminance, haze, contrast, and highlight width—contribute to reduced gloss perception. However, further comprehensive analysis is needed to understand these effects fully.

5. Conclusion

This study investigated how visual conditions affect gloss discrimination by conducting two experiments comparing normal vision with simulated low vision. Overall, gloss discrimination was reduced under low vision; however, sensitivity was preserved in certain conditions, suggesting the use of alternative visual cues such as luminance skewness or highlight sharpness.

Notably, participants under simulated low vision exhibited greater sensitivity to changes in skewness, indicating a possible shift in visual strategy. Analysis of the Specular Reflection–Line Spread Function (SR-LSF), derived from line light images (SR-LLI), revealed that highlight sharpness and spread varied depending on visual condition. Differences in peak luminance, edge definition, contrast, and diffusion were observed between the two visual states, likely contributing to the reduced perception of gloss under low vision.

These findings suggest that visual impairments—specifically changes to the crystalline lens—affect not only visual acuity, but also the way visual cues are utilized in higher-level perceptual processing.

Our findings may have implications for material design and assistive technologies tailored to individuals with low vision and contribute to a deeper understanding of the mechanisms underlying gloss perception.

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Declaration on Generative AI

During the preparation of this work, the authors used GPT-4o and Grammarly in order to check grammar and spelling. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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