The Illuminant in Color Matching and Discrimination

How Good A Duplicate Is One Illuminant For Another

By DOROTHY NICKERSON

A study of the part played by the illuminant in color discrimination may be divided into two broad sections. In one the chief concern is to find an illuminant under which color differences will surely be evident. The single illuminant most satisfactory for this purpose will depend upon the reflectance curve of the samples to be examined. In the other, the choice is limited to an illuminant under which an observer may see the colors with which he is concerned in the same relation to each other as he would if they were observed under an illuminant to which he has become previously accustomed, the most usual example being the selection of an artificial daylight in substitution for natural daylight. Results of studies made in the color-measurements laboratory of Agricultural Marketing Service regarding this latter choice are presented in charts and table form. They include studies of 18 illuminants, actual and theoretical, several pairs of samples expected to show large color differences under a change in illuminant, and 30 samples of cotton, the product with which this laboratory is chiefly concerned. The final results are summarized in a table which gives a relative rating of illuminants as substitutes for each other.

AT THE last annual convention of the I.E.S. a report was made of certain artificial daylighting studies that had been conducted by the color-measurements laboratory of the Agricultural Marketing Service[1]. At that time studies were already under way regarding the adequacy with which one illuminant could be substituted for another. These studies have been continued, and certain results of this work are here reported.

The reports by Le Grand Hardy, Deane B. Judd, and Parry Moon on this program[2, 3, 4] together with the report on artificial daylighting made last year[1] form the necessary general background for the present report.

A paper presented before the Thirty-fourth Annual Convention of the Illuminating Engineering Society, Spring Lake, New Jersey, September 9-12, 1940. Author: Color Technologist, Agricultural Marketing Service, United States Department of Agriculture, Washington, D. C.

The Illuminant Used to Exaggerate Differences

A study of the part that the illuminant plays in color discrimination may be divided into two broad sections. In one the chief concern is to find an illuminant under which color differences, when they exist, will surely be evident. If the illuminant makes these differences easy to see, even though they be very small, or of a peculiar nature, then so much the better. The use of illuminants for this purpose can be illustrated by reference to spectrophotometric measurements*. If a series of illuminants were available, each having energy in the visible spectrum only in wavelength bands 10 mμ wide, the bands adjacent, but not overlapping from 400 to 700 mμ, and if a pair of samples were examined under each of these illuminants in turn, the differences seen under each would compare with the differences that could be calculated from a similar wavelength interval of the spectrophotometric curves for the pair of samples. The single illuminant most satisfactory for purposes of indicating any possible color difference that exists between pairs of samples will depend upon the reflectance curve of the samples to be examined.

Recent studies reporting on the selection of an illuminant for the detection of small color differences by Taylor[5] indicate that the illuminant best adapted to this purpose is one rich in energy in the region of minimum reflectance (maximum absorption) of the samples examined. In other words, if yellow samples are to be examined, an illuminant rich in energy in the blue portion of the spectrum where the spectral reflectances of yellow samples are apt to differ most widely, will enable an observer to discriminate differences more easily than when using an illuminant deficient in the blue portion of the spectrum. When blue samples are to be examined, the reverse is true; i.e., an illuminant rich in energy in the yellow portion of the spectrum will facilitate discrimination.

A very practical example of another application of this general method is one quite generally used in dye houses. When samples are to be matched they are viewed under two illuminants selected at or near the extremes of color temperatures found under daylight use. One illuminant may have a color temperature near that of horizon sunlight, perhaps 2000–2500K, the other near that of blue sky, perhaps 10,000K or above. The greater the difference in color temperature, the more dissimilar will be the spectral energy distributions of the two illuminants, and therefore the greater will be the probability that whatever differences there are between pairs of samples will become evident. This is perhaps the most

---

* Refer to[4] for explanation of spectrophotometric measurements as applied in illumination studies.

common example of using illuminants as "abridged spectrophotometers" and it works successfully even when the energy in the illuminants is not confined to narrow bands of wavelengths. The fact that the energy distributions differ widely, is enough for the purpose.

Under examinations of this sort, it should be remembered that while *differences* may show up, neither the *daylight color* of the samples, nor even a color close to it, will necessarily appear. If only a color-match, or a color-difference judgment is required, this may not be important, and the election of an illuminant will not therefore have to take into consideration any particular reference to color appearance.

The Illuminant Used to Satisfy Conditions of Daylight-Match

The second broad section into which a study of the part illumination plays in color discrimination is that which concerns the choice of an lluminant under which an observer may see the colors with which he is concerned in the same relation to each other as he would if they were observed under an illuminant to which he has become previously accustomed. The most usual example of this use of an illuminant is in the election of an artificial daylight in substitution for natural daylight.

Certain phases of this problem have been studied in our laboratories n connection with color grading of agricultural products, particularly hose products for which standards are prepared in the United States Department of Agriculture.

The first part of these studies concerned the installation of an artificial daylight unit. A source-filter combination, at the time this work was tarted, seemed to be the only satisfactory answer. Specifications based on preferred conditions of natural daylighting were finally worked out s follows: (a) the light to be diffused uniformly over an area large nough that the sample might be moved about freely; (b) the color emperature to be about 7400K–7500K with an energy distribution to match as closely as practicable that of natural daylight of a similar color emperature; (c) illumination on the working plane to be 60–80 foot-candles. The reason for these specifications, the data upon which they re based, and trials based on certain other specifications, have been escribed in previous papers[1, 6].

About the time this installation was completed in Washington we ound that tests were being made with a carbon arc lamp for purposes milar to ours. And our installation was hardly in use before the evelopment of fluorescent tube lighting was announced. Although we ad a unit, satisfactory for color grading purposes, our predicament was

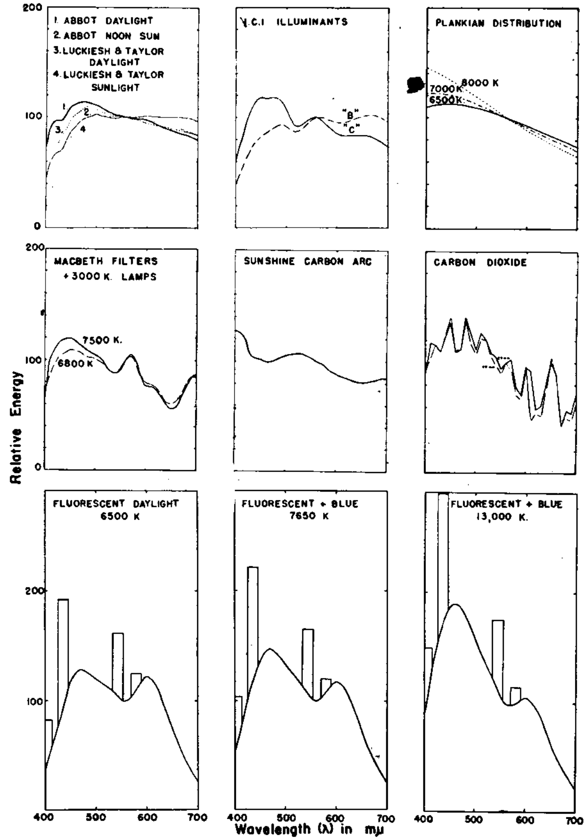

Fig. 1—Relative energy curves, reduced to 100 at 560 mμ, of illuminants and several standards used in this study.

that all kinds of questions regarding the suitability of these and othe units came to us for answer. Since satisfactory answers were not available it therefore became necessary to obtain practical and theoretical dat regarding these and certain other lamps.

Fig. 1 contains curves of relative spectral energy distributions for number of actual and theoretical illuminants that have been considere in this work. The illuminants included are of color temperatures in th range 4800K to about 13,000K, the range of natural daylight in whic we were interested. Fig. 2 indicates the relation of these illuminants on portion of the ICI (x, y) diagram, which shows the Planckian locus an iso-temperature lines in micro-reciprocal degrees (abbr: mireds).

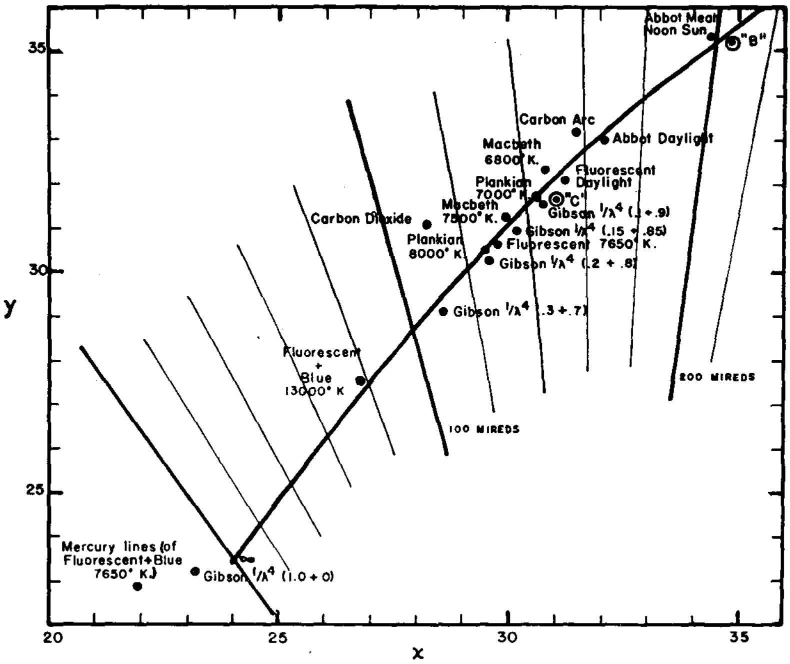

FIG. 2—A portion of the ICI (x, y)-diagram showing the Planckian locus extending from 4800 to ∞. Iso-temperature lines are given in micro-reciprocal degrees (mireds). All actual and theoretical illuminants referred to in this study are shown.

One of the questions to which we needed an answer, and the one about vhich this paper has been prepared, is "How good a duplicate is one lluminant for another?"

Use of Judd Duplication Index

In a report before the Optical Society at Niagara Falls in 1938, a method or obtaining definitions and tolerances for artificial daylight for color natching was suggested by Judd[7]. This method is based upon the principle that if one illuminant is to be considered a duplicate of another for olor matching, it must preserve the same object-color differences. In ther words, if one of two samples appears just noticeably redder than the ther in daylight, it should also appear just noticeably redder in artificial aylight, and if one illuminant shows a color difference to be zero, the ifference should remain zero for the illuminant which is intended as a uplicate. Four pairs of samples were selected to typify those known to equire accurate duplication of daylight for proper rendering of the daylight color difference. Color differences were indicated for each pair by taking differences of apparent reflectance, Y, and trilinear coordinates, r, g, b, for the uniform-chromaticity-scale (UCS) triangle[8]. The variations in these object-color differences corresponding to a change in illuminant were found by taking second differences. If pairs of samples can be found which adequately represent those to be examined under the artificial daylight, then an average of the largest of the second differences for each pair is "an adequate measure of the failure of the artificial illuminant to duplicate natural daylight, and a value of this average may be set as a tolerance."

The four pairs of samples selected for study by Dr. Judd were such that large second differences might be expected. A report by Judd[9] will give complete data on these pairs. Meanwhile, in order that a comparison of differences expected to be large may be made with those expected to be small, Dr. Judd has generously permitted us to base certain of our charts upon his material.

In our own laboratory we selected for study two pairs of curves with large differences in reflectance characteristics for certain portions of the spectrum, 30 cotton samples, one pair of tobacco samples, and one pair of coffee samples. Our interest was in what would happen not only to pairs of samples with differing spectral distribution characteristics, but to samples of cottons and of other products with which our work is chiefly concerned. The 30 cottons studied include twelve which vary only slightly in color within a single high grade, thirteen within a single low grade, and five samples from "spotted" grades.

With few exceptions, data for samples and illuminants are not included in this report since they are so extensive. Tables of data for spectral characteristics of samples and illuminants used in this study, data for all charts presented, and computational tables for deriving trilinear coordinates (x, y) on the ICI system for samples viewed under each of the 18 illuminants are, however, available in a report published by the United States Department of Agriculture[10].

We have supplemented the Judd method by setting up a family of standard curves for daylight of color temperatures in the range in which we are interested; and we have modified the method of computation to permit us to obtain conveniently a measure of the second differences not merely for a few pairs, but for all of the pairs formed by different combinations of the 30 cotton samples taken two at a time.

The requirement of standard curves for daylight almost stopped us before we started. For what could we use as standard curves? The Abbot

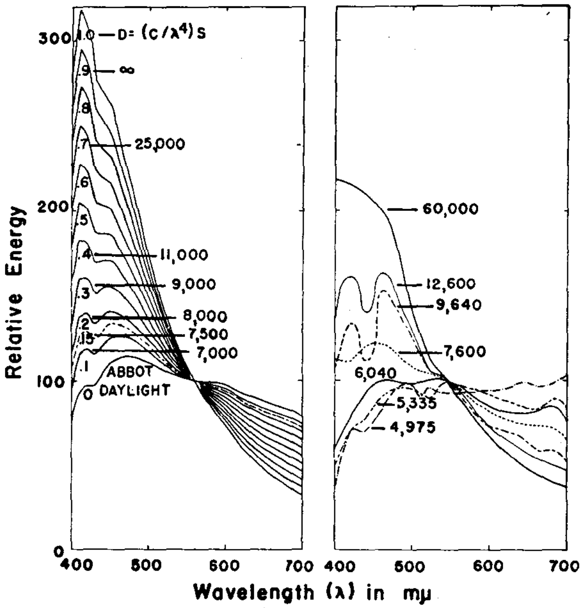

Fig. 3—(Left) Curves representing different proportions of Abbot sun-outside-the-atmosphere and skylight as calculated by use of inverse λ^4 scattering relation by K. S. Gibson[13]. Color temperatures are approximate.

Fig. 4—(Right) Measurements of daylight made in Cleveland by Taylor and Kerr during 1939[14] with approximate color temperatures indicated.

lata, recalculated by Gibson for the Hardy Handbook of Colorimetry[11] vas the most authoritative "outside atmosphere" daylight data we could ind. Those and the Taylor-Luckiesh data of 1930[12] were about all that vere available, and they did not cover the range of color temperatures in vhich we were interested. As reported in a previous paper,[6] "C" illumiıant on actual trial proved too yellow for the moderately overcast north ky preferred by our cotton classers. Therefore daylight of a color temerature as low as 6500K would hardly be a "standard" with which we vould want to compare an illuminant of 7400–7500K to ascertain how atisfactory a substitute it might be.

Fortunately a method was described by Gibson at the 1939 Lake Placid ieeting of the Optical Society[13] that serves our purpose. Each curve epresents a different proportion of sun-outside-the-atmosphere (Abbot ata) and skylight, as calculated by use of the inverse λ^4 scattering relaion. It is realized that there are a number of considerations not included ı these data, but they provide more representative distributions than

ICI "B" and "C", or the curves for Planckian distributions. Curv representing various proportions of sun-outside-the-atmosphere and sk light are illustrated in Fig. 3.

Recently, Taylor has measured and reported[14] additional measuremen on daylight and in Fig. 4 they are shown plotted on a scale selected s that comparisons might be made to the curves in Figs. 1 and 3. Thes curves corroborate fairly well those calculated by Gibson and indica further that there are local variations in spectral energy distributions o daylight not necessarily associated with change in color temperatur These data are not yet included among the illuminants studied.

Included as standards for comparison are ICI "B" and "C", Abb Daylight, Planckian 7000K and 8000K, Gibson $1/\lambda^4$ (.1 + .9), (.15 + .85 (.2 + .8), and (.3 + .7)**. The illuminants studied include the carbo arc, fluorescent tube "daylight", with combinations of blue fluoresce tubes to give color temperatures approximating 7650K and 13,000K Macbeth lamps approximating 6800K and 7500K, the carbon-dioxid vapor lamp, and, for an extreme condition, the mercury line portion of th fluorescent tube combination yielding 7650K, calculated as if it had bee a separate illuminant†.

Pairs Expected to Show Large Differences

Spectral reflectance curves of the four pairs of samples selected by Jud are shown in Fig. 5. Differences in apparent reflectance (Y), and i trilinear coordinates (r, g, b) on the uniform-chromaticity-scale for thes four pairs calculated to four decimal places for each of 15 illuminants, a illustrated in Fig. 6.

As might be expected from inspection of the curves in Fig. 5, the grea est differences caused by different illuminants are shown by the olive pai The difference in apparent reflectance for the pair varies from a maximu of 0.017 when the illuminant is fluorescent tube "daylight" at 6500K to a minimum of 0.008 when the illuminant is the carbon-dioxide vap lamp. Since the apparent reflectance of these olive samples is only abo 8 and 9 per cent to begin with, it is evident that a change from 1 to 2 p cent is of importance. Such a change is of the order of 0.2 of a Munse value step. Changes in relationship due to illuminant between th

---

**Subscripts represent the relative proportion of the energy contributed by sun-outside-the-atmosphere and skylight.

†Special mention and thanks are given both to the Macbeth Daylighting Corporation for their cooperation in maki filters of various thicknesses available for study, and to the Engineering Laboratories of the General Electric Company for t cooperation they have extended in providing an unusually well designed experimental unit for studies of fluorescent light f grading purposes.

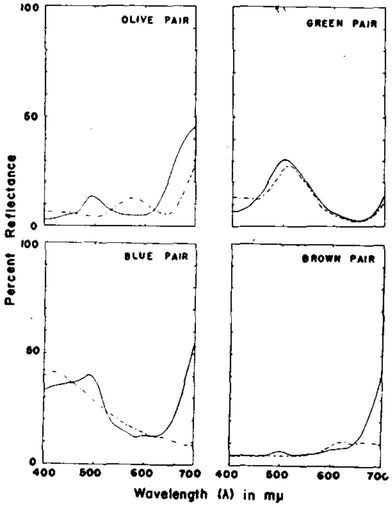

FIG. 5—Spectral reflectance curves of 4 pairs of samples selected by Judd for study.

trilinear coordinate differences in the olive pair vary for r, from 3 in the third decimal place under "B" illuminant to about 4 in the second decimal place under the fluorescent tube at 13,000K; for g, from 1 in the second place for "B" illuminant to 2.5 in the second place for the fluorescent tube

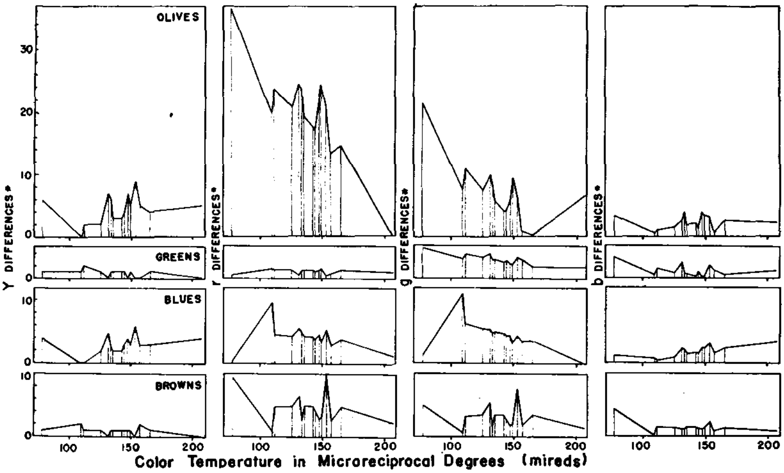

FIG. 6—The Y, r, g, and b differences for 4 pairs of colors studied by Judd (see Figure 5) are indicated for each of 15 illuminants by the relative heights of the vertical lines. The illuminants are plotted in micro-reciprocal degrees of color temperature in the order given in Table I, omitting the mercury lines at 0 mireds, Planckian 8000K at 125 mireds, and the special curve at 151 mireds.

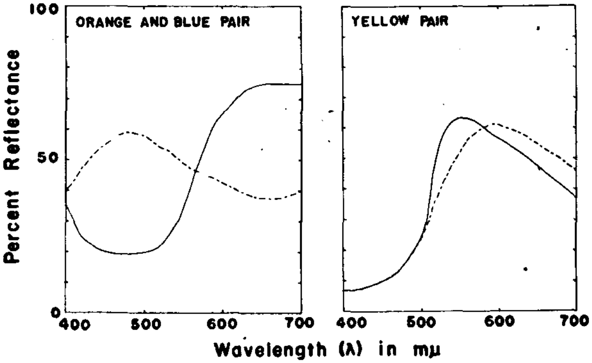

FIG. 7—Spectral reflectance curves of 2 pairs of samples that might be expected to show large changes when viewed under different illuminants.

at 13,000K; and for b, from 1.1 in the second place for the carbon arc to 1.5 in the second place for the Macbeth daylight lamp at 6800K.

It might be expected that there would be a regular change in trilinear coordinate differences as the color temperature of the illuminant is raised, for each set of calculated trilinear coordinates (r, g, b) must be considered in relation to the trilinear coordinates of the illuminant for which each set is calculated. The regularity of this expected change may be verified by observation of the relation of the numbers in each series as they progress through the series of illuminants from Abbot Daylight at 165 mireds through the Gibson curves for 143, 135, 125, and 110 mireds. For the olive pair, the following progressions are shown: for Y: 12, 11, 11, 10, 10; for r: 177, 209, 225, 240, 268; for g: 41, 78, 96, 114, 148; for b: 136, 131, 129, 126, 120. The fact that differences for other illuminants depart from this progression is the important point for our study.

Two other pairs of samples showing large color differences are illustrated in Fig. 7. The progression of apparent reflectance (Y) and trilinear coordinate (r, g, b) differences for 10 illuminants is illustrated in Fig. 8. From a study of the charts, it is again evident that although there is a regular progression in the values of differences resulting from the Gibson Daylight series, differences for many illuminants show important departures from this progression.

Pairs Expected to Show Small Differences

In Fig. 9 are illustrated spectral reflectance curves for five pairs of cotton samples. Inspection of the curves indicates that the differences involved are very small. All calculations of Y, r, g, and b for the cotton

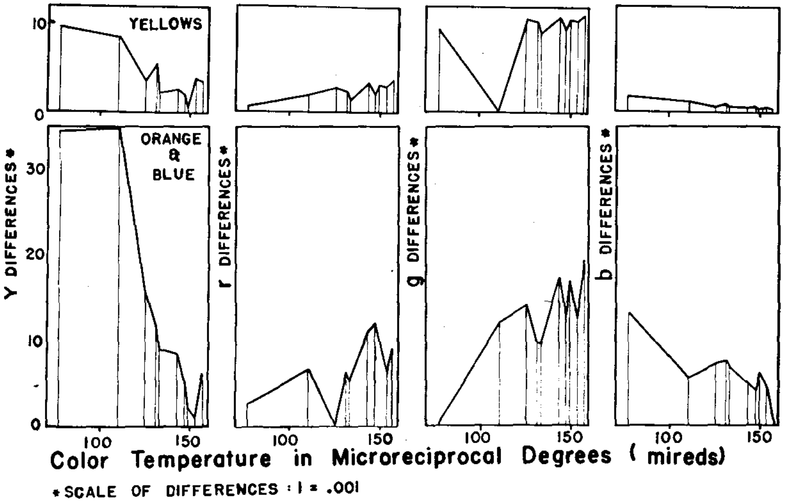

FIG. 8—The Y, r, g, and b differences for 2 pairs of samples for which spectral reflectance curves are given in Fig. 7. The 10 illuminants used are those in Table I, which are numbered: 2, 3, 7, 8, 11, 12, 13, 15, 16.

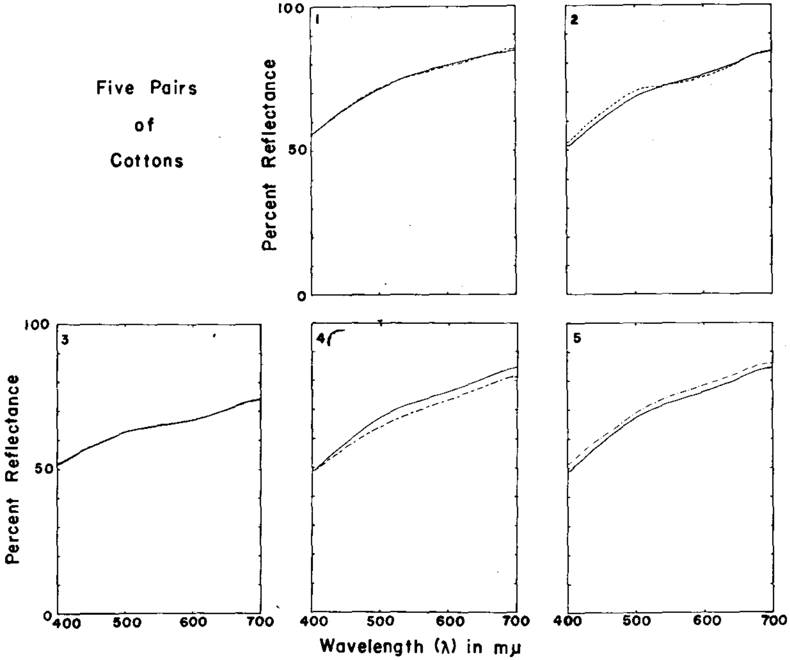

FIG. 9—Spectral reflectance curves for 5 pairs of cottons used in studying color differences due to illuminants.

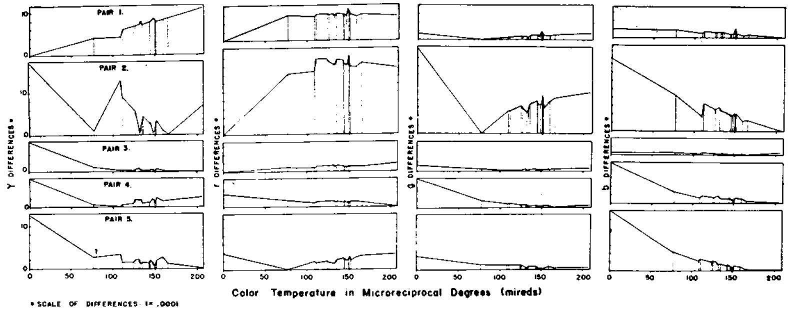

FIG. 10—The Y, r, g, and b differences for 5 pairs of cotton colors are indicated for each of 18 illuminants by the relative heights of the vertical lines. The illuminants are plotted in color temperature order, beginning with the mercury lines at 0 mireds and following through to "B" illuminant at 208 mireds in the order given in Table I. The two illuminants at 110, 125, and 143 mireds are shown slightly separated in the order given in Table I.

colors were therefore carried out to five significant decimal places. Otherwise the change in the differences involved might be masked by errors of rejection. The ordinate scale in Fig. 10 is increased by a factor of 10 over that used in Figs. 6 and 8.

From inspection of the curves in Fig. 9 it would be expected that Cotton Pair No. 2 would show the greatest changes under different illuminants. For this pair the progression of apparent reflectance and trilinear coordinate differences through the Gibson series of illuminants from 165, through 143, 135, 125, and 110 mireds is regular, as it was found to be for the larger differences involved in the pairs selected by Judd. They are: for Y: 5, 35, 50, 65, 94; for r: 308, 314, 315, 317, 318; for g: 99, 91, 84, 81, 69; and for b: 209, 223, 231, 236, 249. As is true for the olive pair, other illuminants do not always fit into this progression.

In order that the significance of the size of the differences might be more easily studied, all of the sample pairs were calculated for a mercury line spectrum. It is misleading to assign a color temperature to such an illuminant, but for purposes of comparison it is indicated as "beyond 0 mireds" and plotted at 0 mireds in Fig. 10. The other illuminants are plotted in order of reciprocal color temperature (in mireds) in the order shown in Table 1.

The important fact to notice is that there is no regular trend of increase or decrease with color temperature except for such regular series as the Planckian or Gibson distributions. Certain illuminants may show a large difference for one pair, a small difference for the next pair, they may be

TABLE I—Illuminants Used in Study of Cotton Pairs

Order	Identification	Approximate color temperature in mireds	ICI trichromatic coefficients based on ICI values for equal energy	
			x	y
1	Mercury lines of Fluorescent 7650K	Beyond 0	0.2190	0.2288
2	Fluorescent 13000K	77	.2679	.2760
3	CO_2 (25 mm)	110	.2820	.3104
4	Gibson $1/\lambda^4$ (.3 + .7)	110	.2854	.2912
5	Gibson $1/\lambda^4$ (.2 + .8)	125	.2959	.3029
6	Planckian 8000K	125	.2952	.3051
7	Fluorescent 7650K	131	.2979	.3063
8	Macbeth 7500K	133	.2996	.3123
9	Gibson $1/\lambda^4$ (.15 + .85)	135	.3016	.3092
10	Gibson $1/\lambda^4$ (.1 + .9)	143	.3076	.3158
11	Planckian 7000K	143	.3063	.3168
12	Macbeth 6800K	147	.3081	.3231
13	ICI "C"	149	.3101	.3163
14	Curve portion of Fluorescent 7650K	151	.3115	.3197
15	Fluorescent 6500K	153	.3129	.3209
16	Carbon Arc	157	.3152	.3321
17	Abbot Daylight	165	.3204	.3301
18	ICI "B"	208	.3485	.3518

greater than would be expected for the general trend in one case, but much less in another case.

Fig. 11 contains a pair of curves for coffee, and one for tobacco. These samples are merely an introduction to a study for such commodities, but since data for a few selected illuminants are available for them, they are shown in Fig. 12.

In his forthcoming paper[9] Dr. Judd will include tables which show duplication indices based on the four pairs of samples he has studied, and he will include illuminants in the color temperature range between "A" to "C" that have not been included in this report (for we have been primarily concerned with illuminants in the "daylight" range).

Modification of Duplication Index for Cotton Studies

The foregoing studies did not give us as complete an answer as we had hoped, so we went at the problem in a slightly different manner by using a modification of the Judd duplication index adapted to analysis of a large group of nearly identical samples representative of a single commodity. First, for each of the samples (30 cottons), we obtained differences in

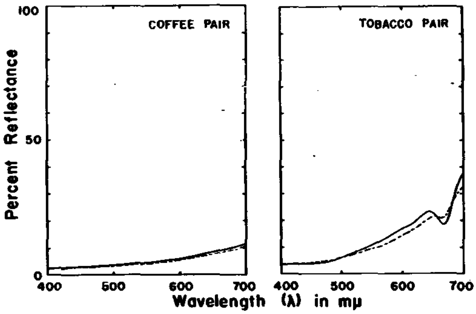

FIG. 11—Spectral reflectance curves for pairs of tobacco and coffee samples.

total apparent reflectance (Y) and in trilinear coordinates (r, g, b) caused by changing from a standard illuminant to a trial illuminant. If each of the series of 30 cottons holds the same relative color position under a trial illuminant as it does under a standard illuminant, then these differences will be constant provided apparent reflectance gives a uniform lightness-scale over the range covered, and provided the trilinear coordinates (r, g, b) yield a true uniform-chromaticity-scale. If the differences are constant, the deviations about the mean difference will be zero; and we may therefore take the standard deviation of these differences about the mean as an inverse measure of the degree of duplication between the trial illuminant and the standard illuminant. In our modification of the Judd method, we have kept separate the deviation of the apparent-reflectance differences and that of the trilinear coordinate (r, g, b) differences which is represented by the sum (without regard to algebraic sign).

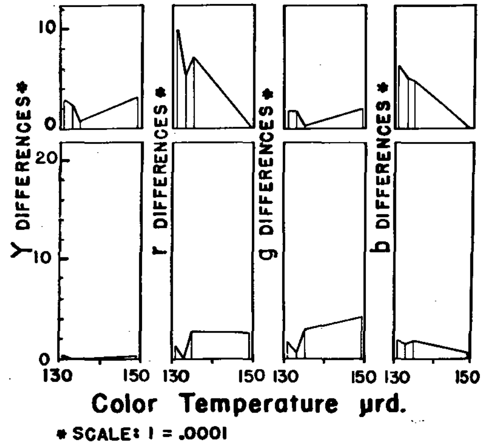

FIG. 12—Y, r, g, and b differences for coffee and tobacco pairs calculated for Fluorescent 7650K, Macbeth 7500K, Gibson 7500K, and "C" (at 131, 133, 135, and 149 mireds).

We have made no attempt to combine, as Judd does, these two indices into a single index, for it is important for cotton work to know that the relation of brightness as well as chromaticity remains constant. It apparent-reflectance differences be neglected, our method for two samples gives the same result with the same computational steps as Judd's for a single pair; but for large numbers of nearly identical samples our method is quicker and, we believe, no less reliable.

The mean differences and the standard deviations are listed in Reference No. 10, and Table II is prepared from these data to show the degree of duplication between one illuminant and another for cotton grading work. The order is based on the size of the deviations about the mean values of the cotton colors. The first of the two small figures listed in columns beside each illuminant indicates the standard deviation found for the Y value, and therefore indicates the degree of duplication or relative degree of satisfaction that may be expected for each illuminant compared with the others in regard to brightness relations. The second figure is the sum of the standard deviations for r, g, and b, used as an index of the degree to which the chromaticity relations of the cottons may be expected to remain constant when one illuminant is substituted for another. An arbitrary figure of ±0.00002 for Y deviations, and ±0.00020 for r + g + b deviations, has been selected for the line of separation of what may be called good from those not-so-good. A second line has been arbitrarily selected at ± 0.00004 for Y and ± 0.00040 for r + g + b to indicate the line of separation for substitutes considered not-so-good to those considered poor for cotton work. Except for illuminants representing extreme conditions of color and energy (ICI "B," the fluorescent tube lamp at 13,000K, and the mercury-vapor illuminants), no listing of illuminants is given for poor substitutes. They are considered too poor to be listed.

From this table one can select any one of 17 illuminants used in this study, and can find its best substitutes listed in order in the column below it, in three groups: group 1 selected to represent satisfactory substitutes; group 2 to represent substitutes not so satisfactory; and group 3 to represent substitutes that should be considered poor.

If, for example, in any work involving cotton samples one selects Abbot Daylight as a standard, and wishes to use the best illuminant (of those included in this study) to represent this standard, he would select a high temperature carbon arc with an energy curve similar to the one hown for carbon arc in Fig. 2. If, however, he selects ICI "C" illuminant as a standard, then the best results would be obtained by the use of

TABLE II—DUPLICATION INDICES OF ILLUMINANTS ON BASIS OF CONSTANCY OF RELATIVE COLOR POSITION FOR 30 COTTON SAMPLES

"B"	
208 Mireds	
3	
Abbot Daylight	4*47
Carbon Arc	5*53
"C"	5*68
Macbeth 6800K	5*68
Gibson 7000K	6*70
Planckian 7000K	6*72
Fluorescent 6500K	4*76
Gibson 7500K	7*81
Macbeth 7500K	6*87
Gibson 8000K	8*92
Planckian 8000K	8*93
Fluorescent 7650K	6*97
Gibson 9000K	10*111
CO_2 (25 mm)	12*134
Fluorescent 13,000K	12*151
Mercury Lines	11*491

Abbot Daylight	
165 Mireds	
1	
Carbon Arc	1*16
2	
"C"	1*25
Gibson 7000K	2*26
Planckian 7000K	2*29
Macbeth 6800K	1*32
Gibson 7500K	3*37
Fluorescent 6500K	2*38

Carbon Arc	
157 Mireds	
1	
Abbot Daylight	1*16
Macbeth 6800K	1*18
2	
"C"	1*22
Gibson 7000K	1*22
Planckian 7000K	1*24
Fluorescent 6500K	2*26
Gibson 7500K	2*33
Macbeth 7500K	1*36

Fluorescent 6500K	
155 Mireds	
1	
Macbeth 6800K	2*10
2	
Macbeth 7500K	3*15
Planckian 7000K	3*17
"C"	2*22
Gibson 7000K	3*22
Gibson 7500K	4*22
Carbon Arc	2*26
Fluorescent 7650K	3*26
Planckian 8000K	4*26
Abbot Daylight	2*38

"C"	
149 Mireds	
1	
Gibson 7000K	1*08
Planckian 7000K	1*12
Gibson 7500K	2*17
Macbeth 6800K	1*20
2	
Carbon Arc	1*22
Fluorescent 6500K	2*22
Abbot Daylight	1*25
Gibson 8000K	3*27
Macbeth 7500K	1*30
Planckian 8000K	3*30

Macbeth 6800K	
147 Mireds	
1	
Fluorescent 6500K	2*10
Planckian 7000K	1*16
Carbon Arc	1*18
Macbeth 7500K	1*19
"C"	1*20
Gibson 7000K	1*20
2	
Gibson 7500K	2*23
Planckian 8000K	3*30
Gibson 8000K	3*31
Abbot Daylight	1*32
Fluorescent 7650K	1*33

Number before star (*) represents standard deviation of Y differences to .00001; number following star (*) represents sum of standard deviations of r, g, and b differences to .00001.

Group 1 contains illuminants that vary no more than 2*20 from the illuminant for which they are to be substituted. Illuminants in this group may be considered satisfactory substitutes.

Planckian 7000K	
143 Mireds	
1	
Gibson 7000K	1*09
Gibson 7500K	1*10
"C"	1*12
Macbeth 6800K	1*16
2	
Fluorescent 6500K	3*17
Macbeth 7500K	1*21
Planckian 8000K	1*21
Gibson 8000K	2*21
Carbon Arc	1*24
Abbot Daylight	2*29
Fluorescent 7650K	1*32

Gibson 7000K	
143 Mireds	
1	
"C"	1*08
Planckian 7000K	1*09
Gibson 7500K	1*12
Macbeth 6800K	1*20
2	
Carbon Arc	2*22
Fluorescent 6500K	3*22
Gibson 8000K	2*24
Planckian 8000K	2*26
Abbot Daylight	2*26
Macbeth 7500K	1*28
Fluorescent 7650K	1*39

Gibson 7500K	
135 Mireds	
1	
Planckian 7000K	1*10
Gibson 8000K	1*10
Gibson 7000K	1*12
"C"	2*17
Planckian 8000K	1*16
Macbeth 7500K	1*19
2	
Macbeth 6800K	2*23
Fluorescent 6500K	4*22
Fluorescent 7650K	1*29
Carbon Arc	2*33
Gibson 9000K	3*32
Abbot Daylight	3*37

Macbeth 7500K	
133 Mireds	
1	
Fluorescent 7650K	1*15
Planckian 8000K	2*15
Macbeth 6800K	1*19
Gibson 7500K	1*19
Gibson 8000K	2*20
2	
Fluorescent 6500K	3*15
Planckian 7000K	1*21
Gibson 7000K	1*28
"C"	1*30
Carbon Arc	1*36
Gibson 9000K	3*37

Fluorescent 7650K	
131 Mireds	
1	
Macbeth 7500K	1*15
Planckian 8000K	2*15
2	
Gibson 8000K	2*21
Gibson 9000K	4*23
Fluorescent 6500K	3*26
Gibson 7500K	1*29
Planckian 7000K	1*32
Macbeth 6800K	1*33
Gibson 7000K	1*39

Planckian 8000K	
125 Mireds	
1	
Gibson 8000K	1*08
Macbeth 7500K	2*15
Fluorescent 7650K	2*15
Gibson 7500K	1*16
2	
Planckian 7000K	2*21
CO_2 (25 mm)	4*21
Gibson 9000K	2*22
Gibson 7000K	2*26
Fluorescent 6500K	4*26
"C"	3*30
Macbeth 6800K	3*30

Group 2 contains those that vary no more than 4*40 from the illuminant for which they are to be substituted.

Group 3 (omitted for all but extremes) contains those that vary more than 4*40. Illuminants in this group should be considered unsatisfactory for substitutes for close color duplication for cotton work.

The order of rating is according to chromaticity rather than brightness. This is an arbitrary choice.

Gibson 8000K		Gibson 9000K		CO_2 (25 mm)[1]	
125 Mireds		110 Mireds		110 Mireds	
1		2		2	
Planckian 8000K	1*08	Gibson 8000K	2*21	Gibson 9000K	2*3
Gibson 7500K	1*10	Planckian 8000K	2*22	Planckian 8000K	4*2
Macbeth 7500K	2*20	Fluorescent 7650K	4*23	Gibson 8000K	4*2
		Gibson 7500K	3*32		
2		CO_2 (25 mm)	2*35	3	
Planckian 7000K	2*21	Macbeth 7500K	3*37	Macbeth 7500K	5*1
Fluorescent 7650K	2*21			Fluorescent 7650K	6*1
Gibson 8000K	2*21			Fluorescent 6500K	8*2
Gibson 7000K	2*24			Macbeth 6800K	6*2
"C"	3*27			Gibson 7500K	5*2
CO_2 (25 mm)	4*28			Planckian 7000K	6*3
Macbeth 6800K	3*31			Gibson 7000K	6*3
				"C"	7*3

---

[1] The brightness differences seem more affected than chromaticity differences whe CO_2 is used as an illuminant.

Fluorescent 13,000K		Mercury lines			
77 Mireds		Beyond 0 Mireds			
3		3			
Gibson 9000K	3*54	Gibson 9000K	8*405		
Fluorescent 7650K	6*56	Planckian 8000K	7*418		
CO_2 (25 mm)	3*64	Gibson 8000K	8*424		
Planckian 8000K	5*66	Gibson 7500K	8*433		
Macbeth 7500K	6*68	Planckian 7000K	8*435		
Gibson 8000K	5*72	Gibson 7000K	8*443		
Fluorescent 6500K	8*78	"C"	8*443		
Gibson 7500K	5*82	Abbot Daylight	8*463		
Planckian 7000K	6*85	"B"	11*491		
Macbeth 6800K	7*86				
Gibson 7000K	6*92				
"C"	7*93				
Carbon Arc	7*103				
Abbot Daylight	8*114				
"B"	12*151				

Macbeth 6800K. If the Gibson curve for 7500K is the standard, the losest illuminant would be Macbeth 7500K. If Planckian 8000K is the tandard then either Macbeth 7500K or Fluorescent 7650K would serve qually well.

Although the rating of illuminants shown in Table 2 is based on the onstancy of color held by the cotton samples which were studied, it is robable that for materials of greater selectivity and of larger differences he results would be no better.

Studies of Other Illuminants

If other investigators are interested in illuminants not included in this tudy, they can calculate values for any of the pairs or for the 30 cottons, nake comparisons similar to those followed in this study, and relate the esults for the illuminants in which they are interested to those reported ere. The data necessary for such calculations are provided in Reference No. 10.

Literature Cited

(1) Nickerson, Dorothy; Artificial Daylighting Studies, *Trans. I. E. S.*, *34*, 1233 (1939).

(2) Hardy, Le Grand H.; The Bases of Color Vision, 1940 I. E. S. Convention Preprint.

(3) Judd, Deane B.; Color Systems and their Inter-relation, 1940 I. E. S. Convention Preprint.

(4) Moon, Parry; Color Determination, 1940 I. E. S. Convention Preprint.

(5) Taylor, A. H.; Lighting for the Detection of Small Color Differences, *Bulletin Am. Phys. Soc.* p. 28 (Abstract), (Feb. 5, 1940).

(6) Nickerson, Dorothy; Artificial Daylighting for Color Grading of Agricultural Products, *J. O. S. A.* *29*, 1 (1939).

(7) Judd, Deane B.; Definition and Tolerances for Artificial Daylight for Color Matching, *J. O. S. A.* *29*, 145, (Abstract), (1939).

(8) Judd, Deane B.; A Maxwell Triangle Yielding Uniform Chromaticity Scales, *J. O. S. A.* *25*, 24 (1935); also *Bu. Stand. J. Res.*, *14*, 1935, (No. 756), 41–52.

(9) Judd, Deane B.; (In press, to appear in *J. O. S. A.*).

(10) Nickerson, Dorothy; Computational Tables for Use in Studies of Artificial Daylight, Agricultural Marketing Service, United States Department of Agriculture, August, 1940. (May be obtained without charge by request from Agricultural Marketing Service, Washington, D. C.)

(11) Hardy, A. C.; Handbook of Colorimetry, Technology Press, 1936.

(12) Taylor, A. H.; The Color of Daylight, *Trans. I. E. S.* *25*, 154 (1930).

(13) Gibson, K. S.; Approximate Spectral Energy Distribution of Skylight, *J. O. S. A.* *30*, 88, (Abstract), (1940).

(14) Taylor, A. H. and Kerr, G. P.; The Spectral Distribution of Energy in Daylight, *J. O. S. A.* *30*, 88, (Abstract), (1940). *Magazine of Light*, *9* (3): 11–12. April 5, 1940.

SYMBOLS AND THEIR DEFINITIONS, AS USED IN PAPERS PRESENTED AT COLC SESSION, 1940 I. E. S. CONVENTION

E	energy (erg).
F	luminous flux (lumen).
G	total irradiation (watt per square meter).
Γ	erythemal flux density (erythemally weighted watt per square meter).
I.C.I.	International Commission on Illumination.
J	total radiosity (watt per square meter).
J_λ	spectral radiosity (watt per square meter per micron).
K	degrees Kelvin.
T_c	color temperature (degrees K).
V_λ	1931 I.C.I. standard luminosity factor for wave-length λ.
W_λ	relative erythemal effect of radiant energy of wave-length λ.
h	Planck's constant (6.54×10^{-27} ergs-second).
m	air mass.
mired	micro-reciprocal degree.
$m\mu$	millimicrons.
P_c	colorimetric purity.
λ	wave-length (in microns unless otherwise specified).
λ_d	dominant wave-length.
ν	frequency of radiant energy (per second).
ρ	reflection factor.
ρ_λ	spectral reflection factor at wave-length λ.
ρ_o	reflection factor of magnesium oxide.
τ_λ	spectral transmission factor at wave-length λ.
X, Y, Z	tristimulus values for a source of radiation*.
$\bar{x}, \bar{y}, \bar{z}$	tristimulus values for one unit of spectrally homogeneous radiant energy wave-length λ.
x, y, z	trilinear coordinates obtained from X, Y, Z (also known as trichromatic c efficients).
U.C.S.	Uniform Chromaticity Scale.
R.U.C.S.	Rectangular Uniform Chromaticity Scale.
R, G, B	linear homogeneous transformations of X, Y, Z (in particular those giving ris to the Uniform Chromaticity Scale and similar scales).
r, g, b	trilinear coordinates of the functions R, G, B.
X′, Y′, Z′	linear transformations of X, Y, Z, in accordance with the R.U.C.S. System.
x′, y′, z′	trilinear coordinates of the functions X′, Y′, Z′.

* Note: If the radiating source is a secondary source formed by the diffusing surface of a opaque sample, Y is proportional to reflection factor of the surface for the primary light sourc If the radiating source is formed by a source-filter combination, Y is proportional to th transmission factor of the filter for the primary light source. These proportionalities aris from the fact that the luminosity factors and the value of $\bar{y}$ are identical.

DISCUSSION

NORMAN MACBETH*: In looking through some correspondence we had in the office some time ago, I found that in 1924 Dr. Judd was requested to develop a method of determining a good substitute for natural daylight, and at that time he suggested the use of the four samples.

We are very happy that last year Dr. Judd prepared this formula on which Miss Nickerson has been working this year; and I might add that Miss Nickerson has spent nearly the whole year and all of her time preparing the data which she has just presented. This paper contains just a small part of the calculations which are also available.

I might add that in addition to this theoretical work, the cotton classer and other people interested in determining the proper illuminants for color grading have investigated all the data and equipment which have been described—filter carbon arc, filter incandescent combination—and their agreement has been very much the same as the theoretical results shown in Miss Nickerson's paper.

In addition to the cotton, in which Miss Nickerson is most interested, this standardization opens up a new field in commodities in grading bread, grain, tobacco and, most recently, silver foxes. The latter represents a terrific problem, and most of the grading has to be done during a period of one month just before the fox pelts are shipped.

I believe that most of these problems can be solved through the work that Miss Nickerson has done.

RICHARD HUNTER**: The phenomenon of color constancy introduces some important considerations that, particularly with the use of fluorescent illuminants, are going to worry the illuminating engineer quite a bit.

We have gone through the steps in seeing the development of color specification. We have seen that the complete spectral specification of a stimulus is its physical specification.

Then we have seen how this imaginary observer—the I. C. I. Observer, chosen to represent an average observer as regards color vision—has been chosen and defined by the I. C. I. distribution curves so that he may be used to locate stimuli according to their chromaticity in a manner that seems logical to other persons with normal color vision.

We have seen an additional step taken. Dr. Judd has developed the uniform chromaticity scale diagram to make the chromaticity steps between different samples seem proper in relation to one another.

---

* Macbeth Daylighting Corp., New York.

** National Bureau of Standards, Washington, D. C.

However, all of these chromaticity diagrams refer to an observer wh is adapted to equal energy; that is, if the I. C. I. observer came to lif he would report the colors of all stimuli, in whatever illuminant, in the relation to the color of equal energy, which is a good substitute for da light. Thus a pale blue sample illuminated by incandescent illuminan would be reported as yellower than a white sample illuminated by da light. However, we all know that under incandescent light a pale blu sample such as this program still appears pale blue.

Thus, to satisfy the illumination expert you are going to have to s up different coordinate systems for each different illuminant in commo use, and these new fluorescent lamps are introducing an embarrassingl large number of these.

Dr. Judd has done some work bearing on the general problem. should like to ask, however, if anyone knows of specific work on colo constancy under the illuminants in common use today.

Deane B. Judd*: I have given directions based on work carried on b Professor Helson of Bryn Mawr College, and myself for computing est mates of hue, saturation and lightness under any illuminant.

The results of those computations could be described as approximat color constancy. Therefore, I think they bear directly on the questio raised by Mr. Hunter.

I should also like to make a comment of my own, if I may. Mis Nickerson has been very generous in crediting me with the idea of thi duplication index for artificial daylight. I wish to pass on the credit t the elder Norman Macbeth, who is no longer with us. I got the essenc of the idea from him. He applied it for years in actual practice b samples, and I merely put it into computational form.

The only difference between my own carrying out of the idea and th one which Miss Nickerson has presented to you in this paper is that went a little further than she did in trying to get a single number whic would characterize the degree to which an artificial daylight duplicate some standard daylight. I tried to work out an index which would b one hundred in case there was perfect duplication; which would be zer in case the illuminant introduced errors of a size equivalent to the differ ence between black and white; and which would be fifty in case the error were such as exist between natural daylight and incandescent lamps a 2360 K.

---

* National Bureau of Standards, Washington, D

I thought perhaps the hypothetical illuminating engineer, of whom we have heard a good deal, would prefer a single number to characterize this very complicated thing. I am not sure it really adds anything at all. I think Miss Nickerson has jumped ahead of me and carried out the Macbeth idea perhaps to what deserves to be the final stage of it.

F. CHAPIN BRECKENRIDGE*: Each of the four speakers who has addressed us today deserves congratulations for having compressed a broad subject within the scope of a brief address, and having so done it that we could both understand and be interested in it.

The subject of colors and color specifications has been neglected by the Illuminating Engineering Society for the past twenty years, and I trust that that mistake will not be repeated during the next two decades.

Many of you who are here may be called upon to assist in establishing some system of color specifications. If you are to do your duty by the future, you will make every effort to avoid the mistakes which were made by those who have established some of the systems of measurement which we have to use today; for example, our feet and inches, our Fahrenheit temperatures, our Baumé specific gravities. Each of those systems was started because it was the simplest thing to do in some laboratory at the time when it was first done, and then, because there was a certain amount of information collected in that system, later investigators refused to leave it, with the result that the generations since have all had to pay the penalty of useless work.

In setting up a system of color specifications, you ought to consider what qualifications are most important and will be most important from the future looking back.

Is it most important that your specification be easily computed? Is it important that it represent color differences truly? Is it important that color relationships fall into some natural formation—for example, that white or achromatic light be represented by a point near the center of the diagram? Is it important that the numerical intervals be simple and easily remembered?

Consider all of the qualities which your system should have and then don't feel that you must adopt a system simply because it is the one which eems to be the "going concern" at the moment.

JAMES A. MEACHAM**: I should like to inquire of Miss Nickerson with elation to the studies, if any have been made for the determination of

---

* National Bureau of Standards, Washington, D. C.

** Sherwin-Williams Company, Cleveland, Ohio.

color values in paint samples as distinguished from the textile and othe agricultural samples. What has been done as regards the proper illuminant or the most effective illuminant for determining color in paint

John M. Chorlton*: I assume from Miss Nickerson's paper that th unit consisting of 18 fluorescent tubes, as described in the paper sh presented last year, has more or less failed to provide a substitute fo north sky light for the grading of cotton. I should also like to as Miss Nickerson to comment on the possible use of fluorescent equipmen for tobacco grading.

A. K. Gaetjens** (Communicated): Miss Nickerson's paper abl reflects the enormous amount of work which has been put into its development. The data she presents and the further calculations she has mad available should be of great value in predicting results in the future wit other combinations of sources.

The development of fluorescent lamps, highly efficient primary source of colored light, has created widespread interest. Of particular importance with regard to color matching and color discrimination is th daylight lamp. Because of the presence of the mercury spectrum (approximately 11 per cent of the light output of the daylight lamp is du to the Hg arc) and a known deficiency in the red end of the spectru (above 6400 λ) it was felt originally that while this source might b suitable for much color work, it might not be satisfactory for the mos accurate discrimination of color. However, experience[1] has indicate that the daylight lamp, when properly used, is a satisfactory high colo temperature (6500 K) source for color matching.

Another and more difficult problem was to ascertain the suitability o fluorescent light to replace natural light. The daylight lamp light alon is, in general, a satisfactory substitute for overcast skylight of equivalen color temperature. On the other hand, it was early discovered in Mis Nickerson's laboratory that cotton classers in particular preferred a highe color temperature light source. Fortunately, combinations of dayligh and blue fluorescent lamps have color coordinates which are close to th Planckian curve from 6500 to approximately 10,000 K. The questio remained as to the suitability of the energy distribution curves of suc combinations as substitutes for natural light.

---

* Hydroelectric Power Commission, Toronto, Ontario, Canada.

** General Electric Company, Nela Park, Cleveland, Ohio.

[1] "Color Matching at the Forbes Varnish Co.", Illuminating Engineering, 35, 1940, 343.

Miss Nickerson's paper indicates that for the color pairs which were selected, such fluorescent combinations are suitable duplicates for the equivalent color temperature natural source, or filament lamp and filter source. An advantage of the combination is the variable ratio of the constituent sources which can be had throughout the practical range.

A. H. Taylor* (Communicated): For a long time natural daylight has been considered the ideal illuminant for color-matching and discrimination, without an adequate consideration of its normal variations. The human eye can accommodate for a wide range of illumination levels, but it is seriously questionable whether it can make due allowances for the great variations in spectral quality which also occur. Any artificial illuminant which varied as greatly as daylight in spectral energy distribution would be considered entirely unsatisfactory for use in this field.

During the past year we have been studying the spectral distribution of energy in Cleveland daylight, for various conditions and exposures. Fig. 4 of Miss Nickerson's paper reproduces a few of the many curves which we have obtained. They are plotted on a basis of equal foot-candles, hence are directly comparable with each other. The highest color-temperature measured, 60,000 K, was obtained for a very clear zenith sky. A slightly hazy north sky gave the curve showing a color temperature of 12,600 K. Smoke in the air reduces the color temperature still further, and a completely cloudy or overcast sky gives an energy distribution having a color temperature of approximately 6500 K.

In Miss Nickerson's paper at the convention last year on lighting for cotton classification, she said[2]: "Because the preferred natural light is that of a moderately overcast north sky (it gives relatively constant conditions over the longest period of time) the color specification for an artificial illuminant should duplicate this color as closely as possible." Our measurements indicate that this type of daylight is far from constant in either illumination level or spectral quality. Light from a clear north sky may have a color temperature of approximately 15,000 to 25,000 K. (In December 1938, I measured the color temperature of the daylight in the cotton-classing room in the Agricultural Department in Washington and found it to be 17,500 K). For a completely overcast north sky the color temperature would be approximately 6500 K. If a partially overcast sky is one in which some clear blue sky is visible, the proportion of clear to cloudy area is likely to change rapidly, with a resultant change

---

* General Electric Company, Cleveland, Ohio.

[2] *Trans. Illuminating Engineering Society*, 34, 1236, December 1939.

in spectral distribution and color temperature. Thus, in a period half an hour the color temperature of daylight from a north sky may var by several thousand degrees.

In Table II it is seen that if Gibson 7500 K is taken as the basis, th duplication index for Gibson 9000 K is 3*32, which is almost as great a the value 4*40 beyond which Miss Nickerson considers an illuminant to b unsatisfactory as a substitute. Obviously the natural variations i daylight from hour to hour are sometimes greater than those betwee most of the illuminants considered, and a suitably chosen consta artificial illuminant would appear to be appreciably superior to natur daylight.

DOROTHY NICKERSON: The question that have been raised cover tw things that I wanted to say and haven't.

First, we have studied only the units described here today. Rece reports from Argentina indicate that they are trying something there th seemed to us so far behind that we did not study it—mercury-plu incandescent. Yet I understand that across the water they, too, a using this combination and think it far ahead of what they have prev ously had for daylight. (The German secretariat of the ICI committ on Natural and Artificial Daylight, in a questionnaire of August 11, 193 asked whether a mixture of this sort, in definite proportions, might b designated as satisfactory). I have written to the Argentina cotto people to find out just what they have developed, and how much the are using these units. If we find that they do use mercury-plus-inca descent to any great extent, we shall obtain spectral distribution cha acteristics of the combination and compute it as we have the illuminan already studied, in order to see where it falls in comparison to the other

Second, the National Carbon Company, who supplied data on th sunshine carbon arc used in our studies, has been working on the proble of a color grading lamp. They have developed one that will be availab soon which consists of a combination with a filter that will raise th color temperature to 7500 K. They have agreed to supply us with spectr distribution data for the combination, and we expect to make comput tions for our cotton series so that comparisons may be made to the seri already reported.

In answer to Mr. Meacham's question about paints (the question abou tobacco refers to fluorescent), I might say that while we used only th cotton series, except for the pairs of widely different spectral energy di tributions shown in Figs. 5 and 7, there is no reason that the results this work cannot be carried over directly to paints. The spectral distributions we used could be considered as if they were painted surfaces, for painted surfaces are well represented by the series we selected and used. In this group are spectral distribution curves that are very similar, and others that are very dissimilar. I do not see why our results cannot be carried over directly to any product which has similar spectral characteristics.

Regarding Mr. Chorlton's question, I reported last year that only preliminary tests on the use of a fluorescent-type unit could then be reported, and he might well assume that I would report more definitely this year. And this report that has been made today probably would have been differently prepared if the paper had not been planned for this particular program to fit into a discussion of color matching and discrimination. As previously indicated, the laboratories of most of the groups who manufacture the lamps we have studied have been very generous in the way they have cooperated with us. At Nela Park they made the fluorescent unit that we experimented with in our Washington laboratories, and that has been sent subsequently to a commercial cotton classification group for many months' use. You can see what the figures show in Table II. Our practical experience was just about the same. Fluorescent 7650 K was pretty good, but not as good as the Macbeth 7500 K reported. We couldn't say "no" to it for our cotton sample, but we couldn't say "yes" either. Our practical men decided they *could* grade under the fluorescent unit, preferably at about 7500 K. They had no trouble at all under the filter-plus-incandescent, but when they took their samples under the fluorescent they did have hesitation—not great enough for them not to be able to grade the sample properly, but great enough to slow them down in their judgments, and give them a feeling of uncertainty.

However, there are lots of places where fluorescent "daylight"—I dislike having it called "daylight"—can be used. Although it has the color temperature of some daylights, it does not have a similar spectral energy distribution. If you understand that there is this difference, and use it accordingly, then there are a great many places where you can use it, and quite successfully.

As for tobacco, we have no records at present other than for the two samples reported, although we do expect, in cooperation with the tobacco standards and grading group of the U. S. Department of Agriculture, to obtain spectral reflectance distributions for the many colors included in the tobacco standards. When this information becomes available, we can then study the effect of illuminants upon tobacco colors.