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Vision Research 45 (2005) 1929–1934
Vision Research
www.elsevier.com/locate/visres

Brief communication

Associating color appearance with the cone chromaticity space

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Received 31 July 2004; received in revised form 20 January 2005

Abstract

A cone chromaticity space, a transform of a colorimetric specification system into coordinates that represent cone excitations, does not provide color appearance information. Boynton and Olson (Color Research and Application **12**, 94–105, 1987) gathered color naming for the 424 Optical Society of America Uniform Color Scales (OSA-UCS) color samples. Here, a computational algorithm was developed that converts OSA-UCS sample values into *L*, *M*, *S* cone excitations based on the 1964 CIE 10° Standard Observer. This makes it possible to plot the cone chromaticities associated with the eight color names used by Boynton and Olsen's observers to describe the non-dark appearing colors.

Keywords: Color appearance; Cone chromaticity diagram; Confidence ellipse; Color boundary

1. Introduction

A cone chromaticity space is a transform of a colorimetric specification system into coordinates that represent cone excitations. Examples of cone chromaticity spaces include the Macleod–Boynton diagram (MacLeod & Boynton, 1979) and its derivatives (Smith & Pokorny, 1996), which are equiluminant chromaticity planes. In a Macleod and Boynton type diagram, the horizontal axis represents reciprocal *L* and *M* cone excitations; the vertical axis represents *S* cone excitation. The physiological basis of the Macleod and Boynton type diagrams has made them widely used for stimulus specification in color appearance and chromatic discrimination studies.

While a cone chromaticity space provides cone excitations, it does not provide any color appearance information. In vision science, a diversity of data is expressed in a cone chromaticity diagram. For example, in studies of chromatic induction (e.g. Monnier & Shevell, 2004), it is possible to characterize the chromaticities matching the test stimulus without and with the inducer present. Chromatic induction data are represented as vectors connecting the matching chromaticities, thus characterizing induction as shifts in direction and magnitude. However, such a diagram provide neither the original color appearance of the test without induction, nor the color appearance after induction. What is provided hear is a means of associating color appearance with chromaticity coordinates in cone chromaticity space.

The motivation for this analysis was a desire to have color appearance information in a cone chromaticity diagram based upon the 10° 1964 CIE Standard Observer so that we could plot data on the appearance of stimuli altered by changes in rod excitation (Cao, Pokorny, & Smith, in press). We began with the Boynton and Olson (1987) color naming data for 424 samples of the Optical Society of America Uniform Color Scales (OSA-UCS). The OSA-UCS is a color order system developed by the Optical Society of America's Committee on Uniform Color Scales and was specified in terms

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doi:10.1016/j.visres.2005.01.033

of the CIE 1964 10° tristimulus values ($X_{10}Y_{10}Z_{10}$). MacAdam (1974) provided equations to convert the $X_{10}Y_{10}Z_{10}$ to OSA-UCS L, j, g coordinates. However, there is no closed form inverse function to convert OSA-UCS L, j, g values into $X_{10}Y_{10}Z_{10}$. We developed a computational algorithm to convert the L, j, g values of OSA-UCS color samples into L, M, S cone excitations. With the algorithm, we employed the color naming results for the OSA-UCS color samples from Boynton and Olson (1987) to associate color appearance with cone chromaticities of the color samples.

2. Methods

2.1. Conversion between OSA-UCS L, j, g values and L, M, S cone excitations

The OSA-UCS consists of a lightness axis (L), a yellow–blue axis (j), and a red–green axis (g). For each color sample, we used a modification of the algorithm described by Moroney (2003), a Newton–Raphson method, to search the $X_{10}Y_{10}Z_{10}$ value for a particular OSA-UCS L, j, g value. Since we were concerned more about accuracy than speed in searching the $X_{10}Y_{10}Z_{10}$ value for an L, j, g value, our starting value, iteration update step size and the criterion error were all smaller than Moroney used. With the starting $X_{10}Y_{10}Z_{10}$ value to be 1, the L, j, g value was computed based on the formula provided by MacAdam (1974). The input and resulting L, j, g values were compared. If the difference in L, j or g value was larger than 0.0001, then the $X_{10}Y_{10}Z_{10}$ value was incremented by 0.5, with the process continuing until the difference in L, j or g was smaller than 0.0001 or 1000 iterations occurred. (The Matlab code to convert L, j, g to $X_{10}Y_{10}Z_{10}$ is available at http://ccp.uchicago.edu/~dcao/vision.html.) An algorithm developed by Kobayasi and Yosiki (2001), searched the $X_{10}Y_{10}Z_{10}$ value for an L, j, g value in two steps using Newton–Raphson methods. First, based on the lightness value L, the modified luminous reflectance Y_0 was searched with a Newton–Raphson method, since L was defined by a monotone increasing function of Y_0. Second, using the fact that Y_0 could be represented by a function of one variable ω, which was a linear combination of $R^{1/3}$, $G^{1/3}$, and $B^{1/3}$, Kobayasi and Yosiki (2001) searched the value of ω based on the value of Y_0, again using a Newton–Raphson method. With the value of ω, the value of $R^{1/3}$, $G^{1/3}$, and $B^{1/3}$ was computed. The $X_{10}Y_{10}Z_{10}$ value was obtained by a linear transformation of R, G, and B value. We used the Moroney (2003) algorithm since it is more straightforward, numerically searching $X_{10}Y_{10}Z_{10}$ value directly.

To convert between $X_{10}Y_{10}Z_{10}$ and L, M, S cone excitation space, we followed Shapiro, Pokorny, and Smith (1996) who used the Smith–Pokorny 2° transformation (1975) applied to the 1964 10° color-matching functions. The 10° cone fundamentals l_{10}, m_{10} and s_{10} are tabulated in Table 1. To our knowledge the only other published estimate of 10° observer cone spectral sensitivities are from Stockman, MacLeod, and Johnson (1993). The creation of a MacLeod–Boynton type of cone chromaticity diagram requires that the S-cone not contribute to the photopic luminous efficiency function, a condition not fulfilled by the Stockman et al. derivation. The differences between these of estimates of the spectral sensitivities are small.

Table 1
The 10° cone fundamentals and the cone chromaticity space chromaticity coordinates

Wavelength (λ)	l_{10}	m_{10}	s_{10}	$l_{10}/(l_{10}+m_{10})$	$s_{10}/(l_{10}+m_{10})$
400	0.00123	0.00078	0.08624	0.61187	43.02300
410	0.00510	0.00365	0.39038	0.58296	44.58449
420	0.01138	0.01001	0.97508	0.53193	45.58362
430	0.01877	0.01991	1.55753	0.48523	40.27130
440	0.02859	0.03349	1.97241	0.46053	31.77364
450	0.04053	0.04893	2.00000	0.45308	22.35741
460	0.05915	0.06905	1.74992	0.46141	13.64984
470	0.08762	0.09757	1.32100	0.47312	7.13320
480	0.12483	0.12876	0.77414	0.49226	3.05273
490	0.17304	0.16610	0.41634	0.51023	1.22765
500	0.24365	0.21713	0.21907	0.52878	0.47544
510	0.33164	0.27510	0.11234	0.54659	0.18515
520	0.42997	0.33179	0.06087	0.56444	0.07990
530	0.51100	0.36421	0.03053	0.58386	0.03488
540	0.58045	0.38154	0.01371	0.60338	0.01425
550	0.62068	0.37108	0.00400	0.62584	0.00403
560	0.65106	0.34628	0	0.65279	0
570	0.65527	0.30028	0	0.68575	0
580	0.62926	0.23968	0	0.72417	0
590	0.59574	0.18166	0	0.76632	0
600	0.53193	0.12641	0	0.80799	0
610	0.44662	0.08135	0	0.84592	0
620	0.34904	0.04902	0	0.87686	0
630	0.25442	0.02907	0	0.89745	0
640	0.16462	0.01521	0	0.91545	0
650	0.10009	0.00755	0	0.92989	0
660	0.05641	0.00387	0	0.93578	0
670	0.05641	0.00387	0	0.93957	0
680	0.01498	0.00093	0	0.94159	0
690	0.00730	0.00045	0	0.94238	0
700	0.00350	0.00021	0	0.94277	0

2.2. Associating color appearance with the cone chromaticity space

Boynton and Olson (1987) studied color naming of 424 OSA-UCS color samples seen on a gray background and presented data from seven observers. They instructed the observers to describe the colors by single words and reported the frequency of color names used by their observers for each OSA-UCS color sample. For six of the observers there were no constraints on color terms, the seventh (author CXO) confined his responses to the eleven basic color terms originally defined by Berlin and Kay (1969). The color names spontaneously used by the six observers corroborated the Berlin and Kay basic color names.

Boynton and Olson reported their data using three indices. *Consensus colors* were those represented by color samples that all observers gave the same color names. *Focal colors* were those consensus colors that exhibited the shortest response times within their categories. Finally, they calculated the centroid L, j, g values of 11 basic colors (red, green, orange, purple, gray, pink, black, white, brown, yellow and blue) for each observer. They further identified the locations of the basic colors in the OSA-UCS space. Here, we excluded from analysis the three basic colors seen under conditions of brightness contrast (gray, black and brown). Using our algorithm, we converted the L, j, g values of any OSA-UCS color sample in Boynton and Olson's study, which was given one of the eight basic colors (red, green, orange, purple, pink, white, yellow and blue), into L, M, S cone excitations. We plotted the computed $L/(L+M)$ and $S/(L+M)$ chromaticities of color samples with their basic color names in a MacLeod and Boynton type diagram, in which the $S/(L+M)$ value for an equal-energy-spectrum light (EES) is normalized to be 1.0. This is called a relative cone troland space (Smith & Pokorny, 1996).

3. Results

3.1. All OSA-UCS color samples

The computed $L/(L+M)$ and $S/(L+M)$ chromaticities from all the L, j, g values of color samples that were named as red, green, orange, purple, pink, white, yellow or blue are shown in Fig. 1a. Color samples with different OSA-UCS L values (thus with different luminance levels) are plotted together in one diagram. In the figure, each chromaticity is represented by a solid circle filled with a color depicting its associated color name. For instance, the cone chromaticities of blue color samples are represented with blue solid circles. The exception is that chromaticities for white color samples are represented by black circles. The figure shows the gamut of chromaticities associated with each color name, the frequency of the use of a color name for a given chromaticity is not represented on the figure.

The region in the cone space for each non-dark appearing basic color is relatively distinct but there is overlap between color regions. White, located around the cone chromaticity of EES (0.66, 1.0), is surrounded by other basic colors. Green is located in the lower-left region in the cone chromaticity space; its region overlaps with the regions of blue, white and yellow. Yellow is located beneath white next to green and orange. Orange is located in the lower-right region in the space, next to

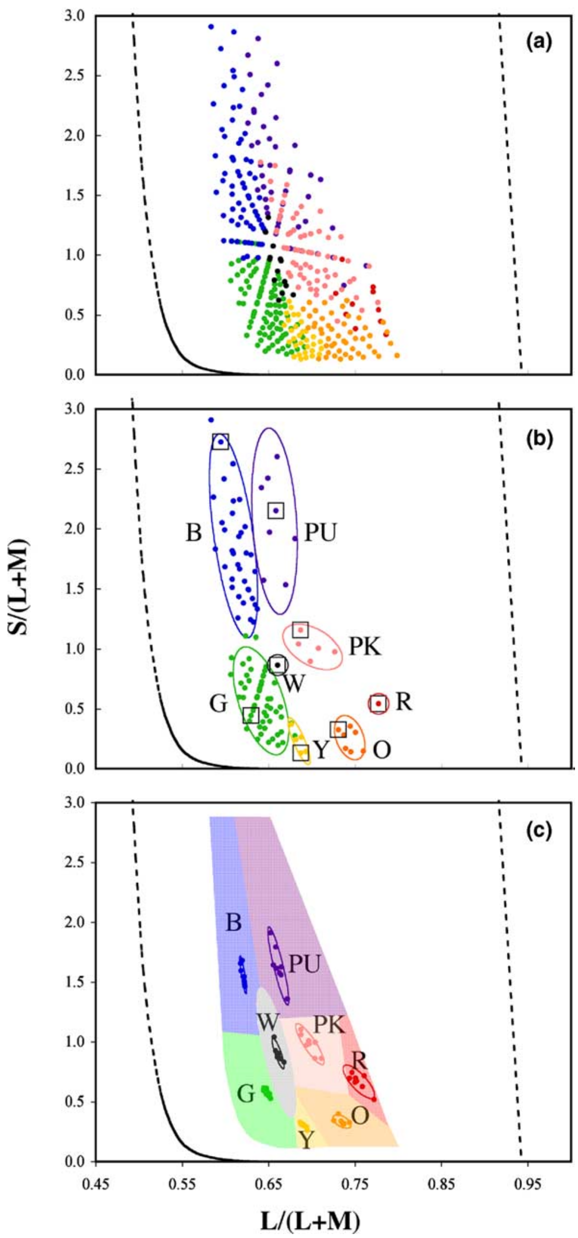

Fig. 1. The cone chromaticities for the OSA-UCS samples used by Boynton and Olson (1987) that were given one of the eight color names associated with non-dark appearing colors. The dashed line shows the spectrum locus in the cone chromaticity space. (a) For all the OSA-UCS samples. (b) For consensus colors (color samples that all observers gave the same color names to). Focal colors (consensus colors that exhibit the shortest response time with their categories) are highlighted with black open squares. For each color, a confidence ellipse with a joint confidence interval of 86% was fitted. (c) For the centroid L, j, g values of each basic color for each observer. The centroids represent average values for all samples called by a particular name for the eight non-dark appearing basic colors. Color segmentation delineating the transitions between color regions was based on the color names for all non-dark appearing OSA-UCS samples. The gamut of the OSA-UCS samples was approximated with straight lines for the upper, bottom, right and left upper boundaries, and a fifth-order polynomial line for the left bottom boundary. The straight lines between color regions represent equal probability of being either color. The white region is represented by an 86% confidence ellipse for the data in Fig. 1a.

yellow, white, red and pink. Red is located in the extreme lower-right region next to orange and pink. Pink is located to the right of white while next to red and purple. Purple is located to the upper-right region of white while next to pink and blue. Blue is located to the upper-left region next to white, green, pink and purple. Note that in Fig. 1a, the area covered by each of the basic colors is not equal: the regions for green, blue, purple and pink are larger than other basic colors, including white, yellow, orange and red.

3.2. Consensus colors

The $L/(L+M)$ and $S/(L+M)$ chromaticities of the OSA-UCS color samples that all observers gave the same color names (consensus colors) are shown in Fig. 1b. For each color name, a confidence ellipse (Douglas, 1993) was fitted based on the $L/(L+M)$ and $S/(L+M)$ chromaticities of the consensus colors, using a package in Stata (StataCorp, 2003) for confidence ellipse fitting developed by Alexandersson (1998). The fitting used a boundary constant of 4, which corresponded to a marginal confidence interval of 95% and a joint confidence interval of 86%. With such a boundary size, an ellipse will have the same first-order moment (mean) and second-order moment (variance) about the centroid as the given distribution (Cramér, 1946). This confidence ellipse is the most representative of the data points without any *a priori* assumptions concerning their origin (McCartin, 2003). Any ellipse can be represented by a standard ellipse $[x^2/a^2 + y^2/b^2 = 1]$ with the center shifted to $[x_0, y_0]$ and the major axis rotated by an angle of θ degree. These parameters of the fitted ellipses for the consensus colors are shown in Table 2 (The Matlab code to plot the ellipses is available at http://ccp.uchicago.edu/~dcao/vision.html). Ellipses were not fitted for red or white since there was only one data point for each. For red or white, a circle of arbitrary size was plotted in Fig. 1b. In contrast to the data plotted in Fig. 1a, where color regions overlapped, the consensus colors are contained within well-defined regions of cone chromaticity space (the exception being two chromaticities overlapping "green" and "yellow"). The focal color in each color category is highlighted with a black open square. The $L/(L+M)$ and $S/(L+M)$ chromaticities of the focal colors are listed in Table 3. Note that in Fig. 1b, the focal colors generally were not concordant with the centers of the confidence ellipses.

Table 3
The cone chromaticities of the focal colors

Focal color	$L/(L+M)$	$S/(L+M)$
Red	0.777	0.54
Green	0.630	0.44
Blue	0.595	2.72
Yellow	0.687	0.13
Purple	0.659	2.15
Orange	0.730	0.33
Pink	0.687	1.15
White	0.660	0.87

It may be noted that the Boynton and Olson focal colors data are generally congruent with data gathered with other color order system samples including Munsell (Sturges & Whitfield, 1995), the Swedish Natural Color System (Sivik & Taft, 1994) and CRT representations of the CIE 1976 UCS (Guest & Van Laar, 2000).

3.3. Centroids

Boynton and Olson computed centroid values for each basic color by averaging the L, j, g values for all samples called by a particular name. The computed $L/(L+M)$ and $S/(L+M)$ chromaticities for the centroid L, j, g values of the eight non-dark appearing basic colors for each observer are shown in Fig. 1c. An 86% confidence ellipse was fitted for each basic color based on the centroid $L/(L+M)$ and $S/(L+M)$ chromaticities from different observers. The confidence ellipses for green and yellow are masked by the data points. The parameters of the fitted ellipses are shown in Table 2. The median $L/(L+M)$ and $S/(L+M)$ chromaticities of the eight observers are (0.66, 0.9) for white, (0.62, 1.6) for blue, (0.66, 1.7) for purple, (0.65, 0.6) for green, (0.69, 0.3) for yellow, and (0.70, 1.0) for pink, (0.75, 0.7) for red, and (0.82, 0.6) for orange.

Color segmentation was conducted based on color naming data in Fig. 1a. The gamut of the OSA-UCS

Table 2
The parameters of the fitted confidence ellipses for the consensus colors and centroid values for the basic colors

Parameters	Censensus color								Centroid color							
	Red	Green	Blue	Yellow	Purple	Orange	Pink	White	Red	Green	Blue	Yellow	Purple	Orange	Pink	White
a	na	0.451	0.851	0.196	0.777	0.185	0.189	na	0.140	0.058	0.157	0.041	0.326	0.057	0.171	0.127
b	na	0.027	0.023	0.007	0.025	0.016	0.030	na	0.011	0.004	0.002	0.003	0.006	0.009	0.008	0.004
θ	na	92.24	91.08	93.16	90.47	91.90	95.11	na	95.83	94.50	91.23	97.28	91.90	95.74	94.78	92.68
x_o	na	0.641	0.609	0.685	0.657	0.744	0.701	na	0.754	0.648	0.620	0.691	0.661	0.735	0.698	0.661
y_o	na	0.567	1.942	0.231	2.063	0.260	1.016	na	0.668	0.576	1.561	0.302	1.637	0.336	0.983	0.905

Any ellipse can be represented by a standard ellipse $[x^2/a^2 + y^2/b^2 = 1]$ with the center shifted to (x_0, y_0) and the major axis rotated by an angle of θ degree.

Table 4
The gamut of the OSA-UCS color samples in the cone space is approximated within the boundary lines defined by the parameters shown here

	a	*b*	*c*	*d*
Gamut boundaries				
Upper	2.91	0.00		
Lower	0.13	0.00		
Right	14.98	−18.50		
Upper left	79.44	−131.18		
Lower left	1417.43	−6522.35	10007.04	−5118.66
Boundaries between colors				
Blue–Purple	31.95	−47.44		
Purple–Pink	0.89	0.47		
Blue–Green	1.74	−1.05		
Green–Yellow	37.17	−54.08		
Yellow–Orange	8.08	−10.98		
Orange–Pink	1.58	−1.32		
Orange–Red	5.02	−5.97		
Red–Pink	−38.40	−50.85		

For the straight segments: $y = a + bx$; for the curved lower left boundary: $y = a + bx + cx^2 + dx^3$.

non-dark appearing color samples in the cone space was approximated with straight lines ($y = a + bx$) for the upper, lower, right, and upper left boundary (for blue), and a third-order polynomial line ($y = a + bx + cx^2 + dx^3$) for the lower left boundary (for green). The parameters for the lines defining the gamut are shown in Table 4. For each color pair, a logistic regression was used to find a straight boundary line, which represented equal probability of being either color. An 86% confidence ellipse for white naming data in Fig. 1a was used to represent the white region. The color regions based on segmentation are shown in Fig. 1c. The parameters for the boundary straight lines ($y = a + bx$) are also shown in Table 4. The color regions based on segmentation were consistent with the centroid ellipses.

4. Discussion

The figures provide color appearance data expressed as cone chromaticities for color samples presented on a gray background. Each non-contrast basic color covers a relatively distinct region in the cone chromaticity space. Overall, the location of each basic color is consistent with classical color vision theory, which states the *L* cone contributes to redness and yellowness, the *M* cone contributes to greenness and yellowness and the *S* cone contributes to redness and blueness. Along the horizontal axis, with an increase in the value of $L/(L + M)$, *L* cone excitation increases or *M* cone excitation decreases. The increase in the value of $L/(L + M)$ changes color from green, yellow, orange to red at low $S/(L + M)$ values (<0.6), from green, white, pink to red with the value of $S/(L + M)$ around 1.0, and from blue to purple with high $S/(L + M)$ values. In other words, the perceived redness increases with an increase in $L/(L + M)$. Along the vertical axis, with an increase in the value $S/(L + M)$, *S* cone excitation increases. The perceived color changes from green to blue with $L/(L + M)$ less than 0.66; from yellow to white, blue or purple for the value of $L/(L + M)$ around 0.66; from orange or red, to pink or purple with a relatively large value of $L/(L + M)$. In other words, the perceived blueness increases (or yellowness decreases) with an increase in $S/(L + M)$.

Some caution should be exercised in interpreting the color appearance data plotted in the cone chromaticity diagram. The figures present color appearance data gathered with samples of varying lightness within a fixed gray background from seven color-normal observers. It is possible that the changes in hue associated with changes in luminance level (the Bezold-Brücke hue shift) produced some of the overlap seen in Fig. 1a. Secondly, Fig. 1a shows results collapsed across observers. Individual difference in color judgment may contribute to the overlaps in color regions. When only consensus colors are plotted in Fig. 1b, the overlaps in effect disappear.

Models based upon the perceptual aspects of color use the four unique hues as parameters (e.g. Jameson & Hurvich, 1955; Schrödinger, 1925). Unique yellow and blue are neither red nor green, and are considered as balance points for the red-green color opponent mechanism. Similarly, unique red and green are considered the balance points for the yellow-blue mechanism. An achromatic chromaticity, appearing neither yellow nor blue nor red nor green, is a balance point for both opponent systems. Linear models predict unique hue loci to be straight lines on a chromaticity diagram, intersecting at the achromatic chromaticity. The experimental course of data connecting red, white and green show major deviations from a linear function both for self-luminous (Ayama, Nakatsue, & Kaiser, 1987; Burns, Elsner, Pokorny, & Smith, 1984) and surface (Otsuki, Toyama, Sakakibara, & Ayama, 1997) colors. This yellow-blue opponent non-linearity is well demonstrated by the central tendencies of the Boynton and Olsen data seen on the figures.

In the literature, a diversity of color vision data are summarized in chromaticity diagram plots including changes in color with desaturation, light level, field size, eccentricity, the presence of an inducing field, and color discrimination. The inclusion of color appearance boundaries in cone chromaticity space allows a link between the physical and perceptual characterizations of a chromaticity shift. We can gain insight when results from color appearance studies such as chromatic induction are plotted in a cone chromaticity space that is segmented by the different basic colors. It is possible to attain a qualitative idea of the magnitude of color shifts and to identify whether a color shift caused by induction is within or across color categories.

The Boynton and Olson consensus colors represent color agreement over both observer and stimuli differing in lightness. The basic color domains defined by the consensus colors likely generalize for color-normal observers to stimulus conditions generally comparable to Boynton and Olson's (neutral adaptation, long exposure time, free viewing, etc.), The applicability for substantially different stimulus situations would have to be established independently.

Acknowledgement

National Eye Institute Research Grant EY00901 supported this work. Publication was supported in part by an unrestricted grant to the Department of Ophthalmology and Visual Science from Research to Prevent Blindness. Joel Pokorny is a Research to Prevent Blindness Senior Scientific Investigator.

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