Designation: E313 – 15$^{\varepsilon 1}$

Standard Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates[1]

This standard is issued under the fixed designation E313; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε^1 NOTE—Section 7 was corrected editorially in June 2015.

1. Scope

1.1 This practice provides numbers that correlate with visual ratings of yellowness or whiteness of white and near-white or colorless object-color specimens, viewed in daylight by an observer with normal color vision. White textiles, paints, and plastics are a few of the materials that can be described by the indices of yellowness or whiteness calculated by this practice.

1.2 For a complete analysis of object colors, by a specified observer and under a specified illuminant, use of three parameters is required. For near-white specimens, however, it is often useful to calculate single-number scales of yellowness or whiteness. This practice provides recommended equations for such scales and discusses their derivations and uses, and limits to their applicability (see also Ref (**1**)[2]).

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D1535 Practice for Specifying Color by the Munsell System
D1729 Practice for Visual Appraisal of Colors and Color Differences of Diffusely-Illuminated Opaque Materials
D1925 Test Method for Yellowness Index of Plastics[4]
E284 Terminology of Appearance
E308 Practice for Computing the Colors of Objects by Using the CIE System
E805 Practice for Identification of Instrumental Methods of Color or Color-Difference Measurement of Materials
E991 Practice for Color Measurement of Fluorescent Specimens Using the One-Monochromator Method
E1164 Practice for Obtaining Spectrometric Data for Object-Color Evaluation
E1247 Practice for Detecting Fluorescence in Object-Color Specimens by Spectrophotometry
E1331 Test Method for Reflectance Factor and Color by Spectrophotometry Using Hemispherical Geometry
E1345 Practice for Reducing the Effect of Variability of Color Measurement by Use of Multiple Measurements
E1347 Test Method for Color and Color-Difference Measurement by Tristimulus Colorimetry
E1348 Test Method for Transmittance and Color by Spectrophotometry Using Hemispherical Geometry
E1349 Test Method for Reflectance Factor and Color by Spectrophotometry Using Bidirectional (45°:0° or 0°:45°) Geometry
E1360 Practice for Specifying Color by Using the Optical Society of America Uniform Color Scales System
E1499 Guide for Selection, Evaluation, and Training of Observers
E1541 Practice for Specifying and Matching Color Using the Colorcurve System (Withdrawn 2007)[5]

3. Terminology

3.1 Terms and definitions in Terminology E284 are applicable to this practice.

3.2 *Definitions:*

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[1] This practice is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.04 on Color and Appearance Analysis.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this practice.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org. Replaced by Section 6 of E313.

[5] The last approved version of this historical standard is referenced on www.astm.org.

3.2.1 *perfect reflecting diffuser, n*—ideal reflecting surface that neither absorbs nor transmits light, but reflects diffusely, with the radiance of the reflecting surface being the same for all reflecting angles, regardless of the angular distribution of the incident light.

3.2.2 *whiteness, n*—the attribute of color perception by which an object color is judged to approach the preferred white.

3.2.3 *whiteness index, WI, n*—a number, computed by a given procedure from colorimetric data, that indicates the degree of departure of an object color from that of a preferred white.

3.2.4 *yellowness, n*—the attribute of color perception by which an object color is judged to depart from colorless or a preferred white toward yellow.

3.2.5 *yellowness index, YI, n*—a number, computed by a given procedure from colorimetric or spectrophotometric data, that indicates the degree of departure of an object color from colorless or from a preferred white, toward yellow.

3.2.5.1 *Discussion*—Negative values of *YI* denote departure toward blue.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *near white, n*—a color having a Munsell value greater than 8.3 (luminous reflectance factor Y = 63) and Munsell chroma no greater than 0.5 for *B* hues, 0.8 for *Y* hues, and 0.3 for all other hues.

3.3.2 *preferred white, n*—color of a white standard used as the basis for calculating indices of whiteness or yellowness as the departure of the color of the specimen from that of the preferred white; *in this practice*, the perfect reflecting diffuser.

4. Summary of Practice

4.1 The calculations described in this practice assume that specimens have been measured according to Practices E1164 and E308 and one of the Test Methods E1331, E1347, E1348, or E1349, depending on the type of specimen and measuring instrument used (see also Practice E805).

4.2 This practice takes as a starting point for the calculations CIE tristimulus values *X, Y*, and *Z* for one of the CIE standard observers and one of the CIE standard or recommended illuminants of daylight quality. Such tristimulus values are available by use of modern color measuring instruments.

4.3 Equations for the preferred methods of calculating *YI* and *WI* are described in Sections 6 and 7, respectively. Equations for calculating other quantities used as indices of yellowness or whiteness are given in Appendix X1 and Appendix X2, respectively.

5. Significance and Use

5.1 This practice should be used only to compare specimens of the same material and same general appearance. For example, a series of specimens to be compared should have generally similar gloss, texture, and (if not opaque) thickness, and translucency.

5.2 For yellowness measurement, this practice is limited to specimens having dominant wavelength in the range 570 to 580 nm, or Munsell hue approximately 2.5*GY* to 2.5*Y*. For whiteness measurement, this practice is limited to specimens having Munsell value greater than 8.3 (CIE *Y* greater than 65) and Munsell chroma no greater than 0.5 for *B* hues, 0.8 for *Y* hues, and 0.3 for all other hues (see 3.3.1).

5.3 The combination of measurement and calculation leading to indices of yellowness or whiteness is a psychophysical process, that is, the procedures specified are designed to provide numbers correlating with visual estimates made under specified typical observing conditions. Because visual observing conditions can vary widely, users should compare calculated indices with visual estimates to ensure applicability. Some standards addressing the visual estimation of color and color difference are Practices D1535, D1729, E1360, and E1541, and Guide E1499.

5.4 This practice does not cover the preparation of specimens, a procedure that may affect significantly the quantities measured. In general, specimens should be prepared and presented for measurement in the manner that is standard for the test being performed. Select enough specimens or specimen areas to provide an average result that is representative of each sample to be tested. See Practice E1345.

6. Yellowness Index

6.1 This section contains two main parts: 6.2 Historical background and 6.3 Calculation of currently recommended Yellowness Index. If the user wants to calculate the currently recommended Yellowness Index (YI), it is recommended to skip directly to 6.3.

6.2 *Background*—The currently recommended equation for the calculation of yellowness index is derived from an equation due to Hunter (**2**) in 1942: $YI = (A - B)/G$, where *A, B*, and *G* are, respectively, amber or red, blue, and green colorimeter readings. Another version, used in the 1940s to 1960s for transparent plastics (**3, 4**), was based on transmittances near the ends of the visible wavelength region: $YI = 100(T_{680} - T_{420})/T_{560}$ (with a factor of 100 introduced to give values of *YI* near unity). This equation failed to account correctly for differences in the spectral transmittance curves of such plastics, especially after the adoption of ultraviolet light absorbers to improve weathering, and was soon abandoned. When, in 1957, ASTM solicited new equations for calculating yellowness indices, Hunter's equation was converted (**5**) into CIE tristimulus value form by using Hunter's approximate relations between colorimeter readings and those tristimulus values; the resulting equation, $YI = 100(1.28X - 1.06Z)/Y$, was adopted for use in Test Method D1925 in 1962.

6.2.1 In the original form of Test Method E313, an alternative equation was recommended for a yellowness index. In terms of colorimeter readings, it was $YI = 100(1 - B/G)$. Its derivation assumed that, because of the limitation of the concept to yellow (or blue) colors, it was not necessary to take account of variations in the amber or red colorimeter reading *A*. This equation is no longer recommended.

6.2.2 *Significant Digits and Precision*—The coefficients of Test Method D1925 equation were rounded to the number of digits shown, commensurate with the precision of then-existing color measurement instrumentation. It was not intended that more significance should be attributed to values of *YI* than that implicit in this number of digits. As instrumentation was improved, however, it was found that some instruments unexpectedly gave nonzero values of *YI* for clear air or the perfect reflecting diffuser. One suggested ((**1**), p. 205) remedy for this presumed failure of the equation was to increase the number of digits in the numerical coefficients from two to ten after the decimal point, despite the obvious lack of significance of most of these digits. With modern instrumentation, it is believed that two digits added to the coefficients in the original Test Method D1925 equation suffice to bring the nonzero value of *YI* below 0.0005 on average. The new coefficients are given to this precision in 6.2.3.

6.2.3 *Derivation of Equations*—Several sets of coefficients are involved in the derivation of the final equations recommended for calculating yellowness indices. With them evaluated, it is possible to derive highly precise equations for both the CIE 1931 standard observer and the 1964 supplementary standard observer, in combination with either CIE standard illuminant C or D_{65}. The results are given in Table 1.

TABLE 1 Quantities Used in the Earlier Forms of Yellowness Index Equations

Quantity	CIE Standard Illuminant and Standard Observer			
	C, 1931	D_{65}, 1931	*C*, 1964	D_{65}, 1964
X_n	98.074	95.047	97.285	94.811
Y_n	100.000	100.000	100.000	100.000
Z_n	118.232	108.883	116.145	107.304
F_A	0.7987	0.8105	0.7987	0.8103
F_B	0.2013	0.1895	0.2013	0.1897
C_X	1.2769	1.2985	1.2871	1.3013
C_Z	1.0592	1.1335	1.0781	1.1498
Residual error	–0.0006	–0.0004	–0.0004	–0.0006

6.2.3.1 The first set of coefficients required, consists of the tristimulus values X_n, Y_n, and Z_n of the perfect reflecting diffuser (or clear air) for the above observer-illuminant combinations. These are established by the CIE, and for the present derivation were taken from the tables of tristimulus weighting factors in Practice E308.

6.2.3.2 From these "white point" values, it is possible to calculate the coefficients in Hunter's equation relating tristimulus value X and colorimeter readings A and B: $X = X_n - (F_A A + F_B B)$, thus improving on the approximation $F_A = 0.8$ and $F_B = 0.2$ originally used.

6.2.3.3 The coefficients in revised Test Method D1925 equations for *YI* can be calculated, rounded, and adjusted in the last retained significant digit to minimize the residual error in the white point values. These coefficients are given in Table 1 as C_X and C_Z. The tabulation of the residual white point error completes the table.

TABLE 2 Coefficients for Yellowness Index Equation (1)

Quantity	CIE Standard Illuminant and Standard Observer			
	C, 1931	D_{65}, 1931	*C*, 1964	D_{65}, 1964
C_x	1.2769	1.2985	1.2871	1.3013
C_z	1.0592	1.1335	1.0781	1.1498

6.3 *Calculation of Yellowness Index (YI)*—YI can be calculated for either illuminant C or D65, and either the CIE 1931 standard colorimetric observer (2°), or the CIE 1964 standard colorimetric observer (10°).

6.3.1 Use Eq 1 to calculate Yellowness Index (YI):

$$YI = 100(C_X X - C_Z Z)/Y \tag{1}$$

where X, Y, Z are the measured tristimulus values of the specimen calculated for either Illuminant C or D_{65}, and either the CIE 1931 standard colorimetric observer (2°), or the CIE 1964 standard colorimetric observer (10°); and coefficients C_x and C_z are selected from Table 2 for the chosen illuminant and observer.

7. Whiteness Index

7.1 *Background*—The earliest equation for whiteness index *WI* appears to be due to MacAdam (**6**) and related *WI* to excitation purity. This and other equations utilizing the purity have largely been abandoned. Judd (**7**) appears to have been the first to recognize that a whiteness index should incorporate two terms, one based on the lightness of the specimen relative to that of a preferred white, and the other describing the difference in chromaticity between the specimen and that preferred white. Much debate has arisen over the years as to the nature of the preferred white, but at the present time the perfect reflecting diffuser is almost always adopted as that reference.

7.1.1 In the original form of Test Method E313, the equation for *WI* was based on the above premise and the use of colorimeter readings G and B only. It was found that the chromaticity factor $G - B$ required three to four times the weighting of the lightness factor G. Hence the equation was written $WI = G - 4(G - B) = 4B - 3G$. This equation is no longer recommended.

7.2 *CIE Equations*—The equations for whiteness recommended in this practice were derived and published (**8**) by the CIE. Two equations are given, one for the whiteness index *WI* and another for a tint index *T*. Their coefficients are given in Table 3. The CIE gave coefficients for both standard observers and Ill. D_{65}; those for the 1931 observer and Ill. C were taken from the American Association of Textile Chemists and Colorists (AATCC) method for *WI*(**9**); and those for the 1964 observer and Ill. C and Ill. D_{50} were estimated by Subcommittee E12.04. Those for Ill. C and Ill. D_{50} and both observers are unofficial and should be used for in-house comparisons only.

7.2.1 *Equation for Whiteness Index WI:*

$$WI = Y + (WI, x)\,(x_n - x) + (WI, y)\,(y_n - y) \tag{2}$$

TABLE 3 Coefficients for the Equations for CIE Whiteness Index and Tint

Value	CIE Standard Illuminant and Observer					
	C, 31	D_{50}, 31	D_{65}, 31	*C*, 64	D_{50}, 64	D_{65}, 64
x_n	0.3101	0.3457	0.3127	0.3104	0.3477	0.3138
y_n	0.3161	0.3585	0.3290	0.3191	0.3595	0.3310
WI, x	800	800	800	800	800	800
WI, y	1700	1700	1700	1700	1700	1700
T, x	1000	1000	1000	900	900	900
T, y	650	650	650	650	650	650

where:

Y, x, y = the luminance factor and the chromaticity coordinates of the specimen,
x_n and y_n = the chromaticity coordinates for the CIE standard illuminant and source used, and
WI, x and WI, y = numerical coefficients.

Values for all these except those measured for the specimen are given in Table 3.

7.2.2 *Equation for Tint Index T:*

$$T = T, x\,(x_n - x) - T, y\,(y_n - y) \tag{3}$$

where the symbols have meanings analogous to those in 7.2.1.

7.3 *Notes and Restrictions to the CIE Equations*—The CIE notes the following regarding the use of equations for *WI* and *T*:

7.3.1 The application of the equations is restricted to specimens that are called "white" commercially, that are similar in color and fluorescence, and that are measured on the same instrument at about the same time. Under these conditions their use should give relative, but not absolute, evaluations of whiteness that are adequate for commercial use.

7.3.2 The higher the value of *WI*, the greater is the indicated whiteness. The more positive the value of *T*, the greater is the indicated greenish tint of the specimen; the more negative the value of *T*, the greater is its reddish tint. Lines of equal *T* are approximately parallel to the line of dominant wavelength 466 nm. For the perfect reflecting diffuser, $WI = 100$ and $T = 0$.

7.3.3 Equal differences in *WI* or *T* do not always represent equal perceptual differences in whiteness or tint, respectively.

7.3.4 These equations should be used only for specimens with $40 < WI < (5Y - 280)$ and $-4 < T < +2$.

8. Apparatus

8.1 *Color Measuring Instrument*—Spectrophotometer or tristimulus (filter) colorimeter, capable of producing CIE tristimulus values and chromaticity coordinates for either CIE standard observer and the desired CIE standard illuminants of daylight quality, for a CIE recommended geometry. The instrument should meet the manufacturer's requirements for calibration.

8.1.1 If the specimens are known or suspected to be fluorescent (see Practice E1247), the choice of instrument optical geometry can affect the measurement results. When hemispherical (integrating sphere) geometry is used for measuring fluorescent specimens, the spectral power distribution of the illuminating system may be altered by the reflected and emitted power from the specimen. The use of bidirectional geometry is therefore preferable. In addition, follow the requirements of Practice E991 with respect to the spectral output of the instrument illuminator.

8.2 *Standards*—The primary standard of reflectance shall be the perfect reflecting diffuser. Instrument standards calibrated in terms of the perfect reflecting diffuser or the perfect transmitting diffuser shall be used in standardizing the instrument.

9. Procedure

9.1 Operate the color measuring instrument according to the manufacturer's instructions for standardization and measurement. Refer to Practices E308 and E1164 and, according to the instrument type and geometry, Test Method E1331, E1347, E1348, or E1349.

9.1.1 In addition to the standards required or furnished by the manufacturer, it is desirable to measure periodically one or more system verification standards with known values of yellowness or whiteness.

9.2 If not carried out automatically by the instrument, print, display, or store values of *X, Y, Z, x, y* for the specimens for use in calculations.

9.2.1 Make as many repeat measurements as required (refer to Practice E1345) and average the resulting values of *X, Y, Z, x, y*. Use the averaged values in calculations.

10. Calculations

10.1 As required, calculate for each specimen the value of *YI* by Eq 1, of *WI* by Eq 2, and of *T* by Eq 3.

10.1.1 Refer to Appendix X1 and Appendix X2 for other equations used in the past for calculating indices of yellowness and whiteness. Such equations may be used if desired, but the resulting values will in all probability differ from those obtained by use of the recommended equations of this practice.

11. Report

11.1 The report shall include the following information:

11.1.1 Manufacturer, model, geometry, and any further identification required for the instrument used,

11.1.2 Illuminant(s) and observer(s) for which data are reported,

11.1.3 Specimen identifications for each measurement,

11.1.3.1 If multiple measurements were made of a single specimen and set of conditions, number of measurements,

11.1.4 Indices of yellowness, whiteness, and tint as required, and

11.1.5 Special considerations including the following:

11.1.5.1 If the specimens were fluorescent, details of the instrument light source as required in Practice E991, and

11.1.5.2 If the specimens were transparent or translucent, the thickness of each specimen.

11.2 It is good practice for the report to include the following information:

11.2.1 Measured values of *X, Y, Z* for each measurement, and

11.2.1.1 If multiple measurements were made of a single specimen and set of conditions, average values of *X, Y, Z*.

12. Keywords

12.1 color; colorimetric analysis; color/light; instrumental measurement; reflectance; reflectivity; whiteness indexes; yellowness indexes

APPENDIXES

(Nonmandatory Information)

X1. ALTERNATIVE MEASURES OF YELLOWNESS

X1.1 *Positive Values of the Yellowness-Blueness Coordinate of Any Opponent-Color Space*:

X1.1.1 Such coordinates include Hunter *b* Refs (**1, 5**); CIELAB *b**, (Refs **1, 8** and Practice E308); and CIELUV *v** (Refs **1, 8**, and Practice E308). The equations for these coordinates are given in the references cited.

X1.2 *Values of the Chroma Coordinate of Any Opponent-Color Space When Expressed in the Coordinates Hue, Lightness, and Chroma*:

X1.2.1 Such coordinates include chroma derived for the Hunter system:

$$C_H = \left(a^2 + b^2\right)^{1/2} \tag{X1.1}$$

and CIELAB and CIELUV chromas. The equations for these quantities are given in the references cited in X1.1.1.

X1.3 Hunter β', Ref (**2**):

$$\beta' = 88.4\,G^{1/4}\,(G - B)/(R + 2G + B) \tag{X1.2}$$

X1.4 Scofield *b* Refs (**1, 10**):

$$b = 2B\,G^{1/2}\,(G - B)/(R + 2G + B) \tag{X1.3}$$

X1.5 Friele's Yellowness Index Refs (**1, 11**):

$$YI = 1/2\,(R + G)/B \tag{X1.4}$$

X1.6 Optical Society of America Uniform Color Scales *j* (Ref **12**, and Practice E1360):

$$j = C\left(R^{1/3} + 8G^{1/3} - 9.7B^{1/3}\right) \tag{X1.5}$$

where the quantities required for the calculation are defined in Eqs 3, Eqs 5, and Eqs 6 of Practice E1360.

X1.7 The equation $YI = 100(1 - B/G)$ discussed in 6.2.1.

X2. ALTERNATIVE MEASURES OF WHITENESS

X2.1 Hunter, 1942 Refs (**1, 2**):

$$WI = 100 - \{[220\,(G - B)/(G + 0.242B)]^2 \tag{X2.1}$$

$$+ [(100 - G)/2]^2\}^{1/2}$$

X2.2 Hunter, 1960 Refs (**1, 12**):

$$WI = L - 3b = 10\,(Y - 21)^{1/2}\,(Y - 0.847Z)/Y^{1/2} \tag{X2.2}$$

X2.2.1 Stensby Refs (**1, 13**):

$$WI = L - 3b + 3a \tag{X2.3}$$

X2.2.2 Berger Ref (**14**):

$$WI = Y + 3.108Z - 3.831X \tag{X2.4}$$

(*For the CIE 2° Standard Observer/Illuminant C*)

X2.2.3 The equation $WI= 4B -3G$discussed in 7.1.1: when written in the equivalent form $WI = 3.388Z - 3Y$, this equation is known as Taube's whiteness equation.

X2.2.4 Equations containing the excitation purity Refs (**1, 6**).

NOTE X2.1—Other compilations of whiteness equations are found in Refs (**15-18**).

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