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Towards a Perceptually-Motivated Color Space for High Dynamic Range Imaging

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Abstract

To reproduce the appearance of real world scenes, a number of color appearance models have been proposed thanks to adapted psycho-visual experiments. Most of them were designed and intended for a limited dynamic range, or address only dynamic range compression applications. However, given the increasing availability of displays with higher luminance and contrast ranges, a detailed analysis of appearance attributes is also necessary for dynamic range expansion scenarios. In this study, we propose a psycho-visual experimental setup, designed by adapting and combining the adjustment and partition scaling methodologies, which we employ for measuring perceptual colorfulness of color patches with different levels of lightness, chroma and hue. The proposed setup reduces the complexity and increases the efficiency relative to previous experimental setups and allows both expert and non-expert participants to be included. From the collected data, a modified color space is obtained and a new saturation model for dynamic range compression and expansion is derived for high dynamic range imaging.

Introduction

When observing an object or material in a real scene, the light reaching our eye is processed and eventually reinterpreted in order to give us an impression of that object's appearance. For many applications, it is thus useful to describe the appearance of objects according to characteristics corresponding to our perceptual processes. For that purpose, several perceptual color spaces and color appearance models have been defined [37, 33, 30].

Most such models have been designed based on reflective objects in the luminance range of slightly above zero and perfect diffuse white [40, 10, 17, 8, 25, 22]. As such, these models may not be directly applicable to high dynamic range (HDR) applications, where higher luminance and contrast ranges need to be considered. To address this limitation, several color and image appearance models have been designed using HDR stimuli as their basis [21, 19, 7, 31]. Although these models offer complete predictions of appearance, covering several complex appearance phenomena, they require a complete description of the scene and viewing environments, making them impractical for many imaging applications.

In contrast, perceptual color appearance models, such as CIELab or IPT [29], offer a reasonable trade-off between perceptual accuracy and complexity of application. Similar to traditional color appearance models, they have also been designed with low dynamic range (LDR) applications in mind. Both spaces were extended to HDR versions recently, however they were found to offer less accurate predictions compared to their original versions when evaluated against perceptual data [14].

Given the increasing availability of HDR displays even in the consumer market, accurate but computationally efficient methods for color management and reproduction that extend to higher luminance and contrast levels are becoming necessary, both for content creation and consumption applications. For instance, recent standards, such as ITU-R BT.2020 [35], are likely to be implemented in upcoming HDR displays and include a very wide color gamut, necessitating gamut transforms. Consequently, perceptually accurate color spaces that can extend to these luminance ranges are necessary.

With this in mind, in this work, we measure the perception of chroma for different levels of adapting luminance, reaching up to 4000 cd/m^2 and evaluate the ability of existing perceptual models at predicting the resulting data. To achieve this, we design and perform a psycho-visual study based on the partition scaling methodology, which provides us access directly into the perception of chroma of the observers.

In the partition scaling methodology, observers find the midpoint between the appearances of two stimuli [24, 18]. Traditionally, this technique has been used for lightness modeling using reflective patches [7, 6]. In contrast to previous work, we employ this technique for measuring chroma, using emissive patches on an HDR display and covering several levels of adapting luminance as well as several hues. By presenting patches with the same hue and perceptual lightness, we can determine equal distances along the chroma dimension as perceived by observers. Combined with absolute radiometric measurements of the experimental stimuli, this data allows us to evaluate the predictions of existing chroma functions for the studied luminance levels.

In addition, we have seen that existing HDR appearance models and color spaces are designed with the intention of dynamic range compression [21, 19, 7, 31]. As shown in a recent perceptual comparison of HDR appearance models and inverse tone mapping operators [2], their non-linear and compressive functions creates more desaturated results in cases of dynamic range expansion applications.

Therefore, for more accurate dynamic range expansion and compression applications, we propose a perceptually motivated space based on the findings from our proposed experimental protocol. The proposed space combines our previous LDR and HDR lightness models together with CIELab based color opponent components computation as well as a new perceptual saturation model. We evaluate the proposed model for the case of dynamic range expansion and compression through comparisons against existing HDR color appearance models, perceptual color spaces as well as a representative reverse tone mapping operator.

Generally, in this work, we present the following contributions:

- A new experimental setup based on the method of adjustment and partition scaling, which is used to measure several perceptual appearance properties of emissive stimuli.
- A detail analysis of color appearance attributes under extended range of luminance levels.
- A complete HDR color space.
- A novel saturation model for HDR imaging application.

Related Work

To understand and model color appearance of simple and complex stimuli, several psycho-visual studies have been performed [33, 11, 38]. The goal of such studies is to link physical properties of patches or images to perceptual appearance qualities, allowing for mathematical models to be constructed that can predict or modify appearance in a controlled and perceptually accurate manner. Here we discuss key studies and experimental methodologies as well as relevant appearance models.

Color Appearance Studies Most traditional color appearance models were designed based on the LUTCHI dataset, which was gathered through a perceptual experiment following the magnitude estimation methodology [23]. The observers estimated lightness, chroma and hue of presented stimuli relative to a provided reference white and reference colorfulness stimuli for different media and viewing conditions. However, the luminance range of the stimuli used was limited to 690 cd/m^2 which affects the models' accuracy for appearance predictions under higher luminance ranges. For this reason, Kim et al. extended the dataset towards a wider range of luminance level, up to 16.860 cd/m^2 [19].

In both experiments, observers were presented with a reference stimulus with arbitrary perceptual attribute values and asked to directly quantify the corresponding perceptual attribute of another stimuli. To accurately quantify a perceptual dimension however, observers need to to be experienced color experts. Also, to sufficiently sample an extended range of luminance, a large number of stimuli is required, increasing the experiment duration. Therefore, in such a type of experiments, observer fatigue may negatively affect the accuracy of results, while at the same time, a large number of appropriate observers is difficult to find.

Another psycho-visual experiment based on the partition scaling methodology was employed for perceptual lightness scaling below and above diffuse white [7]. Observers in this study were presented with three patches printed on glossy paper and mounted on a wall and they were asked to adjust a projector illuminating the right-most patch so that the three patches were equidistant in terms of their perceptual lightness.

Our experiment expands on the ideas presented by [7] in their study of reflective patches, extending their design to emissive stimuli. A new study is necessary as findings from reflective patches cannot be directly applied to emissive display applications: reflective patches induce an 'object' mode of viewing, whereas emissive displays induce a 'non-object' mode of viewing [27, 11]. Our methodology uses emissive high dynamic range displays, and therefore our results, model as well as conclusions pertain to such displays.

Appearance Models and Color Spaces Studies such as the ones described above have led to a multitude of appearance models of varying levels of complexity. At the simplest case, color spaces such as $CIEL^*a^*b^*$ and IPT offer a chromatic adaptation model as well as predictions of lightness, chroma and hue appearance attributes, requiring only an adaptation white point as input. Both are color-opponent spaces with dimension L/I encoding lightness and a/P and b/T encoding the color-opponent dimensions, based on nonlinearly compressed XYZ coordinates [33, 37]. However, such models cannot consider the full appearance of the scene.

For more complete predictions of scene appearance, additional factors like luminance and hue-dependent effects, spatially structured phenomena, and more viewing condition related phenomena should be considered. Therefore, a more complete color appearance model proposed by Hunt et al. [15]. This model included non-invertible formulations of appearance attributes and hence was not widely used. However, together with models proposed by other researchers [26, 11], the model plays a significant role as the main building block in the development process of more practical, simpler and yet complete color appearance models, such as CIECAM97s [17] and CIECAM02 [25].

Although several of these models are widely used and validated, they are not suitable for modeling scene appearances under a wide range of illumination as they are designed based on low dynamic range datasets [23]. In an effort to extend existing models towards HDR, modifications were proposed for both CIELAB and IPT color spaces, termed hdr-CIELAB and hdr-IPT respectively [14]. The $CIEL^*a^*b^*$ and IPT color spaces power function was replaced by the MichaelisMenten equation, following physiological models of human vision. For more complex images with spatially varying structure image appearance models such as s-CIELAB [39] and iCAM [13] have been proposed, considering local adaptation aspects. These have been subsequently extended to HDR, notably with the introduction of iCAM06 [20], followed by the models of [19] and [31].

In recent years, HDR displays have been commercialized, leading to HDR content being increasingly available and therefore necessitating solutions for adapting content to displays of potentially different dynamic range and luminance capabilities. Existing HDR-capable appearance models have been designed with dynamic range compression in mind, however they are less suited to dynamic range expansion applications. A recent study comparing several dynamic range expansion solutions shows that existing appearance models are significantly outperformed by simple reverse tone mapping operators (rTMOs) when comparing the resulting images with the corresponding HDR ground truth, even though rTMOs tested operated only on luminance and did not consider scene or viewing conditions [2].

Effectively, although existing solutions address several aspects of appearance, as of now, no complete model is capable of modeling color appearance in the context of dynamic range compression and expansion, despite a clear need for one. To that end, this work aims to measure and analyze color appearance attributes in order to propose models considering a wider range of dynamic range management and color applications.

An Overview of the Experiment

To measure perceptual attributes under extended luminance levels in an efficient manner, without requiring expert participants, we have conducted a psycho-visual experiment based on a novel methodology combining both methods of adjustment and partition scaling. We let the observers control the colorfulness of a uniform patch until it appeared to be perceptually half-way between an achromatic and a chromatic reference patch. To study colorfulness under different luminance levels, a reference white patch was included during the adjustment of every experimental stimulus.

We used a calibrated 47” SIM2 HDR display, with a maximum luminance level of 4000 cd/m^2, and HDTV resolution (1920x1080 pixels) to display the stimuli [34] in a darkened room. Observers were placed at a distance of 3 times the screen height and used a keyboard connected to a laptop to provide input and adjust the colorfulness of the patch.

Stimuli

To sufficiently represent the entire gamut of the HDR display while keeping the number of stimuli manageable, we sampled the cylindrical representation of the $CIEL^*a^*b^*$ color space based on linearly spaced lightness, chroma and hue levels. For sampling the hue space, we only consider 5 major hues ($35°, 90°, 136°, 306°$ and $345°$) in this study. The $CIEL^*a^*b^*$ $35°, 136°, 306°$ hues correspond to the hues of the RGB primaries of the display, while hues of $90°$ and $345°$ approximately correspond to yellow and purple patches. The $[0, 100]$ range of the lightness space is sampled into 5 linearly spaced levels whereas the $[0, 127]$ range chroma space is sampled into 4 linearly spaced chroma levels. In total we generate 100 stimuli plotted within the $CIExy$ chromaticity diagram in Figure 1, which approximately span the entire color gamut of the HDR display.

For the computation of the Cartesian components of $CIEL^*a^*b^*$ patches which span a wide range of colors within an extended luminance range of up to 4000 cd/m^2, the reference white of the SIM2 HDR display, $X_nY_nZ_n = [3854.4, 4377.2, 4312.6]$ is used. We have transformed the XYZ values to SIM2 display RGB values using the 3×3 matrix M_{sim2} and look-up tables RGB_{LUT} according to Eq. 1, 2 and 3 generated from a characterization of the SIM2 display using the PR670 spectrophotometer.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} \begin{bmatrix} RGB_{LUT}(R') \\ RGB_{LUT}(G') \\ RGB_{LUT}(B') \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_{\text{sim2}} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{2}$$

where,

$$M_{\text{sim2}} = \begin{bmatrix} 3.3704 & -1.3948 & -0.5491 \\ -1.0111 & 1.8606 & 0.0304 \\ -0.0410 & 0.0160 & 0.9633 \end{bmatrix} \tag{3}$$

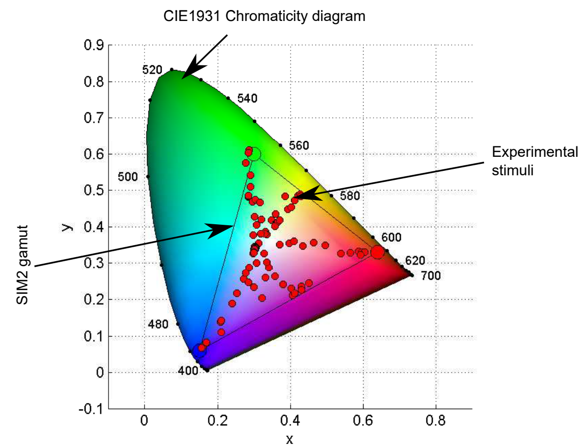


Figure 1. *The tristimulus values of the experimental stimuli and the gamut of SIM2 HDR display plotted in CIE1931 chromaticity diagram.*

As shown in Figure 2, the observers were presented with four patches within each trial. A reference patch of 200×200 pixels set to the value of the reference adaptation white $X_nY_nZ_n = [3854.4, 4377.2, 4312.6]$ was presented at the top center of the display while the other three 400×400 pixel patches were presented at the bottom part of the display. For each individual hue level the observers were presented, on the bottom left side of the screen, with 20 chromatic patches in randomized order, which varied in their lightness and chroma values only. On the bottom right, achromatic patches with the same luminance levels, same hue and zero chroma values were presented. The observers were asked to adjust the central patch of the row which has the same hue and luminance level as the left reference patches. The space between patches was filled with a $1/f$ noise pattern with an average background luminance of 2 cd/m^2 to simulate second order statistics that match those of natural images [28].

Procedure

In total, 15 participants (9 female, 6 male) took part in our experiment, with ages varying between 24 and 57 years ($\mu = 38.4, \sigma = 10.78$). Prior to the experiment, participants were asked to *“adjust the central patch so that it looks to be in the middle of the left and the right patches”*. All observers took a short training of one example trial to allow them to adapt to the viewing environment and to familiarize themselves with the experimental setup and controls. The observers took an average of 40 minutes to complete the entire experiment.

The observers used the provided computer keyboard to adjust the chroma value of the test patches in smaller or larger increments using different keys within the $[0, 100]$ range of chroma. The test patch was initialized at a random chroma level. When the observer finished the adjustment, the return key was used to pass

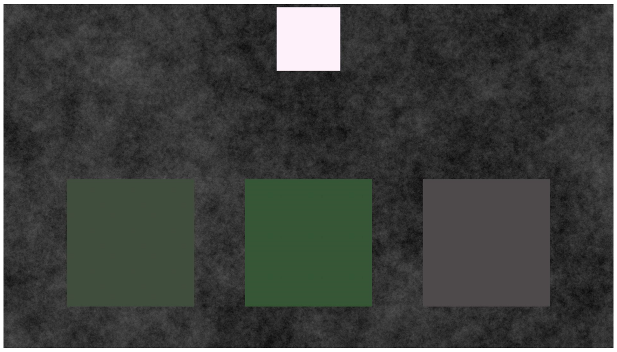


Figure 2. *Colorfulness experiment example stimulus. The top patch represents the reference adapting white point of the display, while the bottom patches depict the maximum Chroma on the left, the minimum Chroma on the right and the observer adjustable patch at the center.*

to the next trial. After each trial, the lightness, chroma and hue values of all three patches were recorded. The same process was repeated for all of the 100 experimental patches.

After the experiment was finished, all the recorded values for each participant were again reproduced on the display and measured using the PR670 spectrophotometer to ensure that accurate physical measurements were used in subsequent evaluations and modeling steps.

Experimental Data

The chroma values of the 100 patches, described in Section , were collected for 15 observers. The summary of the gathered adjusted chroma values for each of the five principal hues (red, green, blue, yellow and purple) with their respective 5 levels of lightness are shown in Figure 3. The bar plots show the observers' mean adjusted chroma values corresponding to the half colorfulness of the reference patches with the corresponding error bars indicating the 95% confidence intervals. The confidence interval bounds are computed based on the respective standard deviation values of the adjustments. In agreement with the Hunt effect [33, 17, 37] observers perceive increased colorfulness with increasing lightness and hence score higher chroma values.

To assess the variation among observers' decisions, we have performed analysis of variance (ANOVA) and the average F and p results of the chroma adjustments for the different hue and luminance levels are given in Table 1. Higher values of p and lower values of F indicate the positive correlation of each observer's decision for all principal hues and lightness ranges. No significant differences were found in individual chroma adjustments, suggesting that participant responses were consistent.

Average correlation of individual observers' adjustments with mean adjusted chroma.

Hues	90°		180°		270°		360°	
LightnessLevels	F	p	F	p	F	p	F	p
$L = 0.1$	2.5093	0.0829	0.7395	0.5389	1.9998	0.1409	0.5721	0.6388
$L = 0.325$	1.6703	0.1999	0.3138	0.8152	1.0361	0.3944	0.9879	0.4152
$L = 0.55$	0.8895	0.4607	0.6809	0.5723	1.1291	0.3571	0.4672	0.7079
$L = 0.775$	0.3992	0.7548	0.5685	0.6411	0.8213	0.4949	0.5220	0.6713
$L = 1.0$	0.7932	0.5097	1.1178	0.3614	0.6748	0.5759	0.9068	0.4524

The visualization of the average tri-stimulus values of the reference and estimated patches in the CIE1931 chromaticity diagram shown in Figure 4 demonstrates the hue variation of the measured experimental patches generated due to the limitation of sRGB color gamut of SIM2 HDR display. From the figure, we can observe the hue changes as the CIELab chroma and luminance values are changed. This in turn shows the inseparability or dependencies of CIELab cylindrical coordinates. In addition, as it can be seen in Figure 5, sRGB gamut has a limited range of chroma values in $CIEL^*a^*b^*$ cylindrical and Cartesian spaces and the range varies with hue. Since the color gamut of the SIM2 display is very close to sRGB, the figures explains the reason why maximum chroma values vary with luminance and hue changes.

Most of the time, chroma is the least uniform dimension of a color space, because not all colors can achieve the same level of chroma. For instance a highly saturated red can have a chroma that exceeds 25, while a green may only reach a chroma of 12-14. In particular, towards the black and white ends of the neutral axis, chroma becomes very limited. This behavior is also demonstrated in the Munsell system and particularly Munsell's color tree where we observe different lengths of chroma for different branches.

Proposed HDR Color Space and Saturation Model

For an accurate perceptual attribute modeling under extended luminance, we have combined the lightness models computed based on our previous findings based on lightness experiment [1] and color-opponent processing of the human visual system to construct an improved HDR color space.

Description of the Color Space

We have designed a $CIEL^*a^*b^*$-like color-opponent space which similarly has dimension L for lightness and, a and b for the color-opponent dimensions, based on nonlinearly compressed XYZ coordinates. For a given XYZ value of a stimulus and $X_nY_nZ_n$ of the reference white our proposed color space is constructed as follows:

$$L_{\text{new}} = f_{\text{new}}(Y, Y_n) \tag{4}$$

$$a_{\text{new}} = f_{\text{new}}(X, X_n) - f_{\text{new}}(Y, Y_n) \tag{5}$$

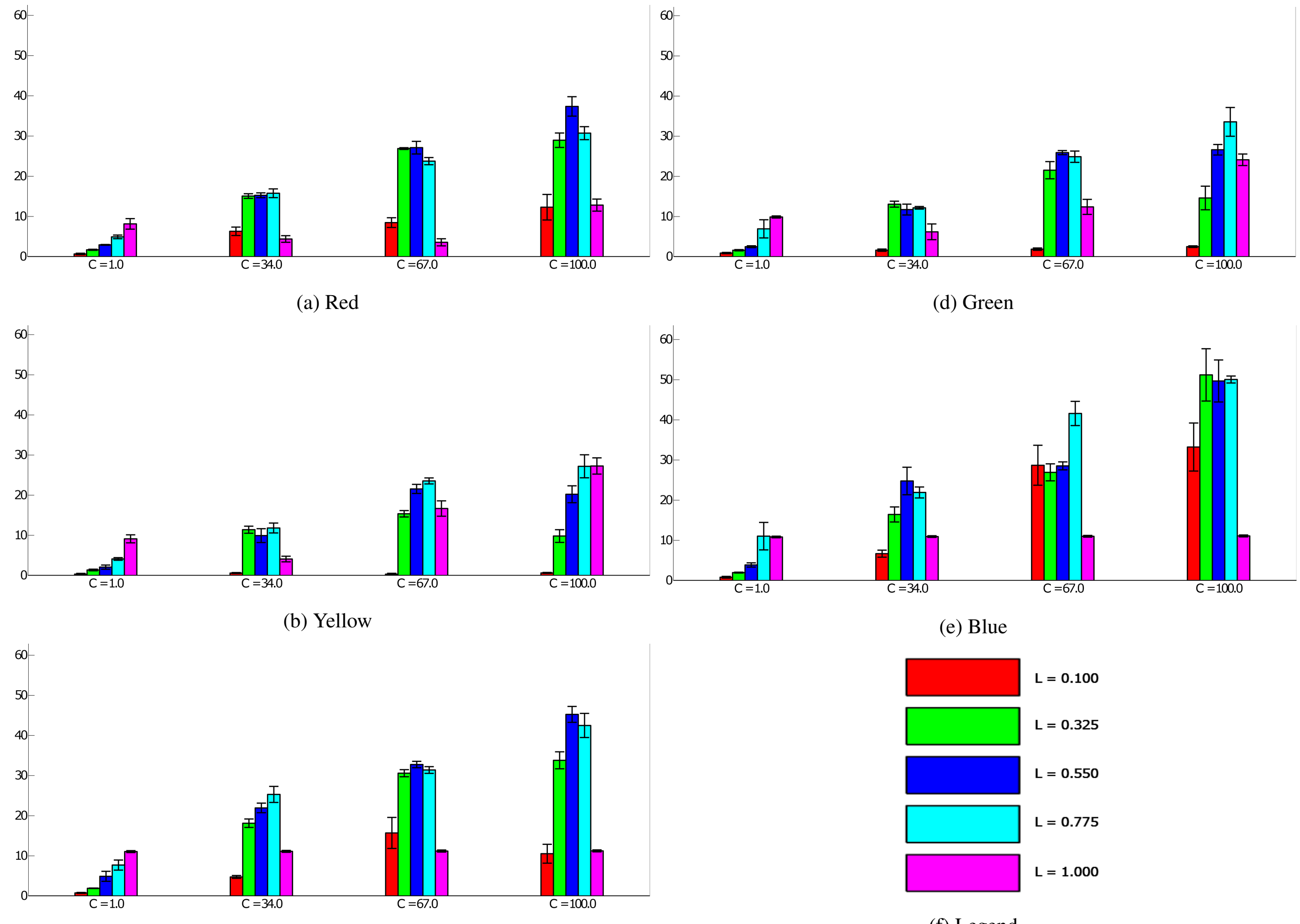
$$b_{\text{new}} = f_{\text{new}}(Y, Y_n) - f_{\text{new}}(Z, Z_n) \tag{6}$$

where,

$$f_{\text{new}}(W, W_n) = \begin{cases} 1.266 \left(\frac{Y}{Y_n}\right)^{0.266} - 0.266 & \text{if} Y_n \leq 100cd/m^2 \\ (1.127) \left(\frac{Y}{Y_n}\right)^{0.23} - 0.127 & \text{if} Y_n > 100cd/m^2 \end{cases} \tag{7}$$

The corresponding lightness L_{new} and opponent color components a_{new} and b_{new} are computed according to Equations 4 - 6, where the function f_{new} is defined as our previously defined power-law lightness model [1] given as in Equations 7.

The lightness L_{new} value of the space ranges from 0 to 1 whereas the values of a_{new} and b_{new} are within the range of [-1,1]. As in the Hunt color appearance model and the $CIEL^*a^*b^*$ color space, the a_{new} and b_{new} components represent neutral gray



(a) Red (d) Green (b) Yellow (e) Blue (c) Purple (f) Legend

Figure 3. *Mean chroma values of the adjusted patches for all the five lightness and hue levels.*

values at $a_{\text{new}} = 0$ and $b_{\text{new}} = 0$. The red/green opponent colors are represented along the a_{new} axis, with green at negative a_{new} values and red at positive a_{new} values. Similarly, the yellow/blue opponent colors are represented along the b_{new} axis with blue at negative b_{new} values and yellow at positive b_{new} values [16, 14]. The three components, L_{new}, a_{new} and b_{new}, together give a Cartesian representation of the color space as shown in Figure 6.

The cylindrical representation of the color space, shown in Figure 6, is also generated from the Cartesian $L_{\text{new}}a_{\text{new}}b_{\text{new}}$ components using the same transformations utilized in different color spaces such as $CIEL^*a^*b^*$ [9, 14]. While the lightness component of the cylindrical representation remains the same as it was in the Cartesian representation, the chroma and hue components are derived according to Equations 8 and 9. The a_{new} and b_{new} components can also be derived from the respective cylindrical representation LCh based on Equations 10 and 11.

$$C = \sqrt{(a_{\text{new}}^2 + b_{\text{new}}^2)} \tag{8}$$

$$h = \arctan\left(\frac{b_{\text{new}}}{a_{\text{new}}}\right) \tag{9}$$

$$a_{\text{new}} = C\cos(h^\circ) \tag{10}$$

$$b_{\text{new}} = C\sin(h^\circ) \tag{11}$$

Optimization for New HDR Saturation Model

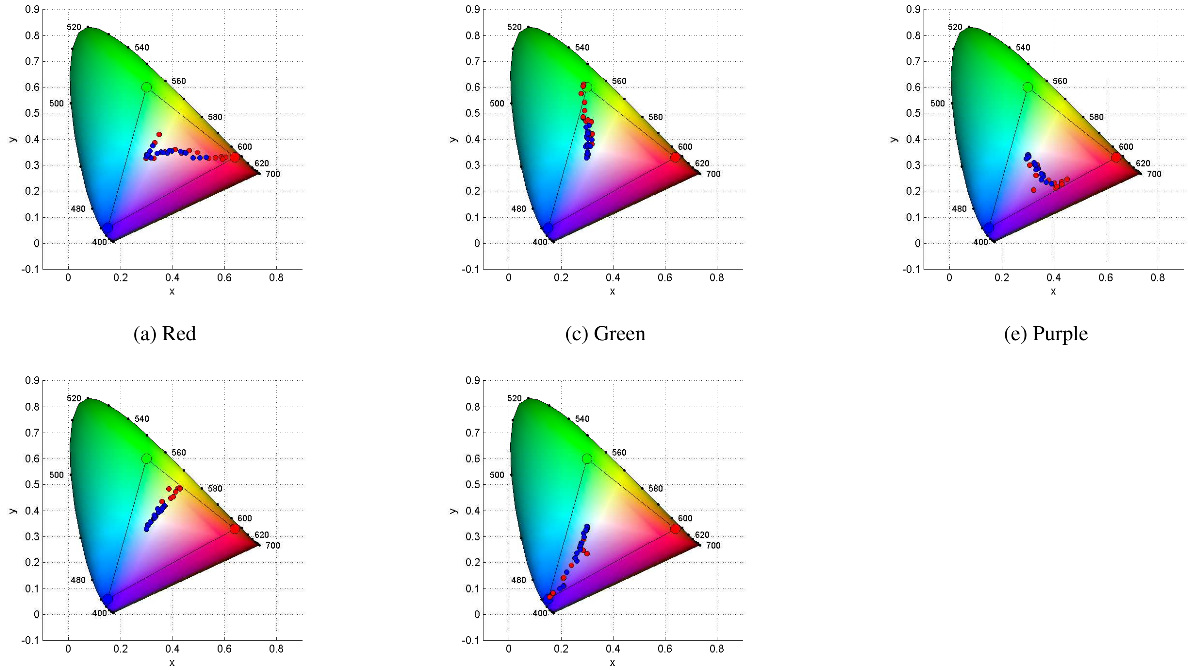
Since our adjustments of patch values performed by observers was done so as to match half the perceptual chroma of the reference patches, we expect that the measured values of the experimental patches satisfy Equations 12, 13, and 14. The hue, $h_{\text{reference}}$, lightness, $L_{\text{reference}}$ and chroma, $C_{\text{reference}}$ of the references patches should match the corresponding hue, h_{adjusted}, lightness, L_{adjusted} and double the chroma, C_{adjusted} of the observer-adjusted patches.

$$h_{\text{adjusted}} = h_{\text{reference}} \tag{12}$$

$$L_{\text{adjusted}} = L_{\text{reference}} \tag{13}$$

$$2 \times C_{\text{adjusted}} = C_{\text{reference}} \tag{14}$$

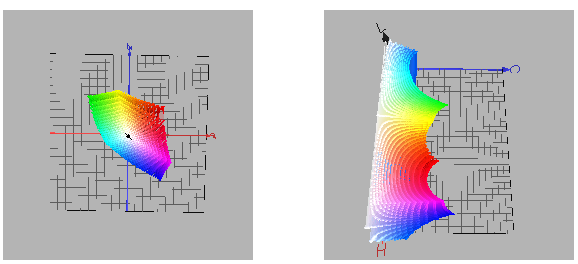
The data plots of lightness, chroma and hue of all the experimental reference patches plotted against the adjusted patches, given in Figure 7, demonstrate the expected behavior in both the proposed and $CIEL^*a^*b^*$ color spaces. The direct relationship between the references patches chroma and double of that of the



(a) Red (c) Green (e) Purple

(b) Yellow (d) Blue

Figure 4. *Mean tristimulus values of the measured reference (Red dots) and adjusted (Blue dots) patches for all chroma and lightness levels.*



(a) Cartesian space (b) Cylindrical space

Figure 5. *3D gamut visualization of sRGB in the Cartesian and cylindrical spaces of CIELab. In the left figure, lightness Cartesian coordinate is made to point towards the reader.*

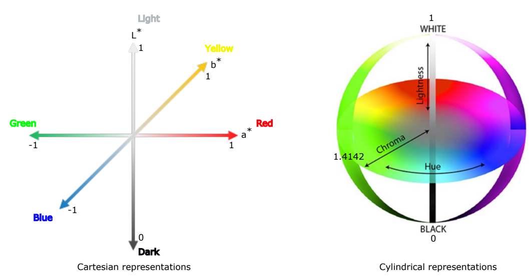


Figure 6. *The Cartesian and cylindrical representations of the proposed HDR color space.*

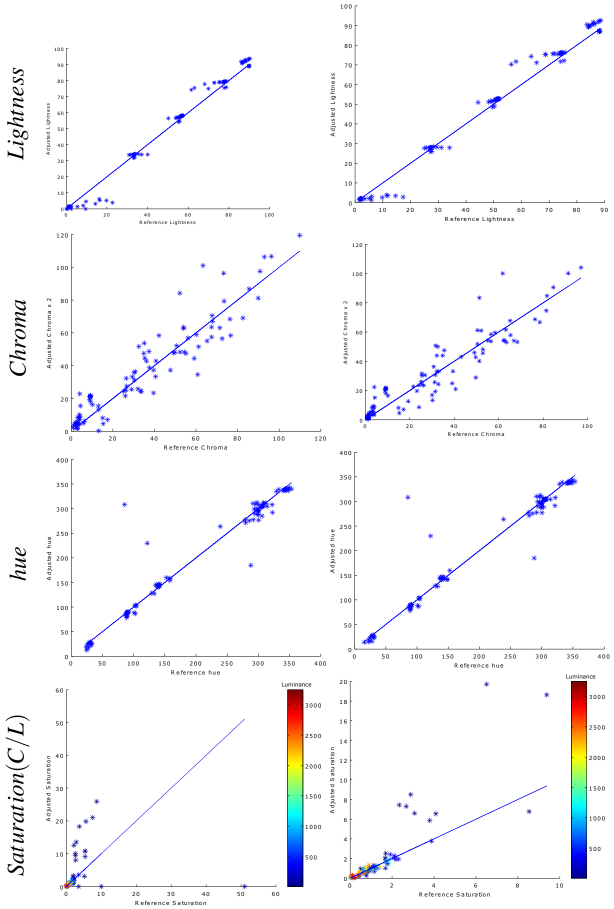
corresponding adjusted patches indicates the linearity of perceptual chroma.

However, the computed saturation, using Equation 15, in both the proposed and CIELab color spaces shows non-linearity, particularly for chromatic patches with luminance values of less than 100 cd/m^2.

$$S_{lab} = \frac{C_{lab}}{L_{lab}} \qquad (15)$$

Additionally, in previous rTMO comparison experiments [2], desaturation problems were observed for most of the dynamic range expansion results of current HDR color appearance models. To a lesser degree, similar issues were observed even with rTMO methods specifically designed for dynamic range expansion applications. Therefore, for accurate modeling of perceptual saturation and to increase the saturation reproduction accuracy of our color space, we have further analyzed and modeled the saturation property of our dataset.

For the new saturation model, we have modified the basic saturation formula given in Equation 15 into the form of a power function, given in Equation 16. The optimal parameter values a_s, b_s, c_s, and d_s are computed from all 100 patches using nonlinear unconstraint optimization of Nelder-Mead simplex direct search method [5]. Since the function to be optimized depends on both C and L, a particular set of parameters, leads to a 3-dimensional surface. As such, our optimization minimizes the prediction difference E_s, given in Equation 17, between the saturation surface of adjusted patches (computed by doubling the adjusted chroma) and reference patches. The variables C and L represent the chroma and lightness values computed in the proposed color space according to Equation 8 and Equation 4. The subscripts $_{stim}$ and $_{ref}$



(a) Proposed Model (b) CIELab

Figure 7. *Computed appearance attributes of the reference patches versus that of the adjusted patches in the proposed and CIELab color spaces. For the chroma and saturation comparisons, the chroma values of the adjusted patches are multiplied by two. Note that the saturation values are computed using the standard C/L formula.*

indicate the corresponding values for adjusted (stimulus) and reference patches, respectively. The total number of patches is then represented as N_p.

$$S_{\text{new}}(C,L) = \frac{a_s C^{b_s}}{c_s L^{d_s}} \tag{16}$$

$$E_s = \sum_{i=1}^{N_p} \frac{|S_{\text{new}}(2C_{stim_i}, L_{stim_i}) - S_{new}(C_{ref_i}, L_{ref_i})|}{N_p} \tag{17}$$

As shown in Figure 8, the difference between the estimated and reference saturation values of the experimental patches reduced in every iteration of the optimization process. The optimization converges after 99 iterations and the final parameter values which minimize the error function given in Equation 17 are $a_s = 0.1533$, $b_s = 0.7604$, $c_s = 0.3331$ and $d_s = 0.5794$. The resulting saturation model, as shown in Figure 9, leads to more perceptually linear predictions.

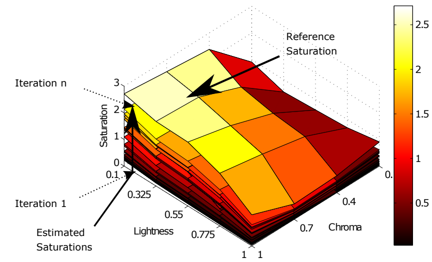


Figure 8. *The demonstration of our surface optimization process of the new saturation model for Red patches.*

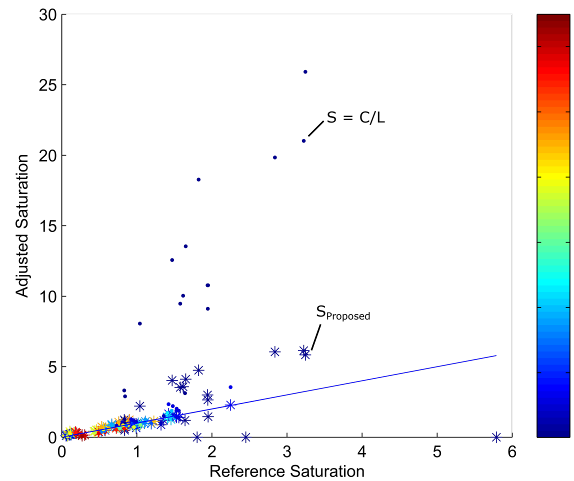


Figure 9. *Saturation predictions of the former and newly corrected saturation formulas for reference and perceptually adjusted patches of our experimental dataset.*

Evaluation of the Proposed Model

The proposed HDR color space and saturation model are evaluated relative to state-of-the-art HDR color appearance models. The models prediction of our experimental perceptual data as well as their accuracies in tone compression and tone expansion applications are compared using image difference metrics, including RMSE, S-CIELab [39] and SSIM [36].

First, the saturation predictions of different HDR color appearance models for our perceptually adjusted patches are compared with their predictions for the measured reference patches. The following models are evaluated: CIELab [40], IPT [40], hdr-CIELab [14], hdr-IPT [14] and the CAM of Kim et al. [19]. We have used the author provided code where available. The standard saturation computation, in the form of Equation 15, is applied to all models, except the CAM of Kim et al. where their provided saturation computation is used. As the adjusted patches have half the perceptual chroma of the reference patches, the saturation value of adjusted patches is computed using double their chroma values. Also, due to the different saturation ranges of the CAMs we normalized saturation results of each CAM by the maximum saturation value of their respective reference and adjusted patches, independently.

The prediction of each method for both the reference and adjusted patches is averaged over each chroma level and given in Figure 12. The corresponding average RMSE values of each method's prediction for the 5 lightness levels and 5 hue levels are given in Table 2 and 3, respectively.

The results in Table 2, show that the prediction accuracy of all the methods increases as the lightness levels of the patches increases. Most of the methods have their higher inaccuracies for patches with lower lightness levels. The proposed model, however, shows consistent and better accuracies for saturation prediction of patches in all tested lightness levels. Table 3, on the other hand, shows different performances of the evaluated methods. IPT [40] and hdr-IPT [14] produce higher error for red, blue and purple hues. The highest error of $CIEL^*a^*b^*$ [40] is around blue hues and the proposed model also shares the same behavior.

RMSE errors for the state of the art HDR color appearance model saturation predictions. The error between the adjusted and reference patches are averaged over all chroma and hue in each luminance levels.

L	1	25.75	50.5	75.25	100
IPT	0.0847	0.0817	0.0814	0.0788	0.0788
CIELab	0.0706	0.0616	0.0602	0.0596	0.0541
Proposed model	0.0649	0.0623	0.0611	0.0590	0.0489
hdr-IPT	0.1019	0.0936	0.0928	0.0924	0.0923
hdr-CIELab	0.0649	0.0622	0.0600	0.0585	0.0581
Kim et al.	0.0704	0.0702	0.0703	0.0705	0.0700

RMSE errors for the state of the art HDR color appearance model saturation predictions. The error between the adjusted and reference patches are averaged over all chroma and lightness levels for each hue values.

hue in degree	35	90	136	306	345
IPT	0.12752	0.02736	0.05214	0.09408	0.09386
CIELab	0.05951	0.00690	0.01187	0.11769	0.07419
Proposed model	0.02880	0.00805	0.04528	0.11508	0.04637
hdr-IPT	0.15595	0.01454	0.05276	0.12347	0.11552
hdr-CIELab	0.05718	0.06502	0.06977	0.05454	0.04959
Kim et al.	0.15020	0.03316	0.01292	0.00731	0.14448

Finally, we have tested the proposed HDR color space for tone compression and tone expansion applications based on a process visualized by the workflow given in Figure 10. We use absolute radiometrically calibrated HDR images, taken from the RIT HDR Photographic Survey [12], and their LDR versions, generated by simulating an exposure bracketing method and selecting the best exposed image in the series [4]. The set of images, shown in Figure 1, covers different scene types and illumination conditions.

State-of-the-art CAMs, such as CIELab [40], hdr-CIELab [14], hdr-IPT [14], iCAM06 [20], the models of [19] and [31] as well as the photographic TMO [32] were used to evaluate the capacity of the new model for dynamic range compression application. The simple color appearance models, namely CIELab, hdr-CIELAB, IPT and hdr-IPT, as well as the model of [19] are again used for evaluation of dynamic range expansion application relative to the proposed model, due to their ability to expand the dynamic range of LDR images. We also included an rTMO proposed by Akyuz et al. [3] due to its performance in previous evaluations [2].

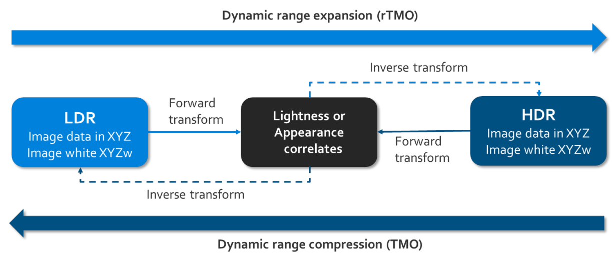


Figure 10. *The steps for HDR image reproduction application using our proposed models.*

Figure 11. *Experimental LDR images generated from the absolute radiometric HDR images, taken from the HDR Photographic Survey [12].*

Example results are shown in Figures 13, 14 and 15. Qualitatively, we observe that our proposed model leads to a satisfactory reproduction of saturation and overall contrast relative to other methods tested (See Table 4). Comparing our complete model with the lightness only model of our previous work [1], we observe a better reproduction of color and saturation. As a tone mapping operator, the proposed model achieved stronger compression while preserving more detail, contrast and over all appearance than most of the other color appearance models and TMOs. Color appearance models like iCAM06 produce better tone mapped results due to their local processing and more complete consideration of most of the factors of color appearance. However, their post-adaptation nonlinear compression function reduces their accuracy during tone expansion applications.

Image difference and Image quality results of the state of the art HDR color appearance models and rTMOs relative to ground truth image.

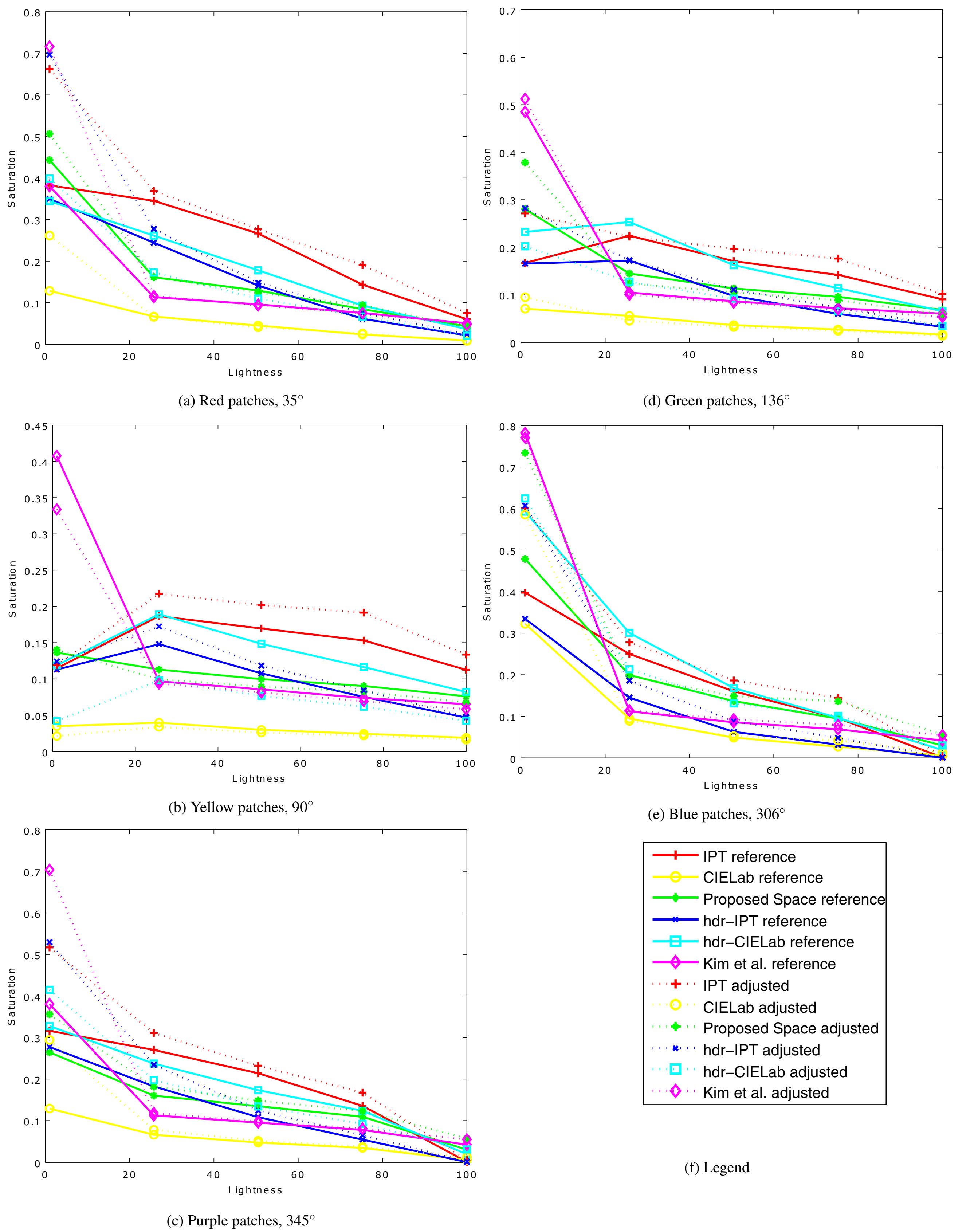
Metrics	Kim et al.	LDR	CIELab	hdr-CIELab	Power_law
S-CILab	23.0959	25.3167	33.5569	38.9337	14.9658
SSIM	0.9956	0.9949	0.9983	0.9975	0.9987
HDR-VDP2-QMOS	81.8173	57.3422	86.4108	58.6302	84.8936

Metrics	Proposed model	Akyuz et al	IPT	hdr-IPT
S-CILab	18.1559	16.2241	25.3885	28.1678
SSIM	0.9988	0.9983	0.9983	0.9944
HDR-VDP2-QMOS	83.4458	88.7996	33.6645	31.6254

Conclusions

We adapted the partition scaling methodology and employed it to measure chroma and saturation perception on an HDR display for different levels of adapting luminance. The collected data demonstrate the linearity of perceptual chroma in all tested luminance levels, matching previous knowledge, but also show slight non-linearity of saturation values for low luminance. To account for this non-linearity, we proposed a corrected saturation model, optimized based on our experimental data.

We also proposed new HDR color space combining our former lightness model with $CIEL^*a^*b^*$ like color-opponent compo-



(a) Red patches, 35°

(d) Green patches, 136°

(b) Yellow patches, 90°

(e) Blue patches, 306°

(c) Purple patches, 345°

(f) Legend

Figure 12. *Saturation predictions of HDR color appearance models for reference and perceptually adjusted patches of our experimental dataset. In each plot, the average saturation values of patches of 4 chroma levels are used in each lightness levels.*

(b) LDR (d) CIELab (f) hdr-CIELab [14] (h) hdr-IPT [14] (j) New model

Figure 13. *Sample rTMO results of 8 color appearance models. All the images for the rTMO results, except the LDR input image, are tone mapped using iCAM06 [20] tone mapping operator for visualization purpose.*

(b) Reinhard [32] (d) CIELab (f) hdr-CIELab [14] (h) hdr-IPT [14] (j) New model

Figure 14. *Sample TMO results of HDR color appearance models and TMOs.*

nents as well as our new saturation correction model. Finally, we compared the proposed color space predictions against the former lightness-only models and evaluated their performances for dynamic range compression and expansion applications.

Our evaluation results show that our proposed model leads to improved reproduction of saturation and overall contrast relative to other methods tested. The model also generates more appealing results with better color and saturation reproduction than our lightness-only model.

Although our proposed model allows for improved color reproduction on an HDR display, it should be noted that chroma in our analysis was computed in $CIEL^*a^*b^*$. This color space was chosen as a basis for our chroma experiment as it is a well-validated space and its lightness, chroma and hue components are independent and reasonably uniform perceptually. But, even with CIELab, we were able to see the lightness effects on the computation of chroma values. As a result, we have experienced a slight change of hue values while we were changing lightness levels of experimental patches. To fully account for such non-linearities, an extensive perceptual experiment with a larger number of hue, lightness and chroma levels would be essential. With more extensive measurements, a new way of color-opponent component derivation with more linear and independent perceptual attributes could be defined in future work.

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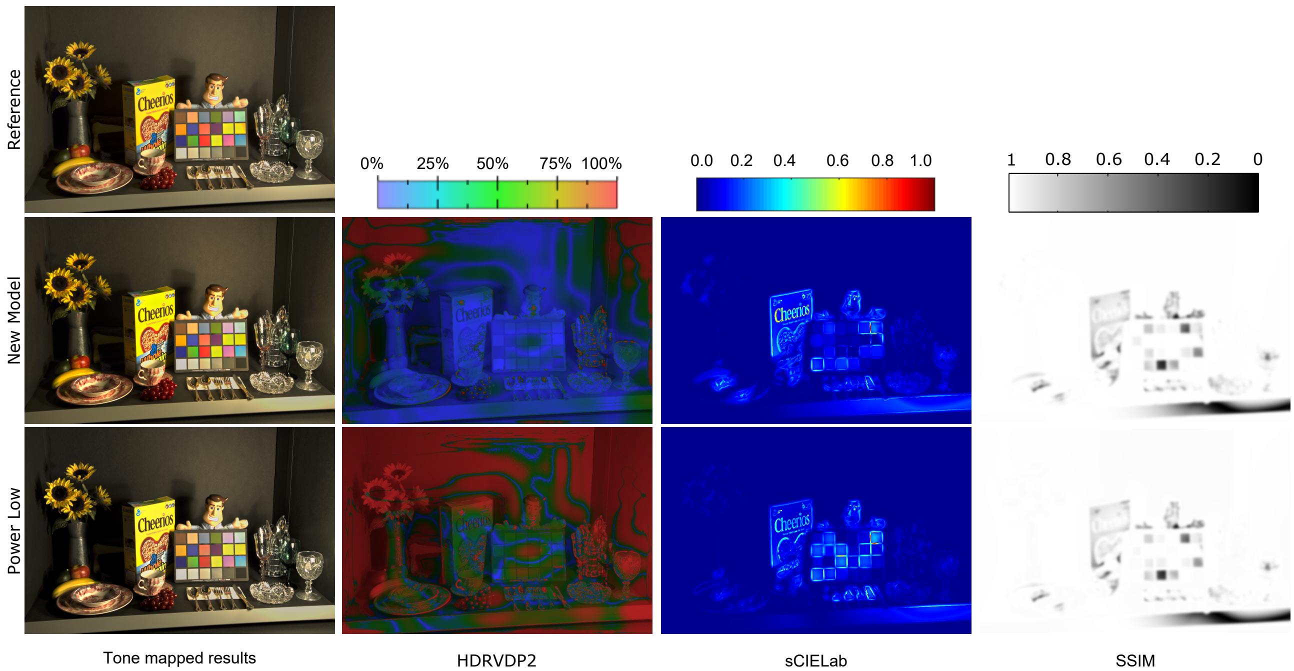

Figure 15. *Comparisons of color appearance, structural and quality differences of the proposed color space and our previous power low lightness model for rTMO application. All the images for the rTMO results, except the LDR input image, are tone mapped using iCAM06 [20] tone mapping operator for visualization purpose.*

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