Deriving Appearance Scales

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Abstract

The concept of color space has come to be an unquestioned three-dimensional representation of color stimuli, or color appearance, intended to simplify the relationships among physically measurable attributes of light, mathematical formulae, and human sensations and perceptions. The notion of three-dimensional mathematical spaces as adjuncts for color is often helpful, but perhaps also misleading at times. Color appearance models requiring five or six dimensions to represent color appearance illustrate some of the limitations of historic spaces. This paper poses the question of whether color appearance would be better represented by independent appearance scales with no requirement that they be related as a higher-dimensional space. In other words, is color better represented by six one-dimensional color scales than one or two three-dimensional color spaces. A framework for implementing such appearance scales is described and one implementation is presented along with discussion of the ramifications for color difference metrics.

Introduction

Color scientists and engineers have become accustomed to the fundamental concept of color space to the point that the concept itself goes unquestioned. Much like most accept the fact that the earth is nearly spherical, those in the color-related fields proceed merrily along without a doubt that color space is three dimensional. Further, some continue to seek the holy grail of a three-dimensional color space in which perceived color differences can be expressed as uniform Euclidean distances despite an apparent lack of psychophysical evidence that such a space might exist. Perhaps it is time to, once again, step back and ask the question of whether the concept of a Euclidean distance metric in three dimensions really makes sense for describing color, even approximately.

Perhaps some insight into appropriate descriptions of color appearance can be gained from a cursory examination of the other human senses.[1,2] Our perception of taste has at least five distinct dimensions, sweetness, bitterness, sourness, saltiness, and umami, and seldom does anyone speak of changes in taste perceptions as a Euclidean difference space. Similarly our sense of smell is served by something on the order of 1000 different receptor types. Some have tried to reduce the dimensionality to approximately six including flowery, foul, fruity, spicy, burnt, and resinous. Our sense of hearing is actually spectral (plus intensity) in terms familiar to color scientists as humans are able to detect frequencies within sounds (no aural metamerism) and the relative intensities of each frequency. Finally our sense of touch might well be too complex to even attempt to summarize in a sentence or two. None of the perceptions arising from any of these senses are commonly expressed in terms of multi-dimensional spaces with Euclidean (or similar) difference metrics. Given these similarities in our other senses, why should we think color is different? Is it the relatively low dimensionality? Is it the seemingly simple perceptual relationships such as color opponency? Is it the nature of additive color mixing? Additive color mixture under photopic conditions provides ample evidence for trichromacy, the three-dimensional nature of color matching/mixture. Adding Grassmann's laws allows expression of color matches in various sets of primaries via simple 3x3 linear transformations analogous to a change of basis in a three-dimensional, linear space (where Euclidean distances mean something mathematically). Perhaps it is this property of color matching, which is not a direct representation of perception or appearance, that leads to an almost irresistible next step to start expressing color matches in three-dimensional Euclidean spaces. And then, apparently without clear justification, the concept is carried forward in attempts to express appearances and differences in similar three-dimensional Euclidean spaces such as the CIELAB color space. Perhaps those attempts were always as doomed as any explorers who might have set out to "circumnavigate" a flat earth.

Color science is not devoid of examples typically described as color spaces that are actually descriptions of color perception one dimension at a time.[3] For example, the Munsell system, despite its common embodiments, was derived as a system of three independent perceptual dimensions, hue, value, and chroma. Similarly, Guth's ATD model of visual perception was typically described in terms of independent dimensions, although the temptation to plot some of them together for some examples proved irresistible. Likewise, color appearance models such as CIECAM02 were developed with independent predictors of the six perceptual dimensions of brightness, lightness, colorfulness, saturation, chroma, and hue. This was somewhat compromised by requests for rectangular color space dimensions which appeared as CIECAM97s evolved to CIECAM02. However it should be noted that cylindrical representations of the appearance spaces were common even before the requests for rectangular coordinates. Lastly, the NCS system provides a useful example of hue being treated separately from whiteness-blackness and chromaticness. And while NCS whiteness-blackness and chromaticness are plotted in two-dimensional trilinear form, the dimensions are largely independent since the anchor of maximal chromaticness appropriately varies from hue to hue.

All of this insight leads to the hypothesis that perhaps color space is actually a one-dimensional space, rather than a three-dimensional space, and that Euclidean distance metrics might indeed be successful in such a space. Of course, color appearance cannot be properly described in a single one-dimensional space. Instead six of them are required. There are three fundamental appearance attributes for related colors, lightness, saturation, and hue. Combined with information about absolute luminance, colorfulness and brightness can be derived from these and are important and useful appearance attributes. Lastly, chroma can be derived from lightness and saturation if desired as an alternative relative colorfulness metric. Thus, color is rightfully and fully described with six one-dimensional appearance spaces (or scales), four of which are fundamental for related colors and two of which are derived from the fundamental scales. This paper provides some detail of the conceptual framework of a color model made up of one-dimensional spaces and an implementation of that framework for future application and investigation. Note: One-dimensional "spaces" are more commonly referred to as "scales" in color science, thus the term "scale" is used preferentially for the remainder of the paper.

Conceptual Framework

A set of color appearance scales (or dimensions, or spaces) following these principles has been derived and an implementation is presented in the next section. This section provides the general framework that could be easily adapted to different specific implementations of the concept. The first step is to apply a chromatic adaptation model to compute corresponding colors for reference viewing conditions (*e.g.* D65, 315 cd/m^2). Then the IPT model, derived specifically for accurate hue representations, is used to compute a hue angle (h) and then a hue composition (H) can be computed based on NCS unique hues. For the defined hue, saturation (S) is computed using the classical formula for excitation purity applied along lines of constant h in the u'v' chromaticity diagram. For that chromaticity, the luminance for zero gray content, G_0, is defined as the reference for lightness (L) computations that follow a power function with offset model found to perform well in recent research for high-dynamic-range lightness-brightness scaling. The remaining dimensions are then derived from L and S along with luminance information. Brightness (B) is lightness (L) scaled by a factor derived from the classic work of Stevens and Stevens that illustrated terminal brightness as a function of adapting luminance. The derived scales are colorfulness (C), which is simply saturation (S) scaled by brightness (B), and chroma (Ch) which is saturation (S) times lightness (L).

This type of formulation allows accurate description of color appearance for lights and objects across a variety of adaptation conditions and for low- or high-dynamic-range scenes. To the degree that each perceptual scale is accurate, differences on each of the dimensions should be easily calculated and, as long as the temptation to combine those differences into a single Euclidean distance metric is resisted, quite effective results can be obtained. The next section steps through a proposed implementation in detail.

Implementation

Fairchild,[4] at ISCC/IS&T/SID meeting on color spaces, outlined a methodology for computing the set of three fundamental appearance attributes of hue, saturation, and lightness for related colors from which the attributes of brightness and colorfulness can be derived as a function of the absolute luminance along with chroma. As the hue-linearized space IPT, based in opponent color theory, is considered exceptionally uniform in hue, the hue scale (h) is computed as a simple hue angle using the IPT model.[5] The required inputs for the IPT hue angle computation are the CIE tristimulus values in XYZ for the corresponding colors in CIE Illuminant D65. A chromatic adaptation transform is required to obtain corresponding colors for Illuminant D65 if the stimuli of interest are viewed under a different state of adaptation. The CAT02 transformation imbedded in the CIECAM02 color appearance model is recommended with a simple von Kries transformation on cone fundamentals a second choice. If luminance information is available and impacted by the selected chromatic adaptation transformation, then transformation to a white-point luminance of cd/m^2 is recommended. Hue composition (H) can be obtained by recognizing that the NCS unique hues fall, on average at hue angles of 27.4, 89.8, 162.2, 231.3 degrees for red, yellow, green, and blue respectively. Hue composition is computed simply as percentages between these four anchor hues as done in other color appearance models.

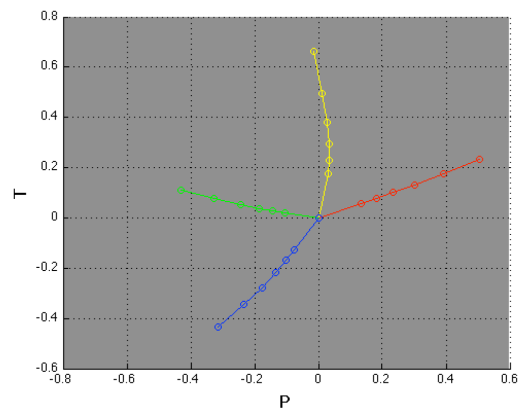

Figure 1. NCS unique hues plotted in IPT to illustrate the definition of hue (h) and hue composition (H).

Saturation (S) is computed in the classical way from excitation purity at the computed IPT hue in the u'v' chromaticity diagram. A slight modification is made in the distances used in the computation however. Saturation is computed as the ratio of the distance from the white point (D65) to the stimulus in question to the distance from the white point (D65) to the spectrum locus stimulus with the same hue angle (h) as the stimulus in question. In cases where IPT constant hue predictions fall on straight lines in the u'v' diagram, this computation is identical with the traditional excitation purity computation. In cases where constant hue contours would be curved in u'v' there are small differences in the calculation. This is illustrated in Fig. 2 and Eq. 1.

Maximum color saturation occurs at the locus of pure color computed in a u'v' chromaticity diagram by cascading the spectra of CIE Illuminant D65 with the 2º Observer and each of the monochromatic stimuli at every integral nanometer from 300 to 830 nanometers of the visible spectrum. A lookup table (LUT) in u'v' as a function of IPT hue was then constructed in one degree increments from the corresponding IPT hue values computed on the locus of pure color. Figure 2 illustrates samples of the resulting locus of pure color in a u'v' chromaticity diagram annotated with IPT hue angle. Saturation S was then computed according to Eq. 1.

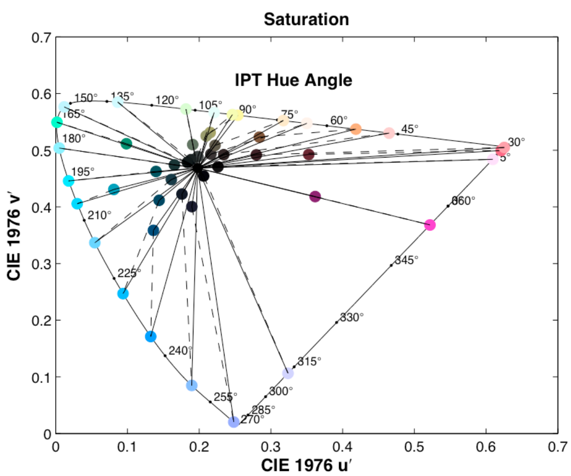

Figure 2. Saturation in a u'v' chromaticity diagram annotated with IPT hue of a random sample from each of the twenty-four (24) NCS Aim Hues.

$$S = \frac{\sqrt{(u'-u'_n)^2+(v'-v'_n)^2}}{\sqrt{(u'_L-u'_n)^2+(v'_L-v'_n)^2}} \quad (1)$$

In this computation, u'v' are the chromaticities of the stimulus, u_n'v_n' those of D65 diffuse white, and u_L'v_L' at the spectrum locus for the same hue angle from the LUT of the chromaticities of pure color in IPT hue. Figure 2 illustrates both the sample color randomly sampled from each of the twenty-four Natural Color System aim hues and the pure color at that same IPT hue. For each hue, vectors are shown as a solid line for the spectrum locus and as dotted lines for the sample color.

Lightness is computed from luminance for each color relative to the corresponding luminance at Evan's G_0 [6] from the relationships given by Nayatani [7]. G_0 defines the luminance for each saturation at which stimuli of higher luminance appear self luminous and stimuli of lower luminance appear to have gray content (or appear like object colors). Thus the G_0 luminance provides an appropriate reference for perceived lightness of object colors that accounts for the Helmholtz-Kohlrausch effect and discrepancies between photopic luminance predictions and heterochromatic brightness matches.

Recently, Chen *et al.*[8] showed that lightness could be scaled both above and below diffuse white and that the perceptual results were well predicted by a lightness function of the form given in Eq. 2. Equation 2 defines the lightness scale as a power function with an offset term and its general form is illustrated in Fig. 3.

$$L = 0.98 Y_g^{1/2.3} + 0.02 \quad (2)$$

In Eq. 2, Y_g is the luminance of the color relative to the luminance Y_{G0} at G_0 and its chromaticity. Y_{G0} is given by finding relative luminance of the NCS color with minimum NCS blackness and the same chromaticities as the sample in question. The minimum value of NCS blackness is zero where grayness is said to be at G_0.

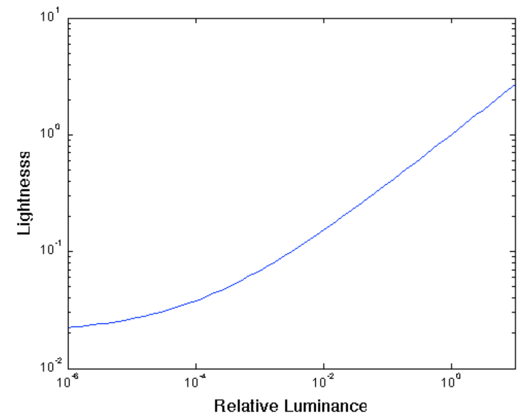

Figure 3. Log Lightness (L) as a function of sample log luminance relative to G_0 luminance for the same hue (h) and saturation (S)

This was accomplished for the value of the NCS blackness (swartz) derived from the chromaticities u'v' of the sample color, according to a method given by Heckaman and Fairchild [9] with basis in Nayatani [7] and the regression technique prescribed by Derrefeldt and Sahlin [10] from conversion data between NCS units of blackness and chromaticness and CIE tristimulus values taken from Bencuya [11] as illustrated in Fig. 4. Figure 5 illustrates the "tent" of the relative luminance of G_0 over the u'v' chromaticity diagram.

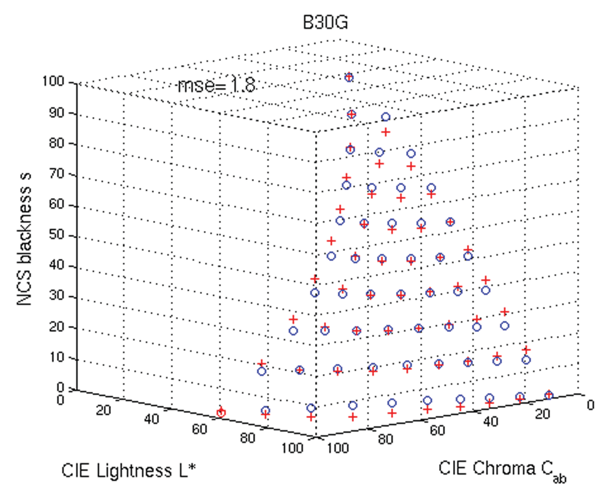

Figure 4. NCS blackness S as a function of CIELAB Lightness and Chroma for the NCS Aim hue B30G. Blue circles are computed from Bencuya [8] measured tristimulus values and the red crosses regressed according to Derrefeldt and Sahlin [7].

Brightness (Q) is computed as a scaled version of lightness (L). The scalar depends on the absolute luminance level and light adaptation to that level. This relationship has been described nicely by both Stevens and Stevens [12] and Evans [13] based on

Marshall and Talbot.[14] In this implementation the terminal brightness locus of Stevens and Stevens is used to define the brightness scalar. (An alternative would be to base it on the F_L function in CIECAM02 which serves a similar purpose.) The terminal brightness locus is the perceived brightness of a stimulus

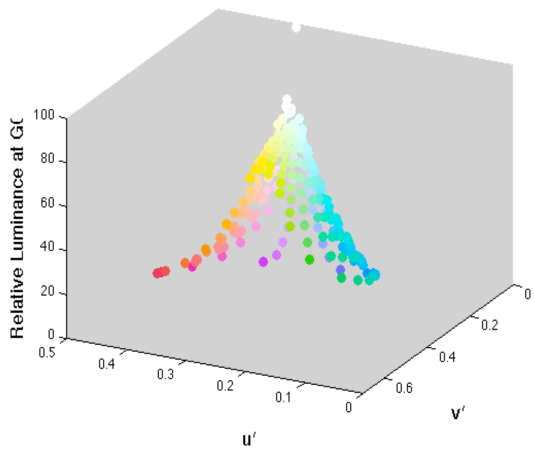

Figure 5. The “tent” of the relative luminance of   in a u'v' chromaticity diagram.

when an observer is adapted to the luminance of the stimulus itself. In other words, it defines how bright white appears as a function of adapting luminance. The brightness function is given by Eq. 3.

$$Q = Q_{tbl} L \quad (3)$$

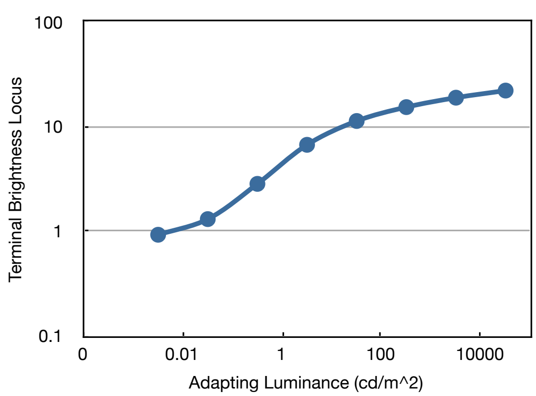

Figure 6. The terminal brightness locus as a function of adapting luminance as fitted to the Stevens and Stevens results.

Q_{tbl} the terminal brightness locus where “ … the level of sensation reached when the eye comes into full equilibrium with the luminance it is viewing.” Q_{tbl} is computed as shown in Eq. 4 which was derived from the brightness-luminance functions published by Stevens and Stevens. Fig. 6 illustrates the fitted terminal brightness locus

$$Q_{tbl} = 0.60\left[\log_{10}(Y_W + 1)\right]^{0.65} + 0.061 \quad (4)$$

where Y_W is the absolute luminance of diffuse white in cd/m^2. Q_{tbl} is defined to be 1.0 at an adapting luminance of 100 cd/m^2. Fig. 7 illustrates brightness as a function of lightness for differing diffuse white luminance levels.

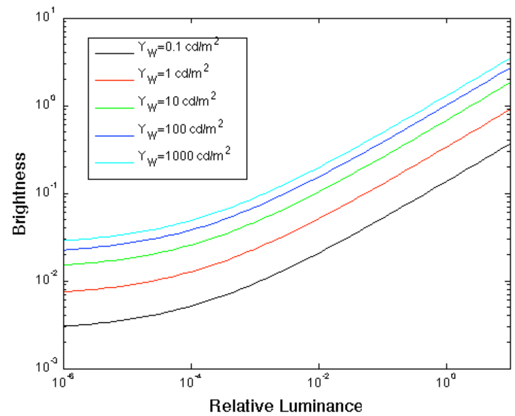

Figure 7. Brightness (Q) as a function of Lightness (L) and diffuse white luminance level (adaptation).

Thus far, scales have been defined for hue (h,H), saturation (S), lightness (L), and brightness (Q). These can be considered the most fundamental color appearance attributes for both related (HLS) and unrelated (HQS) colors. Saturation is considered a more fundamental appearance attribute than the more commonly used chroma and the rarely used colorfulness for a variety of reasons. Among these is that it is a fundamental property of materials (where chroma depends on the material and the illumination and therefore varies for three-dimensional objects made of a single material) and that it more directly relates to the physical stimulus (being constant as the stimulus radiance or relative radiance is scaled). Hunt [15] has provided an useful overview of the nature of saturation relative to other appearance attributes. That said, the final two color appearance scales of chroma and colorfulness can be useful at times and are easily derived from the scales described above. Chroma (C) is simply defined as saturation (S) scaled by the sample lightness (L), C = LS. Likewise colorfulness (M) is simply saturation (S) scaled by brightness (Q), M = QS.

To illustrate the relationships between the various chromatic scales and the performance of the scales proposed in this paper, several computations were made for a series of red samples from the NCS system. The samples are of constant hue (R) and follow an increasing range of chromaticness while possessing zero whiteness as illustrated in Fig. 8.

Fig. 9 illustrates the brightness of the samples as a function of adapting luminance. It can be seen that brightness increases by about a factor of four while luminance increases by a factor of a thousand, an illustration of the power of light adaptation.

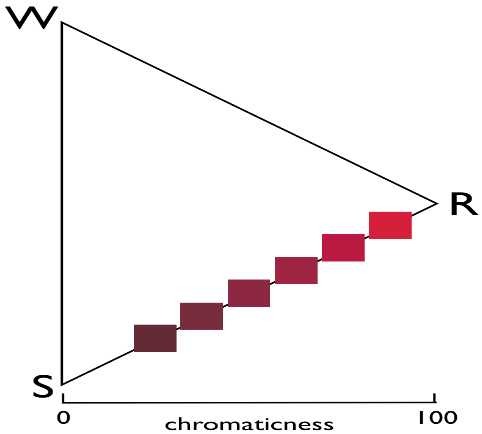

Figure 8. NCS samples of hue R, whiteness zero, and various chromaticness used in the following examples.

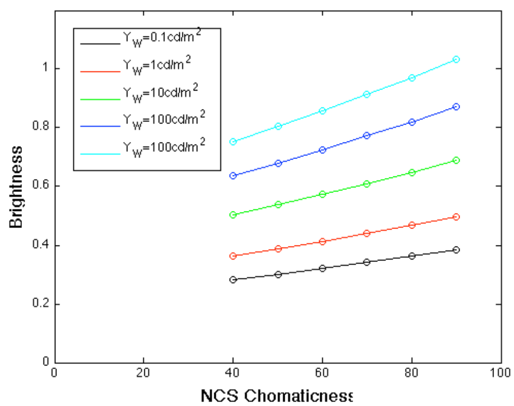

Figure 9. Predicted brightness of the NCS samples for various adapting luminance levels.

Figure 10 shows predicted chroma and saturation for the samples at a single luminance level. Saturation increases with NCS chromaticness for these samples since they are not of constant chromaticity, but rather approach the spectrum locus as chromaticness increases. Chroma has lower values than saturation since the lightness of all these samples is less than 1.0 (as is true for any sample of luminance less than the G_0 luminance) and since the lightness decreases with luminance the chroma becomes a smaller fraction of saturation at the lower chromaticness levels.

Figure 11, similar to Fig. 9, illustrates colorfulness for the NCS samples for various adapting luminance levels. One can see clearly that colorfulness increases with chromaticness at any given adaptation level (it is directly analogous with saturation) and that the overall colorfulness increases with adapting luminance (again following the definition of colorfulness and increasing by about a factor of four with a thousand-fold change in luminance.

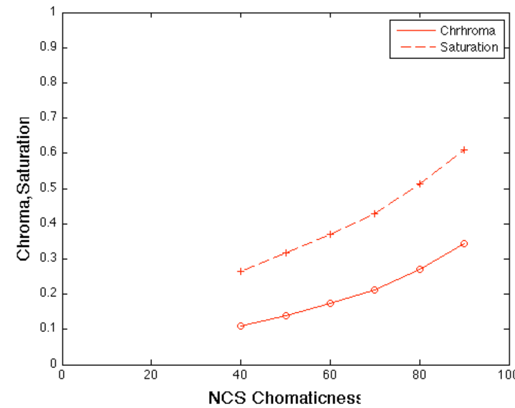

Figure 10. Predicted saturation and chroma of the NCS samples at a single adaptation luminance.

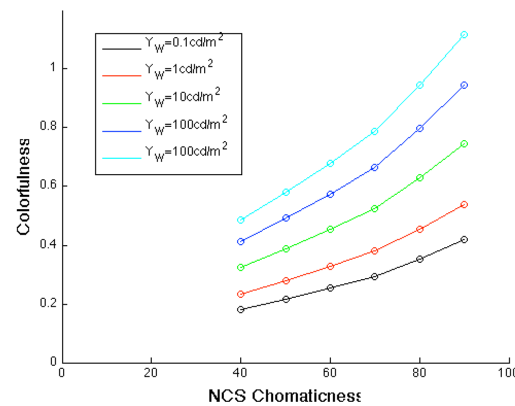

Figure 11. Predicted colorfulness of the NCS samples for various adapting luminance levels.

Finally, the reverse process, going from lightness, saturation, and hue to, say CIE XYZ, is somewhat more difficult as IPT hue is non-linear in CIE XYZ or u'v'. Hence, optimization using the Simplex method [16] is needed to minimize the the difference between the sample hue and the computed hue for trial values of u'v'. In addition the search is constrained such that the saturation values are maintained to match the sample saturation. Once the minimization is complete, the inverted u'v' values have been obtained and a transformation back to XYZ can be completed. :

Color Differences

Color differences are traditionally computed as the Euclidean distance between the coordinates of the two colors in some color space (*e.g.* the CIELAB ΔE^*_{ab}). It has long been recognized that such difference metrics do not correlate well with color difference perceptions, even when the dimensions of the color space seem to correlate well with appearance. As such, a number of weighted color difference equations (*e.g.* CIEDE2000) have been derived in attempts to create a more perceptually uniform color difference metric. These have met with some success, but at the expense of losing any simple relationship with the base color space.

Alternatively, users of color difference formulae are often encouraged to avoid the temptations of "mononumerosis" provided by ΔE metrics and instead examine the individual components of color difference (*e.g.* ΔL*, ΔC* and ΔH* in CIELAB). That is precisely the way color differences should be treated in a comprehensive color appearance model made up of separate one-dimensional appearance scales. In other words, since no geometrical relationship between the appearance scales is claimed or suggested, none should be assumed in the computation of color differences. Instead, only differences in the individual scales should be computed. It is likely that such differences can correlate very well with perceived color differences as either simple difference computations or with simple uni-dimensional weightings to account for differences in scales between suprathreshold appearance differences and overall appearance scales. For tolerances to be derived for individual colors, nothing more than simple differences in the appearance scales is required (this is true of any reasonable color appearance dimensions). Such independent treatment of dimensions and their interactions can also easily be extended to appearance dimensions that are traditionally not considered part of color differences such as gloss, texture, noise, flicker, *etc.*

Future Directions and Conclusions

This paper describes a new concept in the description of color appearance, the use of unidimensional appearance scales instead of multidimensional color spaces, and an initial implementation of the concept.

Color stimuli are described with four fundamental appearance scales: hue (h,H), saturation (S), lightness (L), and brightness (Q). Additionally, the two remaining color appearance attributes, colorfulness (M) and chroma (C) are defined as simple functions of saturation, lightness, and brightness. It is hoped that such a description of color appearance might help free researchers from the restraints sometimes imposed by assumed multidimensional spaces to allow accurate description of appearance, useful definition of color tolerances, and novel ways to encode and process color in imaging, and other, applications.

Further work is clearly needed to refine the definitions of the scales, test them with available and new psychophysical data, explore the interrelationships between the scales, test and define appropriate difference measures, and streamline the computational implementation and inversion if possible. To promote such explorations, the authors are making Matlab code for these scales freely available at <www.cis.rit.edu/fairchild/CAM.html> for others to experiment with.

Acknowledgements

The authors acknowledge the many interesting discussions of this concept over the past year that have helped shape the concept of color-space-free appearance spaces into this first practical implementation.

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