Measurement and Specification of Color Rendition Properties of Light Sources

By DOROTHY NICKERSON

"Before our knowledge of the effects of artificial light is satisfactory we must solve the problem of the part played by color." This statement is as true today as it was in 1910, almost fifty years ago, when Herbert E. Ives[1] first discussed color measurements of illuminants before this Society.

The two methods used in his day to measure color of light sources are essentially the same today, although both are now highly standardized: spectroradiometric, in which the relative intensities of the spectra of various light sources are measured wavelength by wavelength, and colorimetric, in which the color of each source is matched by methods of color mixture. The validity of the color matching method is stated in Grassman's law[2] which says that lights of the same color produce identical effects in mixtures, regardless of their spectral composition. Unfortunately for the illuminating engineer, it does not follow that objects seen under light sources of the same color will appear alike in color. The color distortion due to spectral differences in light sources of the same color is one of the problems of color rendition. This problem is fairly simple compared to that which involves also a shift in the color of the light source, for the eye adapts[3] itself to such shifts. Formulas for computed data must take into account the state of an observer's adaptation if they are to predict correctly the color an observer will perceive. In addition to adaptation to the color of the light source, there is adaptation to the background and surrounding conditions under which the observations are made. This all results in a net shift, and it is this net shift we must hope to predict if the illuminating engineer is to have a color rendition rating (whether one — or multi-numbered) that he can use with confidence in a practical situation.

Colorimetry today is a science on so firm a basis that it is doubtful whether many persons realize how much additional information is needed before color rendition of a light source can be predicted accurately. The purpose of this report is to review some of the basic procedures and information that are available and necessary for this work, and to point out what still is lacking, or available in only a very limited way, and what remains to be done.

What To Use As a Standard

In much color work the first problem is what to use as a standard light source. Back in 1910 Dr. Ives suggested "average daylight," to lie between the extremes of "blue light from the sky" and "the color of low sun," a color that he thought agreed closely with the visible radiation of a black body at 5000K. But even if 5000K were the best choice, obviously one color is not enough, and in 1931 the International Commission on Illumination (CIE) adopted three standard sources, identified as *A*, *B*, and *C*. *A* is intended to be typical of light from a gas-filled incandescent lamp (2854K; *B* is an approximate representation of noon sunlight (4800K); *C* is an approximate representation of average daylight (6740K). For colorimetry of object colors such sources have served an important purpose. But when one wishes to select or compare light sources, even three is not enough. For work involving color grading and color matching the color of CIE Source *C* has been found to be yellower than the color of the daylight used and preferred for this purpose (7400K - 7500K).[4,5]

What is needed is a one-dimensional series with continuous, reasonably smooth spectroradiometric curves that will cover the range from yellowish to bluish whites. For this purpose the one-dimensional series of sources defined by the Planck radiation law has the advantage of having continuous and maximally smooth curves and a convenient and precise definition. But the curves bear little resemblance to those of actual light sources except in the low color temperature range of the incandescent tungsten lamps. Fig 1. In the range of daylight colors use can be made of the one-dimensional series described by Gibson in 1940,[6] known since then as the Abbot-Gibson series. Fig. 2. In this

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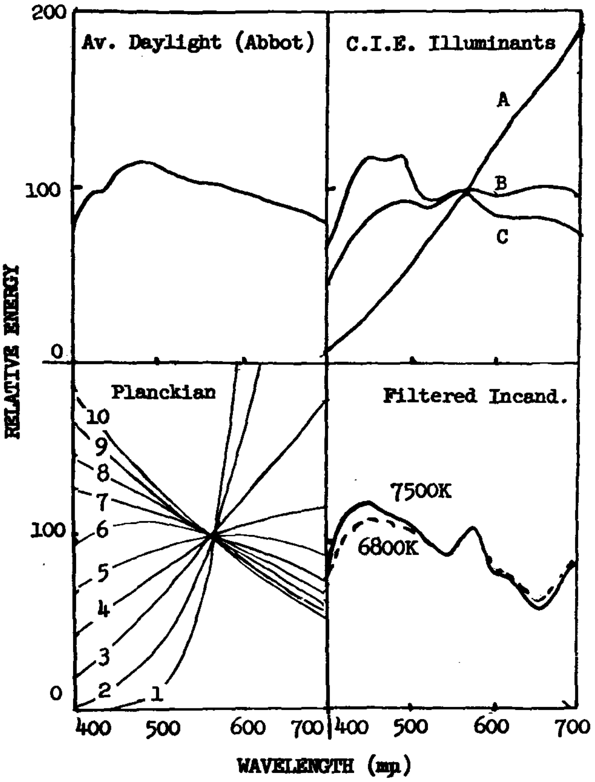

Figure 1. Relative spectral energy distributions for Average Daylight (Abbot); CIE standard Sources *A*, *B*, and *C*; Planckian black-body radiators, 1 to 10 thousand K, and filtered-incandescent (Corning No. 5900 glass) at 6800K and 7500K.

series curves representing sources of desired daylight color may be derived by combining different proportions of Abbot's 1923 measurements of sun-outside-the-atmosphere with the bluest possible skylight, calculated from his data by use of the Rayleigh scattering equation ($1/\lambda^4$). Values of the chromaticity coordinates computed for this series lie on a straight line very close to the Planckian locus. In work involving color rendition of light sources intended to approximate daylight in the 7400K-7500K color temperature range, the Abbot-Gibson curve consisting of 85 per cent Abbot daylight and 15 per cent blue sky has been particularly useful. The curve for Abbot daylight alone computes to a color that plots on the Planckian locus just above 6000K, with 10 per cent blue sky it is about 7000K, with 20 per cent about 8000K, and with 30 per cent about 9000K. Because these data are of considerable current use (and are not available in detail except in a 1940 mimeographed report[7] now out of print) they are given in Table I. By interpolation the approximate spectral energy distribution for any measured color temperature of the sky may be derived

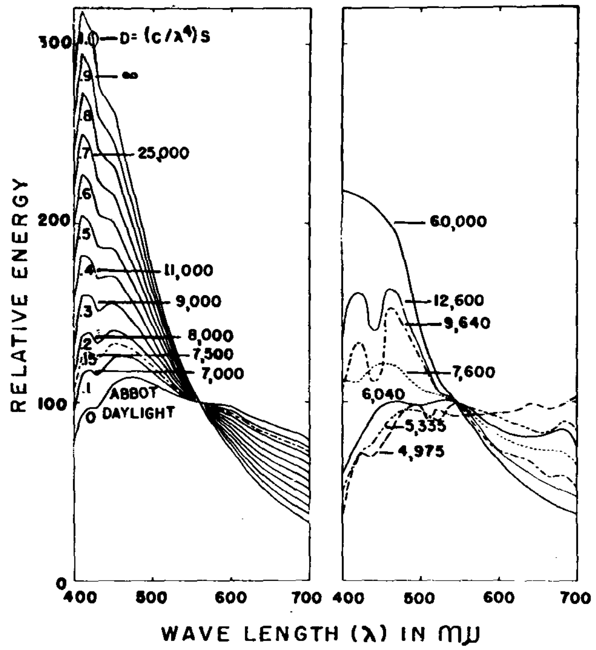

Figure 2. Theoretical daylight curves derived by Gibson from different proportions of Abbot sun-outside-atmosphere and skylight calculated by use of inverse λ^4 scattering relation; and for comparison, curves of daylight measured in 1939 by Taylor and Kerr.

In writing specifications or in performing instrumental colorimetry, the standards discussed are very useful. But when it is necessary to make observations it becomes dishearteningly clear that most of these light sources are either completely theoretical, or quite impractical to use for illuminating objects that are to be observed. Daylight is used most often in making observations of the color of objects, and the "daylight color" certainly is the one most often wanted. But while approximations can be made, no real colorimetric precision is possible for experiments made under a light source that cannot be specified accurately for the duration of the experiment. As we continue to compile colorimetric information it becomes increasingly evident that to solve some of our color rendition problems we need observations made under very precisely measured conditions of illumination.

The three CIE standards include a gas-filled lamp operating at a color temperature of 2845K (1948), and this lamp used with double liquid filters. Use of these liquid filters is possible in instrumentation, but it is not very convenient. For work involving filters, the liquid filters often are supplanted by Corning's glass filter No. 5900, which is designed to convert the color of incandescent lamps to that of daylight with as close a match to

TABLE I — Abbot-Gibson Data for Spectral Energy Distributions of Skylight.

Wave-length mμ	Day-light[1] S_e	Blue Sky[2] S_b	Blue Sky + Average Daylight in Varying Proportions										
			.05+.95[3]	.1+.9	.15+.85	.2+.8	.3+.7	.4+.6	.5+.5	.6+.4	.7+.3	.8+.2	.9+.1
380	62.0	292.4	73.5	85.0	96.6	108.1	131.1	154.2	177.2	200.2	223.3	246.3	269.4
90	63.9	271.6	74.3	84.7	95.1	105.4	126.2	147.0	167.7	188.5	209.3	230.1	250.9
400	73.4	282.0	83.8	94.3	104.7	115.1	136.0	156.8	177.7	198.5	219.4	240.3	261.1
10	91.5	318.4	102.8	114.2	125.5	136.9	159.6	182.3	205.0	227.7	250.4	273.1	295.8
20	97.0	306.6	107.5	118.0	128.4	138.9	159.9	180.8	201.8	222.7	243.7	264.7	285.6
30	96.9	278.7	105.8	115.1	124.2	133.3	151.4	169.6	187.8	206.0	224.2	242.4	260.6
40	102.9	270.0	111.3	119.6	128.0	136.3	153.0	169.7	186.4	203.2	219.9	236.6	253.3
450	109.6	262.8	117.4	124.9	132.6	140.2	155.6	170.9	186.2	201.6	216.9	232.2	248.0
60	112.0	246.0	118.5	125.4	132.1	138.8	152.2	165.6	179.0	192.4	205.8	219.2	232.6
70	113.5	228.8	119.2	125.0	130.8	136.6	148.1	159.6	171.1	182.6	194.2	205.7	217.2
80	113.6	210.5	118.5	123.3	128.1	133.0	142.7	152.3	162.0	171.7	181.4	191.1	200.8
90	112.1	191.2	116.0	120.0	124.0	127.9	135.8	143.8	151.7	159.6	167.5	175.4	183.3
500	110.7	174.2	114.0	117.0	120.2	123.4	129.8	136.1	142.4	148.8	155.1	161.5	167.8
10	108.5	157.7	110.9	113.4	115.9	118.4	123.3	128.2	133.1	138.0	143.0	147.9	152.8
20	105.9	142.4	107.7	109.6	111.4	113.2	116.9	120.5	124.2	127.8	131.5	135.1	138.8
30	103.4	128.9	104.7	106.0	107.2	108.5	111.0	113.6	116.1	118.7	121.2	123.8	126.3
40	101.7	117.6	102.6	103.3	104.1	104.9	106.5	108.1	109.7	111.3	112.8	114.4	116.0
550	100.9	108.4	101.1	101.6	102.0	102.4	103.2	103.9	104.7	105.4	106.2	106.9	107.7
60	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
70	99.1	92.3	98.9	98.4	98.1	97.8	97.1	96.4	95.7	95.0	94.4	93.7	93.0
80	98.6	85.7	98.1	97.3	96.7	96.0	94.7	93.4	92.1	90.8	89.6	88.3	87.0
90	98.3	79.8	97.4	96.4	95.5	94.6	92.7	90.9	89.0	87.2	85.3	83.5	81.6
600	97.4	*73.9*	*96.2*	*95.0*	*93.9*	*92.7*	*90.4*	*88.0*	*85.7*	*83.3*	*81.0*	*78.6*	*76.3*
10	95.2	67.6	93.8	92.4	91.1	89.7	86.9	84.2	81.4	78.6	75.9	73.1	70.4
20	93.1	62.0	91.7	90.0	88.4	86.9	83.8	80.6	77.5	74.4	71.3	68.2	65.1
30	91.0	56.8	89.2	87.6	85.9	84.2	80.7	77.3	73.9	70.5	67.1	63.6	60.2
40	89.3	52.4	87.4	85.6	83.8	81.9	78.2	74.5	70.8	67.1	63.4	59.7	56.0
650	87.5	48.2	85.7	83.6	81.6	79.6	75.7	71.8	67.8	63.9	60.0	56.1	52.1
60	86.0	44.6	84.0	81.9	79.8	77.7	73.6	69.4	65.3	61.1	57.0	52.9	48.7
70	84.6	41.3	82.5	80.3	78.1	75.9	71.6	67.3	62.9	58.6	54.3	49.9	45.6
80	83.3	38.3	80.9	78.8	76.6	74.3	69.8	65.3	60.8	56.3	51.8	47.3	42.8
90	81.4	35.3	79.2	76.8	74.5	72.2	67.6	63.0	58.4	53.8	49.1	44.5	39.9
700	79.1	32.4	76.8	74.4	72.1	69.8	65.1	60.4	55.8	51.1	46.4	41.7	37.1
10	76.8	29.7	74.4	72.1	69.7	67.4	62.7	58.0	53.3	48.6	43.8	39.1	34.4
20	74.4	27.2	72.0	69.7	67.3	65.0	60.2	55.5	50.8	46.1	41.4	36.7	32.0
30	72.2	25.0	69.8	67.5	65.1	62.8	58.0	53.3	48.6	43.9	39.2	34.4	29.7
40	70.2	23.0	67.8	65.5	63.1	60.8	56.1	51.3	46.6	41.9	37.2	32.5	27.8
750	68.2	21.2	65.9	63.5	61.2	58.8	54.1	49.4	44.7	40.0	35.3	30.6	25.9
60	66.1	19.5	63.8	61.4	59.1	56.8	52.1	47.5	42.8	38.1	33.5	28.8	24.2
70	63.9	17.9	61.6	59.3	57.0	54.7	50.1	45.5	41.9	36.3	31.7	27.1	22.5
380–770 x	.3204	.2319	.3139	.3076	.3016	.2959	.2854	.2757	.2669	.2588	.2513	.2444	.2379
380–770 y	.3301	.2318	.3228	.3158	.3092	.3029	.2912	.2804	.2706	.2616	.2533	.2456	.2384
400–700 x	.3204	.2320	.3138	.3075	.3016	.2959	.2854						
400–700 y	.3304	.2322	.3231	.3161	.3095	.3032	.2915						
c.C.T.	6100K	α	6500K	7000K	7400K	8000K	9300K	11,000K	14,000K	18,000K	25,000K	47,000K	60,000K

[1] S_e, Daylight-Outside-Atmosphere (Abbot, 1923).
[2] S_b, $(C/\lambda^4)\ S_e$.
[3] Data are from 1939 K. S. Gibson tables to D. N.

the spectral energy of daylight as can be obtained by use of a glass filter. In this country this filter is used in many instruments, and when the source-filter color temperature matches that of *C*, often it is identified as if it were equivalent to *C*. Used in varying thicknesses this glass can provide a series of colors that vary all the way from the color of the unfiltered light source to that of light of limit-blue-sky. In large size, this same filter is used in lamps to provide a standard source for making color observations.

One of the first questions before your subcommittee* on Color Rendition[8] was what source should be used as a standard against which to check the color rendition of the test source. Three one-dimensional series of sources were considered:

A. The sources defined by the Planck radiation law,
B. Series A to 3000K, and for higher correlated color temperatures an incandescent lamp at 3000K with filters of Corning Daylite glass,
C. Series A to 6000K, and the Abbot-Gibson series from 6000K to limit-blue-sky.

Only one of these was possible for use in practical tests, therefore it was decided that series B would be used in validation, and series C for a formal standard. The very necessity for this division into

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*Subcommittee on Color Rendition, IES Light Sources Committee. Members, past and present: A. C. Barr, E. W. Beggs, C. N. Clark, C. W. Jerome, D. B. Judd, Norman Macbeth, Dorothy Nickerson, Ch., C. R. Stilwell, C. E. Swanson, Luke Thorington, A. W. Weeks; Advisors: R. M. Evans, Günter Wyszecki. The scope is to establish a method of measuring and specifying the color rendition properties of light sources, with priority given to fluorescent lamps.

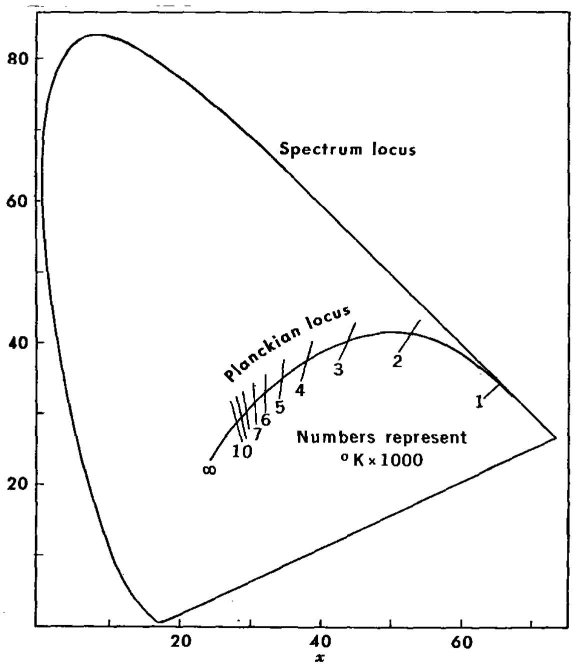

Figure 3. CIE chromaticity diagram in its most widely used (x, y)-form.

a practical and a formal standard indicates how very real the problem of a standard is. But it is the best we can do for the moment.

How Shall Colorimetric Results Be Expressed?

In colorimetry three things are necessary to specify the color of an object: a light source, an object to reflect or transmit the light from that source, and an observer to see it. Since 1931 a considerable amount of careful colorimetric data, much of it based on spectrophotometric measurements, has been compiled in terms that are similar all over the world, wherever modern colorimetry is practiced. This is possible because of the adoption by the CIE of specifications for a standard observer for colorimetry as well as for standard light sources. So often are these two of the necessary three variables kept constant in practice that it has been possible to assemble sufficient data to make great progress not only in specifying color but in correlating the differences in specifications with the size of the color difference they represent.

Tables of data defining the CIE Standard Observer and CIE Standard Light Sources *A, B,* and *C* will be found in the *IES Lighting Handbook* together with an example that illustrates the mechanics of computing the color of a particular sample. For more details see chapters on Psychophysics of Color and Quantitative Data and Methods for Colorimetry in reference 3. Refer also to a paper on this program by Judd.[9]

A CIE color specification consists of three numbers, either the tristimulus values X, Y, and Z that are required to establish a match with the sample color; or the tristimulus value, Y, which is a measuse of luminance, and x, y, two of the three chromaticity coordinates (ratios of the X, Y, Z numbers to their total) that by custom are used as coordinates for the form of the CIE chromaticity diagram illustrated in Fig. 3, the form with which we are most familiar. One very useful fact about this diagram is that additive mixtures of any two colors lie along the straight line connecting the two end colors.

The spectrum locus, the Planckian locus, in fact the locus of any light source is fixed on this diagram. Kelly[10] has worked out a color-name designation for lights in which the name limits are expresed by lines drawn on such a diagram. These instances show a unique use for this diagram. It may be noted that they require only two variables, a light source and an observer. The question, "What is white?" becomes important, and for an anchor point, the color representing an equal energy spectrum is used. It plots at the center of the diagram, $x = 0.3333$, $y = 0.3333$, about 5500K.

The minute that an object enters the picture, a choice of a single light source must be made in order for the color of that object to be specified and plotted on the diagram. In this country it is usual for the CIE specification of object colors to refer to colors perceived by the "standard observer" in "average daylight."

Thus the point representing CIE Source *C* becomes the color center of the diagram, the center to which the colors of all objects seen under that light source are related. A great deal of work has been done for the diagram in which *C* is the center that is not available for diagrams in which other sources are the focal point. There is a psychological concept of equally perceptible differences of object colors in which color differences may equal each other regardless of source. This makes it possible to develop scales of hue, lightness, and saturation such as has been done in developing the concept of the Munsell scales of hue, value, and chroma. A distinction should be made between the concept and its representation, for when the concept is illustrated by samples, the samples must be made for a single set of conditions. When Munsell papers were made to represent these scales, the work was done in daylight.

One of the aims of the extensive studies on the spacing of the Munsell system[11] by a subcommittee of the Optical Society of America was to express in terms of the CIE notation for Source *C* enough surface colors corresponding to their recommendations to define the system adequately. This means that the observations were made in daylight, or under a light source intended to be an equivalent to daylight, and that the results were specified in relation to Source *C*. The loci for constant Munsell hue and chroma for Source *C* are illustrated in Fig. 4 on a CIE chromaticity diagram. Hue and chroma loci for other values show a regular displacement, value by value, for hue and chroma. Thus two important facts become clear: even for daylight conditions and equal luminance, equal distances on the *(x, y)*-diagram do not correspond to colors perceived as equally different, and, for colors that vary in lightness, the same point on the diagram can represent colors that may differ considerably from each other both in hue and in saturation.

The first fact, while it is not always kept in mind, is widely known. For years there has been a search by various workers to find some sort of diagram that would represent more uniform spacing. In a 1947 paper[12] the writer assembled 15 different diagrams in this field, from Judd's first UCS diagram (1935), and covering work by MacAdam, Breckenridge and Schaub, Farnsworth, Scofield-Judd-Hunter, Adams, Moon and Spencer, Saunderson and Milner. There have been others since.[13]

The second fact has not had the attention it deserves, although as a practical matter it is just as important. The most important work that has taken into consideration this change in chromaticness (hue and chroma) for a constant point on the chromaticity diagram (constant dominant wavelength and purity) with change in lightness (or *Y* value), is that of Hunter in his *(a, b)*-diagram and that of Adams in his Chromatic-Value Diagram. The diagram that comes closest to converting CIE data regardless of the value of *Y*, to constant chromaticness is one reported by Nickerson, Judd, and Wyszecki[14] in 1955. This diagram indicates that it is possible to make a close approximation to conversion of CIE data to constant chromaticness as well as to constant chromaticity, but the method is not yet simple enough for practical use, nor is the hue spacing as good as we would like.

While all of this work goes on to find a uniform color space, the *(x, y)*-diagram is still most used. Used with a series of diagrams similar to the one in Fig. 4, but for a range of value levels from dark to light, or used with data based on the MacAdam ellipses of constant size of color difference, it is possible to develop a great deal of information regarding the size of color differences. For daylight conditions we do not yet have all the answers (even now a committee of the Optical Society of America is working on a long-term project regarding uniform color spacing), but we do have enough to make work in colorimetry practical and useful. Munsell notations, directly obtained or converted from CIE specifications, provide a simple and practical method of working with uniform color scales.

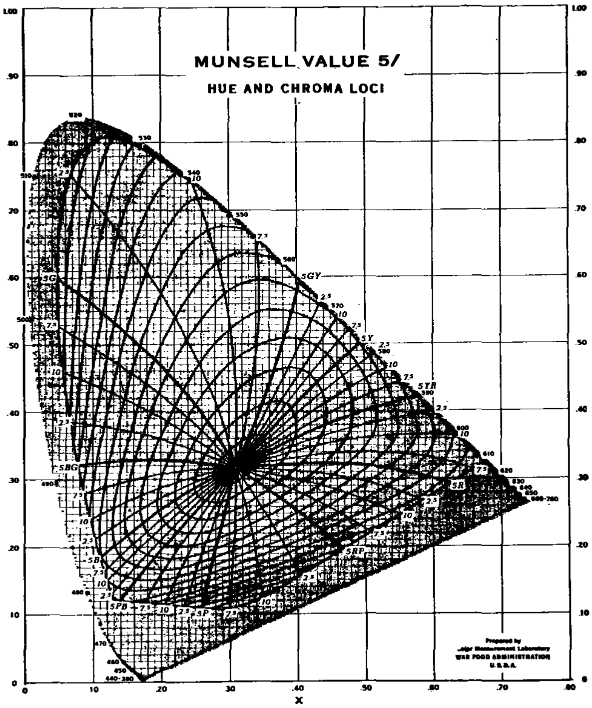

Figure 4. Loci of Munsell constant-hue and constant-chroma for value 5/ in CIE (x, y)-coordinates for Source *C*.

If our color rendition problems could all concern the appearance of samples under light sources that differ in spectral distribution but are all a match in color for Source *C*, we might be able to solve them in a reasonably straightforward manner. For Source *C* we have a Munsell network worked out, so that a method is available for obtaining color specifications for the appearance of a sample under any number of light sources, just so long as they have the color of *C*. No problem of adaptation to the color of the light source would be involved since the adaptation would be the same for each source. There would, of course, be the problem of adaptation to any change in background color, but for the moment let us assume that this is neutral and held constant.

An example will serve to illustrate what is meant. For several years a subcommittee of this society has been working on the problem of color rendition of light sources, and as test objects they have included 18 Munsell 6/ value papers selected by Barr, Clark, and Hessler[15] for studies reported in 1952. Among

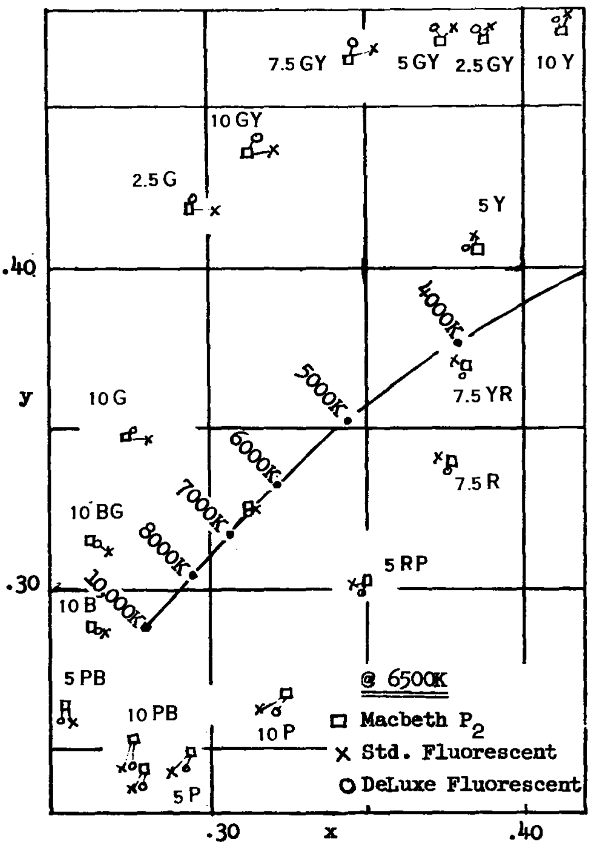

Figure 5. Color rendition of light sources: 18 Munsell samples for three light sources that are the same daylight color (6500K). This illustrates the color difference in samples caused by a difference in spectral distribution of light source.

the light sources used in the subcommittee's tests are three that are color matched in the daylight range. The spectral reflectances of the 18 samples were used to compute chromaticity coordinates according to the CIE Standard Observer for the spectroradiometric distributions of each of the three test sources. The light sources used were an incandescent lamp with Macbeth P_2 filter (Corning No. 5900), a standard fluorescent lamp, and a deluxe fluorescent lamp, all specially made to color-match at 6500K. The results are plotted on a CIE (x, y)-diagram in Fig. 5.

Since the samples are the same, and the color of the light sources is the same, the differences in color are due to differences in the spectroradiometric curves of the three light sources. The points representing the color of the light sources fall close to the Planckian locus between the points marked 6000K and 7000K. For purposes of illustration let us assume they are a close match for Source C so that we can read off the Munsell notations from the standard diagram for 6/ value (similar to the 5/ value diagram illustrated in Fig. 4). (Actually the 6500K light sources are slightly yellower than C, about 0.25 chroma steps on the C diagram, so that the notations will not be as accurate as if the three light sources were precisely at the C point.)

The resulting color differences are listed in Table II in terms of hue, value, and chroma differences, ΔE_N (a number representing the total color difference),[16] and an arbitrary number representing the distance on the (x, y)-diagram between the point

TABLE II — Color Differences Between Color Rendition of 18 Samples Under a Standard Lamp (Incandescent-Plus-Macbeth P_2 Filter) and Under Two Fluorescent Lamps, Deluxe and Standard, All Three Lamps Color-Matched at 6500K.

Color Sample Munsell Notation	No.	ΔHue Deluxe	ΔHue Std.	ΔValue Deluxe	ΔValue Std.	ΔChroma Deluxe	ΔChroma Std.	ΔE_N Deluxe	ΔE_N Std.	(x, y)-distance Deluxe	(x, y)-distance Std.
5 Y 6/4	1	+0.5	+1.0	0	0	0	+0.1	0.9	2.1	15	35
10 Y 6/6	2	+0.5	+0.5	0	+0.1	+0.1	+0.2	1.8	2.7	30	40
2.5 GY 6/6	3	+0.5	0	+0.1	+0.1	+0.1	+0.2	2.3	1.2	30	40
5 GY 6/8	4	+0.3	−0.2	0	0	+0.2	+0.2	1.4	1.2	40	45
7.5 GY 6/6	5	0	−0.5	0	0	+0.2	0	0.6	1.5	40	60
10 GY 6/6	6	−0.3	−0.9	0	0	+0.2	−0.2	1.4	3.1	45	65
2.5 G 6/6	7	−0.3	−1.2	0	−0.1	+0.1	−0.6	1.1	5.8	20	70
10 G 6/4	8	−0.6	−0.9	0	0	0	−0.5	1.0	2.9	20	55
10 BG 6/4	9	0	+1.0	0	−0.1	−0.1	−0.4	0.3	3.2	15	45
10 B 6/4	10	+0.5	+1.5	0	0	−0.1	−0.4	1.0	2.7	10	35
5 PB 6/8	11	+1.0	+1.5	0	0	−0.2	+0.2	2.8	3.9	30	40
10 PB 6/8	12	+0.5	0	0	0	+0.9	+1.0	4.0	3.0	55	65
2.5 P 6/8	13	0	−0.5	0	0	+0.5	+0.5	1.5	3.1	40	50
5 P 6/8	14	−0.3	−1.0	0	0	+0.5	+0.5	2.4	4.5	40	60
10 P 6/8	15	−0.5	−0.5	0	−0.1	+0.4	0	2.6	4.8	40	75
5 RP 6/6	16	−1.0	−1.0	0	−0.1	+0.1	−0.3	2.3	3.5	25	35
7.5 R 6/4	17	−0.5	+2.0	0	0	0	−0.4	0.8	4.4	15	35
7.5 YR 6/4	18	−0.5	+1.5	0	0	0	−0.1	0.7	2.4	15	25
Avg Diff.		0.4	0.9	0.0	0.0[3]	0.2	0.3	1.6	3.1	29	48

[1] ΔE_N = 1936 Nickerson "Index of Fading" = $(C/5)(2\Delta H) + 6\Delta V + 3\Delta C$.
This is a single number measure for color difference that is based on equivalence (for average viewing conditions) of 3 hue steps (at /5 chroma) to 1 value step, to 2 chroma steps. For special conditions the weighting for value may be varied.

[2] Arbitrary units.

representing each sample under the standard lamp and the points under the deluxe and standard fluorescent lamp. While the color differences are small (because at this high color temperature the spectral differences between the lamps are at a minimum), it is clear that the average color rendition of these samples for the deluxe fluorescent lamp is closer to that of the standard (incandescent-plus-filter) lamp than is the average color rendition under the standard fluorescent lamp. This is true whether we compare the hue, value, or chroma differences, the total differences, or the differences measured by distance on the (x, y)-diagram. If we had a diagram of truly uniform spacing, we should expect, if all necessary factors are taken into consideration, that the distances measured on it should correlate well with the perceived differences in chromaticness. Meanwhile, we use the Munsell notation, as read from the diagrams, to give us the best and most practical approximation we know how to get.

What can be done when light sources are not the color of daylight?

For the same 18 samples your subcommittee has worked with two other groups of light sources, each containing three lamps. One group was color-matched at 3000K, and the other at 4500K. In each group there is a standard lamp (incandescent for 3000K, filtered-incandescent for 4500K) and two fluorescent lamps, standard and deluxe. Computations and observations have been made for all conditions. Relative energy curves for the three groups of light sources are shown in Fig. 6. (This paper is not intended as a report of this work, but as a means of clarifying for others interested in problems of color rendition some of the problems that face the subcommittee.)

If we were able to transfer the Munsell network for Source C to the standard sources at 3000K and at 4500K so that it would provide the same spacing of colors that we have in daylight, we could then read off the colors in terms of their daylight appearance, and compare the color rendition of samples under one light source with that under another. This includes the problem of adaptation. But we have no way of doing this yet. The work of Helson[17, 18] and Burnham[19, 20] and their co-workers is providing a beginning toward this, but unfortunately it still looks as if we are a long way from being able to transfer the Munsell network to light sources of other chromaticities.

How then is it possible to put together the data for these different levels of color so that the internal results for each set may be compared with the internal results for the others? The matter is put this way in order still to avoid the problem of adaptation, a problem that must be faced when results are compared under light sources that differ in chromaticity.

Colorimetric results for the 18 samples, under

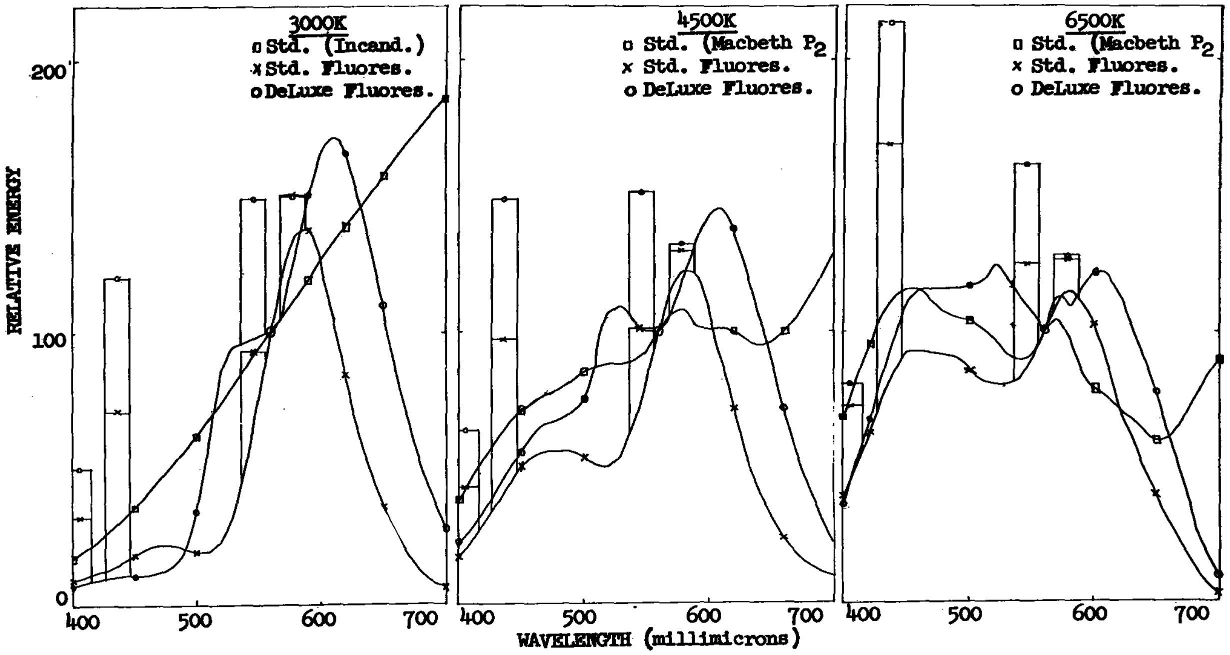

Figure 6. Relative spectral energy curves, adjusted to 100 at 560 mμ, for triads of lamps at 3000K, 4500K, and 6500K. In each group the squares refer to the standard lamp, crosses to standard fluorescent lamps; open circles to deluxe lamps.

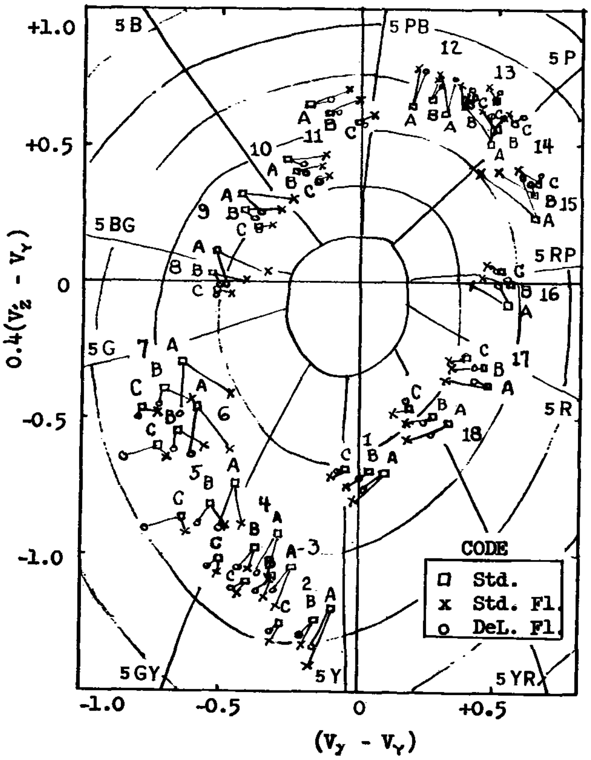

Figure 7. 18 Munsell samples, each calculated for 3 triads of light sources. These are plotted against a Munsell renotation network of hue and chroma on the Adams' Chromatic-Value Diagram to illustrate the relative size and direction of color change caused by change in light source. Code: Group A, at 3000K; Group B, at 4500K; Group C, at 6500K.

three triads of light sources, have been computed and plotted on as many types of diagrams as seemed promising. The only one on which all of the data could be assembled at one time so that some sort of comparison could be made between the results for each group, is the Adams' Chromatic-Value Diagram. All of these data are shown in Fig. 7, a Munsell Renotation Diagram for 6/ (the value of the samples used as test objects), superimposed on the Adams' diagram. From the data on this diagram it is evident that the color differences under the group of lamps at 3000K are much larger than those under 4500K, and that these in turn are larger than those under 6500K. The relative amount, and the direction of change within groups can be compared for similarities and differences. We have no way at present of knowing how the groups should be displaced to account for adaptation to the several light sources, although a correction for adaptation is made by the very use of the vonKries type of transformation that places the light source always at (0, 0) on the Adams' diagram. While it does not agree with all the facts that eventually must be taken into consideration, nevertheless for computing *differences* we can make use of the Munsell network on this Adams diagram and read off the notations and calculate them in terms of ΔE_N. This has been done for the group of lamps at each color level. The results, shown in Table III, provide a preliminary sort of color rendition rating for the several light sources by the size of the average color difference for the 18 samples seen under them. (The Source *C* data for ΔE_N in Table III differ from the data for ΔE_N in Table II because there is a difference in the standard lamp to which each is compared.)

TABLE III — Color Difference (ΔE_N) on 18 Samples.

Color Sample		ΔE_N between					
		3000K Std vs		4500K Std vs		6500K Std vs	
		Fluorescent					
Munsell Notation	No.	Deluxe	Std.	Deluxe	Std.	Deluxe	Std.
5 Y 6/4	1	4.0	6.7	1.8	4.4	2.3	4.3
10 Y 6/6	2	7.4	8.8	3.3	4.5	2.4	3.3
2.5 GY 6/6	3	5.9	4.9	3.1	2.1	4.0	2.9
5 GY 6/8	4	4.7	5.0	2.4	3.6	2.3	0.9
7.5 GY 6/6	5	6.1	7.8	2.1	3.3	3.0	3.1
10 GY 6/6	6	6.9	8.9	3.6	6.0	4.6	2.9
2.5 G 6/6	7	6.6	11.8	3.0	5.4	1.9	3.1
10 G 6/4	8	10.4	10.0	3.5	4.8	0.8	2.0
10 BG 6/4	9	3.7	11.6	3.1	7.7	1.1	3.6
10 B 6/4	10	4.5	10.0	2.3	6.3	0.3	1.8
5 PB 6/8	11	4.6	9.0	1.4	6.9	1.3	3.4
10 PB 6/8	12	5.1	6.4	3.0	3.0	2.2	0.9
2.5 P 6/8	13	9.3	9.9	2.1	6.0	2.6	4.3
5 P 6/8	14	10.0	15.9	3.9	9.6	0.6	5.2
10 P 6/8	15	14.6	22.8	4.2	12.5	2.1	6.4
5 RP 6/6	16	7.4	11.2	0.6	4.1	1.2	3.3
7.5 R 6/4	17	3.2	11.0	2.9	8.0	0	0
7.5 YR 6/4	18	3.7	8.9	1.8	6.4	0.6	1.1
Average		6.6	10.0	2.8	5.8	1.9	3.0

This suggested use of the Adams' diagram is not intended as a final proposal, but it does point the way to the sort of thing that it should be possible some day to do with accuracy and with precision. Some way must be found to pull all the data together, preferably to show their relation to the separate factors of Munsell hue, value, and chroma, as well as to the size of the total color difference.

The Adams' diagram, for those who are not familiar with it, requires the use of CIE data for *X, Y, Z*. After adjustment so that $X = Y = Z$ for the light source (essentially an adjustment for adaptation), the data are then converted to V_x, V_y, V_z by use of the Munsell value scale. $(V_x - V_y)$ is plotted against $0.4(V_z - V_y)$. Since *Y* carries all of the luminance, after its subtraction from the *X* and *Z* factors only the chromatic factors are left, and they are plotted against each other, the neutral series at the center (0, 0), reds in the direction of $+(V_x - V_y)$, greens in the $-$ direction, purple-blues in the direction of $+(V_z - V_y)$, and yellows in the $-$ direction. The calculations are simple to make, they require use of a table of the Munsell Value function and *X, Y, Z* data for the samples.

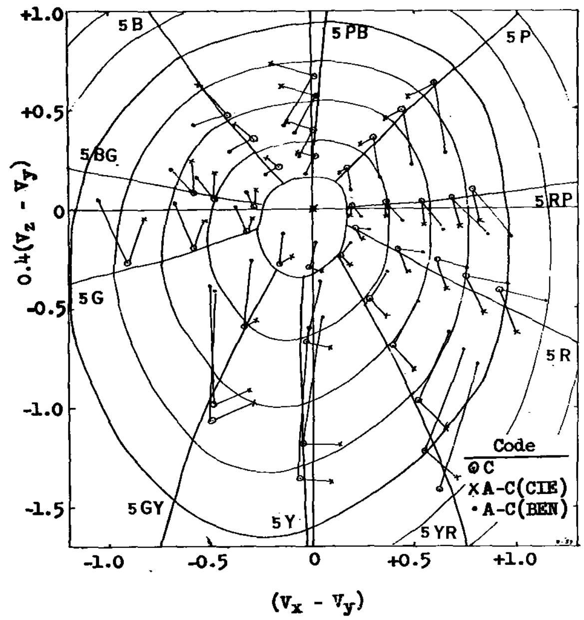

Figure 8. A series of Munsell samples (10 hues on 6/ value) as they plot on the Adams' diagram for Source *C* (circles), the same samples for Source *A* (crosses), and as calculated by the Judd prediction formula based on the Burnham data (solid points) for equal-appearing colors for Source *C* adaptation based on measurements for Source *A*. This illustrates, after conversion to the Adams' diagram, the size and direction of the color changes predicted by the Burnham studies versus those predicted on a basis of CIE primaries.

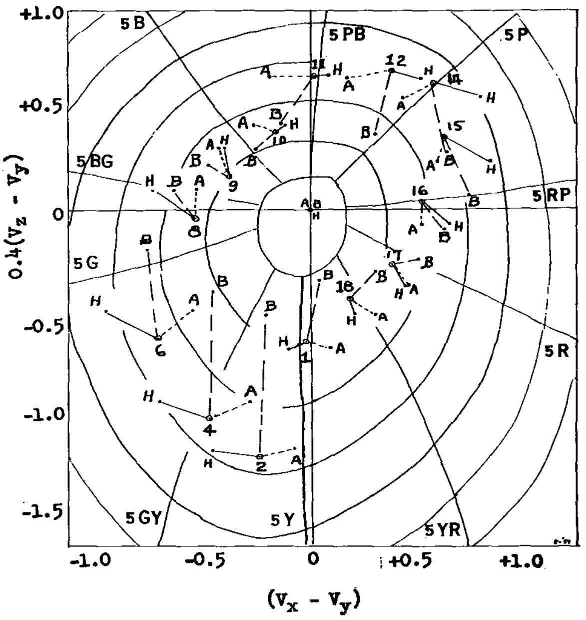

Figure 9. The effect of chromatic adaptation under Source *A* that is predicted in terms of Source *C* by formulas based on three sets of primaries, numbered 1 to 3 in the text, is shown on an Adams' Chromatic-Value Diagram: A (CIE) refers to (1), H (Helson) to (2), and B (Burnham) to (3). Circled points represent the *C* color of each sample; Munsell notations for the sample numbers are listed in Table II; N 6/ is at the center by all three formulas.

This same diagram allows one to study the Helson and Burnham results. In fact, it is possible in paired diagrams to plot the calculated and the observed data, and then compare them to see the extent of the differences between the two methods. This has been done for the Helson data since CIE data already were available[21] for the samples and light sources used in his most recent study.[18] Unfortunately, the scatter of the observations is so great that it is hard to find the pattern, but the data serve for reference involving other observational data. The Burnham results, by use of the prediction formula reported[20] for equal-appearing color with adaptation to Source *C* when the Source *A* color is known, were worked out for the basic series of 420 Munsell samples. However, the illuminants used in the Burnham-Evans-Newhall work were not precisely *A* and *C*, in fact Burnham's approximation to *C* was different enough so that N 6/, instead of reading 0 chroma as it does under CIE$_C$, read almost /2 chroma. Since Judd had worked out some months ago reversible formulas based on the Burnham-Evans-Newhall data that could be applied to light sources other than the precise ones used in making the observations, this Judd *A*-to-*C* formula was applied to Munsell 6 value samples. The results for this formula and for the CIE *A* to *C* conversion are shown in Figure 8, with lines connecting each of the results to the *C* color for each sample.

The communication in which Dr. Judd supplied the formula used for the foregoing conversion also provided similar formulas for two additional sets of primaries, making three in all:

(1) CIE primaries (used in the Adams' chromatic value space).

(2) Judd-Wyszecki primaries (which fit the Helson data and some of the MacAdam[22] data on chromatic adaptation).

(3) Brewer primaries (which fit the Burnham, Evans, Newhall data on chromatic adaptation).

Primaries	From *A* to C	From C to *A*
(1)	$X'=0.892X$ $Y'=1.000Y$ $Z'=3.321Z$	$X'=1.121X$ $Y'=1.000Y$ $Z'=0.301Z$
(2)	$X'=1.155X-0.457Y+0.476Z$ $Y'=1.000Y$ $Z'=3.321Z$	$X'=0.866X+0.396Y-0.124Z$ $Y'=1.000Y$ $Z'=0.301Z$
(3)	$X'=1.092X-0.272Y+0.149Z$ $Y'=1.000Y$ $Z'=-0.284X+0.839Y+1.835Z$	$X'=0.896X+0.306Y-0.073Z$ $Y'=1.000Y$ $Z'=0.139X-0.410Y+0.534Z$

Since these three formulas cover much of the work for which there is any considerable systematic body of observational data, all three have been applied to converting CIE *A* data to terms of *C* for 14 of the samples used in the subcommittee work, plus N 6/. The results indicate the effect of chromatic adaptation under CIE Source *A* compared to CIE Source *C* that is predicted on the basis of the three sets of primaries named. In Figure 9 lines connect to the *C* point for each sample, the points that represent the color of each sample under *A*. These lines represent predicted color shifts.

As can be seen, there seems to be considerable difference in the predictions, depending upon the primaries used, the choice of primaries perhaps depending in turn on the conditions of the experiment. These predicted color shifts are much larger than the color distortions shown in Figure 7 where they are due to changes caused only by spectral differences among commonly used light sources. We know that adaptation results in a shift in the color of many objects, and while we know from a study of this last figure that the formulas here seem to provide results that differ considerably, they do make us hopeful that before too long we shall be able to find a formula that for specified background conditions will predict correctly the daylight color of objects that we see in our living rooms at night under incandescent light. Once a formula will provide this, then ways can be worked out to apply it to illuminants other than *A* and *C*. At present, we still do not know just what formula to use in order to calculate the daylight color of objects seen under tungsten — or other — light sources.

What Is Needed?

Eventually we must have a network representing uniform spacing that can be applied to whatever light source is of interest, one in which the relation between calculated and observed data is satisfactory for standardized conditions. We need a designation (such as the CIE) that can be calculated from measured data, and a designation (such as the Munsell) that will represent the appearance of a color, with some method by which these two can be converted from one to the other for any light source, sample, observer, and background.

As a practical matter we need to have computations for the basic Munsell series for whatever light sources are of most current interest, and we need to have these based on careful spectroradiometric measurements that will represent the average of lamps that are, or can be made available for observation. The eye sees very small differences, and is very critical. It is therefore important that observations and calculations be based on the same conditions, not just *nearly* the same. More work of the sort being done by Helson and Burnham is needed, not isolated studies, but studies precise and well planned, with all of the basic data and materials easily available for others to use (as has been the case with these workers). On the basis of such observations a Judd or a Brewer may find for us equations that will apply to the general, as well as the specific situation.

To date, while we may know the basic principles involved, and have data for a few conditions, we do not have sufficient data to solve the very practical problem of the illuminating engineer — the prediction of color appearance when one walks into a room and becomes well adapted to any one of the present-day light sources that differs from daylight. To solve this problem of the illuminating engineer, colorimetry enters a new phase, one in which the light source replaces the object as the important variable.

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DISCUSSION

C. N. Clark:* Congratulations to Miss Nickerson for an excellent, highly readable and comprehensive paper. As indicated in the first part, choice of a standard source presents many problems. In general, standard sources appear to be chosen primarily so as to provide familiar color rendition, by being spectrally similar to commonly used natural or artificial sources, but with compromises as necessary for practical use in test work. Thus, it is logical to accept as formal standards Planckian radiators to 6000 K, and Abbot-Gibson daylight at higher color temperatures.

There are two drawbacks to these standards, as well as the series B standards mentioned in the paper:

(1) They cannot be made to match test source chromaticities that differ very much from the Planckian locus (such as mercury lamps or soft white fluorescent lamps).

(2) Their energy curves are "bumpy" in the higher color temperature range. Thus a test source with a smooth energy curve (logically a better color rendering source than the "bumpy" standard) would, by most rating systems, be unfairly penalized because it differed from the standard source. This difficulty stems from the fact that the standard source may not be the "best possible" or "ideal" source for color rendering. Of course, there are various opinions of what the ideal source might be, and of the criteria for selecting or defining such a source.

It is difficult to evaluate how serious these two drawbacks may be. Quite possibly they are not significant for today's practical sources. However, there may be a way to find the ideal source for use as a formal standard. Actually, it would be a *series* of ideal sources, one for each possible test source chromaticity in the white area, *on or off* the Planckian locus. It might be determined thus:

First, assume that there is such an ideal source at each chromaticity point (and thus for each possible state of color adaptation, assuming that the observer always adapts to the source color).

Second, assume that each ideal source should provide maximum perceived color separation (maximum color contrast) of a wide gamut of colors lighted by it.

Third, at each of a variety of source chromaticities, find the spectral energy distribution that yields maximum perceived color separation of a set of appropriately selected test object colors. This might be done by using a high speed data processing machine. The procedure would be to systematically vary the energy distribution of sources of constant chromaticity; calculate and average the color shifts of the test colors on a perceptually uniform (or nearly so) scale; and then pick, as the ideal source at that chromaticity, the energy distribution that gives maximum average contrast among the test colors.

Fourth, having done this for a variety of source chromaticities, derive a formula for ideal source spectral energy distribution at any chromaticity, as a function of chromaticity.

I have no idea what such "ideal" source curves may look like. At first thought, they may be similar to Planckian radiators. At any rate, such "ideal source" data, if possible to derive, could give us a better insight into the overall optimum source for seeing colors and color differences in general (that is, the source, regardless of chromaticity, that provides maximum object color separation, for an observer adapted to it), and a better baseline from which to measure the color rendition of practical sources.

The lack of a definite, proven "ideal source" is probably not too serious at this stage of the development of color rendition specification. Certainly, as Miss Nickerson has well stated, the need for continued work toward finding ways of expressing color appearance and color shift as they are perceived in the consciousness of a human observer, rather than in purely objective psychophysical terms, is of greatest importance.

D. B. Judd:* The author is to be congratulated for a clear presentation of the factors that have to be considered in the development of a method for specifying the color-rendition properties of a light source. Considering its brevity the treatment is remarkably exhaustive, and the treatment is made concrete with little additional space by including the results of computations plotted on the Adams chromatic-value diagram (Figs. 7 and 8). Note that Fig. 7 shows the computed chromaticities of all 18 Munsell samples for each of the 9 sources studied. The author points out that the chromaticity differences computed for any given sample caused by changing from one source to another of the same chromaticity (such as from standard warm-white to de luxe warm-white), are correctly shown on this plot, and properly warns us that any interpretation of differences from one group of sources to another would be unwarranted because "we have no way of knowing how the groups should be displaced to account for adaptation to the several light sources." It may be worth while to point out that the "v. Kries type of transformation" built into the Adams chromatic-value diagram is almost certainly wrong because the primaries of the transformation (those of the CIE system) are far outside the range of permissible primaries found by recent studies of chromatic adaptation by Helson,[18] Burnham,[19,20] and MacAdam.[22] These three studies do not agree well, and MacAdam's work, in particular, suggests that no single v. Kries type of transformation, regardless of choice of primaries, can accord precisely with the facts; but the coordinate systems supported by any of these recent studies afford a closer approximation than that yielded by the Adams chromatic-value diagram. The use of this diagram in Fig. 8 with the network of constant Munsell hue lines and constant Munsell chroma lines is still very helpful as long as it is realized that the crosses representing computations for Source *A* are already adjusted to take approximate account of adaptation. Thus if the tri-stimulus values, X_a, Y_a, Z_a, are found by computation for a sample illuminated by Source *A*, the very first step in computing chromatic values, V_x, V_y, V_x, is to find the ratios:

$$X_a/(X_a)_{\mathrm{MgO}},\quad Y_a/(Y_a)_{\mathrm{MgO}},\quad Z_a/(Z_a)_{\mathrm{MgO}}$$

and it is obvious that these ratios will all be unity if the sample is the magnesium-oxide reflectance standard. This accords with the experimental fact that a white surface like MgO, illuminated by a nondaylight source still is judged because of adaptation to appear approximately white. The use of these ratios is a "v. Kries type of transformation" spoken of by the author; but, since the primaries referred to (the CIE primaries) are known to be inapplicable, in general, for an account of the facts of chromatic adaptation, the points (shown as crosses in Fig. 8) give an increasingly poorer approximation to the facts as the chroma of the sample departs more and more from zero. Compare the points (shown as dots on Fig. 8), located by the Burnham prediction formula with the crosses for each sample in turn. Note that the distance between each two such points increases regularly with chroma. The dots give a more reliable indication of the influence of adaptation to source

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

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

TABLE A — Color distortions introduced by the Deluxe daylight fluorescent lamp relative to those introduced by the Standard daylight fluorescent lamp.

Munsell Notation of Color Sample	$\frac{100\,\Delta E_N \text{ (Deluxe)}}{\Delta E_N \text{ (Standard)}}$	$\frac{100\,D \text{ (Deluxe)}}{D \text{ (Standard)}}$
5 Y 6/4	43	43
10 Y 6/6	67	75
2.5 GY 6/6	192	75
5 GY 6/8	117	89
7.5 GY 6/6	40	67
10 GY 6/6	21	69
2.5 G 6/6	19	29
10 G 6/4	24	36
10 BG 6/4	9	33
10 B 6/4	37	29
5 PB 6/8	72	75
10 PB 6/8	133	85
2.5 P 6/8	48	80
5 P 6/8	53	67
10 P 6/8	54	53
5 RP 6/6	66	71
7.5 R 6/4	18	43
7.5 YR 6/4	29	60
Average	52	60

A than the crosses because they are founded upon actual experiment; the crosses are founded only upon the Adams theory of vision[23] whose latest form[24] carries implications regarding chromatic adaptation not supported by any of the presently available, rather widely divergent, sets of experimental data. Compare in Fig. 9 the A-vectors (CIE primaries) with the H- and B-vectors.

I have another comment relating to the simpler, and commercially more urgent, problem of specifying the color rendition of sources relative to a standard of the same chromaticity. This problem is simpler because no general chromatic adaptation is involved, and my comment relative to the number of test samples to be used in the specification and also to the desired color-rendition rating "whether one- or multi-numbered." Although she does not say so explicitly, the author has developed a logical basis for such a rating. This basis is the color distortion introduced by substituting the source to be rated for the standard against which it is rated; see the last four columns of Table II. The first pair of columns (headed ΔE_N) is a thoroughly defensible evaluation of color distortion; the latter pair of columns (headed (x,y)-distance) is a less defensible evaluation chiefly because distance on the (x,y)-diagram in a given region varies importantly in perceptual significance depending on direction. A second defect, minor for this group of test samples, is that (x,y)-distance is a measure simply of the chromatic aspect of the color distortion and neglects the lightness aspect of the distortion. The first row of entries in these four columns indicates that the color distortion, ΔE_N, introduced by the deluxe daylight fluorescent lamp is only $100 \times 0.9/2.1 = 43$ per cent of that introduced by the Standard daylight fluorescent lamp; and the chromatic distortion indicated by (x,y)-distance is likewise $100 \times 15/35 = 43$ per cent. The relative distortion (deluxe to standard) computed this way for all 18 test samples, is given in Table A.

If the 18 test samples used are accepted as a suitable choice for rating fluorescent lamps, either method of rating indicates that this particular deluxe daylight fluorescent lamp causes about half as much color distortion as this particular standard daylight fluorescent lamp. The approximate evaluation of color distortion by means of (x,y)-distance wrongly indicates that the deluxe rendition of each test sample is less distorted than that by the standard fluorescent lamp, but the precise evaluation of color distortion by means of the Nickerson formula indicates that for three of the test samples the deluxe rendition is poorer. The question raised is whether a rating based on the average distortion for a selection of test samples is sufficient for the lamp industry, or should the rating be multi-numbered so as to include the distortions introduced by the lamp for each of a number of individual test samples. Is it valuable to know that this particular deluxe lamp distorts colors in the green-yellow and the purple-blue range more than the standard fluorescent lamp? The subcommittee will have to come up with a good answer to this question.

References

23. Adams, E. Q.: "A Theory of Color Vision," *Psychol. Rev.*, 30, 56 (1923).

24. Adams, E. Q.: "*X-Z* planes in the 1931 ICI System of Colorimetry," *J. Opt. Soc. Amer.*, 32, 168 (1942).

GUNTER WYSZECKI:* Miss Nickerson's paper provides an excellent insight into the problems which are involved in the measurement and specification of color rendition properties of light sources. In particular, the paper shows very clearly the importance of the choice of reference lamps and discusses various methods of interpreting and subsequently measuring color rendition properties of light sources. The major problem, however, which makes a completely general solution difficult, turns out to be the effect of the chromatic adaptation of the eye. By changing from one light source to another of a different chromaticity, the state of chromatic adaptation of the eye is changing in a way which, so far, cannot be described adequately in quantitative terms.

The work of the IES Subcommittee on Color Rendition is mentioned and their present results are essentially included in the paper. It may, however, be of general interest to mention two other aspects of the color rendition problem not being discussed in the paper, although they are being considered by the subcommittee. One aspect is the psychological phenomenon, the color preference problem. It is known that, for example, the quality of food is often judged by its color and that good quality food does not necessarily have to show its natural color, but preferably a slightly different shade in order to appeal to the consumer. It is admitted that a quantitative consideration of color shifts with respect to color preference makes the specification of color rendition extremely difficult, but it is believed that in some practical cases this psychological factor may have an important bearing on the usefulness of a potential solution of the problem.

The second aspect is the choice of a reference sample which should be made when developing a specification method. The subcommittee so far is studying 18 Munsell paint samples providing an approximately uniform hue circuit at value 5/. Properly measured color shifts observed on those samples by going from one light source to another will essentially be used to derive a method to specify the color rendition properties of a light source with respect to a standard. The question remains whether these 18 Munsell paint samples are an adequate choice for most specification problems, since it is very likely that in general, other materials of different spectral characteristics will be illuminated by the light sources to be specified. It therefore is believed that the inclusion of reference colors which are metameric to the given set of colors with respect to the standard source and the standard observer will provide a more general solution of the problem.

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Charles W. Jerome:[*] Since I am a member of the committee whose work is described in this paper I can only corroborate the statements made by Miss Nickerson. I believe she has very lucidly described the crux of the problem and the many complexities which have been encountered in attempting to derive a solution.

I am glad that she can point out the considerable progress that has been made in this direction and can hold out hope that a workable solution will eventually be recommended.

Arthur M. Weeks:[**] This paper presents the progress which has been made by the various committees with which Miss Nickerson has been associated. I congratulate the author on this paper, but more specifically on the long list of contributions which she has made to the science of color measurement.

The question I ask may seem unfair, but certainly it is of general interest to all concerned with the measurement of color, and particularly, color rendition.

Is it possible at this time, to place any sort of time table which will indicate when we may expect a number system of designation of color rendition?

Dorothy Nickerson:[†] Let me reply first to Mr. Clark's comments, for they concern the first section of the paper, then to comments by Dr. Judd, Dr. Wyszecki, Mr. Jerome and Mr. Weeks.

Mr. Clark points out that while it is logical to accept the suggestion that as a standard we use Planckian radiators to 6000K and curves for Abbot-Gibson for higher color temperatures, he finds two drawbacks to these standards as well as to series **B**.

I believe there are two lines of thought involved here; one is that for usual work with color, when one expects to obtain good color rendition, a set of reasonably smooth curves seems needed to represent the range of whites from the low color temperature yellowish whites to higher color temperature bluish whites. In my opinion, such curves should follow the pattern of daylight not only in the range of the visible wavelength but out into the ultraviolet and infrared, as far as they may be expected to have any appreciable effect upon perceived colors. For example, the question of extending the curve for *C* illuminant into the ultraviolet already has been raised within CIE committee (W-1.3.1), as it has been also in the work of the Inter-Society Color Council's subcommitte on Problem 18 (colorimetry of fluorescent materials). I do not consider the Abbot-Gibson too "bumpy," certainly these curves must reach a maximum in the blue and then fall off in energy as they approach the ultraviolet if they are to follow the energy distribution of daylight. Eventually we hope to extend these curves into the ultraviolet so that the color of fluorescent samples assessed by means of these data will provide an answer that will agree with the color seen in an average daylight situation for the same samples.

The fact that the Abbot-Gibson series cannot be made to match all test source chromaticities does not seem a valid objection, for no one-dimensional series of smooth spectroradiometric curves can be expected to do this. If any single color or source is to be used as a standard for color rendition, then this would seem to be some sort of "average daylight." Abbot-Gibson at 7400K has been selected as a practical solution for this single standard. If a mercury lamp or a soft white fluorescent lamp is to be tested for color rendition, as Mr. Clark suggests, then the most simple test is to find out how much either lamp changes the "daylight color" of objects. If there should be a reason to test a lamp whose color lies off the Planckian locus to find out how different its color rendition is from a lamp of similar color, but one with a smooth continuous energy distribution, then a special curve could be set up for that particular situation.

The suggestion that there may be some one point in the range of whites, whether on or off the Planckian locus, that could by calculation be found to be an ideal source (by definition one that would provide a maximum separation of perceived colors for a wide gamut of color samples) is interesting, and I would like to see the answer. But if the specifications for such a source were found, and results under it differed from those under average daylight, then we would be faced with considerable confusion, both in practical color matching work now done in daylight and in current studies of uniform color spacing. To be practical such a light source would have to become so cheap and easy to use that it could compete with daylight as the most-used source for observing colors.

Meanwhile, for industries finding it necessary to specify lamps for use in color appraisal the data published here provide a useful standard. The 7400-7500K curve of Abbot-Gibson has been used since its development in 1940 as a standard to which the lighting of cotton classing rooms has been referred, and within the past year the graphic arts industry has made it a part of a new recommended lighting practice for their industry. (See I.E., September 1957.)

This subject of a standard concerns only one phase of the color rendition problem, but it is a very practical one for those who wish to adopt and use an artificial light source for their color appraisal work. Let us now turn to points raised on other phases of the color rendition work.

Dr. Judd's comments serve to amplify several points, and call attention to their importance. For example, few not familiar with the subject can realize what an important bridge was crossed in this color rendition work when a way was found to pull together in a single graph the results for many samples (spread over the hue circuit) each under as many as nine different illuminants. That is a lot of data, yet if a way is not found to pull it together so that the relative shifts can be seen at one time for a whole series of samples (eventually enough to provide good statistical representation for the most-used part of color space) under several different illuminants, then it will not be possible to understand the problem clearly. For committee work it is an absolute necessity that the data be presented in a way that the color relations may be clear to a group of busy men. As Dr. Judd points out, even now it is necessary to warn those who study these diagrams that we do not yet know how the data for results at different levels of illuminant color should be displaced in relation to each other. His discussion should be very helpful to those who want to get down to fundamentals on this.

In regard to Dr. Judd's next point, as my studies into this work have progressed, I am coming more and more to the point of view that already we have a simple way to find a single or a multi-numbered color rendition index, one that can be based on as many or as few samples as one wishes for any given situation.

Conversion of the color results, however they are first obtained, to an appearance specification in terms of Munsell hue, value or chroma will allow a study of the hue, value or chroma rendition properties of any lamp, and then on the basis of a suitable color difference formula, this could be

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expressed in terms of a single number to cover the overall or average color rendition properties of a light source. Table II illustrates how this is possible.

It should be pointed out that while the "average" or "single-number" result by any other method than one based on uniform color space may sometimes provide an overall figure that agrees with an average for data based on uniform spacing, such a method can be very misleading when it is broken down. Dr. Judd's Table A shows this clearly, for while the "single number" for average results based on the Munsell evaluation is 52, and not too different from 60, which is based on the visually non-uniform space represented by the CIE (x,y) diagram, yet the differences for individual samples vary widely. Dr. Judd raises the question whether a rating based on the average distortion is sufficient for the lamp industry, or should it be multi-numbered so as to include the distortions for any part of color space in which one may be interested. My answer is that if we use the type of method illustrated in Table II we can have both, for in order to obtain a "single number" one already would have the multi-number data.

I should like to point out that Japanese workers Azuma and Mori already have suggested that color rendition results be expressed in terms of Munsell hue, value and chroma differences. My suggestion takes this one step further, and suggests totaling results by use of a color-difference formula as has been done in Tables II and III. It is my considered suggestion that all formulas be developed so that the color of any sample under any or all illuminants can be computed or converted into terms of its "daylight color" (for the present this would be to CIE C), it would then be possible to obtain a Munsell specification for this equivalent "daylight color." Thus already we have at hand an adequate method for a single or a multi-numbered rating of color rendition. To avoid confusion, it might be well to plot these results directly on a Munsell hue-chroma diagram, making note in numbers of the value change. (This too, Dr. Azuma and his co-workers have already done.)

However, it is only *if* or *when*, adequate formulas are developed for predicting the equivalent color in daylight (or C) for colors seen under a given set of standard conditions for such other illuminants as we may be studying, that it will be possible to complete such work. We know how to do it but we still need appropriate information of the Helson and Burnham type of visual studies before we can proceed to wrap up this phase of the work.

The points covered by Dr. Wyszecki are important. He recognizes the lack of information that is mentioned above, and seems to feel less optimistic than the writer about its solution in a not-too-distant future. The preference aspects of color rendition he mentions should be relatively easy to handle if one works on the basis just described, for individual data could be made available for as few or as many samples as needed, and in terms of whatever color factors are important in a given problem. If butter is to be illuminated, then certainly a light source should be used in which the color will not shift toward the green. To be satisfactory, our color rendition specification method must apply to special, as well as to general, cases of color rendition. Perhaps it would help to define these terms (as we have for CIE W-1.3.2) as follows:

Color Rendition: Color rendition (color rendering property) of a light source is a measure of the degree to which the perceived colors of objects illuminated by the source conform to those of the same objects illuminated by a standard source, for specified viewing conditions. The usual conditions are that the observer shall have normal color vision and be adapted to the environment illuminated by each source in turn.

General Color Rendition: Same as color rendition.

Special Color Rendition: Same as color rendition, but restricted to a particular object (or a group of objects of which the particular object is an adequate representative).

To Dr. Wyszecki I would say that no magic is expected of the series of 18 samples being used by the I.E.S. Subcommittee on Color Rendition. They provide for reasonably good hue coverage, and were convenient as a starting point since Barr, Clark and Hessler already had used them in color rendition studies. Their limitation to a single reflectance level, an advantage at present, will have to be remedied for later studies. However, it should be pointed out that groceries, as well as papers, were used by the subcommittee in early tests, and were omitted later after it was found that the shifts recorded for them fell into line with those for the papers when the results were studied in hue order. Papers have the advantage that the same objects can be measured and observed. With groceries or complexions this is not always possible. To be adequate, any final proposal must take into consideration the shifts for colors found in all common situations, and at least some of those not so common.

I want to thank Mr. Jerome for his comments, and Mr. Weeks for his. As for the time table Mr. Weeks inquires about, I believe that the very organization and preparation of the material for this report and its discussion, plus the data requested by the IES subcommittee which is now being assembled for its next meeting, will be enough help in resolving questions about this work so that it should be possible to lay the matter clearly before the committee at its next meeting so that they may then be able to decide whether we should go ahead now on that part of the way we can see clearly, or whether we must wait until we can obtain sufficient information on which to go the whole way in providing a specification for color rendition.