A Uniform and Hue Linear Color Space for Perceptual Image Processing Including HDR and Wide Gamut Image Signals

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Abstract

A color space that is perceptually uniform, linear in iso-hue directions, can uniformly encode high dynamic range and wide gamut signals, and is computationally efficient, has been long desired. The available color spaces do not meet all these requirements satisfactorily and comprehensively. Performance of a recently proposed uniform and hue linear color space, Jzazbz, is compared with the state of the art color spaces and results are presented. This study suggests a single uniform color space for perceptual image processing, wherever desired, in different applications.

Introduction

A uniform color space that can encode color image signals in terms of independent perceptual attributes (lightness, chroma, and hue) is desired for perceptual image processing. A psychophysical study suggested that to satisfy 90% of the viewers, a luminance range of 0.005 to above 3,000 cd/m^2 is needed [1]. While the required luminance to satisfy same percentage of viewers, requirement of peak luminance for highlight pixels increases up to 10,000 cd/m^2 [1]. The International Telecommunication Union (ITU) has recommended Rec.2020 primaries for the next generation ultra high definition (UHD) broadcasting system and its format. An encoding space that can predict perceptual lightness for wide range of luminance and can uniformly encode images with wider color gamut is desired. Typical applications of uniform color space in image processing are gamut mapping, lossy image compression, image segmentation, image enhancement, etc. [2]. For example, a previous study proved that a more uniform color space can achieve better image compression performance with the same visual quality [3].

Current ISO/CIE standard uniform color spaces to predict perceptual color differences for reflective and self-luminous colors are CIELAB and CIELUV, respectively, and CIEDE2000 is the standard color difference formula [4, 5]. The CIE recommended spaces cannot accurately predict color differences and have inter-dependence between chroma and hue. A uniform color space named CAM02-UCS was developed based on CIECAM02 in 2006 to predict perceptual color differences [6]. The problem of unexpected computational failure in CIECAM02 has recently been resolved and a revision, CAM16, has been proposed [8].

During recent years, researchers have focused on encoding of high dynamic range (HDR) images. Fairchild and Wyble [7] proposed modified version of CIELAB and IPT color spaces by replacing their non-linear function by the Michaelis-Menten equation to predict wide-range lightness (lightness above and below diffuse white) data and renamed as hdr-CIELAB and hdr-IPT, respectively. But these new color spaces could not perform better than their original versions. The SMPTE recommended perceptual quantizer (PQ) function to encode high dynamic range luminance that uses smallest detection steps to avoid visible quantization artifacts and can uniformly encode a luminance range of 0.001 to 10,000 cd/m^2 [9]. Two uniform color spaces based on PQ-function named IC_aC_b and IC_TC_P have been proposed by Dolby in 2015 and 2016, respectively [10, 11]. Dolby model, IC_TC_P, do not have hue linearity issue but its uniformity must be tested using more reliable data sets. In a previous study, Dolby model was re-optimized to improve the uniformity. The modified model achieved better uniformity but a big hue shift was observed in the blue region when tested to predict Hung & Berns iso-hue data. This problem has also been reported by other researchers previously [2, 11]. Achieving minimum trade-off between uniformity and hue linearity has long been a challenge.

Authors have recently proposed a uniform and hue linear color space, $J_za_zb_z$, by minimizing trade-off between uniformity and hue linearity [13]. Test performance of $J_za_zb_z$ to predict a comprehensive range of experimental data is compared with three state of the art uniform color spaces including CIELAB (ISO/CIE standard), CAM16-UCS (famous for perceptual uniformity), and IC_TC_P (Dolby's proposal for HDR imaging), and results are presented here.

The next section will introduce the test criteria and corresponding experimental data followed by the model of $J_za_zb_z$. The test results will then be given followed by conclusions.

Test Criteria and Visual Data

A number of test criterions (as defined in [14]) were considered and corresponding experimental data were collected to compare performance of different uniform color spaces. Statistical measures called standard residual sum of squares (STRESS) and standard deviation (SD) were used for quantitative analysis of uniformity and hue linearity, respectively. Four tests are described below.

(1) To predict perceptual color difference, two different data sets including combined visual difference data (COMBVD) and the Optical Society of America (OSA) data representing small and large color differences, respectively, were collected. The two data sets consist of 3813 and 128 pairs of samples, respectively. STRESS was computed between experimental and predicted color difference to test models' performance.

(2) In a uniform color space, color discrimination ellipses should appear rounder (local uniformity) and all of similar size (global uniformity). Two different data sets including COMBVD ellipses (previously used to develop CIEDE2000 formula [5]) and MacAdam just-noticeable-difference ellipses [15] were used. The MacAdam data set was used to test models' performance for uniformity in wide gamut area. The two data sets include 125 and 25 color centers, respectively. STRESS was computed between ratios of semi-major to semi-minor axis of ellipses and a vector of ones to test local uniformity. STRESS was also computed between areas of all ellipses in a data set and average area to test global uniformity.

(3) Two different iso-hue data sets including Hung & Berns [16] and Ebner & Fairchild [17] were used to test hue linearity. These two data sets consist of 48 and 321 samples, respectively.

(4) To test model's performance to predict wide-range lightness data (i.e., lightness above and below diffuse white) collected from two different experiments (Scaling Lightness Experiment 1 (SL1) and Scaling Lightness Experiment 2 (SL2) [18]) were used. These two data sets include total 38 samples. STRESS was computed between experimental and predicted lightness values to test models' performance.

Model of $J_z a_z b_z$ Color Space

In a preliminary study [12], a structure similar to that of IC_TC_P was used to develop a color space with improved uniformity. This model was then extended to also improve hue linearity without affecting its performance for uniformity [13]. The study in [12] did not include testing of three dimensional color difference but just chromatic differences. Hence, further study was inevitable. The model proposed in [13] is described below:

$$\begin{bmatrix} X'_{D65} \\ Y'_{D65} \end{bmatrix} = \begin{bmatrix} lX_{D65} \\ mY_{D65} \end{bmatrix} - \begin{bmatrix} (l-1)Z_{D65} \\ (m-1)X_{D65} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = M_1 \begin{bmatrix} X_{D65}' \\ Y_{D65}' \\ Z_{D65} \end{bmatrix} \quad (2)$$

$$\{L', M', S'\} = \left(\frac{\left(c_1 + c_2 \left(\frac{\{L, M, S\}}{10000} \right)^n \right)}{\left(1 + c_3 \left(\frac{\{L, M, S\}}{10000} \right)^n \right)} \right)^t \quad (3)$$

$$\begin{bmatrix} I_z \\ a_z \\ b_z \end{bmatrix} = M_2 \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} \quad (4)$$

$$J_z = \left(\frac{(1+s) I_z}{1 + sI_z} \right) - s_0 \quad (5)$$

where $c_1 = 3424/2^{12}$, $c_2 = 2413/2^7$, $c_3 = 2392/2^7$, and $n = 2610/2^{14}$. The M_1 and M_2 are 3×3 matrices. Inputs X_{D65}, Y_{D65}, and Z_{D65} belong to the CIE XYZ tristimulus space with CIE standard illuminant D65 as white point. The factors l and m in Eq. (1), t in Eq. (3), and matrices M_1 and M_2, are the variables of optimization fitted using COMBVD data. The factor s in Eq. (5) was optimized using SL2 data set.

In the preliminary study [12], matrix coefficients (in Eq. (2) and Eq. (4)) were re-optimized along with the compression factor (t) of Eq. (2) to improve perceptual uniformity without increasing computational cost. There was a successful improvement of the uniformity compared with Dolby model i.e., uniformity was achieved as good as CAM16-UCS. However, a large hue shift was observed in the blue hue (SD=10.9 for Hung & Berns data set that was reference data for hue linearity). Such a large hue shift is unacceptable in many applications especially gamut mapping.

Knowing that improvement in perceptual uniformity adversely affects the hue linearity (particularly blue hue), the trade-off between uniformity and hue linearity was minimized. The blue hue was corrected by introducing Eq. (1) aiming that even after the optimization for perceptual uniformity the shift in the blue hue remains in a plausible range. Additionally, another correction was applied on Y_{D65} in order to preserve the uniformity in green blue region that was found to be affected by the adjustment of X_{D65} (see Eq. (1)). After adjustment of both X_{D65} and Y_{D65} using Eq. (1), all the matrix coefficients and compression factor (t) were re-optimized again using COMBVD color difference data considering COMBVD ellipses data and Hung & Berns data as reference for uniformity and hue linearity, respectively. The extension of the model using Eq. (1) helped to simultaneously achieve uniformity and hue linearity (especially for blue hue).

Another objective was to accurately predict perceptual lightness in highlights as well as in typical dynamic range. To achieve this, an equation similar to lightness formula of CAM02-UCS [6] was developed and is given in Eq. (5). It is immediately apparent that the model for $J_z a_z b_z$ is invertible.

The values of the optimization variables are: $l = 1.15$, $m = 0.66$, $t = 1.7 \times 2523/2^5$, and $s = -0.56$. The constant $s_0 = 1.6295499532821566 \times 10^{-11}$ was introduced to avoid occurrence of complex numbers in the reverse model. The optimized matrices M_1 and M_2 are given below.

$$M_1 = \begin{bmatrix} 0.41478972 & 0.579999 & 0.0146480 \\ -0.2015100 & 1.120649 & 0.0531008 \\ -0.0166008 & 0.264800 & 0.6684799 \end{bmatrix} \quad (6)$$

$$M_2 = \begin{bmatrix} 0 & 1 & 0 \\ 3.524000 & -4.066708 & 0.542708 \\ 0.199076 & 1.096799 & -1.295875 \end{bmatrix} \quad (7)$$

Model of $J_za_zb_z$ Color Space

Performance of the $J_za_zb_z$ color space was tested to predict wide range of experimental data and was compared with the other three models tested in the current study. Prediction performance of each model is presented in terms of SD (in units of degree) for hue linearity and STRESS (0-100) for other tests. Smaller the value of STRESS or SD, better the model.

The results for prediction of perceptual color difference and perceptual uniformity are shown in **Figure 1**. The results showed that CAM16-UCS best predicted small color difference data (i.e., COMBVD) and $J_za_zb_z$ stood second. When predicting large color difference data (i.e., OSA), $J_za_zb_z$ and CAM16-UCS gave similar and best performance followed by CIELAB. IC_TC_P performed worst to predict both COMBVD and OSA data sets.

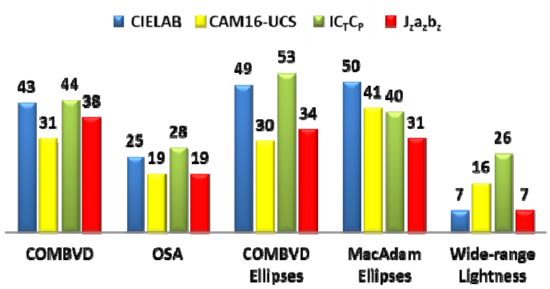

__Figure 1.__ Bar chart for five different data sets plotted in selected four uniform color spaces: CIELAB, CAM16-UCS, IC_TC_P, and $J_za_zb_z$.

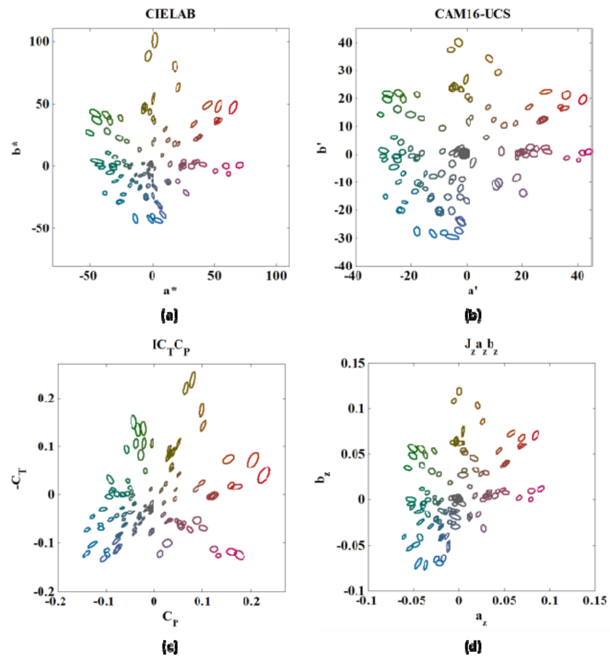

__Figure 2.__ COMBVD ellipses plotted (color coded using corresponding sRGB) in four test spaces: (a) CIELAB, (b) CAM16-UCS, (c) IC_TC_P, and (d) $J_za_zb_z$.

To test the perceptual uniformity along the chromatic axis two different data sets (COMBVD ellipses and MacAdam ellipses) were used. The results in **Figure 1** showed that CAM16-UCS performed the best followed by current $J_za_zb_z$ to predict the COMBVD ellipses data set. IC_TC_P again performed worst. These results were expected to agree with that of prediction of COMBVD color difference data. The COMBVD ellipses plotted in four different color spaces are shown in **Figure 2**. When predicting MacAdam ellipses data, $J_za_zb_z$ gave the best performance followed by IC_TC_P. This also means that $J_za_zb_z$ gives best uniformity in wide gamut applications. The MacAdam ellipses are plotted in IC_TC_P and $J_za_zb_z$ uniform color spaces for visual comparison in **Figure 3**. The CIE 1931 chromaticity scale is also plotted in the corresponding color spaces in **Figure 3**.

Performance of the lightness predictor of all the test spaces was also investigated to predict wide-range lightness data i.e., samples with lightness above and below diffuse white. Average STRESS values for prediction of SL1 and SL2 data sets are shown in Figure 1. The results showed that Jzazbz and CIELAB gave similar performance and outperformed both CAM16-UCS and the worst ICTCP. Also note that Jzazbz can accurately predict standard dynamic range of lightness. Prediction of Munsell value using lightness correlate of Jzazbz is shown in **Figure 4**.

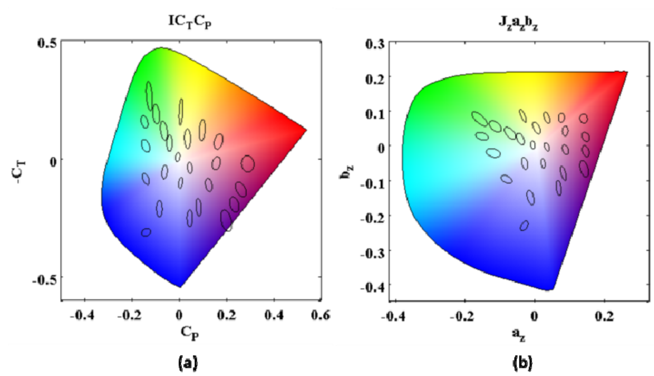

__Figure 3.__ MacAdam ellipses plotted (10 times amplified) in: (a) IC_TC_P, and (b) $J_za_zb_z$. The colored background represent CIE 1931 chromaticity diagram where white point indicates CIE standard illuminant D65.

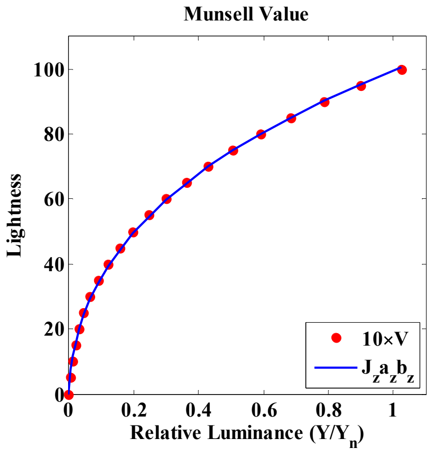

Figure 4. *Munsell Value predictions using $J_za_zb_z$.*

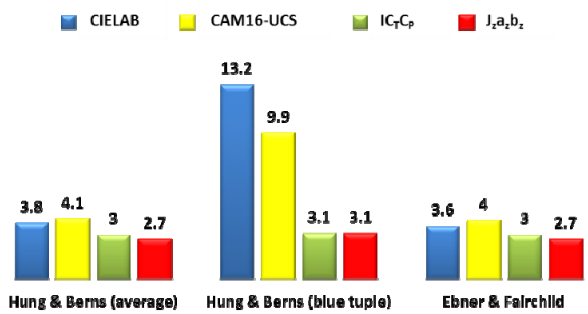

Figure 5. *Bar chart for two different iso-hue data sets plotted in selected four uniform color spaces: CIELAB, CAM16-UCS, IC_TC_P, and $J_za_zb_z$.*

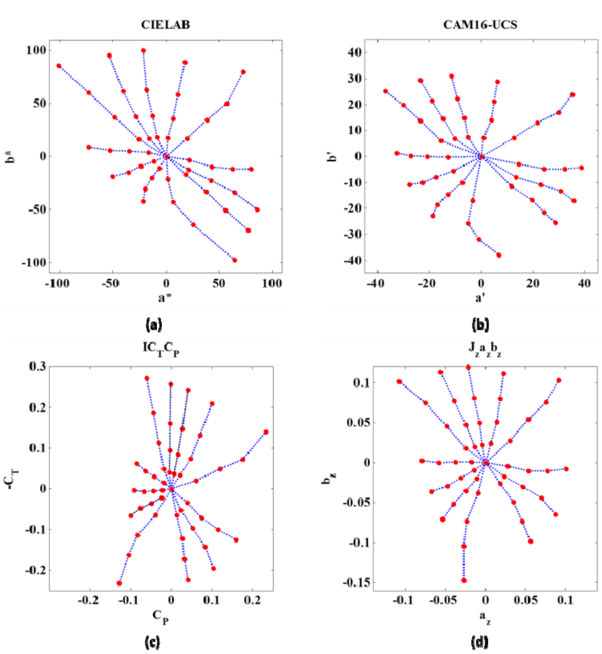

Figure 6. *Hung & Berns constant hue data plotted in four different color spaces: (a) CIELAB, (b) CAM16-UCS, (c) IC_TC_P, and (d) $J_za_zb_z$.*

Selected color spaces were also tested for hue linearity using Hung & Berns [16] and Ebner & Fairchild [17] data sets. The quantitative results for hue linearity in terms of mean standard deviation (SD) of hue angle, together with the SD for the blue hue, are shown in the bar chart in **Figure 5**. The results based on Hung & Berns data showed that CIELAB and CAM16-UCS have large hue shifts in the blue direction with SD value of 13.2 and 9.9, respectively. The $J_za_zb_z$ best predicted iso-hue data sets on average and prediction of blue hue was similar to IC_TC_P which was ranked second overall. The $J_za_zb_z$ outperformed CIELAB and CAM16-UCS for prediction of iso-hue data sets. The Hung & Berns data set is plotted in four different test spaces in **Figure 6**.

Some characteristics of the $J_za_zb_z$ color space are discussed here. For the Rec.2020 gamut, the J_z component ranges from 0 to 1 whereas a_z and b_z range from -0.5 to 0.5. Lightness predictor of $J_za_zb_z$ also predicted Munsell Value quite accurately (see **Figure 6**). Uniform representation of the CIE 1931 chromaticity scale in $J_za_zb_z$, compared with IC_TC_P, can also be seen in **Figure 3**. Further, the computational cost of $J_za_zb_z$ is much less compared with CAM16-UCS while a slightly higher compared with IC_TC_P.

To validate the performance of $J_za_zb_z$, a study was conducted by Zhao *et el.* [19] where they investigated performance of $J_za_zb_z$ compared with that of CAM16-UCS in gamut mapping. They used eight different gamut mapping algorithms and their psychophysical results showed that $J_za_zb_z$ was ranked better than CAM16-UCS for each of the gamut mapping algorithms. Further investigations are needed to test performance of $J_za_zb_z$ for other different image processing applications.

Conclusions

Mainly, four different tests were performed to test performance of the perceptually uniform and hue linear color space, $J_za_zb_z$, compared with the state-of-the-art uniform color spaces. The results showed that $J_za_zb_z$ gave second best performance for small color difference data set followed by CAM16-UCS. The $J_za_zb_z$ gave best performance (similar to CAM16-UCS) to predict large color difference data (i.e., OSA). The proposed color space predicts the most accurate for MacAdam ellipses, wide-range lightness data, and iso-hue data. Both $J_za_zb_z$ and IC_TC_P predicted blue hue with minimum variation and outperformed CIELAB and CAM16-UCS. Considering its overall performance, $J_za_zb_z$ should be confidently used for all imaging applications.

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