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The Coloroid Color System

Developed over two decades at the Technical University, Budapest, the Coloroid color system is an aesthetically uniform system, in which scales of hue, saturation, and lightness appear to change uniformly over their entire length, when viewed as a whole. This is not the same as perceptually uniform in the sense of even intervals of small color differences. This article discusses the concepts and derivation of the Coloroid system, relates it to the Munsell and Ostwald systems, and derives the relations of its coordinates to those of the CIE XYZ system.

Introduction

The color-appearance aspects of surfaces become more and more important in the work of the architects. Color and color harmonies produced by the man-made environment are important aspects in producing the experience of the environment. For the architect designing a colored environment, color may be both a technical and an artistic means. In the first case the possibility of defining technical parameters assigned to different colors, and in the latter case of expressing the compositional relations between colors by numbers, requires that each member of the group of colors be identified by indices. Both requirements relate the problem of color notation to that of color systematization.

During our practical work of preparing colored designs we were unable to find a color system adequate for describing all the relations of the colored environment. Therefore, a new color system called Coloroid was developed.

Research work in connection with the Coloroid color system has been conducted since 1962 at the Technical University, Budapest. The system is built on psychometric scales. Scoring by over 70,000 persons was used in creating these scales. Most of our results have been published previously.[1,2,9-14] This article sums up our results.

The Requirements of Color Design for Color Systematization

A color system can be used in architectural designing if the parameters of the system correspond well with color perception, if colors can be visualized using them, and if these parameters can be transformed into CIE coordinates. The color space created by these parameters should be aesthetically evenly spaced.

Among the above requirements, aesthetical evenness requires some clarification: The colors of our environment belong to various parts of color space. Therefore the planning of a colored environment has to bring about harmony of hue, saturation, and lightness between highly different colors. This is why far greater importance is placed on the aesthetic evenness of the whole color space than on the reliable equality of small color differences.

The concept of aesthetic evenness has been introduced in connection with the Coloroid. A color space is regarded as aesthetically even if it consists of *aesthetically even psychometric scales*. A scale is aesthetically even if the whole scale from its starting point to its end point, viewed simultaneously, seems to be changing evenly. By increasing the number of color samples evenly between each two members of such a scale, one reaches a stage when, although the colors of neighboring samples are still distinctly different, they can no longer be used in a harmonic series. This color difference is called *harmony interval*. Our experiments showed—and this will be discussed later in detail—that in different parts of the color solid the number of just-noticeable color intervals is different.

The Munsell, Ostwald, and Coloroid Systems

Since there are several similarities among the Munsell, Ostwald, and Coloroid systems it seems necessary to deal first with a comparison of them.[3,8]

All three systems try to systematize our color sensations. Not so the CIE system, which describes the physical attributes of color. Objective measures are available only for the Coloroid system, therefore for both the Munsell and the Ostwald systems—in the latter case for the Color Harmony Manual[5]—the CIE notations for a number of color samples were determined. Not so for the Coloroid system, where the transformation equations permit a direct computation of the Coloroid coordinates from CIE XYZ values.[2,12]

Both the Munsell and the Coloroid coordinates describe color-perception parameters. It was a desire of the founders of both systems to create perceptually even scales. There is, however, a major difference in what is called perceptual evenness. In both systems a color perception is described by three parameters, changing between prescribed limits. A color-perception scale, consisting of even steps of one of these color parameters, is described in the two systems by different coordinate series.[12,15,16]

The two color-sensation indices can only be compared by relating indices assigned to color sensations produced by defined stimuli. Lightnesses and saturations in the two color systems are related by:

$$V_c = 10\,[1.2219V_m - 0.23111V_m^2 + 0.23951V_m^3 - 0.021009V_m^4 + 0.0008404V_m^5]^{1/2} \quad (1)$$

and

$$T = ab\,(C^2)^{1/3}, \quad (2)$$

respectively, where V_c and V_m express Coloroid and Munsell lightnesses, T is saturation in the Coloroid system, and C is the Munsell chroma. In the second formula a and b mean that the assignment of both Coloroid and Munsell indices to the saturation of a color depends also on its lightness and hue.

The formulae show that to sensations elicited by identically changing stimuli, a set of indices changing according to a different law is assigned in each system. Thus, the two systems suggest different ways for measuring the color sensation. This is because the two color spaces are different. The literature uses the expression "perceptually even" for the small color differences of the Munsell scale; therefore, we introduced the expression "aesthetically even" to describe the scales built up on harmony intervals of the Coloroid system.[4,17,19]

Differences between the two systems show up, for example, in the fact that lightness gradations between dark colors are smaller in the Munsell system than in the Coloroid. In the Coloroid system, saturation steps are smaller for light colors, while the opposite is true in the Munsell system. In a saturation scale there are more desaturated samples in the Munsell system, while the number of saturated samples becomes higher in the Coloroid scale. A further difference is that in the Munsell system for constant hue, changing saturation and value also changes the dominant wavelength, but no such change occurs in the Coloroid system.[13]

This fact gives rise to a similarity with the Ostwald system: Colors with equal dominant wavelength are regarded as having equal hue. A further similarity is that both systems describe a color as an additive mixture of a saturated color, white, and black. The most important difference is that in the Ostwald system only the basic hues and the proportions for mixing have been fixed. Thus in different Ostwald color atlases (Unesma, Color Harmony Manual) the same coordinates define different colors. Proportions of the mixture, together with a hue number, are regarded as color coordinates in the Ostwald system. In the Coloroid system the color-perception parameters are the color coordinates; the color mixing means only that the XYZ tristimulus values of the Coloroid colors can be described by summing up—in the appropriate proportions—the tristimulus values of the chromatic color, white, and black, the mixture of which is equal to the investigated color.

Also, the color spaces of the two systems are different. In the Ostwald system, along straight lines parallel to the axis, if the lightness decreases, the saturation decreases too; in directions perpendicular to the axis the lightness might change parallel or antiparallel with saturation, depending on hue. The Ostwald system is neither perceptually nor aesthetically even.

Experiments Defining the Coloroid System

The experiments were performed in a room, near to the window looking north. Illumination on the test samples was 1600–1800 lx.

Test subjects were 19 to 23 year old male and female university students. Some experiments were repeated with pupils of elementary schools and with adults.

Test samples 15–18 cm² in area lying on a horizontal surface were lit by the light incident through the window at an angle of about 45°. The observation angle was 90°, the observation distance 100 cm.

The surrounding of the test field was neutral gray, and no colored light was reflected to the samples. Before tests, the subjects spent at least 5 min in the experiment room so their eyes could adapt to the neutral environment. The time for selecting from among the color samples and arranging them into harmonious scales was not restricted.[12]

Relationship between Hue and Dominant Wavelength

The statement found in the literature and involved in establishing the Munsell system that the dominant wavelength changes with saturation and lightness has been checked in two test series.

In the first series the observers had to estimate the hue of samples representing Munsell hues of 2.5G, 2.5Y, 2.5R, 2.5P, and 2.5B. As no original Munsell samples were at our disposal, some 1000 samples were prepared for each of the five hues above, their tristimulus values were measured, and they were carefully selected for the Munsell scales.

The samples corresponding to the hue of 2.5G had the widest scatter of dominant wavelength (526–540 nm), therefore the problem is best illustrated by this experiment.

The observers were presented the appropriate green color series consisting of 15 samples. The seventh sample of the series had Munsell coordinates 2.5G 4/4, and its dominant wavelength was 533 nm. Two neighboring samples were of the same chroma and value, but their hues were yellowish and bluish, respectively. The hue difference between two adjacent samples corresponded to a dominant wavelength difference of 2 nm.

Test subjects had to match the hues of 70 samples with different chroma and lightness, one by one, to the hue of one chip of the sample series. The following conclusions were drawn from the experiments:

(1) Not a single person gave answers in perfect agreement with the Munsell arrangement for all colors.

(2) Only 5% of the observers answered correctly for more than 50% of the samples.

(3) Seventy-five percent of the observers arranged 80% of the samples in the wavelength band ΔH (see Figs. 1 and 2) in an order exhibiting very low correlation between the Munsell sample order and the answers.

In the second experiment two compositions were shown to the observers for choosing the more harmonious one, i.e., that more pleasant to the eye, or for indicating if both compositions were found equally harmonious.

Each composition consisted of ten colors. Composition A consisted of Munsell samples 2.5G 8/4, 8/2, 6/8, 6/6, 4/6, 4/4, 4/2, 2/2, with dominant wavelengths ranging from 526 to 540 nm.

The colors of composition B had only dominant wavelengths of about 533 nm. Lightnesses and chromas equaled those in composition A, and so did the arrangements and frequencies of occurrence.

The same experiment was repeated with Munsell hues 2.5Y, 2.5R, 2.5P, and 2.5B.

The results of these experiments can be summarized as follows:

(1) Sixty-eight percent of the observers found no aesthetic difference between the two compositions.

(2) Seventeen percent of the observers preferred composition B, 15% composition A.

These experiments led us to postulate, in establishing the hue scale, the aesthetic irrelevance of Munsell's suggestion that the hue sensation varies for the same dominant wavelength but varying saturation and lightness. Observers were even found to have difficulties with recognizing this change in dominant wavelength.

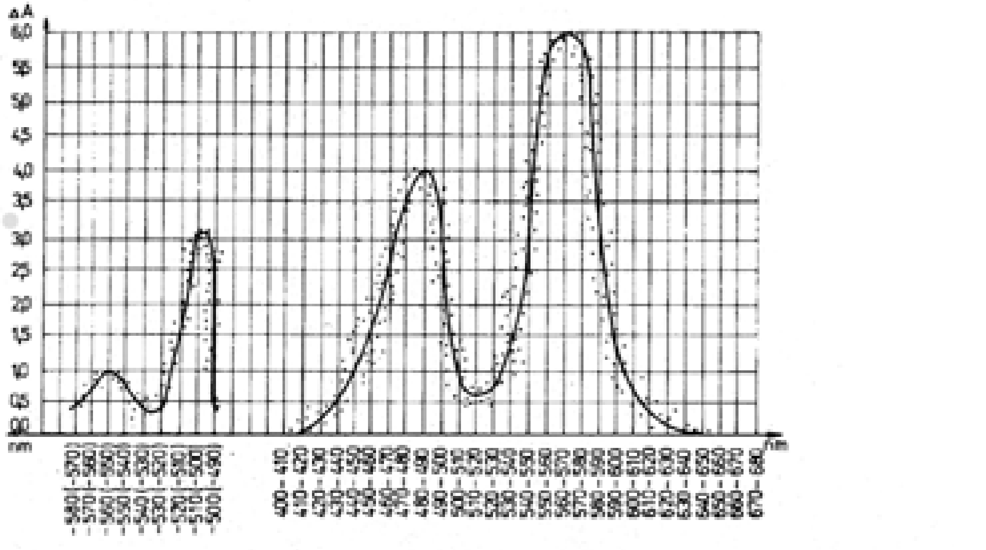

FIG. 1. Aesthetically even hue differences as a function of dominant wavelength.

Aesthetic Evenness of the Hue Scale

From our color sample collection, 150 samples with Munsell value and chroma of 6/12, but with varying hues, were selected.

The test subjects had to build up a color circle with 50 samples chosen and arranged so as to show even steps in hue, if the entire color circle was viewed simultaneously.

The hue differences between two adjacent samples of this circle were regarded as aesthetically equal hue intervals and denoted by ΔA. Test results were summarized by determining the number of hue intervals ΔA in every 10-nm dominant wavelength interval between 400 and 700 nm and

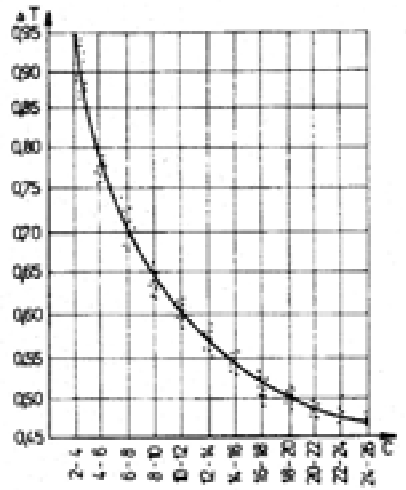

FIG. 2. Relationship between aesthetically even saturation differences and Munsell chroma.

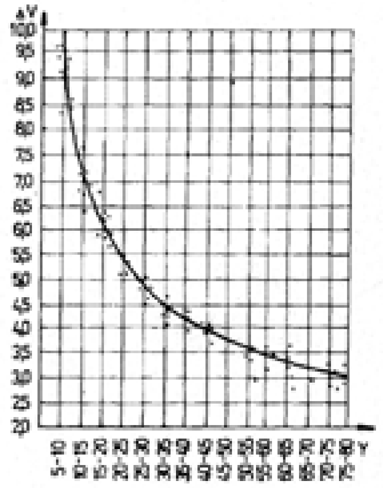

FIG. 3. Relationship between an aesthetically even lightness scale and CIE *Y*.

between complementary wavelengths −490 and −570 nm. The equation of the envelope curve would relate the dominant wavelength to the aesthetically even hue scale (Fig. 1).

Aesthetic Evenness of the Saturation Scale

As a first step, experiments were carried out using Munsell color samples.

Eight groups of approximately 60 color chips each were formed with constant hue and value but varying saturation (chroma) in each group. From each of these an arbitrary number of samples had to be selected, to build up scales of even saturation steps, when viewed simultaneously.

The aesthetically equal saturation difference found between the adjacent samples was denoted by ΔT. The number of steps ΔT found between each two Munsell chroma steps was noted for every observer. The evaluation of the experiments (see Fig. 2) resulted in the following equation:

$$\sum \Delta T^{3/2} = C(a\,b). \tag{3}$$

In this equation *a* and *b* show that both the Coloroid saturation and the Munsell chroma depend on lightness and hue.

After the Munsell chroma scale turned out to be aesthetically uneven, a new experiment was launched: New groups of color chips were produced as additive mixtures of chromatic samples of saturated blue, green, saturated warm yellow, and saturated red, with dominant wavelengths of 484, 520, 579, and 610 nm, respectively, and achromatic white and black surfaces. The samples were attached to Maxwell disks to exhibit various percentages of one chromatic and two acrhomatic surfaces. The perceived color apparent on the rotating disk was reproduced by tempera paints. Several thousand samples were prepared and those with $Y = 60$ and $Y = 30$ selected.

The sample groups equal in hue and lightness but varying in saturation were presented to test subjects asked to select ten chips each and to order them into saturation scales seeming to vary uniformly if viewed simultaneously. It was found that in most cases the amount of color needed for one saturation step to reach the next one was constant on the average:

$$p_{i+1} - p_i = q. \tag{4}$$

Therefore, the Coloroid saturation concept was formulated as follows: Colors are regarded as equally saturated if they can be produced by additively mixing the same percentage of saturated color of the same dominant wavelength with white and black.

Aesthetic Evenness of the Lightness Scale

Additive color mixes were prepared from a saturated color, white, and black at two saturation levels and different lightnesses by using Maxwell disks and were reproduced again by tempera painting.

The saturated colors were used in the experiments in two proportions: They covered either 15 or 50% of the Maxwell disk, resulting in eight groups of about 250 colors, each of equal hue and saturation but different lightness. Tristimulus values were measured and values of *Y* recorded. The values of *Y* ranged between 2 and 80. Each group contained approximately 250 samples.

The observers had to choose 20 samples from each group and to order them for decreasing lightness so that the scale should seem evenly darkening if viewed simultaneously. The lightness difference between two adjacent samples of a lightness scale was called the aesthetic lightness interval and denoted by ΔV. The experiments were evaluated by counting the steps of ΔV in each interval of $5\Delta V$ in the entire range from $Y = 5$ to $Y = 80$. Figure 3 shows the results, described by the equation

$$(\sum \Delta V/10)^2 = Y. \tag{5}$$

The Coloroid System

The Coloroid system accommodates the three-dimensional set of color perceptions—as do most color perception systems—in a cylindrical coordinate system: hue varies along the surface, saturation along the radius, and lightness along the axis of the cylinder. Thus, achromatic colors from absolute black to absolute white are located along this axis. Planes perpendicular to this axis contain colors of equal lightness. Further away from the axis, saturation increases. Colors of equal saturation are located on cylindrical surfaces. Colors of equal hue are found on half-planes containing the axis. The approximately elliptical outline of a skew section of the cylinder is the locus of the spectrum colors and the purples (limit colors). To 48 such limit colors, felt to be aesthetically even spaced, integer numbers were assigned as indices, and these have been designated Coloroid basic colors.

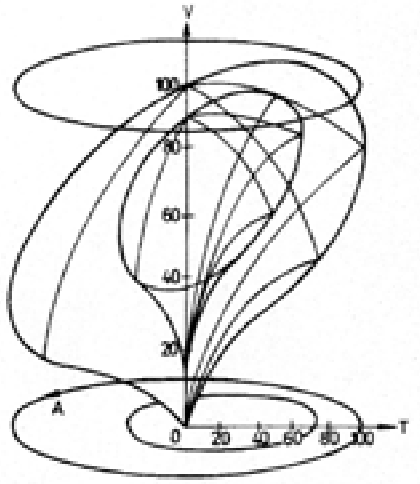

FIG. 4. The Coloroid color space and color solid.

Every limit color is connected to the absolute white and the absolute black by a limit line, which is in the plane defined by the achromatic axis and the limit color. The multitude of these limit lines form the Coloroid color space (Fig. 4): i.e., that part of the three-dimensional space that contains all perceptible colors and orders them according to the designation system of the Coloroid color space.

The achromatic axis of the Coloroid color space has been divided into 100 equal parts, and similarly the radii of the cylinder between the achromatic axis and the cylindrical surface of the limit colors.

The Coloroid color space contains the Coloroid color solid, the locus of the surface colors. The most saturated colors of the Coloroid color solid are located along a curve lying on a noncircular cylinder.

The sections of half-planes within the Coloroid color space are the Coloroid hue planes (*C* hue plane). Within the limit lines lie the sections of the *C* hue planes within the Coloroid color solid, defining the limit lines of surface colors (see Fig. 5). The Coloroid hue and the dominant wavelength of each color in a Coloroid hue plane are identical. Curves of intersection between the Coloroid color solid and the half-plane boundary curves of the surface colors are similar to, and lie inside, the boundary curves.

Points in any Coloroid section along lines parallel to the achromatic axis represent colors of equal Coloroid saturation, and those perpendicular to them, colors of equal Coloroid lightness.

While the configuration of a Coloroid space section depends only on the lightness of the spectrum color or purple at its tip, that of a Coloroid solid section depends on both the Coloroid lightness and saturation of the most saturated surface color in the plane.

In the Coloroid system, every color is regarded as an additive mixture of the specific limit color, absolute white, and absolute black. In the mixture the percentage of the limit color is denoted by *p*, that of absolute white by *w*, and

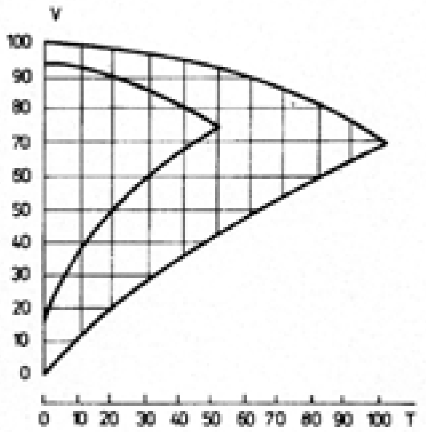

FIG. 5. The Coloroid color plane.

that of absolute black by *s*; these are the color components in the Coloroid system, where *p* is the hue content, *w* the whiteness content, and *s* the blackness content.

The sum of the Coloroid color components of any color point is unity:

$$p + w + s = 1. \tag{6}$$

Accordingly, the *XYZ* tristimulus values of a Coloroid color point can be written as sum of the tristimulus values of the limit color, the absolute white, and the absolute black:

$$\begin{aligned} X &= pX_\lambda + wX_w + sX_s, \\ Y &= pY_\lambda + wY_w + sY_s, \\ Z &= pZ_\lambda + wZ_w + sZ_s, \end{aligned} \tag{7}$$

where *X*, *Y*, *Z* are the CIE tristimulus values of the given color, X_λ, Y_λ, Z_λ those of the limit color, X_w, Y_w, Z_w and X_s, Y_s, Z_s those of absolute white and absolute black, respectively.

Denoting 1% of the sum of the tristimulus values for a color point by ϵ, the 100th part value of the sum of eq. (7) can be written as

$$\epsilon = p\epsilon_\lambda + w\epsilon_w + s\epsilon_s, \tag{8}$$

a convenient form of expressing the Coloroid color points as a sum of the Coloroid color components: hue content, whiteness content, and blackness content. In addition to representing Coloroid color points as additive mixtures of the limit color, absolute white, and absolute black, they can also be described as additive mixtures of a color of equal hue, but higher saturation, and two achromatic colors, one lighter, the other darker than the actual color, if their CIE tristimulus values are known. Thus,

$$p_t + w_t + s_t = 1; \tag{9}$$

hence, in conformity with the Coloroid principle,

$$\begin{aligned} X &= p_t X_{t\lambda} + w_t X_{tw} + s_t X_{ts}, \\ Y &= p_t Y_{t\lambda} + w_t Y_{tw} + s_t Y_{ts}, \end{aligned} \tag{10}$$

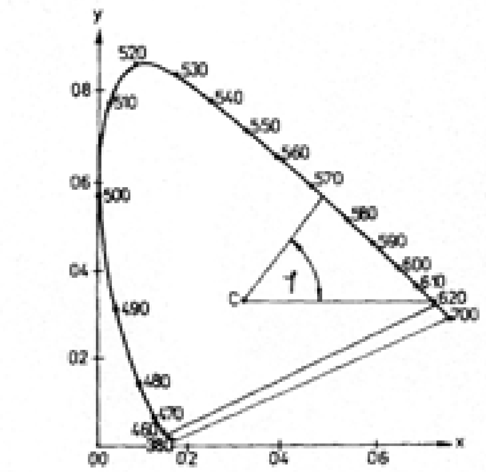

FIG. 6. Limit colors of the Coloroid system and colors of equal Coloroid hue plotted in the CIE x,y diagram.

$$Z = p_t Z_{t\lambda} + w_t Z_{tw} + s_t Z_{ts};$$

and thus

$$\epsilon = p_t \epsilon_{t\lambda} + w_t \epsilon_{tw} + s_t \epsilon_{ts}. \qquad (11)$$

The limit colors, the absolute white, and the absolute black have been defined by their CIE tristimulus values.

Coloroid limit colors are the spectrum colors ranging from 450 to 625 nm in the x,y diagram, as well as colors along the straight line connecting them (Fig. 6). By definition these equal the CIE spectral tristimulus functions, provided $\bar{y}(555) = 100$, where $\bar{y}(\lambda) = V(\lambda)$ (the spectral luminous efficiency). This defines the lightness of the limit colors. Values of Y for the Coloroid limit colors range from 0 to 100 and equal 100 times the spectral tristimulus function $\bar{y}(\lambda)$.

The spectral tristimulus values of the Coloroid limit colors have been tabulated with 1-nm steps, based on Table 3.3 of ref. 19. For purple colors the sums of CIE tristimulus functions of the Coloroid limit colors have been determined by additively mixing blue of $\lambda = 450$ nm and red of $\lambda = 625$ nm. The limit points were defined as the intersection of the lines starting from the chromaticity point of CIE Illuminant C with different values of $\tan \phi$ (where ϕ is the angle between the lines connecting C and the color point, and C and the horizontal) and the line joining the two spectrum colors with wavelengths 450 and 625 nm (Fig. 6). The intersections were determined mathematically using the equations of the lines.

Since the Coloroid saturation of a color also depends on the sum of the tristimulus values of the limit color involved, the low CIE tristimulus values on the purple line caused us to locate the Coloroid limit colors inside, rather than along, the CIE purple line. Otherwise, mixtures with colors at or near the CIE purple line would be rather unsaturated, even short of medium saturation [see eqs. (10), (11), (19), and (20)].[12]

The light of CIE Illuminant C reflected from a surface of a perfect diffuse reflector is regarded as *absolute white*. Its luminance factor $Y = 100$ is in accordance with the values of Y of the Coloroid limit colors. One hundredth of the sum of the tristimulus values of absolute white referred to CIE standard Illuminant C is $\epsilon_w = 3.162955$ and $Y_w = 100$.

The *absolute black* can be visualized by illuminating a perfectly absorbing cavity with zero reflectance by CIE standard Illuminant C. The value of ϵ_s is thus zero, and $Y_s = 0$.

Thus, the absolute Coloroid black is at the intersection of the Coloroid neutral axis and the plane $Y = 0$ of the CIE 1931 chromaticity diagram; hence, in case of a radiation distribution C, its coordinates are $x_s = x_0 = 0.31006$, and $y_s = y_0 = 0.31616$.

The position of a color point in the Coloroid color space is given by its Coloroid coordinates, denoted by the symbols A = Coloroid hue, T = Coloroid saturation, and V = Coloroid lightness.

The color of Coloroid hue 13, Coloroid saturation 22, and Coloroid lightness 56 is coded as 13-22-56, and another color coded 12-22-56 is more green; 14-22-56 is more orange; 13-21-56 is less saturated; 13-23-56 is more saturated; 13-22-55 is darker; and 13-22-57 is lighter.

Colors are of equal Coloroid hue if they can be reproduced by additively mixing a given Coloroid limit color, absolute white, and absolute black. The Coloroid hue depends on the hue of the limit color, defined by its dominant wavelength. Colors with equal Coloroid hue are on a line joining in the x,y diagram the chromaticity of CIE standard Illuminant C with the chromaticity of the given limit color. The hue can also be given as the direction tangent to this line. If ϕ is the angle between this line and the horizontal, then the slope of the line is $m = \tan \phi$, thus

$$A = A_\lambda, \qquad A = f(\phi), \qquad A = f(\tan \phi). \qquad (12)$$

The Coloroid system involves 48 basic hues corresponding to the 48 basic colors, with integer numbers as indices. These correspond to the wavelengths and direction tangents in Table I, which also indicates the tristimulus values, chromaticity coordinates, and values of ϵ_λ for the Coloroid basic colors. Hues lying between the basic ones are denoted by fractions, where the integer part of the hue index denotes the nearest lower basic hue, and the fractional part entering in the hue $A = A_i + \delta$ results by additively mixing δ times the limit hue A_{i+1} with $(1 - \delta)$ times the limit hue A_i. Identical Coloroid saturation is attributed to colors resulting from equal percentages of a limit color with any percentage of absolute white and absolute black, numerically expressed as the product of the saturation of the limit color and the percentage:

$$T = pT_\lambda. \qquad (13)$$

By definition the Coloroid saturation of the limit color is 100, while those of absolute white and absolute black are zero, thus $T_\lambda = 100$, $T_w = 0$, and $T_s = 0$.

TABLE I. The 48 basic colors and basic hues of the Coloroid system in the CIE *XYZ* system.

	The basic hues are defined by				The basic colors are defined by					
A	λ	ϕ	$\tan \phi$	$\cot \phi$	X_λ	Y_λ	Z_λ	x_λ	y_λ	ϵ_λ
10	570.83	59.0		+0.6009	0.775745	0.946572	0.002032	0.44987	0.54895	1.724349
11	572.64	55.3		0.6924	0.805130	0.933804	0.001910	0.46248	0.53641	1.740845
12	574.38	51.7		0.7898	0.832782	0.920395	0.001808	0.47451	0.52444	1.754986
13	576.06	48.2	1.1180	0.8941	0.858841	0.906482	0.001764	0.48601	0.51298	1.767088
14	577.50	44.8	0.9930	1.0070	0.880488	0.893741	0.001724	0.49578	0.50325	1.775953
15	579.31	41.5	0.8847		0.906652	0.876749	0.001672	0.50790	0.49052	1.785074
16	580.95	38.2	0.7869		0.929124	0.860368	0.001612	0.51874	0.48035	1.791104
20	582.65	34.9	0.6976		0.950909	0.842391	0.001531	0.52980	0.46934	1.794831
21	584.46	31.5	0.6128		0.972454	0.824779	0.001431	0.54137	0.45783	1.798665
22	586.43	28.0	0.5317		0.993753	0.799758	0.001308	0.55367	0.44559	1.794822
23	588.59	24.4	0.4536		1.014350	0.774090	0.001170	0.56680	0.43253	1.789610
24	591.06	20.6	0.3759		1.034402	0.774014	0.001067	0.58128	0.41811	1.779484
25	594.00	16.6	0.2974		1.052466	0.707496	0.001021	0.59766	0.40176	1.760984
26	597.74	12.3	0.2180		1.062544	0.660001	0.000898	0.61653	0.38300	1.723444
30	602.72	7.7	0.1352		1.056125	0.596070	0.000696	0.63896	0.36061	1.652892
31	610.14	2.8	0.0489		1.001027	0.501245	0.000335	0.66619	0.33358	1.502608
32	625.00	−2.5	−0.0435		0.751400	0.321000	0.000100	0.70061	0.29930	1.072500
33	−492.79	−8.4	−0.1477		0.726603	0.304093	0.105941	0.63925	0.26753	1.136638
34	−495.28	−19.8	−0.3600		0.689620	0.278886	0.263780	0.55962	0.22631	1.232286
35	−498.45	−31.6	−0.6152		0.659523	0.258373	0.392224	0.50340	0.19721	1.310122
40	−502.69	43.2	−0.9391		0.633815	0.240851	0.501944	0.46041	0.17495	1.376610
41	−509.12	54.6		−0.7107	0.609810	0.224490	0.604392	0.42386	0.15603	1.438692
42	−520.40	65.6		−0.4494	0.585492	0.207915	0.708175	0.38991	0.13846	1.501583
43	−536.31	76.8		−0.2345	0.558865	0.189767	0.821815	0.35586	0.12083	1.570447
44	−548.11	86.8		−0.0559	0.529811	0.169965	0.945807	0.32195	0.10328	1.645584
45	−555.96	95.8		+0.1016	0.496364	0.147168	1.088551	0.28657	0.08496	1.732085
46	−564.18	−108.4		+0.3327	0.425346	0.098764	1.391643	0.22202	0.05155	1.915754
50	+450	−117.2		0.5141	0.336200	0.038000	1.772110	0.15664	0.01771	2.146310
51	468.71	−124.7		0.6924	0.210174	0.086198	1.353567	0.12736	0.05227	1.649940
52	475.44	−131.8		0.8941	0.137734	0.114770	1.020911	0.10813	0.09020	1.273415
53	479	−138.5	+0.8847		0.101787	0.135067	0.843955	0.09414	0.12506	1.080809
54	482.04	−145.1	0.6976		0.079004	0.150709	0.727863	0.08249	0.15741	0.957577
55	484.29	−152.0	0.5317		0.062658	0.164626	0.641692	0.07206	0.18958	0.868977
56	487.31	−163.4	0.2981		0.044691	0.185940	0.541091	0.05787	0.24109	0.771732
60	490.40	−177.2	0.0489		0.030372	0.211659	0.455077	0.04353	0.30378	0.697110
61	492.72	171.6	−0.1477		0.021655	0.234022	0.400126	0.03291	0.35696	0.655804
62	495.28	125.4	−0.3600		0.013989	0.261843	0.348136	0.02240	0.41971	0.623969
63	498.45	148.4	−0.6152		0.007215	0.301137	0.287685	0.01196	0.49954	0.596037
64	502.69	136.8	−0.9391	−1.065	0.002586	0.366425	0.238402	0.00425	0.60321	0.607414
65	509.12	125.4	−1.4070	−0.7107	0.007260	0.485346	0.167317	0.01099	0.73542	0.659924
66	520.40	114.2		−0.4494	0.066010	0.717274	0.076233	0.08050	0.83391	0.859523
70	536.31	103.2		−0.2345	0.242272	0.926325	0.027086	0.20259	0.77474	1.195684
71	548.11	93.2		−0.0559	0.406663	0.990587	0.010284	0.28807	0.70460	1.410097
72	555.96	84.2		0.1016	0.527646	0.999862	0.005321	0.34422	0.65230	1.532830
73	560.74	77.3		0.2254	0.605873	0.993224	0.003695	0.37838	0.61930	1.603793
74	564.18	71.6		0.3327	0.664599	0.981981	0.002868	0.40290	0.59533	1.649449
75	566.78	66.9		0.4265	0.708358	0.970252	0.002470	0.42141	0.57716	1.681081
76	568.92	62.8		0.5140	0.744182	0.958592	0.002205	0.43647	0.56222	1.704981

The Coloroid saturation of a color can also be expressed in terms of the saturation of a more saturated surface color of equal hue:

$$T = p_t T_{t\lambda}. \qquad (14)$$

Coloroid lightnesses are equal for numerically equal tristimulus values Y, converted to Coloroid lightness

$$V = 10\, Y^{1/2}. \qquad (15)$$

The Coloroid lightness of absolute white is 100, that of absolute black is 0, i.e., $V_w = 100$, $V_s = 0$.

The Coloroid lightness of a color is ten times the square root of percentage sums of tristimulus values Y of its limit color, of absolute white, and absolute black:

$$V = 10\, (pY_\lambda + 100\, w)^{1/2}, \qquad (16)$$

or, using tristimulus values Y of a surface color of the same Coloroid hue but higher Coloroid saturation, of a real white and a real black:

$$V = 10\, (p_t Y_{t\lambda} + w_t Y_{tw} + s_t Y_{ts})^{1/2}. \qquad (17)$$

Conversion between Coloroid Designations and CIE Tristimulus Values

The CIE and Coloroid systems have an unambiguous relationship so that Coloroid color space designations and CIE coordinates are easy to convert in either direction.[12]

Conversion from the CIE system to the Coloroid system starts from given values of x,y,Y to calculate the values of A, T, and V.

The Coloroid hue is read from a table of limit colors with $\Delta\lambda = 1$ nm,[12] using the relation

$$\tan \phi = \frac{y - y_0}{x - x_0}. \qquad (18)$$

If necessary, linear interpolation may be used.

The Coloroid saturation is given by the following equations:

$$T = 100 \times \frac{Y(x_0\varepsilon_w - x\varepsilon_w)}{100(y\varepsilon_\lambda - x_\lambda\varepsilon_\lambda) + Y_\lambda(x_0\varepsilon_w - x\varepsilon_w)}, \qquad (19)$$

$$T = 100 \times \frac{Y(1 - y\varepsilon_w)}{100(y\varepsilon_\lambda - y_\lambda\varepsilon_\lambda) + Y_\lambda(1 - y\varepsilon_w)}. \qquad (20)$$

The values of x, y, Y, and ε_λ are found in the Coloroid tables for limit colors with $\Delta\lambda = 1$-nm steps, namely: $x_\lambda = f(\tan\phi)$; $y_\lambda = f(\tan\phi)$; $Y_\lambda = f(\tan\phi)$; $\varepsilon_\lambda = f(\tan\phi)$.

The Coloroid lightness is calculated using eq. (15).

Conversion from the Coloroid system into the CIE XYZ *system* requires calculating x, y, Y from given values of A, T, V:

$$x = \frac{\varepsilon_w x_0(V^2 - 100T\bar{y}_\lambda) + 100T\varepsilon_\lambda x_\lambda}{\varepsilon_w(V^2 - 100T\bar{y}_\lambda) + 100T\varepsilon_\lambda}, \qquad (21)$$

$$y = \frac{V^2}{\varepsilon_w(V^2 + 100T\bar{y}_\lambda) + 100T\varepsilon_\lambda}, \qquad (22)$$

$$Y = (V/10)^2. \qquad (23)$$

Values of $\bar{x}_\lambda$, $\bar{y}_\lambda$, ε_λ can be read from the table containing the Coloroid limit colors with $\Delta\lambda = 1$ nm steps, as $\bar{x}_\lambda = f(A)$, $\bar{y}_\lambda = f(A)$, and $\varepsilon_\lambda = f(A)$.

Conclusions

Color is both a technical and an artistic tool for designers of colored environment. Unambiguous distinction by designations is required in the first case to assign technical parameters to colors, and in the second case, to express numerically color composition relations.

Today, to describe color compositions by color designations is imperative for color dynamics, necessitating requirements for color systems different from those of colorimetry.

Two decades of work were spent on the development of the Coloroid color system at the Technical University, Budapest, taking the color-dynamic requirements into account. Experiments on the aesthetically even Coloroid color space have been described in detail, the concepts defined, its relations to the CIE *XYZ* systems established, and the architectural use of Coloroid designations outlined.

The development of the Coloroid color system aimed at providing a means for architects, color designers, and artists to express color-composition relationships, which has a direct relationship with the CIE *XYZ* system. As a result, new fields of activity are opened for the Coloroid system. Those areas of science and technology, where aesthetic aspects of color are important but up to now only the CIE *XYZ* system was used, might gain by the introduction of the Coloroid system.

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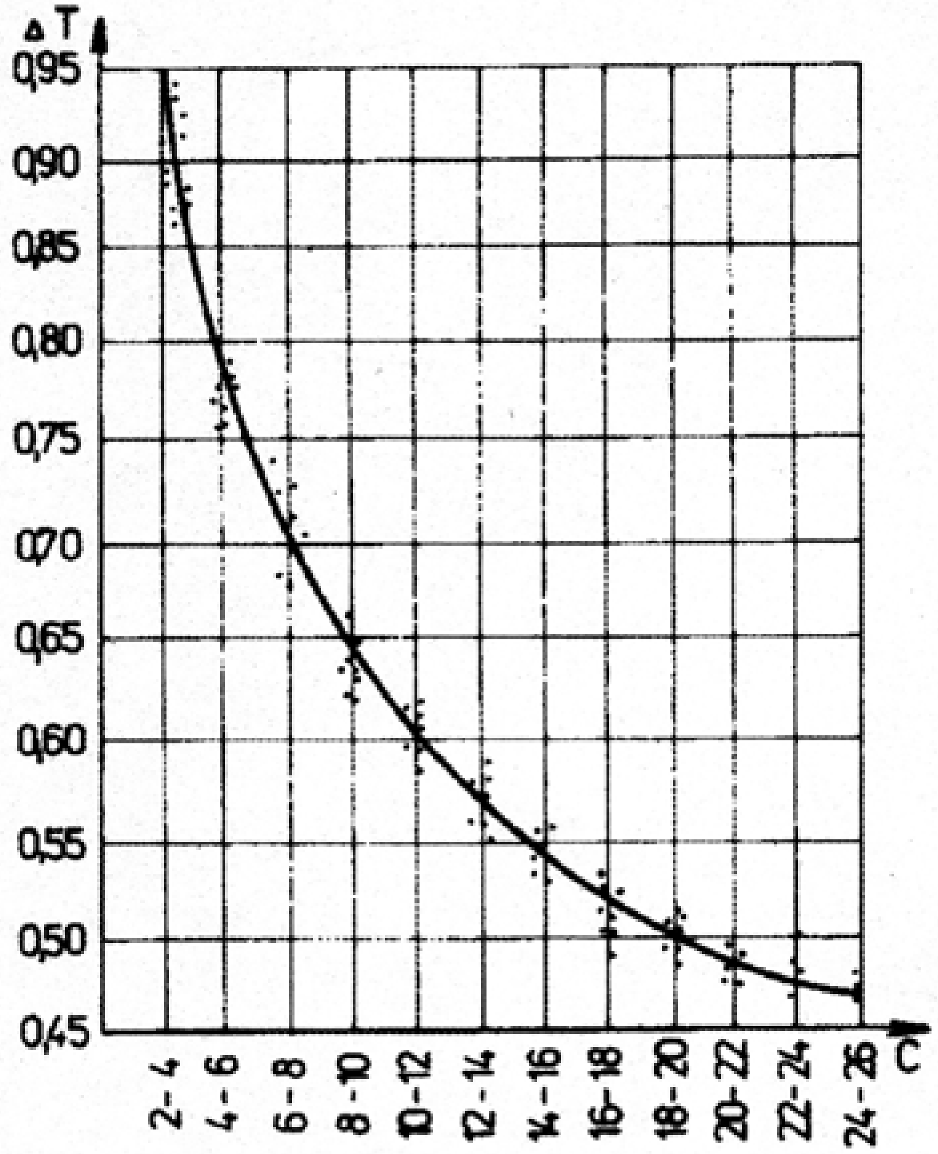
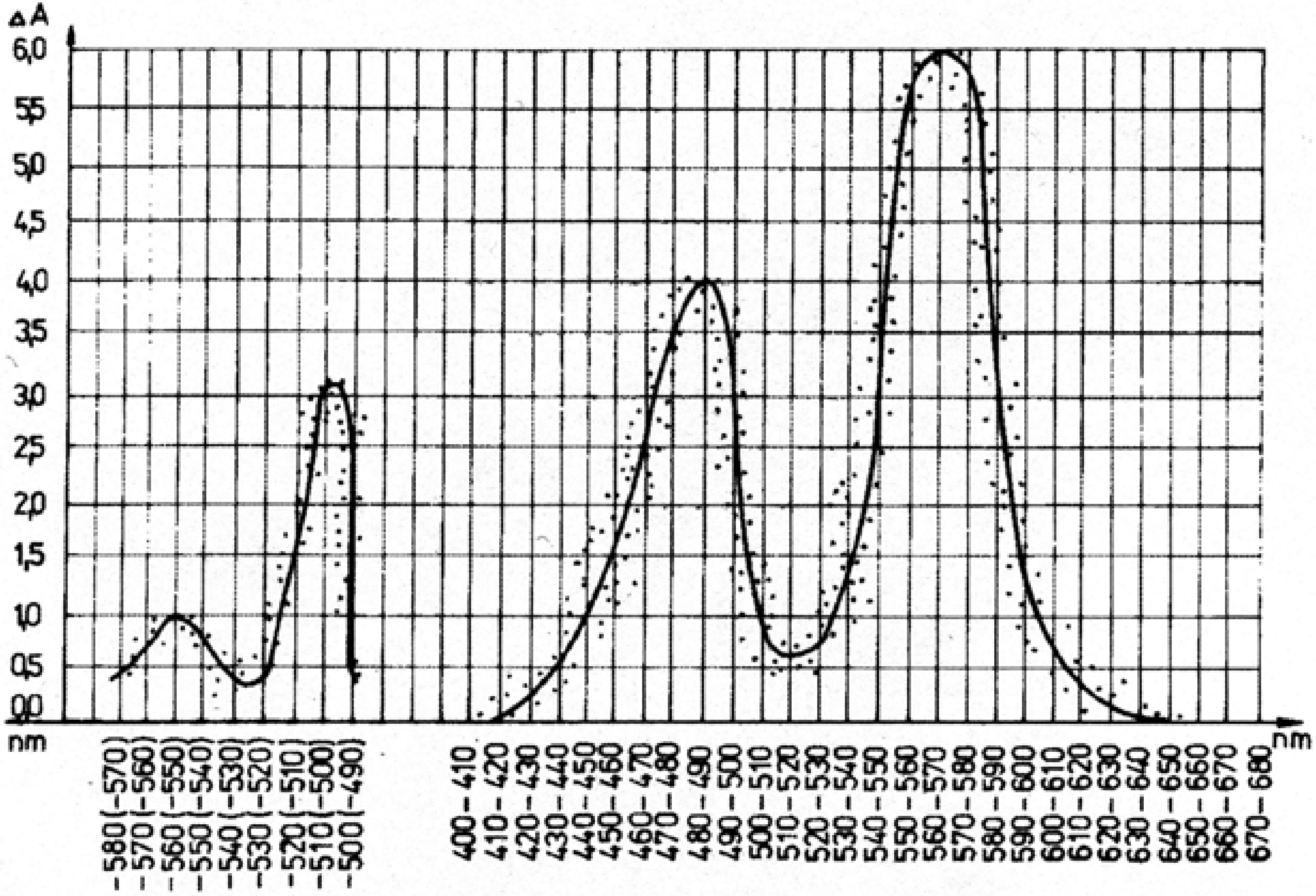


FIG. 2. Relationship between aesthetically even saturation differences and Munsell chroma.



Aesthetically even hue differences as a function of dominant wavelength.