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The determination of instrumental color differences

1. Scope

This standard practice provides a general introduction to the use of color differences and a list of the most widely used equations to obtain them. Color differences can be used 1) as a guide to establishing color tolerances in the production of pulp, paper, and paperboard, 2) for the determination of buying and selling tolerances of color, 3) to provide a method of determining the adequacy of color matches.

2. Significance

Although the eye is unsurpassed as a detector of a difference in color between two samples, it is, however, very poor in assessing the size and nature of that difference. Two common examples will attest to this statement: The redder yellow of a pair of yellows will generally be assessed as the stronger one; the brighter of a pair of colors will generally be assessed as weaker. This is no fault of the individual, but rather a defect of the visual process, for human vision is not designed to distinguish between the various attributes of color (hue, saturation and lightness) but rather to give an assessment based on an integration of all three. In addition, many other factors influence the visual process: health, lighting, age, etc.

3. Safety precautions

There are no specific safety precautions associated with this standard practice.

4. Development

4.1 Around 1930 several developments laid the foundation for most of the important developments we have had in color instrumentation to date. Ostwald, Munsell, the CIE, and Adams all described color spaces which would help to attach a number designation to a color. Further, the Ostwald, Munsell, and Adams systems attempted to space the

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colors equally in all directions. The CIE set up the specifications for the Tristimulus Values X , Y and Z in 1931. All data were laboriously hand calculated which was far from a simple routine.

4.2 Several others collaborated during the 1930s and 1940s to develop colorimeters to measure tristimulus values or some modification of them directly. These led to the widely used filter colorimeters.

4.3 Many papers were published which were aimed at giving a more uniform color space in the 1940's. The color difference formulae of MacAdam, Adams, Saunderson-Milner, etc. were developed, but the calculations were still too long to be done practically on a production level. In the 1950s came the computational aids: nomographs, tables, charts, and even slide rules. Nickerson (1) and Buc (2) published tables of data to assist in the computation of the Adams color difference equation. Davidson & Hanlon (3), and Simon & Goodwin (4) put out charts for calculating color differences according to the MacAdam formula (5, 6, 7). Adams, et al (8), produced a set of nomographs to simplify the Adams calculations. The introduction of the CODIC (Color Difference Computer), an analog computer, made the calculation in MacAdam's system.

4.4 Digital computers became generally available in the 1970's and for the first time in almost 40 years, calculations were no longer an obstacle. Most systems could be readily programmed and computed results from the various formulae compared. MacAdam's system which was first to be rendered usable in a routine manner was simply computerized because constants must be determined from a graph. He published a new procedure for use on a computer. Several modifications were made to give closer agreement to answers received from the charts. In 1964, the CIE adopted a new color space called UCS, and with it an easily programmed color difference formula. This, however, was superseded by the 1976 CIE $u'v'$ system. The Adams equation required Munsell values which are found in tables using the tristimulus values, or by computer using the Bridgeman Inversion (9). In 1976 the $L^*a^*b^*$ (CIELAB) equation superseded the AN-40 equation using a simple cube root equation. The resulting E values from the CIELAB equation are 10% larger than those from AN-40.

4.5 The main purpose of color difference systems is to give a single number value which represents the size of a visual difference between two colors. All of these color difference formulae are composed of chromaticity and of lightness differences. Since many routes were followed to develop a uniform color space (Table 1) and color difference formula, it is not surprising that there is not good correlation between the results of one system and those of any other. A completely uniform space will probably never be developed since it does not conform to Euclidean Geometry.

4.6 The positions of visually equal color differences from a standard were plotted throughout the color space in MacAdam's 1942 paper (5). These plots were made on the 1931 CIE chromaticity diagram where the proportions of the tristimulus values are plotted. They showed that the locus of points around a standard is not a circle but rather an ellipse and the major axis is oriented differently in each area of the space. This means, for example, in a green, one can tolerate much more of a saturation difference than a hue difference while the reverse is true of a purple.

5. Procedure

5.1 Reflectance data are obtained for the standard and sample specimens. Two types of instruments are available for this purpose, colorimeters, and spectrophotometers. Colorimeters provide tristimulus data directly such as X , Y , Z ; L , a , b ; or R , G , B . These data are directly substituted in the appropriate color difference equation and the color difference calculated. Manufacturers of the colorimeters may give the conversion formulae needed to convert from one set of reading to another, so that color differences can be computed in other color systems. Some colorimeters have been internally programmed to read out color differences directly. Some instruments can provide color differences in more than one system, illuminant, and standard observer.

5.2 Spectrophotometers provide percent reflectance data at discreet intervals throughout the visible spectrum. The spectral range is commonly 400 to 700 nanometers (nm) at 10 or 20 nanometer intervals. The range may be expanded to include 380 to 740 nm, and the interval may be only 5 nm. These data must be converted to tristimulus values (10, 11, 12) before color differences can be calculated. A programmed digital computer is required for this operation. The tristimulus data are then used to compute the color difference between specimens as was described for colorimeters.

6. Official recommendations

6.1 No one color difference formula has been shown to be superior so as to receive the official endorsement of a major standardization body. The CIE (12, 13,) recommended the study of four (1964 CIE, Cube-Root, Munsell

Renotation, and the FMC II) with a view toward adoption as an international standard. The Helmholtz Memorial Symposium on Color Metrics reported the disappointing results of seven years of the study (14). Two new equations were set forth for the possible adoption (CIE $L^*U^*V^*$, and CIE $L^*a^*b^*$) in 1976 (16). Additional terms were defined for hue and saturation.

6.2 The Textile Committee of the International Standards Organization (16) suggested the Adams-Nickerson equation be used until a better one is found. They recommended that the factor of 40, as recommended by Nickerson (1), be used and the color difference unit be designated AN-40. This unit is commonly, but erroneously, referred to as the NBS unit. The American Association of Textile Chemists & Colorists (AATCC) has used this formula for many years. Both organizations have since recommended the CIELAB system with metric hue angle and chroma because of the similarity with AN-40 results, and its simplicity of calculation. AATCC have more recently adopted the CMC color difference formula as an official test method (17).

7. Color difference equations

7.1 The following list contains the better known and more widely used color difference equations. Detailed information about them can be found in the references given. The references also include surveys and comparisons of many of the formulae (18, 19). Some recommended practices are given in ASTM-D-2244 (20) for several equations.

7.2 In the following list, X , Y , Z refer to Tristimulus values and x , y to the chromaticity coordinates defined as:

$$x = X/(X + Y + Z)$$

$$y = Y/(X + Y + Z)$$

7.3 The formulae shown in section 8 are limited to those which are currently in use in the pulp and paper industry. Those equations which predate 1975 and are not currently in use, are considered historical and are not included in this method.

8. Color difference formulae

8.1 Hunter (27, 28) Hunter L , a_L , b_L system

$$\Delta E [(\Delta L)^2 + (\Delta a_L)^2 + (\Delta b_L)^2]^{0.5}$$

where:

$$L = 10Y^{0.5}$$

$$a_L = 17.5(1.02X - Y)/Y^{0.5}$$

$$b_L = 7.0(Y - 0.847Z)/Y^{0.5}$$

8.2 CIE 1976 ($L^*u^*v^*$)

$$\Delta E = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2}$$

where:

$$L^* = 25(100Y/Y_0)^{1/3} - 16; 1 \leq Y \leq 100$$

$$u^* = 13 L^*(u' - u'_0)$$

$$v^* = 13 L^*(v' - v'_0)$$