Antal Nemcsics
Department of Drawing and Composition
Technical University, Budapest
1111 Budapest XI, Hungary

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 Manual3—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.1,2

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

\[ V = \frac{1}{2} \left( \frac{1}{2} - \frac{1}{2} \right) \left( 1 + \pi \right) \left( 1 + \pi \right) \]

and

\[ T = ab \left( C^* \right) \]

respectively, where \( V \) and \( V' \) express Coloroid and Munsell lightness, \( T \) saturation in the Coloroid system, and \( C \) and \( M \) are 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 also depends on its lightness and hue.

The formula shows that sensations elicited by intensity-changed 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 scales 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.3,4

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 dark colors, while the opposite is true in the Munsell system. In a saturation scale there are more saturated samples in the Munsell system, while the number of saturated samples is 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.1,2

This fact gives rise to a similarity with the Ostwald system. Colors with equal dominant wavelengths 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 mixings have been fixed. Thus, there are no differences in the Ostwald color states (Luminosity, Color Harmon by Munsell) 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 makes only that the XYZ tristimulus values of the Coloroid colors can be described by summing up the appropriate proportions—the two basic hues 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 Coloroid system, a white light projects 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 1000-1100 lx.

Test subjects were 19 to 21 year old male and female university students. Some experiments were repeated with pupils of elementary schools and with adults.

Test samples 13-14 cm 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.

Relationship between Hue and Dominant Wavelength

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

In the first series of the experiments, we had to estimate the hue of samples representing Munsell hue of 2.5G, 2.5Y, 2.5R, 2.5P, and 2.5B. In order to obtain 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 value of 2.5G had the widest range of samples (256-549 nm), therefore the problem is best illustrated by this experiment.

The observer were presented the appropriate green color series consisting of 15 samples. The seventh sample of the series had Munsell coordinates 2.5G 4/5, 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 78 samples with different chroma and lightness, one by one, to the hues of

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

Aesthetic Evenness of the Hue Scale

From our color sample collection, 160 samples with Munsell values and chroma of 4/2, but with varying hues, were selected.

The test subjects had to build a color circle with 50 samples chosen and arranged so as to show every step 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 and denoted by \( a \). Test results were summarized by determining the number of hue intervals \( 2a \) in every 10 nm dominant wavelength interval between 400 and 700 nm and

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

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The separate groups equal in hue and lightness but varying in saturation were presented to test subjects asked to select ice chips each and to order them into saturation scales seeming 'very 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:

\[ p_M = p_T \times q \]  

(9)

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 wavelengths with white and black.

Aesthetic Euness of the Saturation Scales

As a first step, experiments were carried out usingxxxx Masuelli color samples. Eight groups of approximately 60 color chips each were formed with constant hue and value but varying saturations (chroma) in each group. From each of these in arbitrary number of samples had to be selected, to build up series of even saturation steps, when viewed simultaneously.

The aesthetically equal saturation difference found between the adjacent samples was denoted by \( \Delta T \). The number set \( \Delta T \) found between two Maxuselli chroms steps was noted for every observer. The evaluation of the experiments (see Fig. 2) resulted in the following equation:

\[ \sum \Delta T / \Delta T^0 = C (a, b) \]  

(5)

In this equation a and b show that both the Coloroid saturation and the Masuelli chroms depend on lightness and hue.

After the Masuelli chrom 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 yellow, and saturated red, with dominant wavelengths of 484, 510, 579, and 630 nm, respectively, and achromatic white and black surfaces. The samples were attached to Maxuselli disks to exhibit various percentages of one chromatic and two achromatic surfaces. The perceived color apparent on the rotating disk was reproduced by tempera paints. Several thousand samples were prepared and those with \( W = 60 \) and \( W = 30 \) selected.

\[ p_T + w + 1 = 1 \]  

(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:

\[ X = \beta X_1 + \alpha X_2 + \delta X_1 \]  

(7)

\[ Y = \beta Y_1 + \alpha Y_2 + \delta Y_1 \]  

(7)

where \( X, Y, Z \) are the CIE tristimulus values of the given color, \( X_1, Y_1, Z_1 \) those of the limit color, \( X_2, Y_2, Z_2 \) and \( X_3, Y_3, Z_3 \) these of absolute white and absolute black, respectively.

Thus the sum of the tristimulus values for a color point by \( c \), the 100th part value of the sum of \( c \) (7) can be written as

\[ p_T + 1 = \alpha \]  

(8)

The Coloroid System

The Coloroid system accommodates the three-dimensional set of color perceptions as a most color perception system—i.e., 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. From this axis, saturation increases. Colors of equal saturations are located on cylindrical surfaces. Colors of equal hue are found on half planes containing the axis. The approximately elliptical outline of a three section of the cylinder is the locus of the spectrum colors and the purples (first colors). To 40 such limit colors, felt to be esthetically even spaced, integer numbers were assigned as indices, and these have been described as Coloroid basic colors.

\[ X = p \delta X_1 + \alpha X_2 + \delta X_1 \]  

(9)

\[ Y = p \delta Y_1 + \alpha Y_2 + \delta Y_1 \]  

(9)
The absolute black color can be visualized by illuminating a perfectly absorbing cavity with zero reflectance (the CIE standard illuminant C). The value of \( c_{A} \) is thus zero, and \( Y_{C} = 0 \).

Thus, the absolute black color is at the intersection of the CIE standard illuminant and the plane \( Y = 0 \) of the CIE 1931 chromaticity diagram; hence, in case of a radiation distribution \( C \), its coordinates are \( x_{C} = \frac{X_{C}}{X_{C} + Y_{C} + Z_{C}} \), and \( Y_{C} = 0 \).  

The color of a color point in the CIE 1931 chromaticity space is given by its CIE color coordinates, denoted by the symbols \( A \) and \( T \):  

\[
A = \sum_{i} a_{i}, \quad T = \sum_{i} t_{i},
\]

where \( a_{i} \) and \( t_{i} \) are the color coordinates of the i-th color (\( i \) = 1, 2, 3).  

The color of the pure light (13, CIELAB space) and the color of the pure dark (13, CIELAB space) are also discussed in this context.

The CIELAB color space provides a basis for expressing the tristimulus values, with numerical co-ordinates, for any color, and for any light source.

The CIELAB color system involves basic 48 base colors, each with different tristimulus values, which are indexed by integer numbers as indices. These correspond to the wavelengths and directions present in Table I, which also indicates the tristimulus values, chromaticity coordinates, and values of \( L^{*} \) for the CIELAB color system. Each color is denoted by a point in the CIELAB color space, with coordinates \( L^{*}, a^{*}, b^{*} \). The CIELAB color system is based on the assumption that the human visual system is linear, and that the tristimulus values of any color can be expressed as linear combinations of the tristimulus values of the basic colors.

The CIELAB color space is expressed in the form of a mathematical function, with each color represented as a point in the 3D color space, with coordinates \( L^{*}, a^{*}, b^{*} \). The coordinates \( L^{*}, a^{*}, b^{*} \) are related to the color coordinates \( L, a, b \) by the following equations:

\[
L^{*} = L + 16 \left( \frac{Y - Y_{n}}{Y_{n} - Y_{m}} \right)^{1.0}, \quad a^{*} = a + 16 \left( \frac{X - X_{n}}{X_{n} - X_{m}} \right)^{1.0}, \quad b^{*} = b + 16 \left( \frac{Y - Y_{n}}{Y_{n} - Y_{m}} \right)^{1.0},
\]

where \( X_{n}, Y_{n}, Z_{n} \) are the standard chromaticity coordinates of the light source, and \( X_{m}, Y_{m}, Z_{m} \) are the standard chromaticity coordinates of the standard white light. The color coordinates \( L, a, b \) are related to the color coordinates \( L^{*}, a^{*}, b^{*} \) by the following equations:

\[
L = \frac{L^{*} - 16}{\left( \frac{L^{*} + 16}{16} \right)^{1.0}}, \quad a = \frac{a^{*} - 16}{\left( \frac{a^{*} + 16}{16} \right)^{1.0}}, \quad b = \frac{b^{*} - 16}{\left( \frac{b^{*} + 16}{16} \right)^{1.0}}.
\]
The colored hue is read from a table of limits colored with

\[ \Delta \lambda = 1 \text{ unit} \] using the relation

\[ \text{tan} \theta - \frac{2}{\lambda} = \frac{\Delta \lambda}{\lambda} \]  

(30)

If necessary, linear interpolation may be used.

The colored saturation is given by the following equations:

\[ P = \frac{100 \times \left(100m_s + 2 \times \frac{m_s - 1}{s}ight)}{\left(100m_s + 2 \times \frac{m_s - 1}{s}ight) + (1 - \frac{m_s - 1}{s})} \]  

(31)

\[ P = \frac{(m_s - 1) + y}{y} \]  

(32)

The values of \( m \), \( x \), \( y \), and \( \lambda \) are read in the Colored Intensity Interpolation with \( \Delta \lambda = 1 \text{ unit} \) step, namely: \( m_s = \frac{100m_s + 2 \times \frac{m_s - 1}{s}}{100m_s + 2 \times \frac{m_s - 1}{s} + (1 - \frac{m_s - 1}{s})} \).

The Colored intensities calculated using (32) are converted into the CIE XYZ system required for each \( m, x, y \) from given values of \( P, \lambda, \).

\[ x = \frac{x_0 \left(100 - P \times \frac{x}{x_0} + 100m_s \right)}{100m_s - 2 \times \frac{m_s - 1}{s} + 100} \]  

(22)

\[ y = \frac{y_0 \left(100 - P \times \frac{y}{y_0} + 100m_s \right)}{100m_s - 2 \times \frac{m_s - 1}{s} + 100} \]  

(23)

Values of \( E_s, \), \( s \) can be used from the table containing the CIE 1976 color space with \( z = 1 \text{ unit} \) step, \( z_s = \frac{z}{z_s}, \) and \( s_s = \frac{s}{s_s}. \)

Conclusions

Color is both a technical and an aesthetic tool for designers of colored environments. Its use as a tool for designers is in the first place due to its aesthetic properties, and in the second place, to express emotional and aesthetic concepts.

Today, the color experts focus on the technical and aesthetic properties of colors for aesthetic and technical solutions. Today, the color is often characterized by the technical and aesthetic properties of colors for aesthetic and technical solutions.

The use of color in modern design is based on the technical and aesthetic properties of colors for aesthetic and technical solutions. Today, the color is often characterized by the technical and aesthetic properties of colors for aesthetic and technical solutions. Today, the color is often characterized by the technical and aesthetic properties of colors for aesthetic and technical solutions.

Two decades of work were spent on the development of the Colored color system at the Technical University, Budapest, taking the colorimetric requirements into account. Experiments on the aesthetically even Colored color space have been described in detail; the requirements, the properties, and the suitability of the Colored color system were established, and the aesthetic and technical use of Colored designs outlined.

The development of the Colored color system aimed at providing a means for solving color, scale, and order problems. This system is established for use only in the CIE XYZ system. When the Colored color system was used, eight years later, the introduction of the Colored system.

FIG. 2. Relationship between aesthetically even saturation differences and Munsell chroma.
Aesthetically even hue differences as a function of dominant wavelength.