https://doi.org/10.2352/CIC.2022.30.1.16

Constant hue loci in Rec. 2020 gamut under an HDR condition

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Abstract

Hue linearity is critically important to uniform color spaces and color appearance models. Past studies investigating hue linearity only covered relatively small color gamuts, which was generally acceptable for conventional display technologies. The recent development of HDR and WCG display technologies has motivated the development of new color spaces (e.g., IC_TC_P and $J_za_zb_z$). The hue linearity of these new color spaces, however, was not verified for the claimed HDR and WCG conditions, due to the lack of constant hue loci data. In this study, an experiment setup was carefully developed to produce HDR and WCG conditions, with the stimulus luminance of 3400 cd/m^2 and the diffuse white luminance of 1000 cd/m^2 and the stimulus chromaticities almost covering the Rec. 2020 gamut. The human observers performed a hue matching task, adjusting the hue of the test stimulus, with a hue angle step of 0.2°, at various chroma levels to match that of the reference stimulus at 21 different hues. The derived constant hue loci were used to test the various UCSs and suggested the need to improve the hue linearity of these spaces.

Introduction

Hue linearity is a critically important characteristic of uniform color spaces (UCS) and color appearance models (CAM), as various image processing and fine tuning, such as tone mapping, gamut mapping, saturation enhancement, and contrast enhancement, are performed in the lightness-chroma plane of a constant hue. Thus, a great number of psychophysical experiments have been carried out to test the hue linearity in different UCSs and CAMs, or to collect data for derive constant hue loci, using the hue matching and unique hue estimation/adjustment techniques.

For example, Hung and Berns [1] and Ebner and Fairchild [2] used the hue matching technique to derive the constant hue loci by presenting stimuli on CRT displays. In contrast, Shamey et al [3] and Xiao et al [4] used the unique hue estimation/adjustment technique to test the performance of various existing CAMs and UCSs, using surface colors and displays. Bao et al [5] used a spectrally tunable LED device to produce stimuli under a uniform illumination condition, which allowed to produce a smaller step of hue angle for investigating the unique hue loci. The stimuli used in these studies covered relatively small color gamuts, with the maximum chroma levels around 100 in the CIELAB color space, and had the luminance below the diffuse white point. In 2020, Zhao and Luo [6] carried out an experiment using both the hue matching and unique hue estimation methods, with the stimuli produced by an SDR display having a maximum chroma level of around 120 in the CIELAB color space and having the luminance below the diffuse white point.

In recent years, HDR and WCG displays are becoming available in the market, which can produce much wider ranges of luminance and colors than conventional displays. For instance, HDR displays can produce a peak white luminance around 4000 nits and a Rec. 2020 color gamut [7]. Such a change also motivated the development of two new UCSs (i.e., IC_TC_P [8] and $J_za_zb_z$ [9]), both of which adopt the Perceptual Quantizer (PQ) curve to describe the non-linear compressive response in the human visual system. The hue linearity of these two spaces, however, was only tested or verified using the constant hue loci derived from the above studies, which actually do not cover the specified HDR and WCG conditions. This is mainly because constant hue loci were never carefully derived under HDR and WCG conditions.

This study aims to derive constant hue loci covering the Rec. 2020 color gamut, which was never achieved in the past. Moreover, the viewing condition of the experiment was designed to HDR, with the stimulus luminance being much greater than the diffuse white luminance.

Methods

Apparatus

The experiment apparatus and setup were the same as those used in a recent work [10]. During the experiment, the observer was seated in front of a viewing booth, with his or her chin fixed on a chin rest, to view three diffuse stimuli under an adapting condition, as shown in Figure 1. The left and center stimuli were produced using two spectrally tunable LED devices, which were placed behind the viewing booth; the right stimulus was produced using a diffuse black sheet, with a reflectance of around 4%. Each stimulus occupied around a field of view (FOV) of around 5°. The adapting condition was provided by another spectrally tunable LED device that was placed above the viewing booth.

The two LED devices that produced the two stimuli had four channels, with three chromatic channels (i.e., red, green, and blue) and a warm white channel. The devices were calibrated using a gain-off-gamma model to build the relationship between the 16-bit input signal of each channel and the tristimulus values XYZ of the two stimuli.

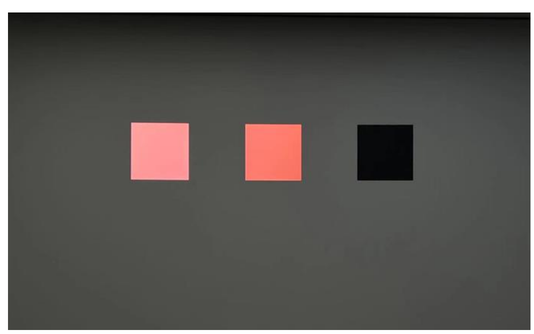

Figure 1 Photograph of the experiment setup. The left and middle stimuli were produced using two spectrally tunable LED devices, and the right stimuli was produced using a black sheet with a reflectance of around 4%.

Adapting condition and stimuli

The adapting condition was calibrated to have a diffuse white luminance of 1000 cd/m^2 with the chromaticities of the CIE D65 at the center of the back wall using a PhotoResearch PR-655 spectroradiometer and a Labsphere reflectance standard. The left and right stimuli were calibrated to have a luminance of 3400 cd/m^2, so that the viewing condition was high dynamic range.

The stimulus on the left was the reference stimulus whose luminance and chromaticities were fixed during the experiment; the stimulus in the middle was the test stimulus. During the experiment, the observer was asked to adjust the hue of the test stimulus, so that its hue appeared the same as the hue of the reference stimulus. The adjustment of the hue was performed in CIELAB color space, with the luminance and chroma of the stimulus remained constant. A customized program was developed for adjusting the hue angle with a step of 0.2° based on the calibrated gain-offset-gamma model.

The reference stimulus was designed to cover 21 different hues, with the hue angles uniformly distributed between the three primaries of the spectrally tunable LED device in the a^*-b^* plane of the CIELAB color space, and the chroma level of the reference stimulus was set to the largest at the given hue angle, as shown in Figure 2.

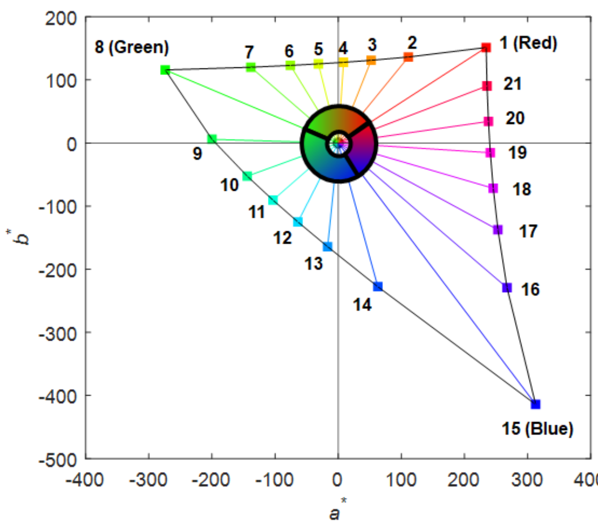

Figure 2 Illustration of the 11 reference stimuli used in the experiment, whose hue angles were uniformly distributed between the three primaries of the spectrally tunable LED device and the chroma level was the greatest in the given hue angle, in the a-b* plane of the CIELAB color space.*

The chroma level of the test stimulus was then carefully designed based on that of the reference stimulus, so that each hue angle had two to four chroma levels for the test stimulus. In order to create an obvious hue difference at the beginning, the hue angle of the test stimulus was designed to shift 5° clockwise from that of the reference stimulus. Figure 3 shows the chromaticities of the reference stimuli and those of the test stimuli in the CIE 1976 *u'v'* chromaticity diagram, all of which were calibrated using the spectroradiometer.

It is worthwhile to mention that in order to minimize the effect of observer metamerism, all the test and reference stimuli were produced using the warm white channel and two of the three chromatic channels. Taking the reflection from the diffuse panel into consideration, the stimuli all had smooth spectral power distributions (SPDs).

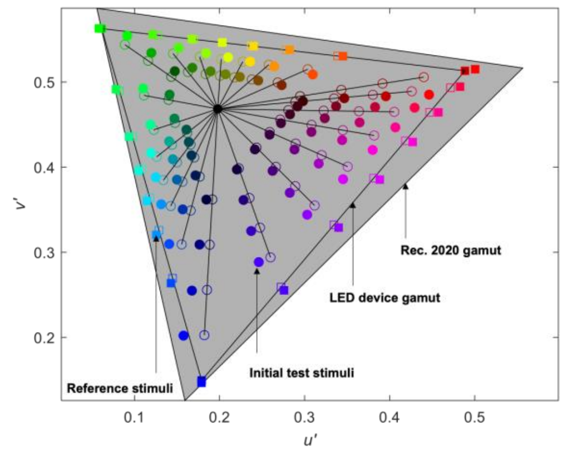

Figure 3 Chromaticities of the reference stimuli and the initial chromaticities of the test stimuli in the CIE 1976 u'v' chromaticity diagram, together with the gamut of the LED device and Rec. 2020. The initial chromaticities of the test stimuli had a 5° clockwise hue-angle difference to the corresponding reference stimulus for creating an obvious hue difference.

Observers

A total of seven observers (four males and three females) with ages ranging between 24 and 34 (mean = 27.71, std. dev. = 2.98) participated in the experiment. All the observers had a normal color vision as tested using the Ishihara Color Vision Test.

Experimental process

Upon arrival, the observer completed the general information survey and the Ishihara Color Vision Test. Then the observer was seated in front of the viewing booth, with his or her chin fixed on the chin-rest, and the general illumination in the experiment space was switched off.

The observer was asked to look into the viewing booth for 90 seconds for a chromatic adaptation. Then the test and reference stimuli were presented to the observer, and the observer was asked to adjust the hue of the test stimulus using a rotary knob with a step of 0.2° so that it appeared to have the same hue as the reference stimulus. A small note was placed in the viewing booth to instruct the observer about how the adjustment of the hue angle corresponded to the change of the hue (e.g., clockwise and counterclockwise changed to the red towards blue and yellow respectively). Once the observer was satisfied with the adjustment, he or she pressed a key to confirm, with the input signals to the LED device recorded. The same procedure was repeated for all the reference stimuli. In particular, four adjustments with the reference stimulus of 1, 4, 8, and 15 and the test stimulus having the greatest chroma level were repeated for evaluating the intra-observer variations. Therefore, each observer completed 67 adjustments in total, with the sequence randomized.

Results and discussions

After the experiment, recorded signals were sent to the LED device to reproduce the test stimuli that were adjusted by the observers, with the SPDs measured using the spectroradiometer.

Inter- and intra-observer variations

The intra- and the inter-observer variations were characterized using hue angle differences in the CIELAB color space. In particular, the intra-observer variations were characterized based on the two hue angles that were repeated adjusted by each observer; the inter-observer variations were characterized based on the average hue angles adjusted by all the observers (i.e., an average observer) and the hue angles adjusted by each observer. Figure 4 shows the intra-observer variations, with the mean hue angle difference from the mean ranging between 0.91° and 1.99° (mean = 1.41°). No systematic difference among the four hues can be observed. Figure 5 shows the inter-observer variations, with the mean hue angle difference from the mean ranging between 4.44° and 9.03° (mean = 5.79°).

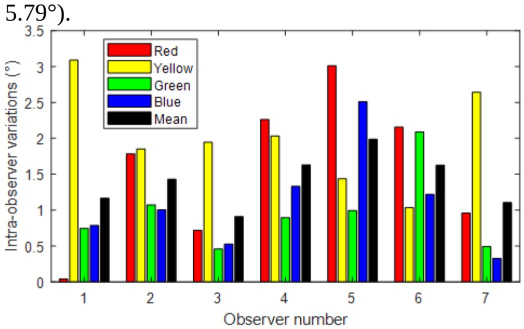

Figure 4 Summary of the intra-observer variations.

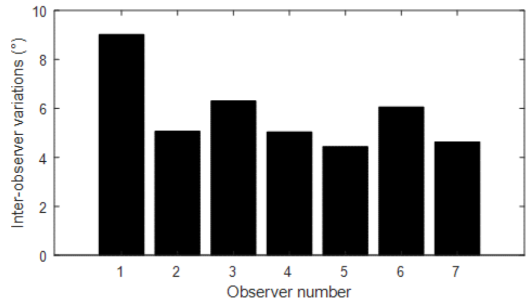

Figure 5 Summary of the inter-observer variations.

Constant hue loci in various uniform color spaces

The measured SPDs of the stimuli adjusted by the observers, the SPDs of the reference stimuli, and the SPD of the adapting condition (i.e., the diffuse white) were used to derive the chromaticities of the test and reference stimuli in nine different color spaces. Figure 6 shows the average chromaticities and the fitted constant hue loci.

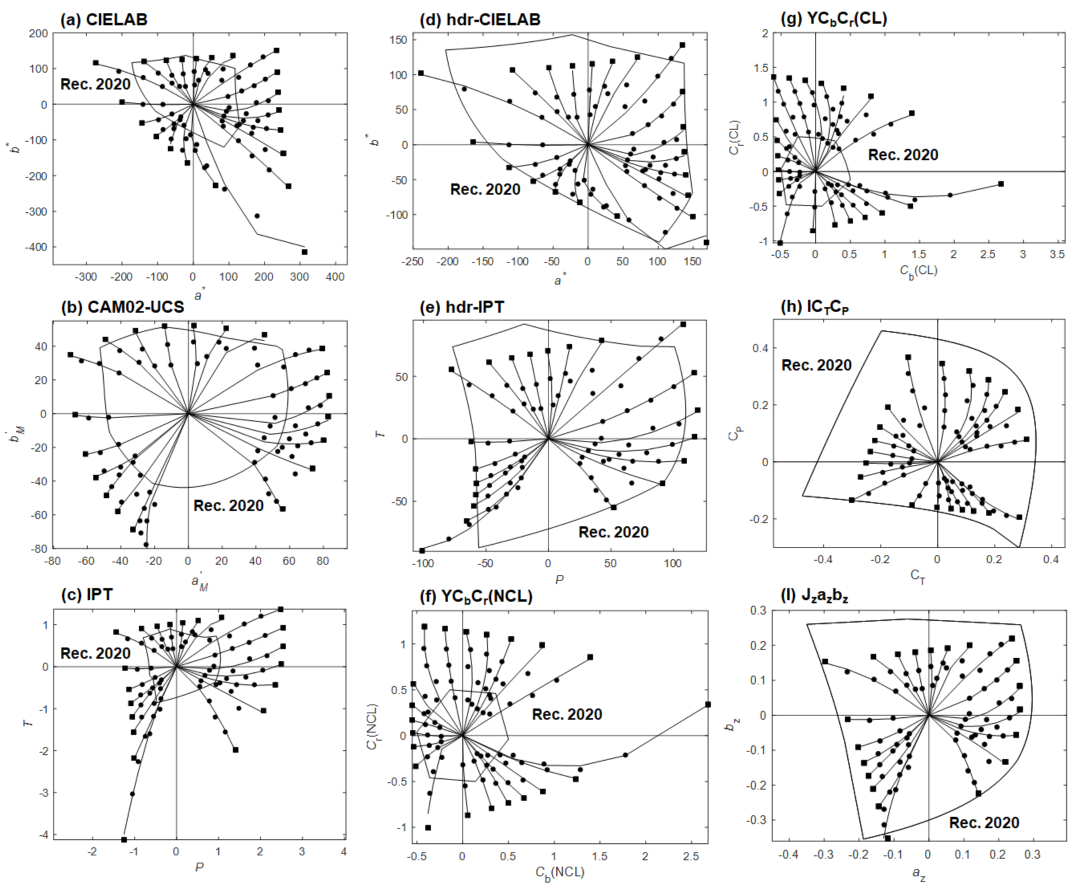

Figure 6 Constant hue loci that were derived using the average chromaticites of the test stimuli adjusted by the observers and the chromaticites of the reference stimuli in different color spaces. The enclosed area shows the Rec. 2020 color gamut. (a) CIELAB; (b) CAM02-UCS; (c) IPT; (d) hdr-CIELAB, (e) hdr-IPT; (f) YC_bC_r (NCL); (g) YC_bC_r (CL); (h) IC_TC_P; (i) $J_za_zb_z$.

A color space with a better hue linearity should have all the constant hue loci be straight lines that go through the origin. It can be observed that the CIELAB color space has poor hue linearity in the blue region, which corroborated the various past studies (e.g., [1, 2]). Among the color spaces that were designed for SDR conditions (i.e., CIELAB, CAM02-UCS, IPT, YCbCr with a non-constant luminance "YC_bC_r (NCL), and YC_bC_r with a constant luminance "YC_bC_r (CL)", IPT seems to have the best performance. For the other four color spaces that were designed for HDR conditions (i.e., hdr-CIELAB, hdr-IPT, IC_TC_P, and $J_za_zb_z$), IC_TC_P seemed to have the best performance.

Conclusion

Constant hue loci are critically important to color spaces. Past studies mainly derived the constant hue loci for small color gamut (e.g., sRGB) and SDR conditions. In this study, we carefully designed an experiment to derive constant hue loci for Rec. 2020 color gamut and an HDR condition. The human observer viewed a reference stimulus, a test stimulus, and a black stimulus under a D65 adapting condition with an L_w of 1000 cd/m^2. The observer adjusted the hue angle of the test stimulus, in an interval of 0.2°, in the CIELAB color space to match the perceived hue of the reference stimulus, with the chroma and luminance of the test stimulus held constant. In total, there were 11 reference stimuli covering 11 different hue angles and 63 test stimuli, with each reference stimulus having two to four test stimuli. The test stimuli that were adjusted by the observers were used to test the hue linearity of nine different color spaces. It was found the IPT color space had the best hue linearity among the five spaces that were designed for SDR conditions (i.e., CIELAB, CAM02-UCS, IPT, YC_bC_r (NCL), and YC_bC_r (CL)). Moreover, IC_TC_P was found to have the best hue linearity among the four color spaces that were designed for HDR conditions (i.e., hdr-CIELAB, hdr-IPT, IC_TC_P, and $J_za_zb_z$).

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