Development and Testing of a Color Space (IPT) with Improved Hue Uniformity

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Abstract

A simple, uniform color space (the IPT color space) has been derived that accurately models constant perceived hue.[1,2] The model accurately predicts hue without detrimentally affecting other color appearance attributes. Several psychophysical data sets have been modeled in the new color space and appear to perform as well as or better than CIELAB and CIECAM97s color spaces. Data sets tested and compared to CIELAB and CIECAM97s include Munsell re-notation colors at Value 5,[3] OSA color system uniform scale data,[4] MacAdam's (observer PGN) equi-luminant color tolerance ellipses,[5] suprathreshold color-difference ellipsoids (RIT-DuPont visual color difference data),[6] lightness of chromatic object colors (Helmholtz-Kohlrausch effect),[7] and the two constant hue data sets. Quantitative analysis is discussed for the constant hue data sets and the Helmholtz-Kohlrausch effect data. A verification experiment that compares the new space to Hung and Berns'[1], and Ebner and Fairchild's[2] constant hue data sets has been performed. Results show that the new space is judged to be at least as uniform as table based hue corrections derived from the data sets.

Introduction

A color appearance model is composed primarily of adaptation transforms and a method to predict color appearance attributes. Adaptation transforms predict corresponding colors and can model chromatic adaptation, luminance adaptation, and changes in viewing conditions. Appearance attributes are descriptors of color perception, i.e. lightness, chroma, hue, brightness and colorfulness. Additionally, color appearance spaces may attempt to predict various color appearance phenomena such as the Hunt effect or the Abney effect.[8]

There has been significant attention paid to various appearance attributes over the past several decades. Recently, interest in hue uniformity has grown because of its importance when applied to gamut mapping. Before Hung and Berns' experiment, the only significant body of perceptual hue data existed in the Munsell data set (which is limited to rather low chroma levels). This data set is relatively well modeled with simple color appearance models such as CIELAB and CIELUV. With the advent of Hung and Berns', and Ebner and Fairchild's data sets, modeling of perceived hue can be performed with much more representative data. The IPT color space described herein models those data sets much more uniformly. Additionally, the color space does not make worse predictions for other attributes of appearance.

The IPT color space is named such that its coordinates have some degree of relationship to the meaning of the dimensions. The lightness dimension is denoted as I, which can be loosely related to the word intensity, providing a clue to it's meaning. The red-green dimension is denoted as P, which can be related to the fact that it is "dominated" by the red response (protan) and is the dimension lost by protanopes. The yellow-blue dimension is denoted as T, using the same argument for the tritan response. IPT is also short for Image Processing Transform since it is useful for transformations such as gamut mapping.

Approach

The problem can be described as needing to find an invertable, functional mapping between XYZ (or some other fundamental color description) and an opponent (has a neutral axis along one of the dimensions) three dimensional space that exhibits the attributes we are interested in. The primary attributes of interest in this work have been linearity of constant hue lines, close correspondence to RLAB with neutral color response, and reasonable Munsell chroma representation. Additionally, it is desirable to have a model that is extremely simple, so it can be implemented easily.

The model assumes that the problems of adaptation and appearance attribute description are separable. Adaptation transformation should be done to convert the color coordinates to a viewing conditions independent space, as in the RLAB model.[9] Appearance attributes can then be described through a transformation from viewing conditions independent tristimulus values. In this way, the IPT color space could be used to extend or enhance the CIECAM97s color appearance model. One would simply use the chromatic adaptation transform from CIECAM97s to calculate corresponding colors and then the IPT color space to determine appearance attributes.

The model consists of a 3x3 matrix, followed by a non-linearity, followed by another 3x3 matrix. The model assumes input data is in CIEXYZ for the 1931 2-deg. observer with an illuminant of D65. The parameters are shown in matrix form in equation 1.

$$
\begin{aligned}
&\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.4002 & 0.7075 & -0.0807 \\ -0.2280 & 1.1500 & 0.0612 \\ 0.0 & 0.0 & 0.9184 \end{bmatrix} \begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} \\
&L' = L^{0.43}; L >= 0 \\
&L' = -(-L)^{0.43}; L < 0 \\
&M' = M^{0.43}; M >= 0 \\
&M' = -(-M)^{0.43}; M < 0 \\
&S' = S^{0.43}; S >= 0 \\
&S' = -(-S)^{0.43}; S < 0 \\
&\begin{bmatrix} I \\ P \\ T \end{bmatrix} = \begin{bmatrix} 0.4000 & 0.4000 & 0.2000 \\ 4.4550 & -4.8510 & 0.3960 \\ 0.8056 & 0.3572 & -1.1628 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}
\end{aligned}
\qquad (1)
$$

It is immediately apparent that this model is invertable. The range of the color space is 0 to 1 for the lightness axis, I, and about –1 to 1 for both opponent axes. To scale the range to be roughly equivalent to CIELAB, multiply I by 100, and P and T by 150.

By examining the coefficients of the matrices and the non-linearity, several points are seen. The first 3x3 matrix converts the tristimulus data into a description that is very near the Hunt-Pointer-Estevez cone primaries normalized to D65.[9] The compression factor (power function with exponent = 0.43) is nearly identical to that of the RLAB color space for average surround conditions, as is the lightness response along the neutral axis.[10] Figure 1 shows the neutral response compared to that of CIELAB L*.

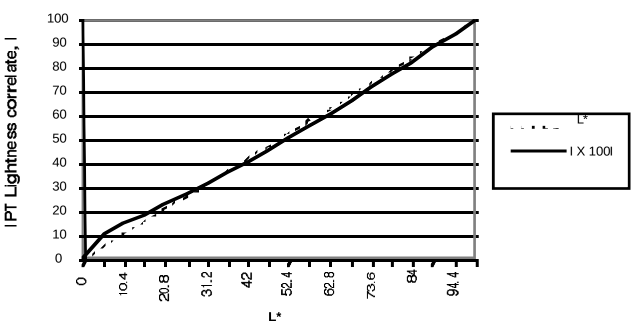

*Figure 1. IPT I along the neutral axis compared to CIELAB L**

The most important of the attributes to model with this effort is the uniformity of hue. The hue uniformity of the IPT color space is contrasted to the uniformity of CIELAB and CIECAM97s in figure 2. The data shown are for Ebner and Fairchild's constant hue data set, and Hung and Berns' data set.

Psychophysical Data Set Analyses and Comparison with CIELAB and CIECAM97s

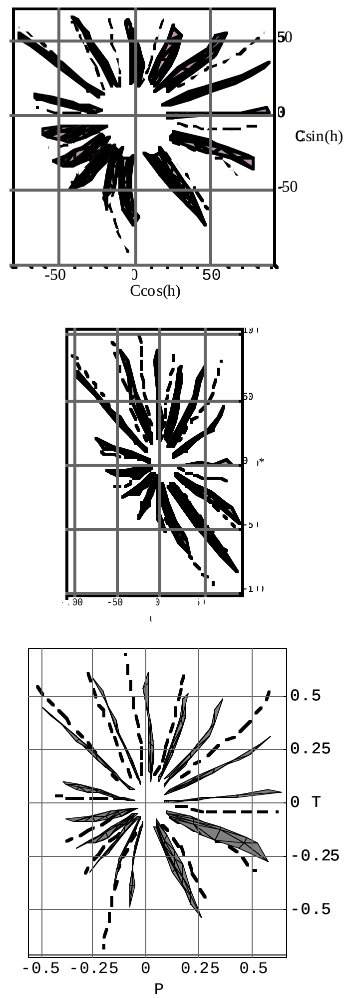

Figure 2. Constant perceived hue surfaces from Ebner and Fairchild, and loci from Hung and Berns plotted in CIECAM97s (top), CIELAB (middle), and IPT (bottom). Hung and Berns loci are shown as dotted lines.

Table 1. Viewing Parameters for CIECAM97s Calculations

Data set	White	L_A	Y_b	c	N_c	F_{LL}	F
Ebner	D65	14.2	35	0.525	0.8	1	0.9
Hung	C	10	20	0.525	0.8	1	0.9
Munsell	C	64	20	0.69	1	1	1
OSA	D65	64	20	0.69	1	0	1
MacAdam	C	24	20	0.69	1	1	1
RIT-DuPont	D65	64	20	0.69	1	0	1
Pirrotta-Fairchild	D65	64	20	0.69	1	0	1
spectral	D65	64	20	0.69	1	1	1

Table 1 shows the set of parameters used to calculate CIECAM97s[11] coordinates for each of the psychophysical data sets.

Figure 3 shows quantification of hue nonuniformity using two different metrics, mean hue angle from the mean hue angle, and maximum hue angle from the mean hue angle. For CIECAM97s, for simplicity, hue angle calculation was done from the origin. If the hue angles were calculated from the coordinates of neutral gray (-3.6, -7.3), the hue error in the blue region would be even worse.

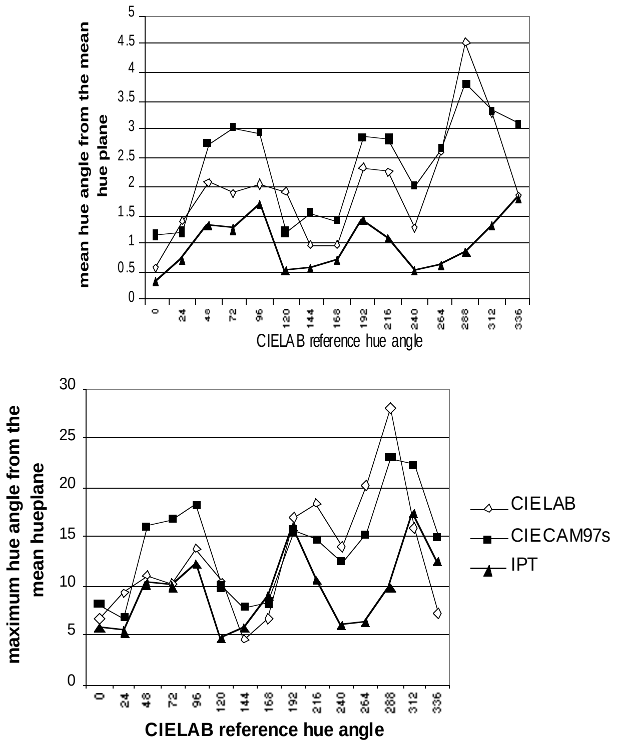

Figure 3. Quantification of hue non-uniformity for CIELAB, CIECAM97s, and IPT color spaces.

Clearly, the IPT color space has the lowest mean hue error from the mean hue plane. The IPT color space is at worst equivalent to the other two spaces in the maximum hue angle deviation from the mean hue plane.

Figure 4 shows Munsell Value 5 renotation data set in each of the CIECAM97s, CIELAB, and IPT color spaces. Note the increased chroma value of the low chroma colors in CIECAM97s. Although CIELAB seems to be the most uniform with respect to chroma circles, the differences are not large.

Figure 5 shows the OSA color system uniform scale data at Lightness 0 (middle lightness). Note the curvature of the data in CIELAB. Again, CIECAM97s spaces the near neutral colors quite widely. The IPT color space shows a slight opposite effect to CIELAB in curvature of vertical loci.

Color difference data sets are visualized in figures 6 and 7. Figure 6 shows MacAdam's famous color discrimination ellipses at constant luminance factor along with the spectral locus. Figure 7 shows the RIT-DuPont suprathreshold color difference ellipses.

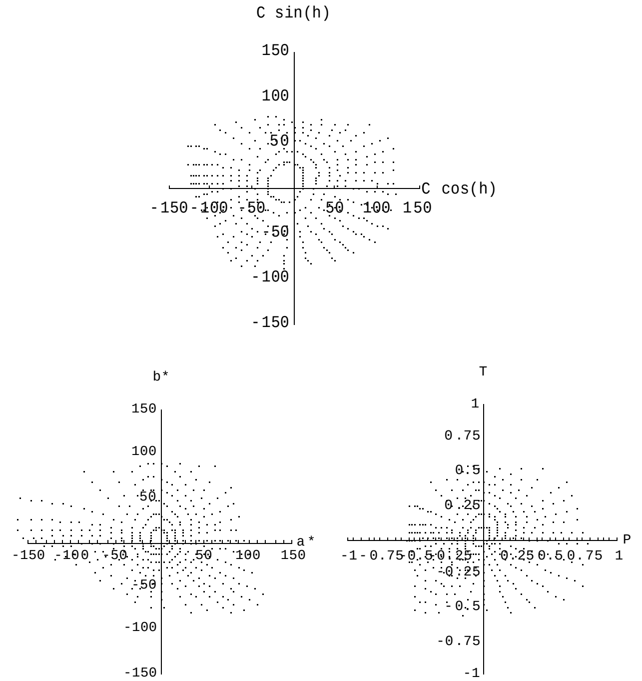

Figure 4. Munsell renotation data for Value 5 in CIECAM97s (top), CIELAB (bottom left), and IPT (bottom right).

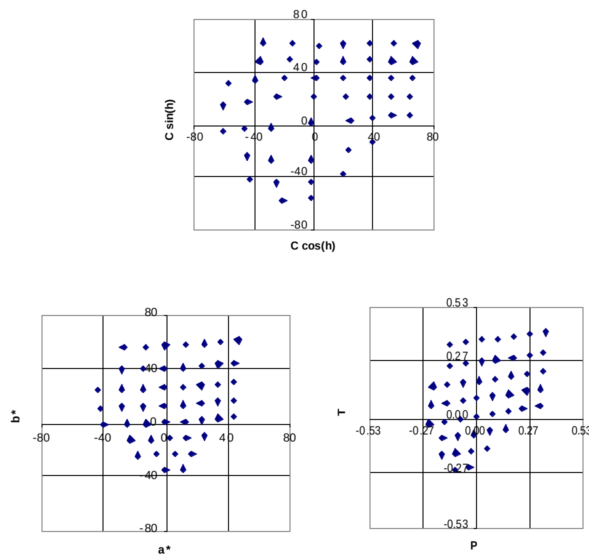

Figure 5. OSA color system uniform scale data at lightness = 0 for CIECAM97s (top), CIELAB (bottom left), and IPT (bottom right).

Note the shape and direction of the ellipses in each space. CIECAM97s exhibits larger ellipses near neutral. Ellipses in the blue region (negative T, near 0 P) point toward the origin in IPT more than the other spaces.

Note similar behavior between MacAdam's and suprathreshold ellipses in both the size of the near neutral ellipses in CIECAM97s, and in the direction of the major axis of the ellipses in the blue region in IPT.

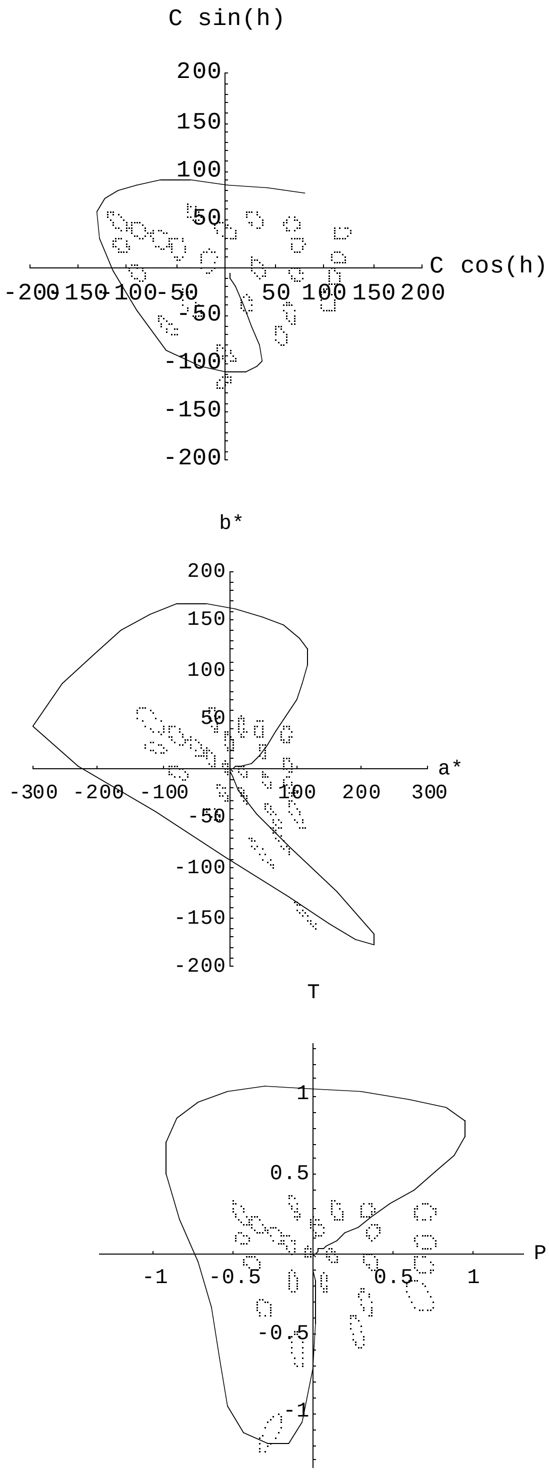

Figure 6. MacAdam (observer PGN) equi-luminant discrimination ellipses and spectral locus for CIECAM97s (top), CIELAB (middle) and IPT (bottom)

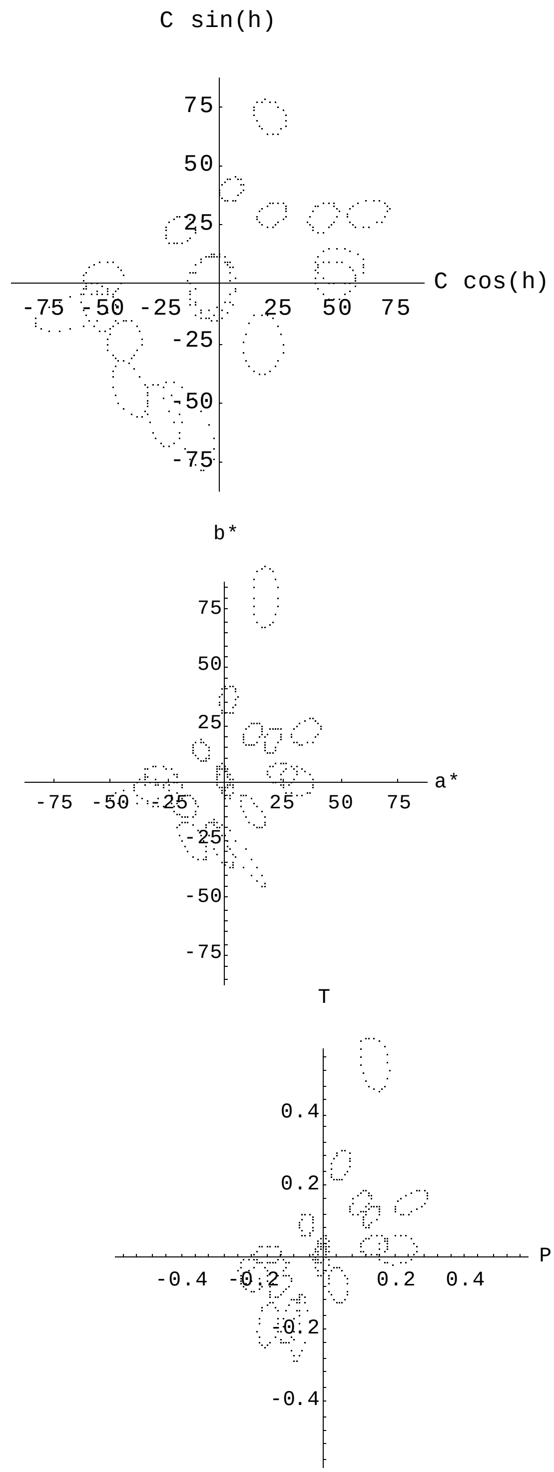

Figure 7. Suprathreshold color difference ellipses for surface colors from RIT-DuPont color difference data set. CIECAM97s (top), CIELAB (middle), and IPT (bottom)

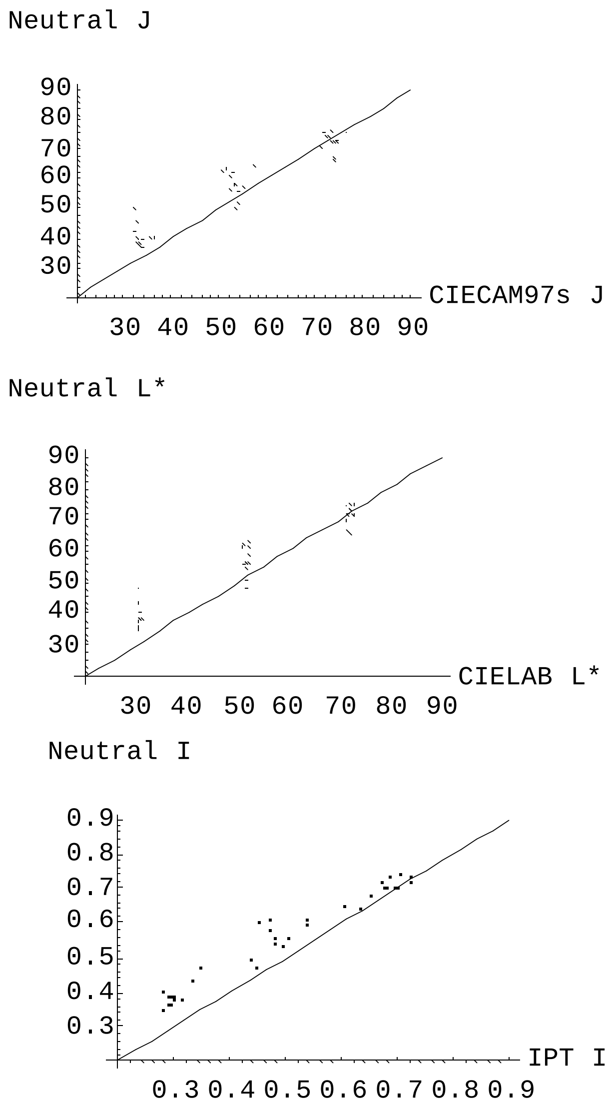

Figure 8. Heterochromatic lightness match data in CIECAM97s (top), CIELAB (middle), and IPT (bottom). RMS error is 6.9, 7.1, 6.7 respectively.

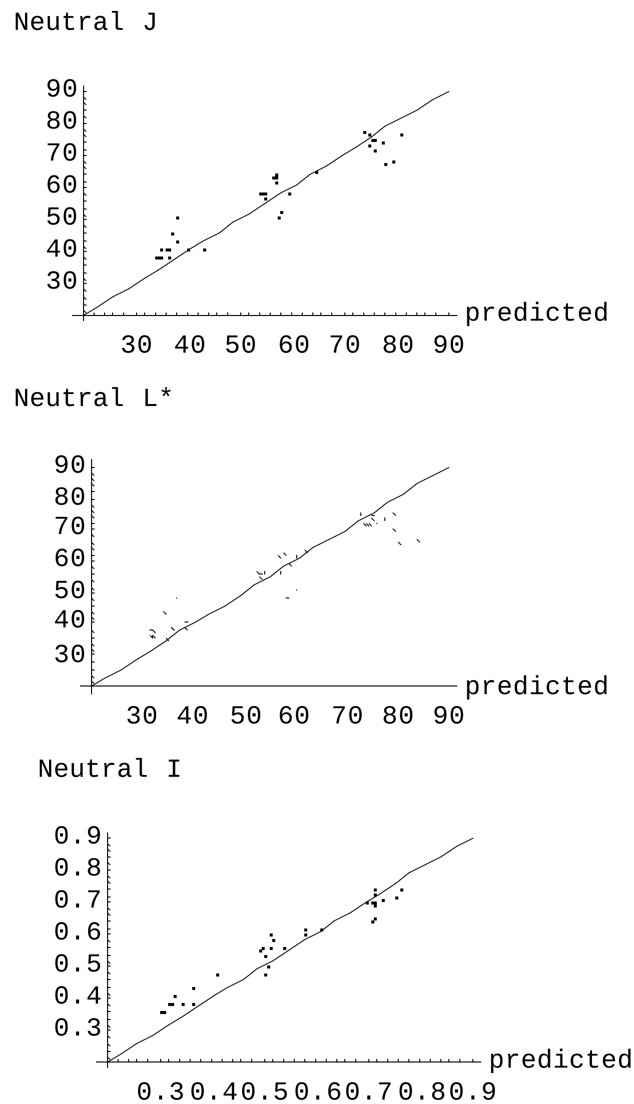

Figure 9. Predicted lightness response as a function of chroma in CIECAM97s (top), CIELAB (middle), and IPT (bottom).

Figure 8 shows heterochromatic lightness response data in the three color spaces. The data show observer lightness matches between chromatic and neutral colors that illustrate the Helmholtz-Kohlrausch effect. This effect shows that chromatic object colors appear lighter than achromatic object colors of the same luminance factor. The RMS error in lightness matches between neutral and chromatic colors is 7.1 for CIELAB, 6.9 for CIECAM97s, and 6.7 for IPT. Though the difference is not significant, the improvement with a simple model to predict chromatic lightness responses is greatest with IPT. The L** function derived by Pirrotta and Fairchild to predict observed lightness of chromatic colors is a function of lightness, chroma and hue. This function predicted lightness matches with an RMS error of 4.2, which is the same as the interobserver standard deviation of these data.

Figure 9 shows the improvement in RMS error when a simple function of chroma is applied to the observer matches. The functions were derived from linear regression and are shown in equation 2 for each of the color spaces. The RMS error between predicted match and observer match is also shown.

CIECAM97s: Predicted J = J + 0.084 C RMS error: 5.2
CIELAB: Predicted L=L* + 0.143* C^*_{ab} *RMS error: 6.2* (2)
IPT: Predicted I = I + 0.202 C_{IPT} *RMS error: 4.3*

Note that the RMS error for IPT is almost identical to the interobserver standard deviation of 4.2. This shows that both the hue dependency and the lightness modulation dependency can be removed from the lightness prediction of chromatic colors if the calculation is performed in the appropriate color space.

Verification Experiment

A verification experiment was conducted to test whether observers could distinguish better uniformity with the IPT color space. A forced choice, paired comparison experiment was conducted to test the hue uniformity difference between two uniform perceived hue data sets and the IPT color space.

Hung and Berns'[1] constant lightness data set was used by Braun[12] to derive a two dimensional table lookup scheme that enabled forward and inverse transformation between CIELAB color space and the Hung and Berns uniform hue data space. Ebner's[2] data set of constant perceived hue was used to derive a three dimensional table to enable transformation between CIELAB color space and the respective uniform hue data space.

Fifteen hue angles were uniformly sampled in lightness and chroma within the respective color spaces, then transformed to CIELAB for display on the calibrated CRT display. Out of gamut colors were converted to CIELAB coordinates 50,0,0. For each hue angle sampled, the three color spaces were compared, requiring three presentations. For each observation, two repeats of the data set were presented to the user to account for screen non-uniformity. Each observation session required 90 judgements (15 hues X 3 images X 2 repeats). The list of pairs of hue comparisons was pseudo-randomly shuffled for each observation session. Figure 10 shows results from the paired comparison experiment.

Thirty observations of the entire data set were made. Nine observers took part in the experiment. All observers had experience with color, and were familiar with the terminology, and with the concept of hue uniformity. Using Thurstone's law of comparative judgement[13] (version V), fifteen interval scales were derived, one for each hue angle sampled, that compared relative hue uniformity of the three color spaces.

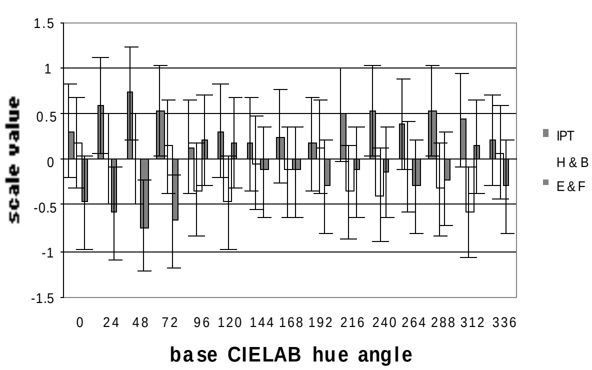

Figure 10. Comparison of uniformity judgements between the IPT color space and the two uniform hue data sets. H&B are Hung and Berns' data, E&F are Ebner and Fairchild's data.

Clearly, the IPT color space is judged either more uniform (when the confidence limits are beyond the mean of the other two spaces, such as with reference hue 48), or no less uniform (e.g. reference hue 144) than the constant hue data sets. A parallel experiment has shown that for the reference hue of 48 degrees, CIELAB was judged more uniform than either of the constant hue data sets. The magnitude of uniformity difference between CIELAB and the next judgement was about 0.5 units, which is contrasted to roughly 0.75 units in figure 10 (for reference hue angle 48). From this we can conclude that the IPT space is roughly as uniform as CIELAB at the reference hue of 48 degrees, and at least as uniform as as the constant hue data sets.

Conclusions

A color space named IPT has been developed that is more uniform in perceived hue than existing popular color spaces. It is simple to implement and invertable, thus lending itself to imaging applications. The IPT color space is similar in model to CIELAB color space, although the coefficients are different. Visualization of several psychophysical data sets were shown for IPT, CIELAB, and CIECAM97s. In all cases shown, IPT appears to perform as well as (and in some cases performs better than) either CIELAB or CIECAM97s. A verification experiment was performed the results of which show that IPT is judged to be more uniform than two constant hue data sets.

References

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