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HDR Image Visual Matching and Tone Mapping based on CAM16-UCS

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Abstract

A controlled experimental setup used multichannel LED lighting to create HDR scenes. Ten observers performed visual matching tasks between real illuminated scenes and HDR display content across eight lighting conditions. $J_za_zb_z$, CIECAM16, and CAM16-UCS were evaluated, analysis using STRESS metrics showed CAM16-UCS achieved the best performance for both lightness and colorfulness predictions. Based on these findings, a tone mapping operator was developed utilizing CAM16-UCS color space with local adaptation and gamma adjustments derived from experimental data. The results demonstrate that CAM16-UCS provides superior color appearance prediction for HDR content and serves as an effective foundation for tone mapping applications.

Introduction

High dynamic range (HDR) imaging has become increasingly important in various applications including photography, cinematography, and display technology. HDR images capture a wider range of luminance levels than traditional standard dynamic range (SDR) images, more closely representing the visual experience of real-world scenes. However, displaying HDR content presents significant challenges due to the limited dynamic range of most display devices and the complex nature of human visual perception under varying lighting conditions.

Tone mapping operators (TMO) are essential for compressing the dynamic range of HDR images to match display capabilities while preserving perceptual attributes such as lightness, colorfulness, and overall appearance. The effectiveness of TMOs largely depends on their ability to predict how colors appear under different viewing conditions, making color appearance model (CAM) crucial component in their design.

Traditional color spaces and appearance models were primarily developed for SDR content and may not adequately handle the extended luminance ranges and viewing conditions associated with HDR imagery. Recent developments in color science have introduced new models specifically designed for HDR applications, including $J_za_zb_z$ [1], CIECAM16 , and CAM16-UCS [2]. However, their relative performance for HDR content has not been thoroughly evaluated through controlled psychophysical experiments.

This research addresses these challenges through a systematic approach combining experimental validation with practical implementation. Controlled visual matching experiments were conducted where observers matched HDR display content to real illuminated scenes under various lighting conditions. The experimental data was used to evaluate the performance of different color appearance models and uniform color spaces to develop an improved tone mapping operator.

HDR Matching Experiment

The experiment is about ‘matching’ the carefully designed illumination to simulate real scene and HDR contents on a display, then the images will be analysis based on tristimulus values.

Matching Settings

We have established carefully designed illumination room to simulate real HDR scene using multichannel tunable LED lighting system. A painting was illuminated by two sets of lights, named global lighting and local lighting, the former includes four large LED light panels, providing an uniform lighting on the painting at a contrast of 20:1 by the reflectance difference between white and black ink. Local lighting is a separate LED spotlight equipped with Fresnel lens illuminate the sun area to simulate highlight, which can illuminate up to 5000:1 contrast ratio between brightest sun area and darkest shadow area without unnatural looks. Figure 1 illustrates the painting under the two-part lighting that creates controllable HDR contrast.

Figure 1. *Painting illuminated by two lightings to create a controllable HDR scene up to 10000 cd/m^2 and 5000:1 contrast ratio.*

An experimental room is devoted for this type of cross media color matching experiment. It includes two separate rooms side by side. In this experiment, a painting and lighting system are placed in one dark room, while the other rooms include a display and observer . The wall between two rooms has a square window in a suitable position, to make the painting to cover observers’ entire view. In the other room, an HDR display with peak luminance of 1600 cd/m^2 and P3-D65 color gamut has been placed beside the window. This setup allows observers to see the real painting and image side by side to perform precise matching. Figure 2 shows the two-room side-by-side matching arrangement and Figure 3 shows the observer’s view and task at the HDR display.

Images are captured by a full-frame digital camera Nikon Z6 with multiple exposure shots to reduce noise or clipping. To

Figure 2. *Matching experiment setup: left is a dark room where observer and HDR display, right is lighting system and the painting, the wall in center has a square hole.*

Figure 3. *HDR display is put beside the square hole, observer can only see the painting through the hole, the task for observer is to match the content on screen with scene in the hole.*

achieve HDR peak luminance on display and advanced adjustments, including localized region masking and highlight/shadow control for professional users to use, observer will use Adobe Camera Raw ® to process images and color manipulation.

Ten observers have participated the experiment, each observer needs to match in 8 different lighting settings listed in table 1. All observers are art and design students, or professional photographers. Prior to the experiment, are taught how to use the software before matching and use another image and scene setting as practice. The start point for them is a basic white balanced and color corrected image with linear opto-optical transfer function.

Table 1: Lighting settings by control two parts of light, the unit for luminance in the table is cd/m^2.

Index	Peak	Background	Darkest	Contrast
1	600	9.8	2.9	207
2	3000	49.4	14.7	204
3	6000	98.7	29.2	205
4	1538	49.4	15.0	103
5	1318	9.8	3.0	439
6	1269	1.0	0.3	4881
7	1347	242.5	66.0	20
8	273.9	49.3	13.0	21

Each observer took about 15 minutes to match one image, settings with high overall luminance or contrast need more time to adjust in general. After the observer finished all eight images, the scene was played back and their results were displayed again. They should be satisfied with their results otherwise they could do further refinement.

Camera and Display Characterization

After image capturing and observer adjustment, the camera's RGB and display RGB values for each pixel is obtained, which are in device-dependent color space and need a conversion from RGB to device-independent tristimulus values for further analysis or so called characterization.

Camera characterization model was developed by measuring the spectral power distributions (SPD) on two color charts and the corresponding camera response values. Two color charts are Digital SG from X-rite (140 patches, 96 used) and preferred memory color chart (PMCC, 30 patches), SG for training and PMCC for testing. Tristimulus values calculated from SPD using CIE 1964 10 degrees standard observer's color matching function, the matrix between XYZ and RGB is ninth-degree polynomial [3] shown in Eq. (1) and least squares method.

$$\rho_9 = \{R,\ G,\ B,\ RG,\ GB,\ RB,\ R^2,\ G^2,\ B^2\} \tag{1}$$

The ninth-degree polynomial has slightly better performance than traditional 3-by-3 matrix in this fixed high quality lighting case, average CIEDE2000 [4] between estimated XYZ values and ground truth XYZ values on PMCC is 2.36.

Two characterization models for HDR display have been compared: Piecewise Linear assuming Chromaticity Constancy (PLCC) [5] and 3D Lookup Table (LUT) [6]. For Apple ProDisplay XDR in our case, it has clipping strategy after beyond peak luminance for PQ signal and constant chromaticity coordinates, the PLCC has better performance than 3D-LUT with fewer sampling points, the average CIEDE2000 between 30 PMCC color RGB signals' corresponding XYZ values and estimated XYZ values is 0.56.

After characterization, absolute XYZ values for both scene and display are successfully estimated. These images in XYZ color space can be considered as pairs of corresponding images that match under the experimental viewing conditions.

Analysis

The images in XYZ color space from experiment can be used to compare different color appearance models and uniform color spaces.

For HDR applications, three color appearance models and uniform color spaces—$J_za_zb_z$, CIECAM16, and CAM16-UCS—were selected for comparison. STRESS was used to evaluate the performance of each model's predictions, as shown in Eq. (2), where V_i is the perceptual attribute (e.g., lightness) predicted from the scene XYZ and E_i is the corresponding value predicted from the display XYZ using the same appearance model. STRESS quantifies the relative perceptual error across all pixels, a lower value indicates better predictive performance. The ratio between the scene and display attribute values should be close to 1.

$$\mathrm{STRESS} = 100\sqrt{\frac{\sum(E_i - V_i)^2}{\sum V_i^2}} \tag{2}$$

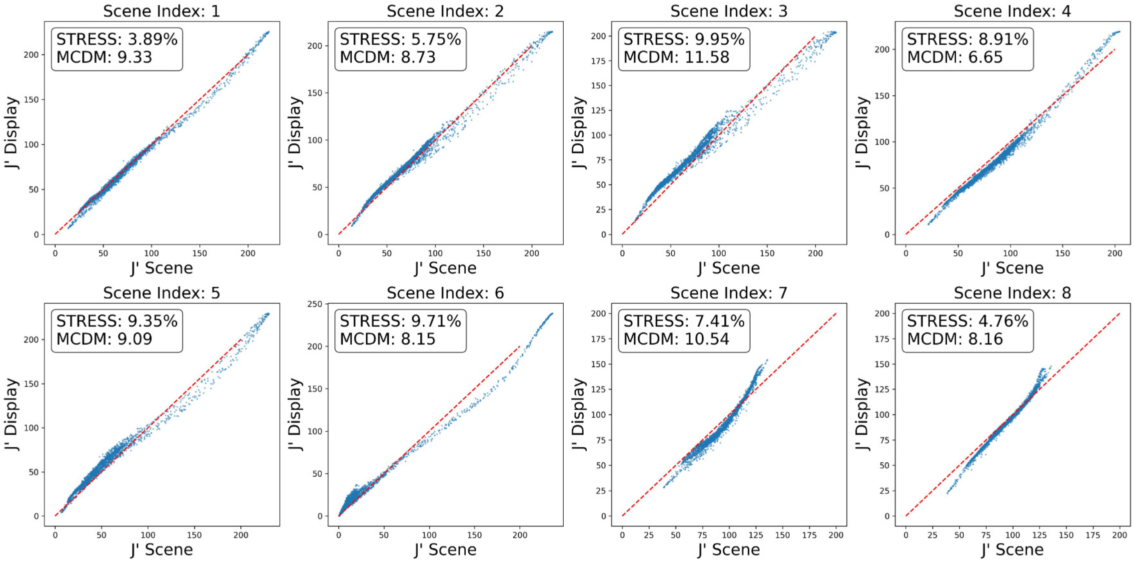


Figure 4. *Lightness prediction based on CAM16-UCS demonstrates consistently high performance across a diverse set of scenes, as indicated by the low STRESS values in most cases. MCDM (Mean of Color Differnece from Mean) has been used to analyze inter-observer variation, the results indicate a reasonabe consistency between observers.*

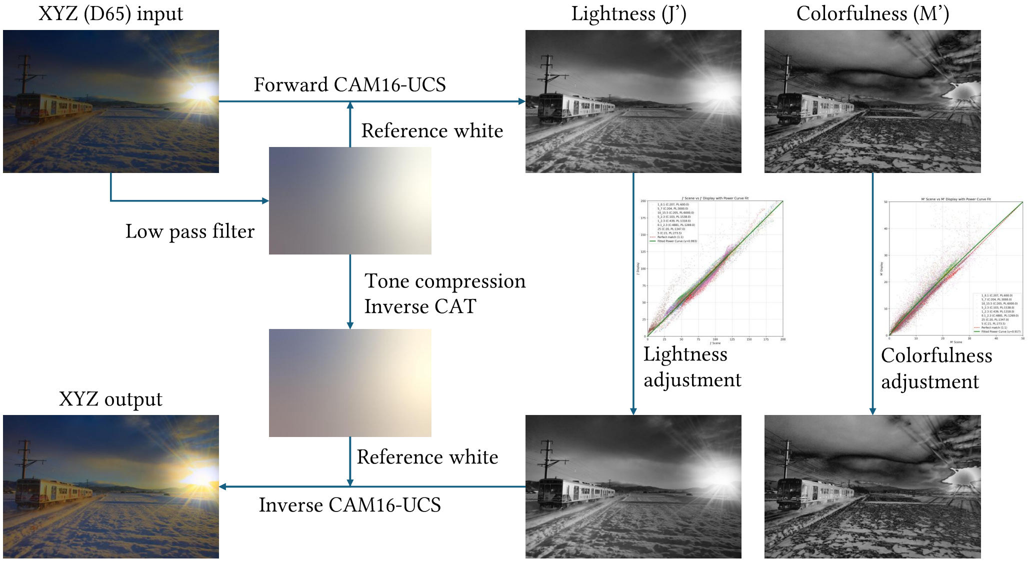


Figure 5. *The pipeline of tone mapping method based on CAM16-UCS and experiment result.*

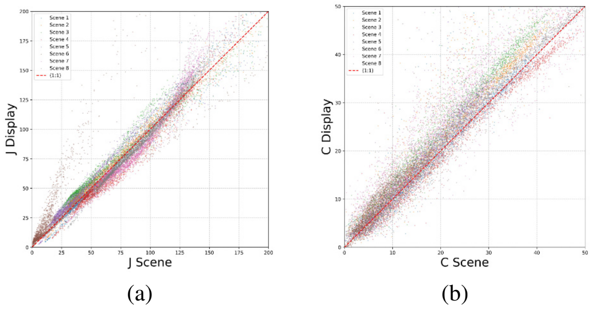
When calculating color appearance attributes, its important to choose a proper reference white and viewing conditions, especially for HDR usage. The iCAM framework [7, 8] was used to apply a low pass filter to blur the image and use as the white point for corresponding pixel, which serves as a local adaptation reference and improve the performance for high contrast and HDR situation.

Lightness predictions for every scene have been plot in Figure.4 using CAM16-UCS.

Table 2: STRESS values for lightness and colorfulness predictions.

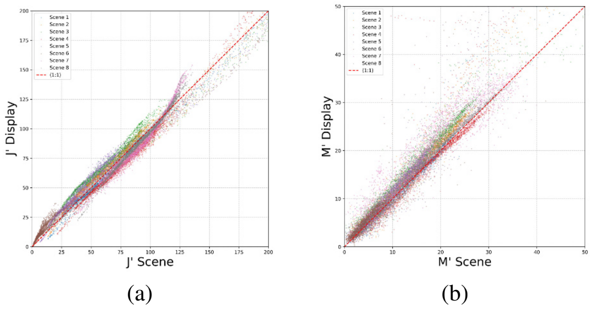
Model	Lightness	Colorfulness
$J_z a_z b_z$	13.07	28.08
CAM16-UCS	**7.58**	**19.65**
CIECAM16	14.64	25.11

CAM16-UCS achieves the lowest STRESS values for both lightness and colorfulness, indicating the best overall prediction accuracy among the tested models. $J_z a_z b_z$ shows competitive performance for lightness but performs less well in terms of colorfulness STRESS. CIECAM16 lags slightly behind CAM16-UCS for both attributes.



(a) (b)

Figure 6. Lightness (a) and Chroma (b) comparison in CIECAM16



(a) (b)

Figure 7. Lightness (a) and Colorfulness (b) comparison in CAM16-UCS

2D-Scale derived from uniform color space [9] can also be used to analysis the relationship between two corresponding images. Here, vividness from CAM16-UCS has been discussed, it can be calculated from lightness and colorfulness as Eq. (3).

$$V = \sqrt{J'^2 + 2.6M'^2} \tag{3}$$

By adjusting the coefficients of lightness and colorfulness, vividness could be optimized slightly on the STRESS scale (7.54 to 7.48), the improvement is limited.

$$V = \sqrt{1.635J'^2 + 2.215M'^2} \tag{4}$$

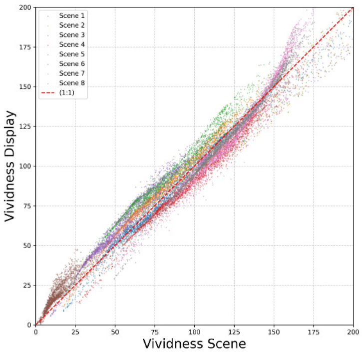
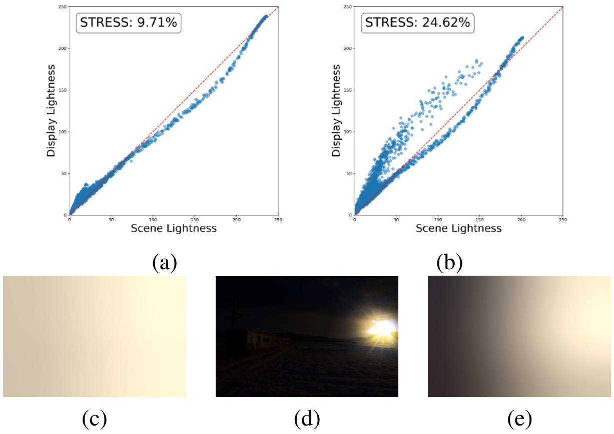


Figure 8. Vividness derived from CAM16-UCS after optimizing coefficients, STRESS: 7.48, R^2: 0.976

It is worth noting that, for high-contrast scenes such as Index 6, the degree of blurring in the white reference image is crucial, as shown in Figure 9. If an insufficiently blurred image is used as the reference white to calculate CAM16-UCS, as in (e), the lightness of dark areas will be overestimated, resulting in two distinct trends in (b) and leading to poor performance. Using a higher degree of blurring can help fix this issue.



(a) (b)

(c) (d) (e)

Figure 9. Effect of reference image blurring on CAM16-UCS lightness mapping accuracy, quantified by the STRESS metric. (a) Using a highly blurred reference white image yields a decent STRESS (9.71) and a coherent lightness relationship. (b) Using an insufficiently blurred reference white image severely disrupts lightness prediction, produces dual clustering and results in a much higher STRESS (24.62). (d) Original Scene image. (c, e) Visualization of reference white images at different blur levels.

Tone Mapping Based on CAM16-UCS

A tone mapping method has been developed based on results above and CAM16-UCS, as shown in Figure 5. Similar to previous iCAM and TMOz [10], the method adopts a blurred image for reference white point determination in calculation of color appearance.

The input should be absolute XYZ tristimulus values, which can be predicted from camera response and exposure parameters or HDR content with known transfer functions.

Then, use CAT16 to predict XYZ under D65 condition, because the model and experiment data performs best under D65 illuminant, the original white point will be consider in the inverse CAT16.

Apply a low pass filter to get a blurred “White” reference from original XYZ, the blur should be strong to avoid inconsistency. Then, apply CIECAM16 and CAM16-UCS with white for individual pixel and viewing condition from absolute luminance or user to predict lightness and colorfulness for every pixel.

From experiment above, a slight adjustment is applied for colorfulness to fit visual results better, here a gamma function derived from experiment has been used as shown in Eq. (5), with the colorfulness normalized at 50, respectively, according to the general HDR image M' distribution in our dataset is between 0-50. As demonstrated in Table 3, the performance shows slight improvement after attribute adjustments. The lightness cannot be effectively optimized using a simple mathematical function so no adjustment will be applied for J'.

$$M'_{\text{output}} = \left(\frac{M'}{50}\right)^{0.91} \times 50 \tag{5}$$

Table 3: STRESS values for appearance attributes before/after adjustment.

Attribute	Before	After
Colorfulness	19.65	18.13
Vividness	7.54	7.37

Other adjustments to fine tune the effect can also be applied on CAM16-UCS attributes, such as an S-shape curve on lightness to increase the contrast, or increase vividness by adjusting lightness and colorfulness.

The reference white image before need to do tone compression and inverse CAT to predict the reference white for display, this controls the overall contrast and predicts the incomplete chromatic adaptation from original white point to D65.

Using inverse CAM16-UCS and CIECAM16 to convert lightness and colorfulness back to XYZ values under display viewing condition, then the XYZ values can be convert to device-dependent RGB color space and apply transfer function for display.

Original image GT from observer Our TMO

Figure 10. The result of tone mapping method based on CAM16-UCS and experiment result.

The compute cost of the current pipeline is high, primarily due to one low-pass filtering and two full CAM16-UCS conversions. This implementation is a conceptual validation and has not been optimized for practical use. We are aware of the need for comparative performance evaluation and plan to address it in future work. Meanwhile, computational optimizations such as reducing unnecessary color attribute calculations, employing simpler filters, and developing GPU-friendly implementations are under consideration to improve runtime efficiency.

Conclusion

This study confirms, through controlled psychophysical experiments, that CAM16-UCS provides better performance for predicting color appearance in HDR scenes compared to $J_z a_z b_z$ and CIECAM16. Leveraging this finding, a tone mapping operator was developed. The operator integrates CAM16-UCS with local adaptation and gamma adjustments derived from the experimental data. The results validate CAM16-UCS as an effective foundation for HDR applications and provide a perceptually-grounded tool for faithful HDR image reproduction.

Our observer pool (N=10) consists of art/photography-experienced participants, which benefits stable controls but may bias judgments relative to naive viewers. Moreover, we used a single scene under eight lighting conditions; while the luminance and contrast span is broad, content diversity remains limited.

Future work will expand the participant demographics, scene types, and materials, conduct inter-lab replications, and explore the model’s performance under extreme contrast conditions, while extending the evaluation to include more diverse scene content and viewing environments to further validate the generalizability of these findings.

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