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Investigating Performance of Uniform Color Spaces for High Dynamic Range and Wide Gamut Color Difference Applications

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Abstract

This study investigated that which of the available color spaces performs best in different aspects when encoding high dynamic range and wide gamut color difference signals. Six different color spaces including CIELAB, CIELUV, CAM16-UCS, ICtCp, ICaCb, and zICaCb (current modification of ICaCb), were investigated for their performance in terms of local and global uniformity, hue linearity, encoding of Rec.2020 signals, convergence of iso-hue lines at single point (locus), distance between locus and origin, and computational cost. A new metric was developed for hue linearity test. Comprehensive testing was performed using the most reliable datasets and some modifications were proposed in the recently developed color space named ICaCb. Results showed that the current zICaCb outperformed other spaces tested for most of the measures and gave similar performance for other measures.

Introduction

Extensive studies on luminance and high dynamic range (HDR) image encoding have been done by different researchers [1-3]. Future displays will likely offer videos with large range of luminance and wide color gamut (WCG). To account for the variation, display mapping will become a routine process. An efficient representation of color signals is needed to perform mentioned tasks with reduced complexity, increased speed, and minimal error. It is desirable to transmit video signals in color space that is not only suitable for efficient image encoding but also for tone and gamut mapping often referred to as color volume mapping. Distortions become more prevalent due to non-uniformity of the color space with the improvement in display capabilities. For these reasons, currently available uniform color spaces need to be investigated and ranked. Therefore, a color space that meets all the mentioned requirements need to be recommended. This was the main purpose of the current study.

A number of perceptually uniform color spaces such as CIELAB, CIELUV, IPT [4], CAM02-UCS [5], and CAM16-UCS [6] have previously been proposed. All of these color spaces are based on device independent XYZ tristimulus space. The CIELAB and CIELUV are CIE standard uniform color spaces, IPT was developed for better hue linearity, CAM02-UCS and CAM16-UCS are uniform color spaces based on color appearance models named CIECAM02 and CAM16 (a revision of CIECAM02), respectively. Most of these color spaces have widely been used for the typical dynamic range such as below 500cd/m^2. Researchers have tested the performance of uniform color spaces by incorporating into image processing tasks and visual assessments of image quality [7-8]. These color spaces need to be further investigated to know how good they meet the requirements for high dynamic range and wide gamut imagery.

Recently, Froehlich *et al.* [9] has proposed a model named ICaCb for color difference signals encoding for high dynamic range and wide color gamut (WCG) imagery. They verified the efficiency of ICaCb by comparing with state of the art HDR color encodings including proposal of BluRay Disc Association called Rec.2020 PQ [11], Rec.2020 BBC [12], and Phillips' proposal for HDR and WCG encoding called Y"u"v" [13]. Another model for HDR and WCG image encoding scheme was proposed by Dolby named ICtCp based on similar approach as ICaCb but with different transformation matrices [14].

One of the challenges in designing an efficient HDR color encoding scheme is that in contrast to color appearance model expectations, neither surround luminance nor observer adaptation are known for HDR entertainment imaging scenarios. As a result, a static color difference formula designed for standard dynamic range like CIEDE2000 [15] cannot be used to accurately estimate color differences. Instead, the quantization in any part of an HDR color space should be always determined by the adaptation parameters. It results in the smallest detection step in that area to make sure visible quantization artifacts to be avoided for any content on any display in any viewing environment [9]. The PQ curve follows exactly this approach for luminance encoding. For this reason the PQ curve was incorporated into recently developed color spaces known as ICtCp and ICaCb. The data previously used to train and test the uniformity of ICtCp and ICaCb is MacAdam 1942 'just noticeable difference' (JND) ellipses [16]. This data is based on observations of a single observer who used aperture mode of a visual colorimeter. And the hue linearity of above models was tested using Hung and Berns (1995) constant hue data [17]. There are more reliable data available (see later) but they were not employed to test the models.

The next section will explain the requirements for the desired color space followed by introduction to color spaces investigated and test data used. The currently developed color space will then be explained followed by results and conclusions.

Criteria and Metrics

A number of criterions were considered to test the performance of uniform color space for HDR and WCG color difference applications. These criterions are given in **Table 1** along with description and metrics used.

Color Spaces Investigated

Five different uniform color spaces were considered including CIELAB, CIELUV, CAM16-UCS, ICtCp, and ICaCb. The CIELAB and CIELUV are the CIE recommended uniform color spaces. The CAM16-UCS is a uniform color space based on color appearance model named CAM16. These color spaces have extensively been studied under typical luminance range but not for high dynamic range and wide color gamut. In the current study, all the color spaces were tested if they can encode Rec.2020 signals with high contrast of luminance. The ICtCp and ICaCb are recently developed color spaces proposed for modern HDR imagery especially to meet requirements of Rec.2020 primaries. In the current study, ICaCb was re-optimized (see later) using more reliable visual data and the modified version will be called zICaCb hereafter. The performance of zICaCb, when tested in different aspects using wide range of visual data, was compared with previously proposed color spaces.

Table 1. Criterions for testing performance of uniform color spaces, their description, and metrics used for testing.

Criterions	Description	Metrics
Local uniformity	All the color discrimination ellipses should be presented as circles i.e., ratio of major to minor axis of each ellipse should be equal to 1.	Standardized residual sum of squares (STRESS) [10] computed between ratios of major to minor axis and 1.
Global uniformity	All the color discrimination ellipses should be presented with constant size i.e., size of each ellipse is equal to same constant value.	Standardized residual sum of squares (STRESS) [10] computed between areas of ellipses and the median value of areas.
Hue linearity	All the iso-hue colors should be presented on a linear line.	Hue linearity coefficient (HLC) defined as scaled average (to range 0-100) of smaller angles between linear orthogonal fitting line of a color tuple and a line connecting kth and next consecutive color sample.
Convergence of iso-hue lines	All the iso-hue lines should converge to a single point.	Visual analysis of plots of iso-hue lines.
Neutral point error	The convergence point of iso-hue lines should be at the origin (0,0).	Average color difference (in CIEDE2000 units [15]) computed between origin and each intersection point of unique hue lines.
High dynamic range support	To support high contrast of luminance. For entertainment imaging, a dynamic range of 0.005-10,000cd/m^2 is required to satisfy the viewers [9].	All color spaces were tested if they can encode Rec.2020 gamut hull with dynamic range of 0.005-10,000cd/m^2.
Wide Gamut Support	To encode large gamut signals such as Rec.2020 [9] which is the minimum requirement for the modern video encoding.	All color spaces were tested if they can encode Rec.2020 signals with gamma of 2.8.
Computational Cost	To low the color transformation complexity to allow mass deployment in a wide range of devices.	CPU time (MATLAB function)

For hue linearity, three different data sets were used. Xiao *et al.* [18], conducted visual assessments to judge four unique hues (unique red (UR), unique green (UG), unique yellow (UY), and unique blue (UB)) at varying luminance and chroma assessed by 185 observers, and each observer repeated three times. This dataset denoted as Xiao-UH data was also used for calculating color difference between the origin (0,0) and locus point of each of test color spaces. Hung and Berns [17], collected two different sets of constant hue data, with 12 different hues, using constant luminance (CL) and varying luminance (VL), respectively. These two datasets will hereafter be called the H&B-CL and H&B-VL.

Test Data

Color space uniformity was tested using two different datasets. Their original data were fitted in terms of color discrimination ellipses for each color center. One set was MacAdam data which consists of 25 color centers and covers wide range of color gamut [16]. Secondly, a combined dataset from the BFD and RIT-DuPont used for the development of CIEDE2000 color difference formula [15] was adopted. This data was collected using more number of observers. Both the BFD and RIT-DuPont data are based on the surface colors. This combined dataset will hereafter be denoted as BFD&RIT-DuPont data.

Modeling zICaCb

ICaCb [9] has a similar structure as ICtCp [14] but different transformation matrices, both developed for the applications of high dynamic range and wide gamut imagery. After testing all the models using wide range of test data (see later), ICaCb was chosen for further refinement due to its better performance and simple structure. The new version of ICaCb is named zICaCb. The mathematical model of zICaCb color space is given below:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.394077 & 0.642105 & -0.036182 \\ -0.21649 & 1.14744 & 0.05356 \\ 0.02567 & 0.16713 & 0.74235 \end{bmatrix} \begin{bmatrix} X_{d65} \\ Y_{d65} \\ Z_{d65} \end{bmatrix} \quad (1)$$

$$\{R', G', B'\} = \left(\frac{\left(c1 + c2\left(\frac{\{R,G,B\}}{10000} \right)^{n} \right)}{\left(1 + c3\left(\frac{\{R,G,B\}}{10000} \right)^{n} \right)} \right)^{p} \quad (2)$$

$$\begin{bmatrix} I' \\ Ca' \\ Cb' \end{bmatrix} = \begin{bmatrix} 0.394077 & 0.642105 & -0.036182 \\ -0.21649 & 1.14744 & 0.05356 \\ 0.02567 & 0.16713 & 0.74235 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \quad (3)$$

Three changes can be seen in the above model. Elements of transformation matrices were changed and exponent 'm' was replaced with p, where $p = 2.3 \times m$ (see Eq. (2)). A simple cost function given in Eq. (4) was used to optimize the color space to achieve local uniformity, global uniformity, hue linearity, and minimum distance of locus from the origin.

$$\xi_{total} = w_1\xi_1 + w_2\xi_2 + w_3\xi_3 + w_4\xi_4 \quad (4)$$

The cost functions ξ_1 to ξ_4 correspond to STRESS computed for local uniformity, STRESS computed for global uniformity, HLC for hue linearity (defined later), and color difference (in CIEDE2000 units) for neutral point error, respectively (see **Table 1**). The datasets used to optimize the model are BFD&RIT-DuPoint for uniformity and Xiao-UH for uniformity and hue linearity, respectively. The other datasets were used as testing sets.

Results and Discussions

The six color spaces were tested using above mentioned datasets. The experimental reference conditions for respective data were used for color transformations using CIELAB, CIELUV, and CAM16-UCS. The white point was transformed to CIE d65 and 1931 CIE color matching functions using CAT16 (chromatic adaptation transform 2016 [6]) for ICtCp, ICaCb, and zICaCb. The uniformity was tested using the BFD&RIT-DuPont data for training and testing, and the MacAdam data for testing only. **Table 2** shows the results in terms of STRESS (best values underlined). The average STRESS values in the last column of **Table 2** showed that the best overall uniformity was achieved by the new zICaCb color space while CAM16-UCS and ICaCb were ranked second and third, respectively. The ICaCb which was developed for HDR and WCG applications has not been optimized or tested for the surface color samples previously. When we re-optimized ICaCb, its performance was improved significantly for the surface color data and performed reasonably well for MacAdam data (see **Table 2**). The worst performance of ICtCp was noted for BFD&RIT-DuPont data and that of CIELAB for MacAdam data. From these results, it can be concluded that the newly developed zICaCb can give most accurate prediction amongst all the color spaces tested. **Figure 1(a-c)** shows the plots of the BFD&RIT-DuPont ellipses using CAM16-UCS (performed best amongst color spaces developed for typical dynamic range), ICaCb (which was chosen for refinement), and zICaCb (currently developed space). **Figure 1(d-f)** shows the plots of the MacAdam ellipses using CIELUV (performed best amongst color spaces developed for typical dynamic range), ICaCb, and zICaCb. For a more uniform color space, all ellipses should be close to circle and have similar size.

Table 2. Quantitative results for local and global uniformity in terms of STRESS. Best values are underlined.

Color Spaces	BFD&RIT-DuPont			MacAdam			Avg (%)
	Loc	Glob	Avg	Loc	Glob	Avg	
CIELAB	38	61	49	53	47	50	50
CIELUV	43	53	48	40	41	40	44
CAM16-UCS	31	39	35	39	47	43	39
ICtCp	40	68	54	42	<u>38</u>	40	47
ICaCb	35	62	49	32	<u>38</u>	<u>35</u>	42
zICaCb	<u>30</u>	<u>38</u>	<u>34</u>	<u>30</u>	46	38	<u>36</u>

The hue linearity of test color spaces was investigated using three different datasets including the Xiao-UH for training and testing, and H&B-CL and H&B-VL for testing only. The results were computed in terms of hue linearity coefficient (HCL) which ranges from 0 to 100. The HLC was defined as scaled average of smaller angles between linear orthogonal fitting line of a color tuple (iso-hue line) and a line connecting kth and next consecutive color sample (see **Figure 2**). Then the average HCL was calculated for all of the color tuples. The quantitative results for hue linearity are given in **Table 3** (best values underlined).

Table 3. Results for hue linearity and neutral point error are given in terms of HLC and CIEDE2000, respectively.

Spaces	Hue Linearity Coefficient HLC (0-100)				ΔE_{00}
	Xiao-UH	H&B-CL	H&B-VL	Mean (%)	Xiao-UH
CIELAB	8.9	5.8	12.8	9.2	2.2
CIELUV	<u>5.3</u>	6.0	12.2	<u>7.8</u>	2.4
CAM16-UCS	11.3	7.9	18.3	12.5	6.6
ICtCp	5.7	5.1	16.4	9.1	6.9
ICaCb	5.7	<u>4.6</u>	17.2	9.2	6.8
zICaCb	8.3	<u>4.6</u>	<u>12.1</u>	8.3	<u>1.2</u>

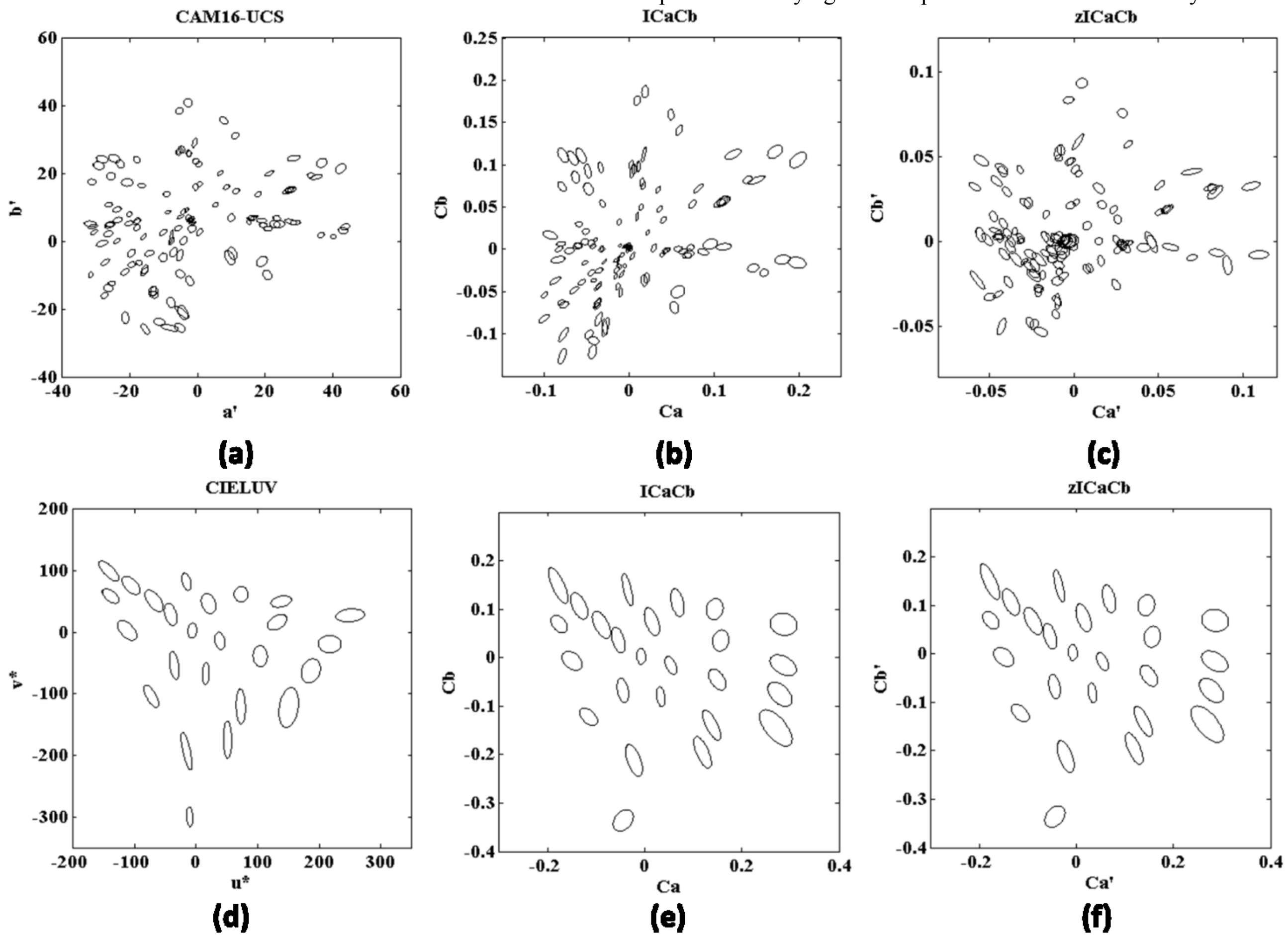

Figure 1. Color discrimination ellipses plotted using BFD&RIT-DuPont data for a) CAM16-UCS, b) ICaCb, and c) zICaCb; and using MacAdam data (enlarged 10 times) for d) CIELUV, e) ICaCb, and f) zICaCb.

The metrics used by Xiao *et al.* [19], and Froehlich *et al.* [9], are standard deviation (SD) and hue linearity cost function (C_{hl}), respectively. The SD and C_{hl} are based on the values of hue, and both hue and chroma, respectively. It was found that such metrics do not give true representation of hue linearity when the iso-hue lines do not pass through the origin which is true for most of the color spaces and hue linear datasets. The values of hue angles may not represent the actual hues when calculated for a color tuple which does not pass through the origin. Further, the chroma value needs scaling (may not be fair) for different color spaces. The current metric named HCL gives fair analysis for different color spaces and datasets as it does not depend on values of chroma or hue angle. We believe that hue linearity and distance between origin and locus are two different issues and must be addressed separately. The distance between origin and locus point was computed in terms of color difference in units of CIEDE2000.

The minimum values of HLC for each different dataset are underlined in **Table 3**. None of the color spaces was found consistent for hue linearity performance for different datasets. The new zICaCb gave best performance for hue linearity for the H&B-CL and the H&B-VL datasets, and CIELUV performed best for the Xiao-UH data. During current re-optimization of ICaCb, the middle performance showed that with an increase of uniformity, hue linearity performance worsens, and vice versa. Previous studies [9, 14] also reported that this is a fundamental problem for any color space when trying to co-optimize for both uniformity and hue linearity. **Figure 3(a-d)** and **Figure 4(a-d)** plot the Xiao-UH data and the H&B-CL data, respectively for CIELAB, CAM16-UCS, ICaCb, and zICaCb color spaces to observe hue linearity.

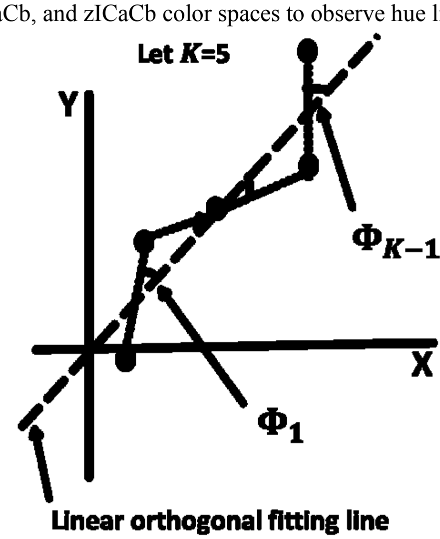

Figure 2. An example (considering just one color tuple and five levels of colorfulness) to explain computation of the hue linearity coefficient (HLC).

The test color spaces were also investigated for neutral point error using the Xiao-UH data. The results were presented in terms of mean value of color difference (CIEDE2000 units) between origin and each of intersection points (red-yellow, red-blue, green-yellow, green-blue) of fitting lines of four color tuples of unique hues (see **Table 3**). The zICaCb gave minimum neutral point error and CIELAB was ranked number two. The four unique hue lines converge to single point for zICaCb and the color difference from the origin is also significantly better (smaller color difference) compared with CAM16-UCS, ICaCb, and ICtCp (see **Figure 2**). The distance between origin and locus point causes errors in hue values as quadrants are defined by the origin not the locus point. So the locus point should ideally be at the origin for correct calculation of true hue angle.

Finally, computational cost was also considered for each color space. The Rec.2020 gamut hull was transformed to different models and CPU time was noted. The results showed that CIELUV has the least computational cost. The ICtCp, ICaCb, and zICaCb performed about the same and ranked second while CAM16-UCS was significantly expensive compared with the other spaces tested. It was also found that all the tested color spaces can encode Rec.2020 signals with high level of luminance contrast and wide gamut except the CAM02-UCS. The lightness and colorfulness attributes of CIECAM02 turned out to be complex values while encoding Rec.2020 signals. But refined version of CIECAM02 called CAM16 did not have this issue. So, the performance of CAM16-UCS was investigated instead of CAM02-UCS in the current study.

Conclusions

A comprehensive testing method was used to investigate six different color spaces including five previously proposed and a current modification of ICaCb (zICaCb). The color spaces were tested for their uniformity (local and global), hue linearity, neutral point error, and computational complexity. The performance of the

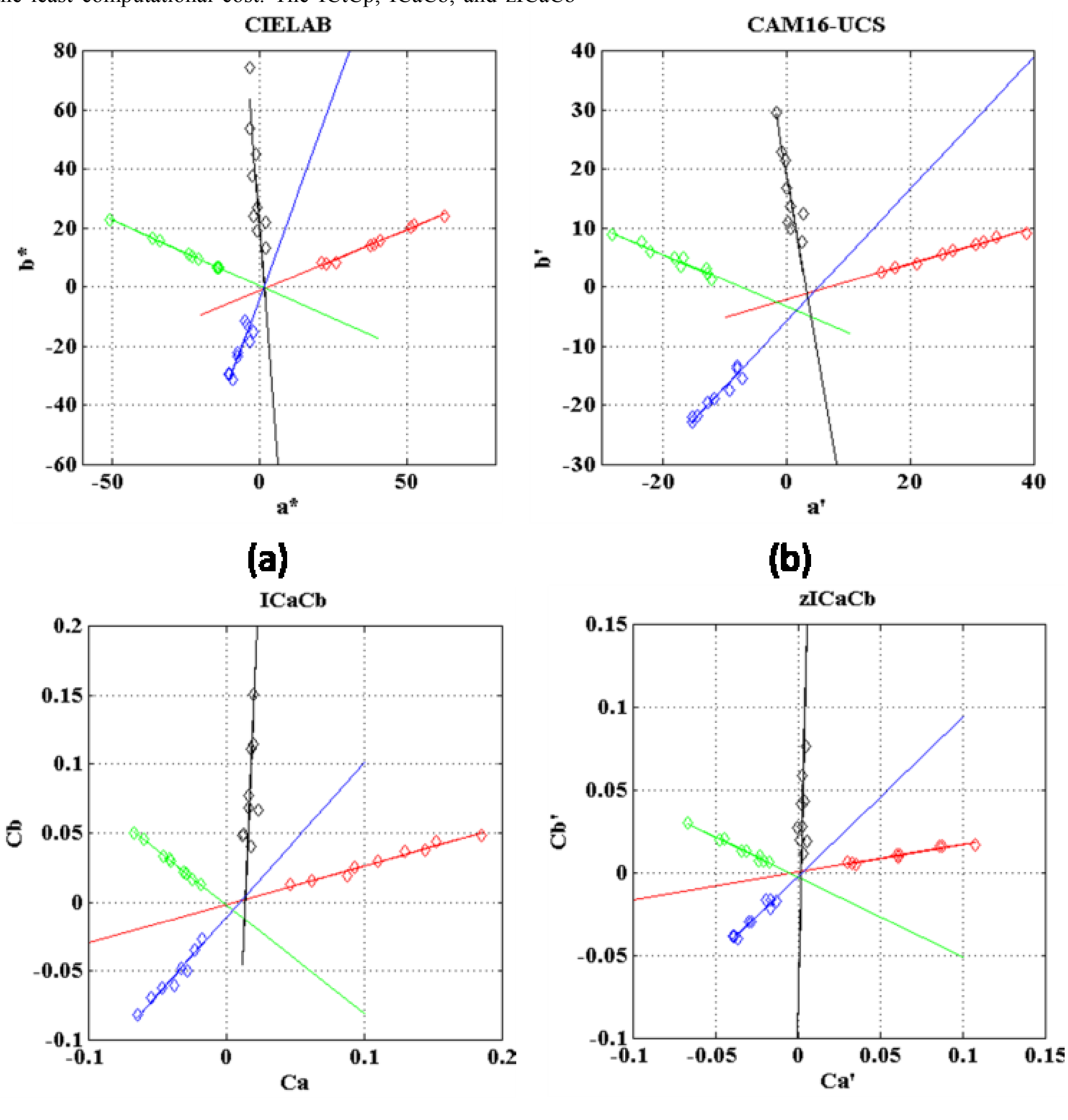

Figure3. Iso-hue data (Xiao-UH) plotted (yellow hue is plotted in black color and other three (red, green, and blue) are plotted in their respective colors) for four different color spaces including a) CIELAB, b) CAM16-UCS,c) ICaCb, and d) zICaCb.

recently proposed spaces (ICaCb and ICtCp) and new zICaCb for high dynamic range and wide color gamut imagery was compared with that of traditional uniform color spaces including CIELAB, CIELUV, and CAM16-UCS. The results showed that zICaCb outperformed other spaces in most of the measures. It could be recommended as an encoding space for high dynamic range and wide color gamut applications.

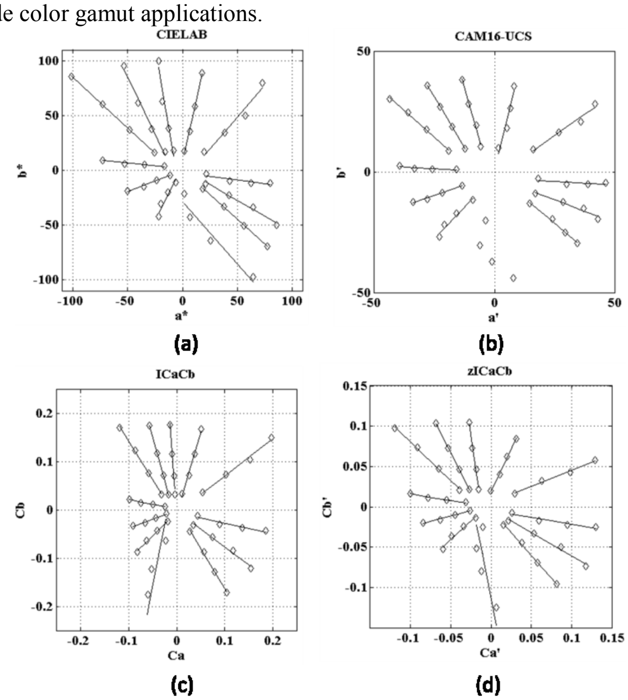

Figure 4. Iso-hue data (H&B-CL) plotted for four different color spaces including a) CIELAB, b) CAM16-UCS, c) ICaCb, and d) zICaCb.

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