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Rendering emissive colors in HDR scenes: The role of reference-white placement and highlight tone mapping

Alireza Rabbanifar, Soroush Shahbaznezhad, Mark D. Fairchild, Mekides A. Abebe
Munsell Color Science Laboratory, Rochester Institute of Technology, Rochester, NY, USA

Abstract

Reference-white placement is a central issue in HDR rendering because it determines the viewer's adaptation state and strongly influences perceived color appearance. In HDR scenes that contain both reflective surfaces and bright emissive elements, it remains unclear how diffuse white should be placed on the display and how highlights should be tone mapped to preserve appearance.

In this work, we investigate how reference-white placement and highlight tone mapping affect the perceptual reproduction of emissive colors in HDR scenes. To address this question, we captured a controlled HDR scene containing both reflective and emissive color targets and rendered it on a professional HDR display using different rendering strategies. These included varying the displayed diffuse-white luminance and comparing global tone mapping with selective processing of emissive regions. Due to scene complexities and the absence of standard color-difference metrics designed for such applications, our work relies on perceptual assessments. Observers viewed the real scene and then evaluated the display renderings in terms of appearance-based criteria. The results show that reference-white placement and tone-mapping strategy jointly influence perceived image quality and color appearance. In particular, the initial findings suggest that separately processing reflective and emissive regions—preserving colorimetric reproduction for reflective areas while compressing emissive highlights—produces the most favorable overall renderings.

Introduction

High dynamic range (HDR) imaging introduces significant challenges when rendering scenes with extremely wide luminance variation on displays with more limited capabilities. A central issue is the placement of reference white, which anchors tone reproduction and strongly influences perceived brightness and color appearance. Reference white is a system-defined signal level that does not necessarily correspond to a physically present diffuse white in the scene [6]. In contrast, diffuse white depends on scene illumination and observer adaptation. Traditionally, diffuse white is mapped below display peak luminance to preserve headroom for highlights, but its optimal placement varies with scene content and viewing context [17, 12]. In HDR standards such as PQ (ITU-R BT.2084), reference white is typically defined around 203 cd/m², reserving higher luminance levels for highlights [9, 10]. However, this headroom is generally defined in signal terms rather than perceptual ones, and tone mapping often relies on fixed thresholds that do not account for scene-dependent visual characteristics.

These challenges are amplified by the limitations of current HDR rendering pipelines and the behavior of the human visual system. Viewers adapt to a perceived white that may differ from both scene diffuse white and encoded reference white, making rendering highly sensitive to white placement. Improper placement can either compress midtones or reduce highlight visibility, leading to loss of realism. Furthermore, most pipelines rely on global tone mapping, which applies a uniform transformation across the image. This is a critical limitation because emissive and specular highlights occupy a different perceptual regime than diffuse content. Treating them identically often results in reduced color fidelity, diminished contrast, and loss of perceptual separation. More fundamentally, current HDR frameworks lack explicit modeling of adaptation, do not smoothly represent the transition between diffuse and emissive regimes, and identify highlights using signal-based rather than perceptual criteria.

To address these limitations, HDR rendering should preserve the colorimetric accuracy of reflective regions while selectively processing emissive and highlight components. By maintaining diffuse white near its scene-referred level and allocating headroom based on perceptual relevance, it becomes possible to avoid clipping, preserve highlight structure, and maintain contrast between reflective and emissive content. In this work, we investigate how reference-white placement and highlight tone mapping jointly affect the perceptual reproduction of emissive colors in HDR scenes. We evaluate colorimetric accuracy, perceptual fidelity, and observer preference under different rendering strategies, comparing global and selective tone mapping approaches. By combining objective analysis with perceptual assessment, this study provides insights into more effective HDR rendering practices that better align with human visual perception.

Methods

HDR Scene and Data Acquisition

We created a controlled HDR scene containing both emissive and reflective color targets (Figure 1). The scene was illuminated by two sources: a uniform LED light box for the emissive target and a tungsten source at 45° illuminating reflective surfaces and a perfect reflecting diffuser. The sources had slightly different color temperatures (approximately 2920 K and 2900 K), and images were processed both with manual white balancing (during acquisition) and with and without CIE CAT16 chromatic adaptation to thedisplay white (during rendering). An HDR radiance map was generated from multi-exposure captures using a calibrated, scene-referred pipeline [3]. The scene spans a luminance range of approximately 3–9286 cd/m², as shown in Figure 1. This setup enables controlled evaluation of rendering strategies involving reference-white placement and highlight handling.

System Calibration Overview

Camera Calibration

The HDR radiance map was obtained from RAW images captured using a Sony a7R III and processed using standard HDR merging techniques [3]. Camera characterization was performed using a reflective color checker, and accuracy was evaluated using ΔE_{00} for reflective, emissive, and combined targets (Table 1). As expected, higher errors were observed for emissive patches due to dynamic range limitations. A detailed investigation of camera characterization under emissive conditions is relevant but remains out of the scope of this study.

	Mean	p95	Max
ΔE_{00} for reflective color checker	3.91	10.72	15.1
ΔE_{00} for emissive color checker	12.19	16.7	24.36
Average ΔE_{00} for all color targets	10.08		

Table 1: Camera characterization accuracy: ΔE_{00} between measured scene XYZ values and XYZ values estimated using the camera transformation matrix.

Display Calibration

The stimuli were presented on a Sony PVM-X3200 HDR mastering display (with measured peak luminance level of 800 nits) using a PQ pipeline (ITU-R BT.2100). The images were sent to the display in linear space using display LUT and a color transformation matrix through MATLAB Psychtoolbox. For an accurate display transformation, the display was characterized using measured RGB ramps and a color transformation matrix. The validation results of the display characterization are summarized in Table 2.

	Mean	p95	Max
ΔE_{00} for a sample of 18 patches	5.99	9.81	10.1

Table 2: Display characterization validation: ΔE_{00} between measured RGB ramp responses and those predicted by the display transformation matrix.

End-to-end system accuracy for reflective targets is shown in Table 3. Significantly higher color differences were observed for the emissive regions due to clipping, and this aspect of display rendering is a primary focus of our subjective study, discussed in the following sections.

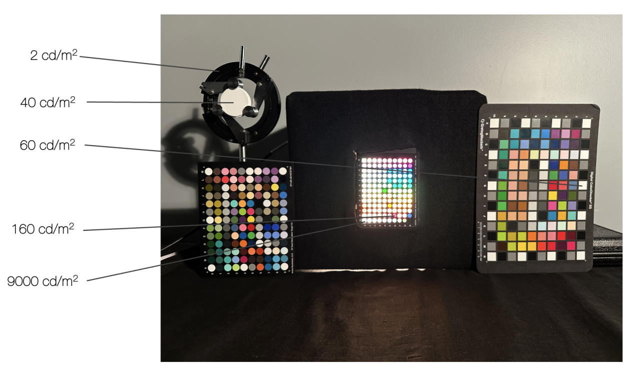

Figure 1: A photograph of the physical HDR scene setup with corresponding measured luminance levels. The central high-luminance target is an emissive LED-backlit element. It is significantly clipped here for visualization purposes, whereas the full color details are preserved in the real scene

	Mean	p95	Max
ΔE_{00} for reflective colors	5.78	14.13	14.21

Table 3: System characterization validation: the differences between the measured XYZ values of the physical reflective patches under the experimental scene conditions and those rendered on the HDR display under the experimental viewing conditions.

Stimuli Generation and Rendering Design

HDR radiance values obtained from the captured scene were first converted from linear camera RGB to CIE XYZ tristimulus values using the camera characterization matrix. These values were then mapped to display linear RGB using the display characterization matrix:

$$\mathbf{RGB}_{\text{display}} = \mathbf{M}_{\text{XYZ}\to\text{RGB}} \cdot \mathbf{M}_{\text{cam}\to\text{XYZ}} \cdot \mathbf{RGB}_{\text{camera}} \quad (1)$$

The resulting linear RGB values were sent to the HDR display using MATLAB Psychtoolbox, which applies the inverse PQ transfer function to ensure accurate luminance reproduction. To investigate the effects of reference-white placement and highlight handling, eight rendering conditions were generated, grouped into three main categories:

(1–2) Colorimetric rendering with linear scaling: *Rendering 1:* Scene-referred colorimetric relationships were preserved, with reflective regions displayed at their physical luminance levels (diffuse white $\approx 60\ \text{cd/m}^2$). Values exceeding display capability were clipped. *Rendering 2:* A global linear scaling was applied to map diffuse white to the HDR reference white level ($\approx 203\ \text{cd/m}^2$):

$$\mathbf{RGB}'_{\text{display}} = \alpha \cdot \mathbf{RGB}_{\text{display}} \quad (2)$$

where α is a constant scaling factor. Clipping still occurs for high-luminance regions.

(3–4) Global normalization to display peak: The scene was normalized such that the maximum luminance in the image is mapped to the display peak:

$$\mathbf{RGB}_{\text{display}} = \beta \cdot (\mathbf{M}_{\text{XYZ}\to\text{RGB}} \cdot \mathbf{M}_{\text{cam}\to\text{XYZ}} \cdot \mathbf{RGB}_{\text{camera}}) \quad (3)$$

where β is chosen so that the brightest pixel in the scene reaches the display peak luminance.
Rendering 3: Unlike Rendering 2, where the scaling is defined by the diffuse white level, here the maximum luminance in the scene is mapped to the display peak, and all other pixel values are scaled linearly relative to it. This ensures that no values are clipped. However, because the scene contains a large dynamic range and the mapping is anchored to the brightest pixel, most of the image—particularly reflective regions—falls into a lower portion of the display range, resulting in a darker overall appearance.
Rendering 4: A global gamma correction is applied to enhance visibility:

$$\mathbf{RGB}'_{\text{display}} = \mathbf{RGB}_{\text{display}}^{1/1.8} \quad (4)$$

The radiance map of the global tone-mapped results are illustrated in Figure 2. The maps show that the visibility of the reflective targets is significantly reduced due to the limited peak luminance of the display (800 nits) and the high luminance levels of the emissive regions in the scene, as shown in Figure 1.

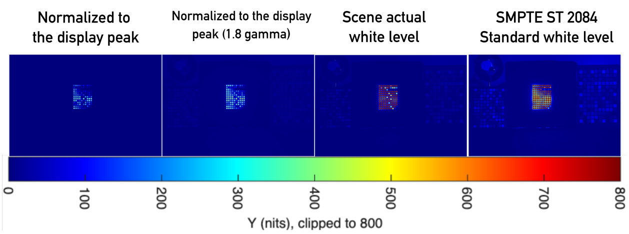

Figure 2: Radiance maps of the final HDR renderings following application of the global tone mapping methods.

(5–8) Selective tone mapping of emissive regions: Emissive regions, shown at the center of Figure 1, were segmented using a binary mask and processed independently. Their luminance was normalized to the display peak:

$$\mathbf{RGB}_{\text{emissive}} = \alpha \cdot \mathbf{RGB}_{\text{display}}, \quad \alpha = \frac{L_{\text{peak}}}{\max(L_{\text{emissive}})} \tag{5}$$

Renderings 5–6: Reflective regions were either preserved at scene luminance (Rendering 5) or scaled to HDR reference white (Rendering 6), while emissive regions were independently normalized. *Renderings 7–8:* An additional nonlinear transformation was applied to emissive regions to enhance perceptual detail:

$$\mathbf{RGB}'_{\text{emissive}} = \mathbf{RGB}^{1/1.8}_{\text{emissive}} \tag{6}$$

Background treatment follows Renderings 5 and 6, respectively. The radiance map of these selectively tone-mapped results are shown in Figure 3.

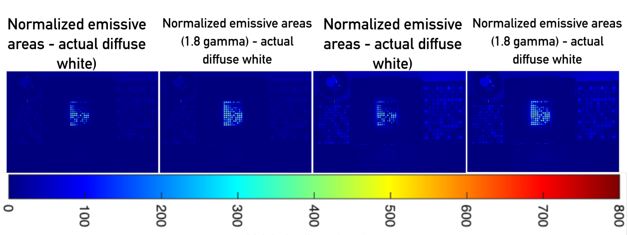

Figure 3: Radiance maps of the final HDR renderings following application of the selective tone mapping methods

Finally, chromatic adaptation (CAT16) was optionally applied to map scene illumination (∼2900 K) to the display white point (D65), enabling comparison between adapted and non-adapted conditions.

Perceptual Experiment Design

To assess the effects of reference-white placement and both global and local tone-mapped renderings, a psychophysical experiment was conducted to evaluate perceptual quality. Observers viewed the real physical scene as well as the eight rendering variations individually on an HDR display in a dark room and perceptually assess them. The evaluations were based on five criteria (**color appearance fidelity**, **sharpness**, **saturation**, **naturalness**, and **overall preference**). Observer ratings for each criterion were collected using a GUI slider with a scale ranging from 0 to 100. The experiment consisted of two phases:

- **Before scene exposure:** Observers evaluated all renderings without seeing the real scene.
- **After scene exposure:** Observers seen and analyzed the real scene (after a minimum of 60 seconds adaptation period) and then repeated the evaluation of the renderings, with optional revisits to the scene between trials.

Both chromatically adapted and non-adapted renderings were included to assess the effect of chromatic adaptation.

Results

In the subjective study, a total of 12 observers (6 male, 6 female) participated, with ages ranging from 25 to 40 years. All observers had normal or corrected color vision and were affiliated with the color science department, with prior experience in image and color quality evaluation experiments.

Global vs selective rendering

The average observer scores for each rendering are shown in the box plots in Figures 4 and 5, corresponding to the two phases of the evaluations, before and after exposure to the real scene. 16 rendering conditions were tested, comprising eight rendering strategies, each under two chromatic conditions: with and without chromatic adaptation (CAT). The average ratings of renderings using the selective (local) tone mapping of emissive regions are shown in blue, while those using global (uniform) tone mapping are shown in orange. The corresponding averages are presented grouped by CAT condition (with - CAT and without - no CAT).

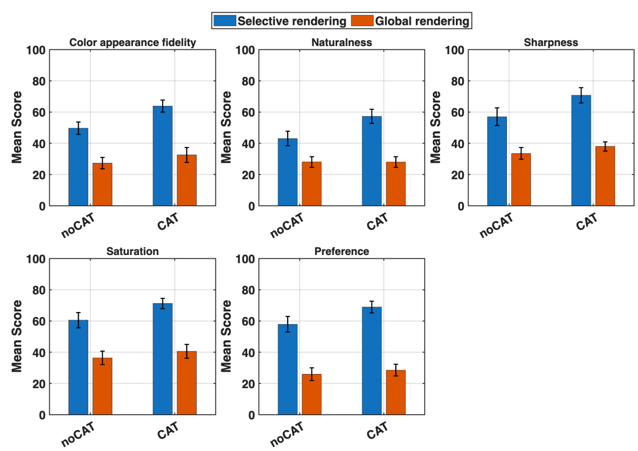

Figure 4: Average perceptual ratings of experimental HDR renderings with the Selective vs Global rendering, before viewing the real scene

Figures 6 and 7 presents the Holm–Bonferroni corrected pairwise comparisons, highlighting statistically significant differences between rendering methods.

The results show that regardless of the observer exposure to the scene and CAT application, the samples that are rendered selectively achieved a higher score in all criteria and were strongly preferred over the globally rendered ones. Pairwise comparison

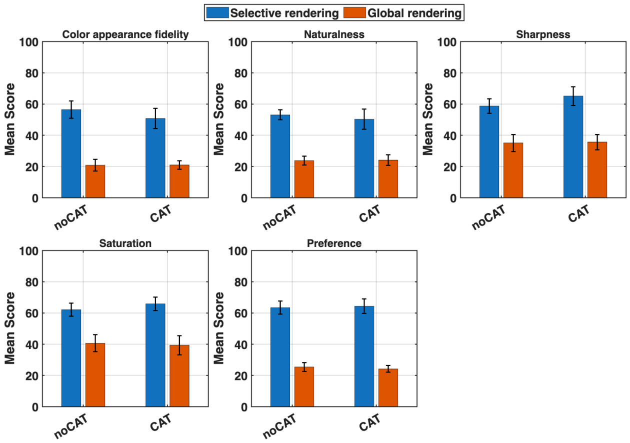

Figure 5: Average perceptual ratings of experimental HDR renderings with the Selective vs Global rendering, after viewing the real scene

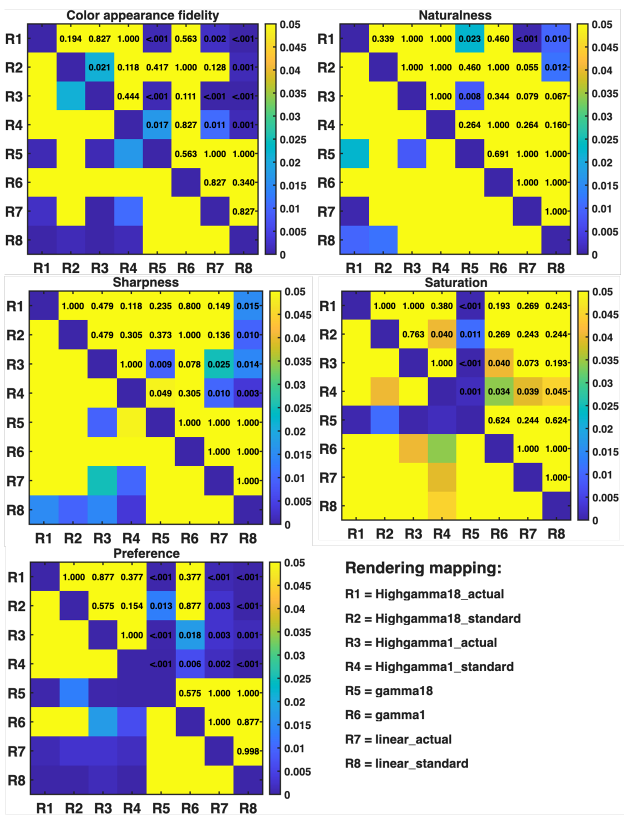

Figure 6: Holm–Bonferroni corrected pairwise comparison of observer ratings, before viewing the real scene (Darker-blue color means more significant difference)

of all of the renderings (Figures 6 and 7), also shows that selectively tone mapping the emissive parts of the scene (samples showed with their name starting with ”Highgamma” in the figures) achieved significantly higher scores in color appearance fidelity and overall preference. Although, the difference is not significant in evaluation of naturalness, sharpness, and saturation of the images.

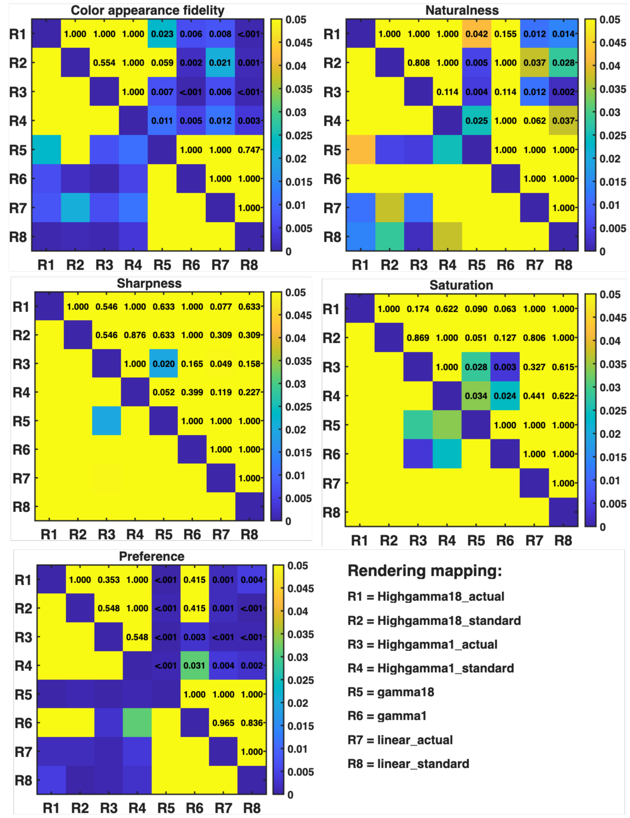

Figure 7: Holm–Bonferroni corrected pairwise comparison of observer ratings, after viewing the real scene (Darker-blue color means more significant difference)

Actual vs standard diffuse white level

Here we compare the samples where the diffuse white in the scene was mapped to its actual luminance level (60 cd/m2), with the samples whose diffuse white was mapped to the standard suggested luminance level (about 203 cd/m2) on the display. The results are shown in Figure 8 and 9, for the experiment before and after exposure to the scene.

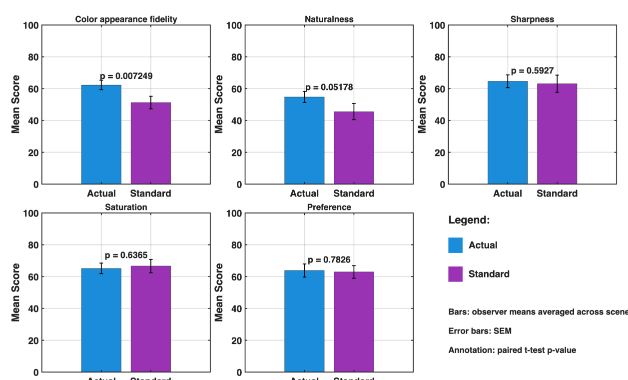

Figure 8: Actual vs Standard reference white level, before viewing the real scene

We applied a paired t-test on the two groups of samples to verify the difference between their mean scores. The actual luminance level samples achieved slightly higher color appearance fi-

Table 4: Comparison of observer ratings between CAT and NoCAT conditions before and after viewing the real scene. Reported values are mean scores, paired-samples t-test results, and corresponding p-values. Statistically significant differences ($p < 0.05$) are shown in bold.

Criterion	Condition	NoCAT Mean	CAT Mean	$t(df)$	p-value	Significance
Color appearance fidelity	Before	49.67	63.85	$t(11) = 2.894$	**0.0146**	Significant
	After	56.46	50.77	$t(11) = -0.841$	0.4182	Not significant
Naturalness	Before	43.04	57.25	$t(11) = 2.720$	**0.0199**	Significant
	After	53.08	50.27	$t(11) = -0.481$	0.6401	Not significant
Sharpness	Before	56.98	70.75	$t(11) = 2.606$	**0.0244**	Significant
	After	58.71	65.12	$t(11) = 0.962$	0.3569	Not significant
Saturation	Before	60.56	71.23	$t(11) = 2.392$	**0.0357**	Significant
	After	62.12	65.85	$t(11) = 0.668$	0.5177	Not significant
Preference	Before	57.90	68.92	$t(11) = 2.392$	**0.0357**	Significant
	After	63.42	64.33	$t(11) = 0.174$	0.8649	Not significant

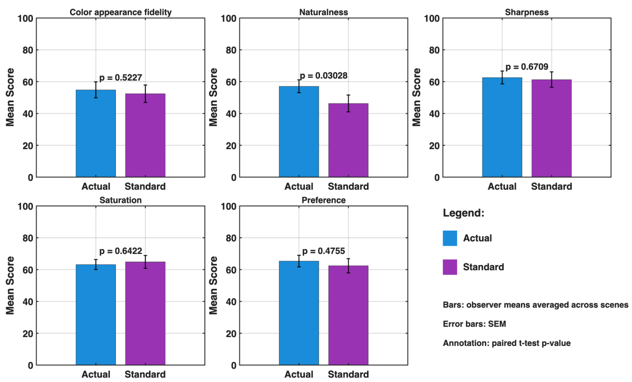

Figure 9: Actual vs Standard reference white level, after viewing the real scene

delity before viewing the scene, and higher naturalness score after viewing the scene. Although for the other criteria, there is no significant difference between the two groups in the scores and preference overall. In this study, we considered only a single HDR scene composed of color targets. However, the preferred placement of diffuse white is known to be scene-dependent, and a more comprehensive analysis should include a wider variety of scene content.

CAT effect

To evaluate the effect of applying chromatic adaptation transformation (CAT) to the display white point (D65), we compared the mean observer scores between CAT and no-CAT conditions across all five criteria and summarized in Table 4. Performing a paired t-test on each pair, shows that before exposure to the real scene, in all 5 criteria, the CAT applied sample achieved a significantly higher score, while after viewing the real scene with the real lighting, there was no significant difference between the two set of samples in any of the criteria. The reason might be that in general, observers tend to favor more neutral renderings; however, after viewing the scene under its warmer illumination, their perception appears to change. Although some adaptation time was provided, it is likely that visual adaptation was not fully achieved, causing the real scene to appear more yellowish. As a result, the renderings without CAT, which also exhibited a warmer, more yellowish appearance, were judged as more faithful, natural, and preferable compared to the evaluations made before viewing the real scene.

Discussion

In this study, we investigated the perceptual impact of rendering strategies, diffuse white level selection, and chromatic adaptation in HDR image reproduction through a controlled observer experiment. The results consistently demonstrate that selective rendering of emissive regions leads to significantly higher perceptual quality compared to globally uniform tone mapping. In particular, selectively rendered images achieved higher scores in color appearance fidelity and overall preference, both before and after exposure to the real scene. This highlights the importance of treating high-luminance emissive elements separately, as global tone mapping fails to preserve their perceptual distinctiveness and visual impact.

The comparison between actual and standard diffuse white levels revealed only minor perceptual differences. While mapping diffuse white to its scene-referred luminance resulted in slightly improved fidelity before scene exposure and higher naturalness after exposure, no consistent or statistically significant advantage was observed across all criteria. This suggests that the preferred diffuse white level is context-dependent and influenced by both scene content and observer interpretation, rather than being governed by a single optimal standard.

The effect of chromatic adaptation (CAT) also depended strongly on observer context. Before viewing the real scene, applying CAT to align the display white with the scene illumination significantly improved all perceptual attributes. However, after exposure to the real scene, this advantage diminished, and no significant differences were observed between CAT and non-CAT conditions. This indicates that visual adaptation to the actual scene illumination plays a critical role, reducing the necessity of explicit chromatic adaptation in the rendering pipeline.

A limitation of this study is the use of a single HDR scene with controlled color targets. While this setup enables accurate measurement and analysis, key aspects of HDR rendering—such as diffuse white placement and emissive tone mapping—are inherently scene-dependent. Future work should therefore investigate perceptually guided approaches for emissive tone mapping and diffuse white selection across a broader range of scene types and content.

Conclusion

Overall, the results demonstrate that selective tone mapping of emissive regions is a critical factor for achieving high perceptual quality in HDR rendering. By preserving highlight structure and avoiding clipping, selective approaches provide improved fidelity and preference compared to global methods. In contrast, the effects of diffuse white placement and chromatic adaptation are more context-dependent and influenced by viewing conditions and observer adaptation.

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