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Complementary colors: Composition and efficiency in producing various whites[*]

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Various wavelengths are compared with complementary combinations of pairs of short and long wavelengths to determine their relative efficiencies for neutralizing unit power of the complementary color. For 14 whites defined by Planckian sources from 2000 K to infinite K color temperature and beyond, single wavelengths shorter or longer than a "primary-waveband" (e.g., 437.5–614 nm, for D_{65} white) are less efficient than combinations of short and long wavelengths. The "primary-waveband" varies according to the color temperature of the white. Equations are given to find "primary-waveband" intervals and limits in all whites from 2000 K to infinite K color temperature.

I. INTRODUCTION

Complementary efficiency of a color is the power, watts of radiant flux, required by the complementary color to neutralize 1 W of the first color.

A color composed of a pair of short and long wavelengths may be specified by its dominant or complementary wavelength. The suffix "*c*" may be used to denote any complementary wavelength, besides nonspectral hues, e.g., 700*c*.

The wavelengths at which the complementary efficiencies of spectral hues are less than the efficiencies of optimum combinations of short and long wavelengths, have never been determined. In fact, it is widely assumed that there are no specific limits to the visual relevance of wavelengths, because they can theoretically be made visible out to infinitely short and long wavelengths given sufficient power, watts.

One purpose of this paper is to determine the short and the long wavelength that has a complementary efficiency just equal to the maximum efficiency of an additive combination of a pair of wavelengths that has the same dominant wavelength.

II. METHOD

The data used were derived from the CIE 1931 observer for colorimetry.[1] To facilitate accurate determination of complementary wavelengths and proportions of compound components, at short wavelengths particularly, the chromaticity diagram was plotted to a large scale, 50 cm = 0.1*x* or *y*. The procedures and formulas employed to compute complementary efficiencies are basically those established by MacAdam.[2] To compute the complementary efficiency of color it is necessary first to establish the luminosity ratio *Y* of the color and its complementary color, thus,

$$\bar{y}/\bar{y}_c = Y \quad , \tag{1}$$

where $\bar{y}$, $\bar{y}_c$ are the values of the luminosity function of the wavelengths of the color and its complementary, respectively. Next, it is necessary to establish the luminance ratio *L*,

$$L = (y'/y)(y - y_n)/(y_n - y') \quad , \tag{2a}$$

$$L = (y'/y)(x - x_n)/(x_n - x') \quad , \tag{2b}$$

where *x*, *y* are the chromaticity coordinates of the color; x', y' are the coordinates of the complementary color;

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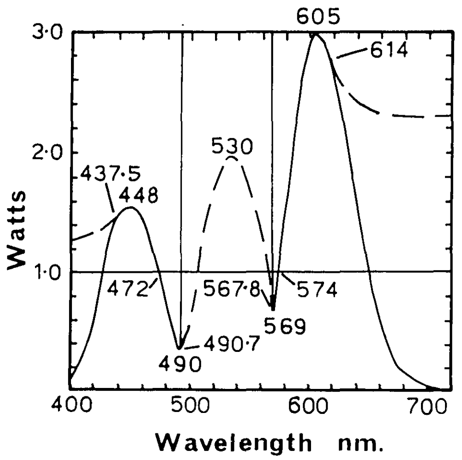

FIG. 1. Complementary efficiency for illuminant C.

and x_n, y_n represent the coordinates of the white, or neutral point. Equation (2b) should be used when the y coordinates of the complementaries are nearly equal, that is, when two complementary colors are in a line significantly less than 45° from the horizontal. For example, for whites that match illuminants C or D_{65}, Eq. (2b) should be used when either of the complementaries is between 485 and 496 nm. To find the complementary efficiency E in watts of radiant flux, the luminance ratio L is multiplied by the luminosity ratio Y,

$$E = YL \ . \qquad (3)$$

The complementary efficiency E of any color is the reciprocal of that of its complementary color.

To determine the complementary efficiency of compound colors, such as nonspectral colors, it is necessary to compute the efficiencies of the various pairs of short and long wavelengths that can form the compound color, in order to find the most efficient pair; the luminosity value of each component is adjusted by the proportion of that component in the compound chromaticity.

Extreme wavelengths beyond about 420 and 620 nm rarely form compound colors of optimum complementary efficiency.

III. COMPOSITION AND EFFICIENCY

Figures 1 and 2 indicate the complementary efficiencies of spectral and nonspectral hues for whites that match illuminants C and D_{65}, respectively. Figure 1 is adapted from MacAdam's paper[2]; only the dotted lines and related detail are added. The dotted line 490.7 – 567.8 indicates the power of the most efficient compound hues required to neutralize the indicated green (and greenish) wavelengths; that power, indicated on vertical axis, also represents the complementary efficiency of the indicated green wavelengths.

The almost vertical solid lines at about 492 and 568 nm indicate the complementary efficiencies of those wavelengths relative to the complementary red and violet wavelengths, respectively; evidently the latter extreme wavelengths are inefficient complementaries. The inefficiency of single wavelengths (relative to additive combinations of pairs of wavelengths) commences at 437.5 nm (complementary to 567.8 nm) and at 614 nm (complementary to 490.7 nm) and tends to zero efficiency as violet wavelengths become shorter and as red wavelengths become longer. Similarly, in Fig. 2 (for D_{65}) wavelengths shorter than 437.5 nm (complementary to 567.2 nm) and longer than 614 nm (complementary to 491.7 nm) are inefficient in comparison to combinations of pairs of wavelengths. The dotted lines to the left and right, respectively, of 437.5 and 614 nm, in both Figs. 1 and 2, indicate the complementary efficiencies of compound violets and compound reds, respectively, of the indicated dominant wavelengths. Immediately below the dotted lines, the solid lines indicate the low complementary efficiencies of single violet and red wavelengths; thus in Fig. 2, at 390 nm, the single-wavelength color has a complementary efficiency of 0.019, thus requiring 53 W (1/0.019) to neutralize 1 W of the complementary color; at 390 nm, the most efficient compound color of that dominant wavelength has a complementary efficiency of 1.36, thus requiring only 0.736 W to neutralize the same complementary color. The compound color is thus 72 times more efficient than the single-wavelength color. The dotted lines tend to become horizontal at extreme wavelengths 390 and 670 nm, because the rate of change of wavelengths complementary to the violets and reds tend toward zero; those wavelengths stabilize at approximately 566.5 and 493.3 nm (D_{65}). A stable or constant color, of course, is associated with one constant most-efficient complementary color. The practice of specifying hue by the wavelength that has the same hue, results in a range of wavelengths (390–360 and 670–830 nm) that in fact represent almost-constant violet and red chromaticities that correspond to almost-constant proportions of the compound components. Thus the compound colors that have the same hues as extreme spectral wavelengths tend to constant complementary efficiency, whereas the single-wavelength colors are

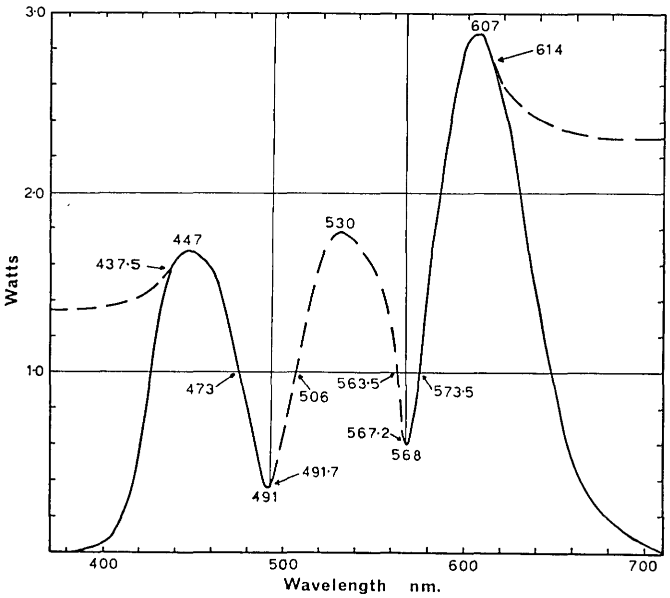

FIG. 2. Complementary efficiency for illuminant D_{65}.

TABLE I. Optimum complementary efficiencies for illuminant D_{65}, and representative list of compound components. Wavelengths in parentheses have same hue as the compound color, but lower efficiency. Any not in parentheses has same efficiency as compound color of same hue, if any is indicated on the same line.

Wavelength nm	Compound components	Complementary efficiency	Complementary wavelength, nm
530		1.78	530*c*
510		1.21	510*c*
492.1		0.38	618
470		1.16	572
445		1.68	567.8
440		1.62	567.4
437.5	438 + 600	1.58	567.2
(430)	440 + 600	1.50	567
(410)	440 + 600	1.36	566.65
(390)	440 + 601.5	1.36	566.5
565*c*	440 + 600	1.14	565
560*c*	440 + 610	0.84	560
550*c*	450 + 610	0.64	550
540*c*	445 + 609	0.58	540
535*c*	440 + 606	0.57	535
530*c*	440 + 604	0.56	530
525*c*	440 + 610	0.57	525
520*c*	440 + 610	0.61	520
510*c*	440 + 610	0.83	510
500*c*	430 + 615	1.37	500
495*c*	430 + 615	2.0	495
(670)	430 + 615	2.32	493.3
(640)	430 + 615	2.4	492.9
(620)	430 + 615	2.62	492.2
614	430 + 613	2.76	491.7
605		2.88	490.7
590		2.36	487.2
567.5		0.61	441.5
550		1.56	550*c*
530		1.78	530*c*

nearly indeterminate and tend toward zero luminosity and therefore toward zero complementary efficiency.

Table I lists complementary efficiencies and best/near-best compositions of compound wavelengths, at critical points or representative intervals. The listed components were computed at (generally) 5 nm intervals; minor improvement of complementary efficiencies is therefore possible.

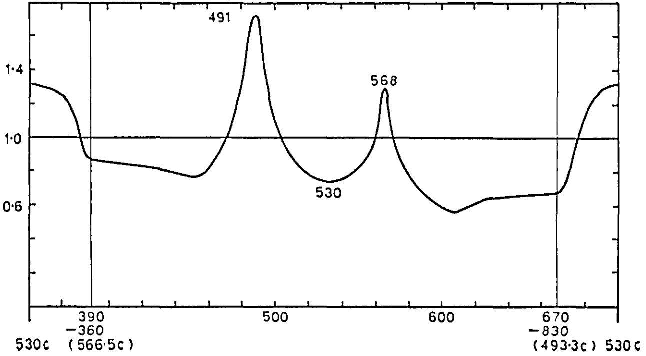

FIG. 3. Power distribution of most-efficient complementary wavelengths to match illuminant D_{65}.

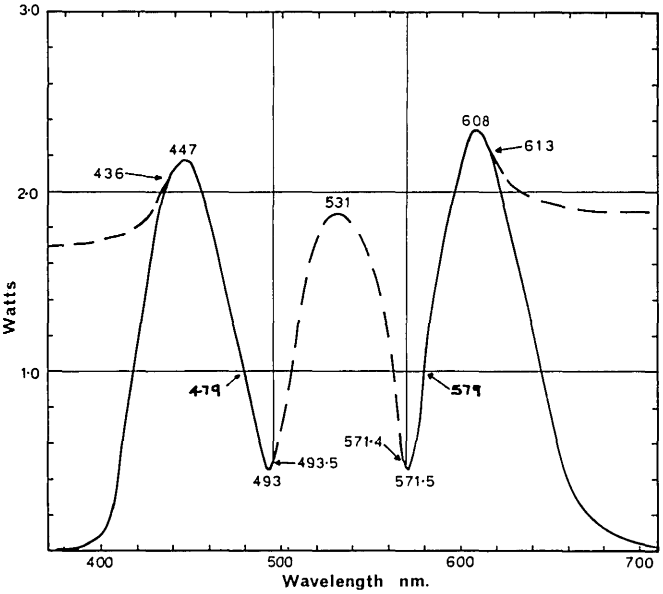

FIG. 4. Complementary efficiency for illuminant *B*.

Figure 3 indicates the power distribution of a hypothetical white light (equating to the chromaticity of illuminant D_{65}) that contains all spectral and nonspectral hues of optimum complementary efficiency, such that each wavelength or compound color has the correct power required to neutralize its complementary. Each pair of complementary colors therefore requires a ratio of powers that is the optimum complementary efficiency indicated at Fig. 2 and Table I. The power (W) of each wavelength is therefore the reciprocal square root of the optimum complementary efficiency. The nonspectral colors are indicated in Fig. 3 by an arbitrarily chosen horizontal interval equal to the wavelength interval of their complementary wavelength. It will be noted that the power of all wavelengths is in the range of approximately 0.6–0.9 W, except for peaks at cyan, yellow, and magenta; in these three wavebands, namely, 473–506 nm, 563.5–574 nm, and 506*c*–563.5*c*, are contained all the wavelengths complementary to the entire remaining cycle of hues. It is notable that the shape of the magenta peak (half-peaks at left and right extremes of Fig. 3) is quite dissimilar to the narrow yellow and cyan peaks. The distortion is probably caused by the arbitrary choice of horizontal interval, and/or the arbitrary choice of 390 and 670 nm to represent the ends of the spectrum. The matter is considered in Sec. IV.

Figures 4 and 5 demonstrate that the limits of optimum complementary efficiency of single wavelengths lie at 436 and 613 nm for illuminant *B*, and at 433.5 and 614 nm for illuminant *A*. Illuminant *A* is further described by the data in Table II.

IV. DISCUSSION

Figures 1, 2, 4, and 5 demonstrate a progressive and radical change in the balance of the curve. From a short-wavelength peak of complementary efficiency 1.55

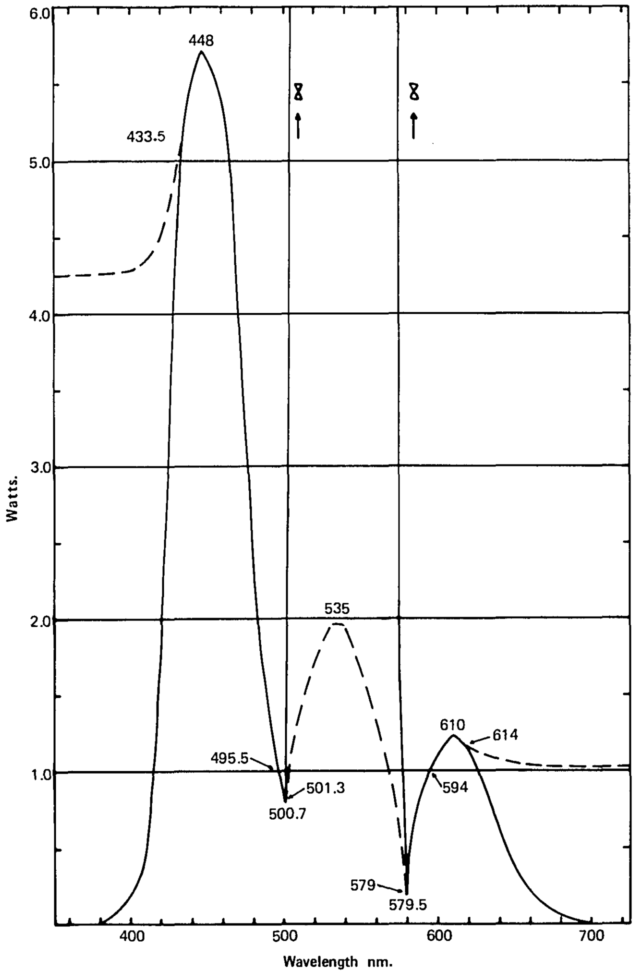

FIG. 5. Complementary efficiency for illuminant *A*.

for illuminant *C*, the efficiency rises to 5.75 for illuminant *A*. Similarly, the long-wavelength peak falls from 2.97 to 1.24 over the same range of illuminants. Illuminant *B* demonstrates an even balance of peaks in comparison to the uneven balances of the other illuminants.

Illuminant *A* (Fig. 5) is well known, by artists and interior decorators for example, to "blacken" or desaturate blue surfaces, significantly reducing blue chroma. Evidently, in low-color-temperature illuminants whose neutral is yellowish in comparison to the "white" neutral of noon sky light, the desaturation of blue wavelengths is compensated by increased complementary efficiency. Similarly, bluer illuminants, such as illuminant *C*, compensate the yellow and orange wavelengths with increased complementary efficiency. (This tendency is demonstrated to extremes by illuminants 1 and 10, Sec. V.)

Illuminant *B* (Fig. 4) represents noon sunlight; it represents a natural illuminant approximately median to the yellowish/reddish light of some sunsets, and the blueish light of some twilights. It is approximately median, therefore, to the range of natural illuminants in which human vision has evolved. The evenly balanced structure of the curve suggests that human vision is best adapted to illuminant *B*.

TABLE II. Optimum complementary efficiencies for illuminant *A*, and representative list of compound components. Wavelengths in parentheses have same hue as the compound color, but lower efficiency. Any not in parentheses has same efficiency as compound color of same hue, if any is indicated on the same line.

Wavelength nm	Compound components	Complementary efficiency	Complementary wavelength, nm
535		1.922	535*c*
520		1.72	520*c*
501.7		0.85	618
433.5	434 + 600	5.15	579.1
(430)	433 + 600	5.05	579
(400)	440 + 615	4.3	579
(360)	440 + 615	4.3	579
560*c*	420 + 610	0.77	560
540*c*	430 + 610	0.527	540
535*c*	420 + 610	0.520	535
530*c*	420 + 610	0.521	530
520*c*	420 + 610	0.58	520
(700)	450 + 610	1.04	503.8
(670)	450 + 610	1.04	503.7
(650)	450 + 610	1.07	503.4
(635)	450 + 610	1.09	502.9
614	480 + 613	1.21	501.3
610		1.24	500.7
560		1.3	560*c*
535		1.922	535*c*

Each illuminant results in a specific waveband, variable according to illuminant, of wavelengths of optimum complementary efficiency. Beyond this waveband, the efficiency of single wavelengths is less than those of combinations of pairs of short and long wavelengths. Single wavelengths within this waveband are of primary relevance to color vision; wavelengths outside of that waveband are of optimum efficiency only when compounded with other wavelengths of the opposite extreme; such wavelengths are unable, alone, to achieve optimum efficiency. For the sake of brevity, the waveband of discrete wavelengths of optimum complementary efficiency shall be termed the *primary waveband*. The remainder of the hue cycle, in which combinations of pairs of wavelengths (including nonspectral colors) dominate the complementary efficiency function, shall be termed the *secondary band*.

For whites that match the four illuminants examined, there are specific limits beyond which the efficiencies of single wavelengths are less than the efficiencies of combinations of pairs of wavelengths. In color mixtures, these combinations require less power, watts, than do single wavelengths of the same hue, in achieving the same resultant color.

Figure 3 shows a power distribution (watts) over a horizontal axis that represents the full cycle of hues of single wavelengths and combinations of pairs of short and long wavelengths. The horizontal interval accorded to the nonspectral hues was chosen arbitrarily; irregularities of curve shape are apparent. The irregularities consist of (a) the broad magenta peak, complementary

TABLE III. Primary-waveband data for 14 whites. *I* is wavelength (λ) interval of band *S* (short-λ limit) to *L* (long-λ limit). Complementary λ has reciprocal efficiency. Wavelengths in parentheses have less complementary efficiency than combination of indicated pair of wavelengths of same hue.

White	Wavelength (λ) nm	Compound components	Complementary efficiency		Complementary wavelength, nm
			single	compound	
1	435		12.98		586.7
x.525, y.410	432	433 + 600	11.95		586.6
S432, L614.5	(430)	431 + 600	11.10	11.35	586.6
I 182.5	611		0.642		507
	614.5	613 + 450	0.645		507.6
	(616)	615 + 450	0.634	0.635	508
A	435		5.24		579.2
x.4476, y.4075	433.5	434 + 600	5.15		579.1
S433.5, L614	(432)	433 + 600	5.05	5.09	579
I 180.5	610		1.24		500.7
	614	613 + 480	1.21		501.3
	(616)	615 + 480	1.17	1.18	501.5
2	440		4.34		576.9
x.42, y.40	434	435 + 600	3.95		576.75
S434, L614	(433)	434 + 600	3.89	3.93	576.7
I 180	611		1.50		499
	614	613 + 440	1.47		499.4
	(615)	614 + 440	1.46	1.464	499.5
3	440		2.97		573.5
x.38, y.38	436	438 + 620	2.77		573.4
S436, L614	(435)	437 + 620	2.72	2.74	573.4
I 178	613		1.90		496.35
	614	613 + 440	1.88		496.5
	(615)	614 + 440	1.86	1.87	496.6
B	440		2.15		571.2
x.3485, y.3518	436	438 + 600	2.06		571.1
S436, L613	(433)	435 + 600	1.903	1.924	571
I 177	612		2.29		493.5
	613	612 + 430	2.273		493.55
	(615)	614 + 430	2.23	2.24	493.8
D_{65}	438		1.603		567.32
x.3127, y.3290	437.5	438 + 590	1.585		567.25
S437.5, L614	(435)	436 + 600	1.523	1.536	567.1
I 176.5	612		2.79		491.5
	614	613 + 430	2.76		491.7
	(615)	614 + 430	2.74	2.75	491.8
C	438		1.52		568
x.3101, y.3162	437.5	438 + 600	1.48		567.85
S437.5, L614	(435)	436 + 600	1.41	1.453	567.8
I 176.5	613		2.82		490.6
	614	613 + 430	2.78		490.75
	(618)	616 + 430	2.64	2.69	491.1
4	438		1.39		565.1
x.295, y.315	436	437 + 600	1.36		565
S436, L615	(435)	436 + 600	1.324	1.327	565
I 179	612		3.14		490.5
	615	614 + 430	3.02		490.8
	(618)	617 + 430	2.918	2.925	491.0
5	435		1.10		564.25

TABLE III. (*Continued*)

White	Wavelength (λ) nm	Compound components	Complementary efficiency		Complementary wavelength, nm
			single	compound	
x.28, y.29	434	435 + 590	1.07		564.2
S434, L614	(430)	435 + 590	0.942	1.03	564
I 180	613		2.13		488.8
	614	613 + 440	2.1		488.9
	(617)	610 + 440	2.06	2.1	489.1
6	436		0.975		564
x.27, y.27	434	435 + 590	0.93		563.8
S434, L613	(432)	433 + 590	0.88	0.90	563.6
I 179	611		3.61		487.2
	613	612 + 450	3.55		487.4
	(615)	614 + 450	3.47	3.49	487.6
7	436		0.817		560.7
x.25, y.25	434	440 + 590	0.77		560.5
S434, L610.5	(430)	440 + 590	0.686	0.73	560.1
I 176.5	609		4.15		485.6
	610.5	610 + 460	4.1		485.8
	(612)	611 + 458	4.06	4.08	486
8	436		0.72		559.4
x.24, y.2342	434.5	435 + 590	0.705		559.15
S434.5, L608.5	(434)	435 + 590	0.69	0.70	559.1
I 174	607		4.6		484.3
	608.5	608 + 415	4.55		484.5
	(610)	609.5 + 415	4.5	4.52	484.6
9	435		0.536		552.25
x.205, y.20	434.5	435 + 580	0.531		552.2
S434.5, L608	(434)	435 + 580	0.524	0.527	552.15
I 173.5	606		6.07		482
	608	607 + 415	6.01		482.15
	(610)	609 + 415	5.93	5.95	482.25
10	434		0.208		554
x.19, y.10	433	434 + 580	0.202		553
S433, L626	(430)	431 + 580	0.184	0.189	552.5
I 193	615		6.47		472
	626	620 + 430	4.1		472.7
	(630)	625 + 430	4.51	4.8	478

to a similar broad (inverted) peak in the green hues, whereas other peaks (in the cyan and yellow-green) are narrow; (b) the nearly horizontal lines that represent extreme short and long dominant wavelengths; (c) the sharp curves at the commencement of the nonspectral hues (493.3c and 566.5c).

Wavelength intervals (e.g., 1 nm) outside the primary waveband can not be of significance comparable to those within the primary waveband, e.g., (for D_{65}) from 437.5 to 614 nm. The fact that the limits of optimum efficiency of single wavelengths lie at 437.5 and 614 nm, means that from those limits outwards, (i) single wavelengths commence to degrade in relevance and (ii) there is a need to specify combinations of pairs of wavelengths. No strictly physical single quantity may be used to specify combinations of wavelengths. To specify compound colors such as reds, crimsons, purples, and violets, in correct interval relationship to other hues, a numerical measure of interval is necessary. The desired measure should be a psychophysical quantity, similar to dominant wavelength (e.g., 580 nm) whose numerical value does not necessarily contain a discrete wavelength of that value.

V. COLOR TEMPERATURES 2000 K TO INFINITE K AND BEYOND

Figure 6, whites, illustrates the chromaticity coordinates and relative color temperatures of 14 selected whites, including CIE standard illuminants C, D_{65}, B, and A. Whites 1 to 8 correspond to color temperatures from 2000 K to infinite K. Whites 9 and 10 are bluer than a blackbody at infinite K, and therefore beyond the locus of complete (Planckian) radiators (the solid curve that terminates at white 8). Whites 9 and 10 are ex-

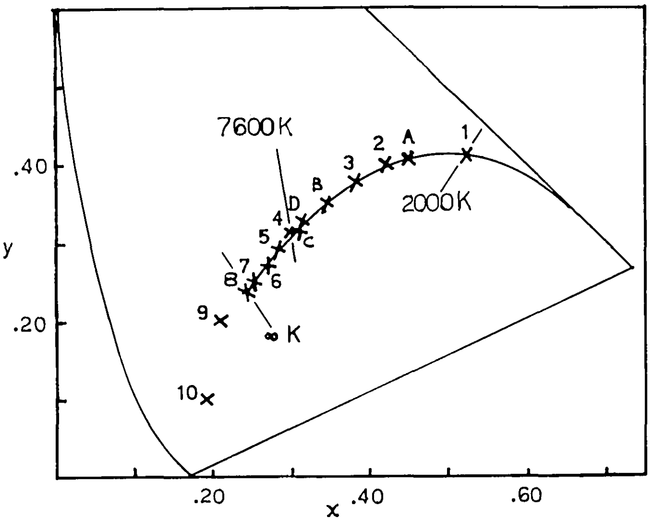

FIG. 6. Whites.

amined in order to learn whether the characteristics of whites up to infinite K are measurably different from those beyond infinite K.

Table III gives primary waveband data for the 14 selected whites. These data are considered to be sufficiently representative of the total range of natural illuminants (and artificial imitations thereof) as to permit accurate induction of constant characteristics of the complementary color function. Wavelengths (or combinations of pairs as applicable) to either side of each limit are specified to indicate the tendency of the curve near each limit. The data are accurate to ± 0.75 nm.

In Table III, the "White" column gives the chromaticity coordinates of the illuminant. In the same column of Table III are listed the short-wavelength limit (S), the long-wavelength limit (L), and the wavelength interval between these limits (I).

VI. DISCUSSION

It is notable that $L = 614$ nm(± 1 nm) in whites of color temperature 2000–7000 K; and that $S = 434$ nm(± 0.5 nm) in whites of color temperature 8000 to infinite K. These near-constants may be used to find both S and L to 1 nm accuracy by application of either Eqs. (4) or (5) below:

(a) In whites of color temperature 2000–7000 K,

$$I = \tfrac{1}{3}M \ , \tag{4}$$

(b) In whites of color temperature 8000 to infinite K,

$$L = M + \tfrac{1}{6}M \ , \tag{5}$$

where M is the median wavelength to Lc and Sc, and which may be found, in any white, by

$$M = \tfrac{1}{2}(360c + 700c) - 0.7 \, . \tag{6}$$

In white of infinite K color temperature, both Eqs. (4) and (5) apply. Bluer whites, such as whites 9 and 10, do not conform with either Eqs. (4) and (5), or with any constant relationship to M that could be found. In whites of color temperatures between 7000 and 8000 K, S and L may be found by interpolating Eqs. (4) and (5). It may be shown that single wavelengths shorter or longer than the primary waveband in any white are less efficient than optimum compound colors in contributing to color mixtures. This stems from their relative inefficiency in neutralizing their complementaries, since complementary colors are an extreme condition of additive color mixtures.

VII. CONCLUSIONS

(1) The complementary efficiency function, in any white from 2000 to infinite K color temperature and beyond, consists of two bands: a primary waveband in which optimum complementary efficiencies are achieved by single wavelengths, and a secondary band in which optimum complementary efficiencies are achieved by additive combinations of short and long wavelengths. The two bands have limits common to each other, at a specific short wavelength and a specific long wavelength, and therefore form a complete cycle.

(2) Secondary band colors are compound colors of no single specific wavelength. No strictly physical single quantity may be used to specify these combinations of wavelengths in correct interval relationship to colors of single wavelengths. Complementary wavelengths (e.g., 520c) do not represent the correct interval relationships. A psychophysical measure of interval is required to specify the entire cyclic function.

(3) In any CIE standard illuminant or other specific white, single wavelengths shorter or longer than the primary waveband are less efficient, in terms of power, watts, than secondary band optimum compound colors, in contributing to additive color mixtures and in neutralizing complementaries.

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*This paper derives from private research.

[1] CIE Publication No. 15 (E-1.3.1), 1971, Table 2.1.

[2] D. L. MacAdam "Photometric relationships between complementary colors," J. Opt. Soc. Am. 28, 103–107 (1938).

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Optical Society of America. Journal A: Optics, Image Science, and Vision

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0030-3941 - (2)
0361-2317 - (1)

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Basic Description

Title	Optical Society of America. Journal A: Optics, Image Science, and Vision
ISSN	1084-7529
Publisher	Optical Society of America
Country	United States
Status	Active
Start Year	1984
Frequency	Monthly
Volume Ends	Dec
Language of Text	Text in: English
Refereed	Yes
Abstracted / Indexed	Yes
Serial Type	Journal
Content Type	Academic / Scholarly
Format	Print
Website	http://www.opticsinfobase.org/josaa/journal/josaa/about.cfm
Email	jamss@osa.org
Description	Covers basic research on optical phenomena. Includes atmospheric, physiological and statistical optics; image processing; scattering and coherence theory, machine and color vision; design and diffraction.

Subject Classifications

Additional Title Details

Title History Details

Formerly (until 1993): Optical Society of America. Journal A, Optics and Image Science (United States) (0740-3232)

Which superseded in part (in 1983): Optical Society of America. Journal (United States) (0030-3941)

Which superseded in part (in 1929): Optical Society of America. Journal. Review of Scientific Instruments (United States) (0093-4119)

Which was formerly (until 1922): Optical Society of America. Journal (United States) (0093-5433)

Publisher & Ordering Details

Price Data

Abstracting & Indexing

Other Availability