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Observer Differences in Color-Mixture Functions Studied by Means of a Pair of Metameric Grays

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The Granville metameric gray panels have served to characterize the color vision of observers in an approximate but useful way. Thus, the 39 observers studied, and the four color-mixture functions were classed into five groups according to their indicated amounts of ocular pigmentation. These panels were also used to measure the correlation of lens and macular pigmentations with observer age, sex, and eye and hair colors. Of the three sets of color-mixture functions intended to refer to 2° field observation, the 1931 Commission Internationale de L'Éclairage standard observer agrees best. These data thus afford no basis for supplanting the 1931 Commission Internationale de L'Éclairage standard observer with either the Judd "i" or the 1955 Stiles' 2° color-mixture functions. The 1955 Stiles' 10° functions, however, agree fairly well.

1. Introduction

The standard observer and coordinate system, now widely used in the interpretation of spectrophotometric and colorimetric data, were recommended in 1931 by the CIE (the Commission Internationale de L'Éclairage) for this purpose so that all subsequent data would be expressed in the same tristimulus system and would therefore be immediately comparable. This system was based on the work done by Guild and by Wright in England and until recently has proved quite satisfactory. However, it was reported to fail in several instances to account correctly for the differences in color between two samples whose spectrophotometric curves differ in the short wavelength end of the spectrum, especially below 420 mμ.

These reported failures resulted in much discussion looking toward a possible revision of this standard observer and led Judd to suggest in 1951 a modified set of color-mixture functions based on the data of Wright and Guild combined with the standard luminosity function modified below 460 mμ according to luminous-efficiency data by Gibson-Tyndall, Wald, Weaver, Thomson, and Ishak. Now Dr. W. S. Stiles of the National Physical Laboratory in England has undertaken the first careful direct determination of the color-mixture functions of average normal observers which the standard observer should represent.

In these discussions, use of a field size larger than the 2° field used for the 1931 standard observer has been advanced to accord more closely with viewing conditions in industry. Dr. Stiles is therefore making his measurements with both 2° and 10° fields and has already reported color-mixture data for a pilot group of 10 observers whose average age is about 31 yr [8].[1]

In 1949, Walter Granville, then of the Container Corp. of America, painted several metameric gray panels to illustrate the possible effect of angular subtense on color matching [2]. Two of these were chosen for the work herein reported; a nearly nonselective gray produced by a mixture of white and black pigments called the simplex gray (No. 1), and a selective gray produced by a mixture of yellow, green, purple, and white pigments called the complex gray (No. 8). Figure 1 and table 1 show the spectral directional reflectances of these two grays obtained on the General Electric recording spectrophotometer.

According to the 1931 standard observer, the complex gray will appear greener in daylight (source C) than the simplex, and the reverse will be true when source A (color temperature 2,854°K, representative of incandescent lamp light) is used. The same effect results from changing the angular subtense of the sample from 10° to 2°; the retinal area stimulated first will include the macula and also a portion of the surrounding retina, and second will lie inside the macula only. This change from 10° to 2° will have an effect at least partly analogous to placing a yellow filter (macular pigment) in front of the eye for the 10° condition and, thus should have somewhat the same effect as reducing the color temperature of the source.

The purpose of the present study is to establish a criterion by means of which it will be possible to determine whether any set of color-mixture functions gives predictions of the character of the color difference between the Granville grays in accord with observers known to have normal vision by the ac-

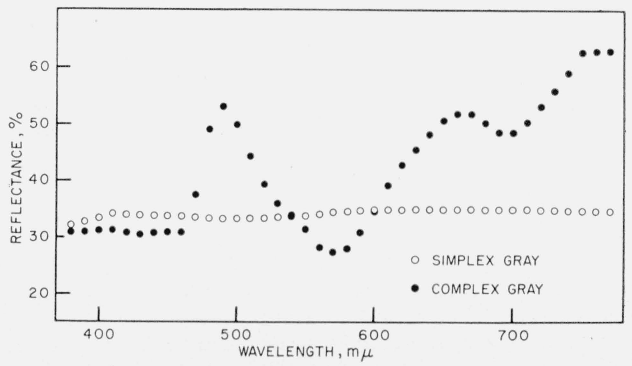

FIGURE 1. *Spectrophotometric curves of the two metameric Granville grays.*

[1] Figures in brackets indicate the literature references at the end of this paper.

TABLE 1. *Spectral directional reflectances of the two Granville grays*

Wavelength	Simplex (No. 1)	Complex (No. 8)
380	[a] 0.317	[a] 0.305
390	[a] .324	[a] .307
400	.331	.309
410	.338	.310
420	.337	.304
430	.336	.301
440	.335	.305
450	.334	.306
460	.334	.316
470	.332	.373
480	.331	.488
490	.330	.528
500	.330	.497
510	.331	.441
520	.331	.391
530	.332	.357
540	.334	.337
550	.336	.311
560	.338	.289
570	.342	.281
580	.343	.287
590	.345	.306
600	.346	.342
610	.347	.389
620	.347	.425
630	.347	.452
640	.347	.480
650	.347	.504
660	.348	.517
670	.347	.516
680	.347	.500
690	.348	.484
700	.348	.483
710	.348	.502
720	.347	.528
730	.346	.556
740	.346	.589
750	.345	.626
760	[a] .344	[a] .627
770	[a] .343	[a] .627

[a] Extrapolated.

cepted tests. In particular, this criterion is to be applied to the four sets of color-mixture functions already mentioned.

2. Experimental Method

The experiment consisted of placing the two gray panels side by side in a nearly vertical position illuminated by CIE source A and viewing them through a Davis-Gibson (CIE) C filter prepared in February 1955. The spectral transmittances of this filter determined in July 1956 at the start of the observations are given in table 2. The observer was asked to stand at a line that would cause the retinal image of the two panels to subtend a 10° angle and to disregard the Maxwell spot [7] if present. First he was to describe the color of the simplex gray with respect to that of the complex gray and then, as the operator reduced the voltage on the lamp and thereby its color temperature, to note when neither panel appeared redder or greener than the other. The voltage of the source at this point was recorded along with the observer's age, sex, and hair and eye colors. Observers not passing the 5th Edition Ishihara Tests for Colour Blindness were eliminated.

TABLE 2. *The spectral transmittances and change in reciprocal color temperature for the daylight filters used*

Wavelength	Davis-Gibson "C"	Filter G90A 2.13 mm	Davis-Gibson plus G90A	Filter No. 8331	Davis-Gibson plus No. 8331
$m\mu$					
380	[a] 0.69	[a] 0.751	0.5182	[a] 0.47	0.32
390	[a] .71	[a] .774	.5495	[a] .59	.42
400	.7268	.7967	.5790	.685	.498
410	.7501	.8066	.6050	.712	.534
420	.7475	.7800	.5830	.656	.490
430	.7180	.7585	.5446	.617	.443
440	.6623	.7279	.4821	.555	.368
450	.5836	.6982	.4075	.498	.291
460	.5090	.6647	.3383	.440	.224
470	.4557	.6345	.2891	.388	.177
480	.4056	.6029	.2445	.344	.140
490	.3532	.5777	.2040	.309	.109
500	.2956	.5551	.1641	.280	.0828
510	.2479	.5323	.1320	.254	.0630
520	.2178	.5088	.1108	.228	.0497
530	.2027	.4805	.0974	.199	.0403
540	.1961	.4602	.0902	.179	.0351
550	.1891	.4547	.0860	.172	.0325
560	.1765	.4600	.0812	.176	.0311
570	.1600	.4560	.0730	.171	.0274
580	.1420	.4310	.0612	.150	.0213
590	.1250	.3950	.0494	.119	.0149
600	.1115	.3805	.0424	.109	.0122
610	.1015	.3750	.0381	.103	.0105
620	.0940	.3650	.0343	.094	.0088
630	.0880	.3498	.0308	.083	.0073
640	.0825	.3318	.0274	.072	.0059
650	.0779	.3207	.0250	.066	.0051
660	.0724	.3217	.0233	.068	.0049
670	.0684	.3330	.0228	.072	.0049
680	.0634	.3493	.0221	.078	.0049
690	.0584	.3618	.0211	.083	.0048
700	.0534	.3646	.0195	.082	.0044
710	.0489	.3626	.0177	.080	.0039
720	.0444	.3569	.0158	.076	.0034
730	.0404	.3509	.0142	.073	.0029
740	.0369	.3463	.0128	.068	.0025
750	.0344	.3418	.0118	.067	.0023
760	[a] .033	[a] .337	.0111	[a] .066	.0022
770	[a] .032	[a] .333	.0107	[a] .064	.0020
Δ μrd	202.5	77.9	280.4	187.5	390.0

[a] Extrapolated.

The observer was then asked to step back to another line from which the retinal image would subtend an angle of 2° and the experiment was repeated. The combination of source and Davis-Gibson filter resulted in a maximum color temperature of 6,750° K, but for those observers requiring a source of higher color temperature, one or more measured blue daylight glasses (table 2) were used with the Davis-Gibson filter. Therefore, by varying the voltage on the lamp and by using combinations of these filters, color temperatures could be obtained from 1,800° K up and, indeed, it was found that some sources bluer than a source corresponding to infinite color temperature were required. The voltage and filter combinations were noted for each red-green balance point for each observer and the corresponding reciprocal color temperatures were determined from table 3 by subtracting the change in microreciprocal degrees Kelvin (μrd) produced by the filter combination from the reciprocal color temperature of the bare lamp.

TABLE 3. *Color temperature (θ) in ° K of the lamp, and the reciprocal color temperature in μrd of the lamp and the lamp with one or more of the daylight filters against voltage on the lamp*

Voltage	Θ of lamp alone	$10^6/\Theta$ of lamp	$10^6/\Theta$ of lamp and Davis-Gibson filter	$10^6/\Theta$ of lamp and Davis-Gibson with G90A	$10^6/\Theta$ of lamp and Davis-Gibson with 8331	$10^6/\Theta$ of lamp and Davis-Gibson with G90A and 8331
36.0	1800	556	353	275	166	88
42.7	1900	526	324	246	137	58
49.9	2000	500	298	220	110	32
57.6	2100	476	274	196	86	8
66	2200	455	252	174	65	−13
75	2300	435	233	154	45	−33
84	2400	417	214	137	27	−51
94	2500	400	198	119	10	−68
104	2600	385	182	104	−5	−83
115	2700	370	168	90	−20	−98
126	2800	357	155	77	−33	−111
133	2854	350.4	148	70	−40	−118

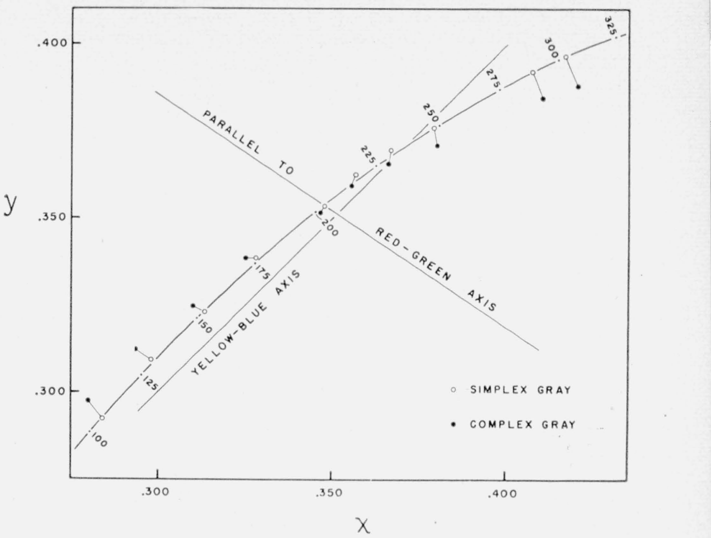

FIGURE 2. *Illustration of the change in relative position and distance apart of the CIE (x,y)-points of the Granville grays as the color temperature of the source is changed.*

3. Red-Green Balance Points for the Four Color-Mixture Functions

The red-green balance points for the four color-mixture functions were determined by first computing the chromaticity coordinates for the two gray panels for each of the functions for three Planckian sources (277, 221, and 191 μrd), for nine Planckian sources (666, 571, 500, 488, 486, 444, 400, 350, and 308 μrd) combined with the Davis-Gibson "C" filter ($\Delta 10^6/\Theta = 202$ μrd), and for the same Planckian sources combined with the double filter Davis-Gibson "C" plus G90A ($\Delta 10^6/\Theta = 280$ μrd). These data were plotted on the (x,y)-chromaticity diagram and fall close to the Planckian locus.

It was noted that the direction of the straight line connecting each pair of points as well as the distance between them (indicative of color difference) varies regularly with the correlated color temperature of the energy reflected by the simplex gray regardless of whether the computation is based on a Planckian source or on a Planckian source modified by the single or the double filter. Figure 2 shows the Planckian locus and 10 of the 21 pairs of computed points plotted on the (x,y)-diagram for the CIE standard observer. Note that near 300 μrd the simplex gray is seen by this observer as greener than the complex, whereas at source C (148 μrd), the reverse is true.

The red-green balance points for the two Stiles color-mixture functions were easily determined because they each predicted that under a certain one of the illuminants the two gray panels would be a chromaticity match; that is, the chromaticity points for them were found not to be significantly different. The reciprocal color temperature of the source satisfying this condition for the Stiles' 2° color-mixture functions is 210 μrd, while that for the Stiles' 10° color-mixture function is 267 μrd.

The other two color-mixture functions predict that at the red-green balance point there will be a residual yellow-blue difference. Therefore it was necessary to establish some criterion to determine when the red-green difference equals zero. The first criterion used in determining the corresponding reciprocal color temperature of source was that the line joining the chromaticity points of the two grays be parallel to the yellow-blue axis on the (x,y)-diagram. This axis, having an inclination of 45°, was drawn between the 476 and 578 mμ points on the spectrum locus. These are the proposed centers of the yellow and blue segments of the boundary of real colors on this diagram [6]. The corresponding values of reciprocal color temperature of source satisfying this criterion for the 1931 CIE and 1951 Judd "i" color-mixture functions are 192 and 202 μrd, respectively.

The second criterion used in determining the corresponding reciprocal color temperature of source was that the line joining the chromaticity points of the grays be perpendicular to the red-green axis on a uniform chromaticity scale diagram [4]. This axis was drawn from the 508 mμ point on the spectrum locus to the intersection of the line drawn through the 493 mμ point and the "C" illuminant point with the line connecting the red and violet ends of the spectrum locus. These are the proposed centers of the red and green segments of the boundary of real colors on the (x,y)-diagram [6].

A perpendicular to this axis was drawn through the "C" illuminant point and was found to intersect the spectrum locus at 567 mμ. This perpendicular was transferred to the (x,y)-diagram by drawing it also through the "C" illuminant point and the 567 mμ point on the spectrum locus. The angle of inclination of this perpendicular is found to be 66.5° and the corresponding values of the reciprocal color temperature of source satisfying this criterion for the two color-mixture functions are 206 and 213 μrd, respectively. Table 4 summarizes the values of reciprocal color temperature computed by these criteria to correspond to these balance points for the four sets of color-mixture functions.

TABLE 4. *Values of reciprocal color temperature of red-green balance points for the four color-mixture functions by different criteria*

Color-mixture functions	Reciprocal color temperature of source in μrd yielding red-green balance	
	By chromaticity match	
Stiles' 2°	210	
Stiles' 10°	267	
	Parallel to Y–B axis	Perpendicular on UCS triangle to R–G axis
1931 CIE	192	206
1951 Judd "i"	202	213

4. Results and Discussion

Table 5 contains the individual data for the 39 observers studied with their descriptions of the two panels and the reciprocal color temperature of their red-green balance points. Note that observer 39 was able to obtain a match at the 10° position but that it was not possible to run the lamp at a sufficiently high color temperature for him to obtain a match at the 2° position, presumably due to his very heavy ocular pigmentation.

Because the image of a 2° field falls wholly within the macula, the 2°-field results depend both on the macula and on the lens pigmentations. Likewise, since the image of a 10° field covers the macula and a large region of the surrounding retina of which the area of the macula represents about 10 percent, the 10°-field results depend only on the lens pigmentation provided the observers disregard the Maxwell spot as instructed. Also, the difference between the two may be taken as a measure of the macular pigmentation on the assumption that the spectral sensitivities of the receptors apart from pigmentation are the same throughout the 10° field [7].

The degree of pigmentation of an observer is indicated by his red-green balance point. By this interpretation, Stiles' 10° average observer (balance point at 267 μrd, see table 4) would be the least pigmented of the four.

TABLE 5. *Observer initials, age, sex, eye, and hair color, descriptions of colors of gray panels illuminated by source C at the 10° and 2° positions, and reciprocal color temperature of source required by each observer for red-green balance at both positions and the difference between them*

Observer		Sex and age	Eye color	Hair color	Color of simplex relative to complex		Reciprocal color temperature of match point		
					10°	2°	10°	2°	Difference
1	DBJ	M55	blue	brown	red	green	204	91	113
2	KLK	M45	hazel	brown	red	green	238	103	135
3	GWH	F56	brown	brown	red	green	179	47	132
4	MRF	M27	hazel	dark brown	pink	pink	278	196	82
5	CAD	M44	blue	brown	red	green	196	84	112
6	MMB	F39	blue	dark brown	red	green	213	132	81
7	LEB	M51	dark brown	black	slightly pink	green	213	78	135
8	THP	M41	blue	blond	pink	green	256	149	107
9	IN	M38	blue	red	pink	green	200	110	90
10	CDC	M21	hazel	auburn	pink	green	238	84	154
11	--------	F50	hazel	brown	pink	slightly pink	256	189	67
12	HKH	M39	blue	blond	pink	pink	250	179	71
13	FCB	M62	blue	brown	pink	green	172	118	54
14	RTV	M34	blue	brown	red	green	222	135	87
15	RWC	M46	blue	brown	pink	green	213	71	142
16	WAH	M29	dark brown	black	pink	green	263	182	81
17	GHL	M34	dark brown	black	pink	pink	286	213	73
18	WHA	M47	blue	brown	match	green	189	65	124
19	RLM	F44	brown	dark brown	pink	green	238	159	79
20	WRD	M42	brown	brown	pink	match	227	149	78
21	ECW	M48	brown	brown	pink	green	222	175	47
22	BPG	F37	dark brown	dark brown	lavender	green	227	127	100
23	WBF	F23	brown	brown	pink	pink	256	164	92
24	SAC	F19	brown	brown	lavender	lavender	270	208	62
25	JJ	F29	blue	brown	red	match	278	154	124
26	CAL	F25	hazel	light brown	lavender	match	250	170	80
27	RPT	M53	blue	brown	match	green	95	−14	109
28	HJK	M52	brown	brown	match	green	170	2	168
29	VIB	F42	dark brown	dark brown	pink	slightly pink	256	175	81
30	KSG	M66	blue	brown	green	green	91	−40	131
31	RD	M68	blue	brown	green	green	130	−28	158
32	WLH	M21	hazel	blond	red	green	233	110	123
33	WFM	M36	blue	blond	red	green	196	29	167
34	PI	F18.5	hazel	brown	pink	pink	278	170	108
35	JCS	M28	green	blond	pink	pink	270	161	109
36	TOT	M38	brown	light brown	pink	pink	263	192	71
37	RS	M56	blue	brown	red	green	196	84	112
38	JWL	M31	dark brown	black	pink	pink	256	182	74
39	CB	M77	blue	brown	green	green	−118	<−118	--------
Averages		41.3					214	<114	>100

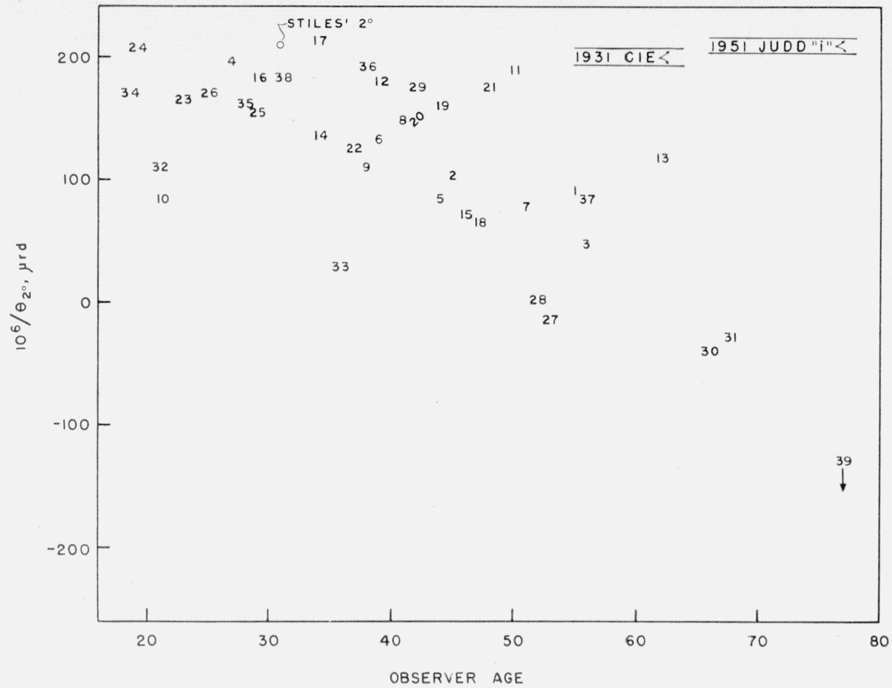

FIGURE 3. *Reciprocal color temperature of source required in a 2° field by 39 observers to produce red-green balance between the Granville grays plotted against observer age.*

Note the tendency of older observers to require lower reciprocal color temperatures. This tendency suggests that the amount of lens and macular pigmentations combined increases with age.

In figure 3, the reciprocal color temperature ($10^6/\Theta_2$) of the 2° red-green balance points for the 39 observers studied (see table 5) are plotted with observer number against observer age. Since no age has been given for the 1931 CIE and 1951 Judd "i" color-mixture functions, the spread in reciprocal color temperatures required by them for red-green balance as given in table 4, are indicated by a pair of lines which should extend across the graph but have been shown as short sections only to avoid complicating the figure. Stiles gives the average age of his pilot group of 10 observers as 31. It may be seen from figure 3 that only four of the 39 observers studied seem to have less pigmentation than the 1931 CIE standard observer, only two less than the 1951 Judd "i" (both of these on the basis of yellow-blue criterion) and only one less than the Stiles' 2° color-mixture functions by this test. It also indicates that the CIE and Judd color-mixture functions both correspond to very young observers in regard to balance point for the Granville grays.

The rank correlation (Spearman's) between $10^6/\Theta_2$ for red-green balance and age of the observers at the 2° position is 0.60 with an uncertainty of plus or minus 0.22, the uncertainty being 4.9 times the probable error. Thus, it is suggested that there is a poor but significant correlation of lens and macular pigmentations with age. Figure 4 shows the correlation of $10^6/\Theta_{10}$ with age; the rank correlation is better being 0.76 plus or minus 0.13. This correlation is attributable to the known increase in lens pigmentation with age. Here again, there are only six observers apparently less pigmented than Stiles' 10° color-mixture functions. From figure 5 it will be noted that there is no correlation of macular pigmentation with age, the rank correlation being −0.145 plus or minus 0.61. Also, there is no significant correlation of macular or lens pigmentations with either eye color or hair color.

From table 5 and figures 3, 4, and 5, it is possible to classify the oberservers and the four color-mixture functions into five groups, depending on their amounts of ocular pigmentation. From table 5, it will be seen that certain observers describe the simplex gray as redder than the complex at both the 10° and 2° positions. These are the young observers and those tentatively considered to have the least ocular pigmentation and constitute group 1. Those in group 2 apparently have a little more pigmentation and so call the simplex redder at the 10° position but a match at the 2° position. Group 3, comprising the majority of the observers, contains those who call the simplex redder at the 10° position and greener at the 2° position. With more pigmentation, the observers in group 4 call the simplex a match at the 10° position and greener at the 2° position. The most heavily pigmented observers, and these contain the oldest observers, call the simplex greener at both positions. Thus, these groups are called red-red, red-match, red-green, match-green, and green-green. The same grouping may be made with respect to the color temperature or reciprocal color temperature of the red-green balance points at the 10° and 2° positions. The three criteria for the five groups are

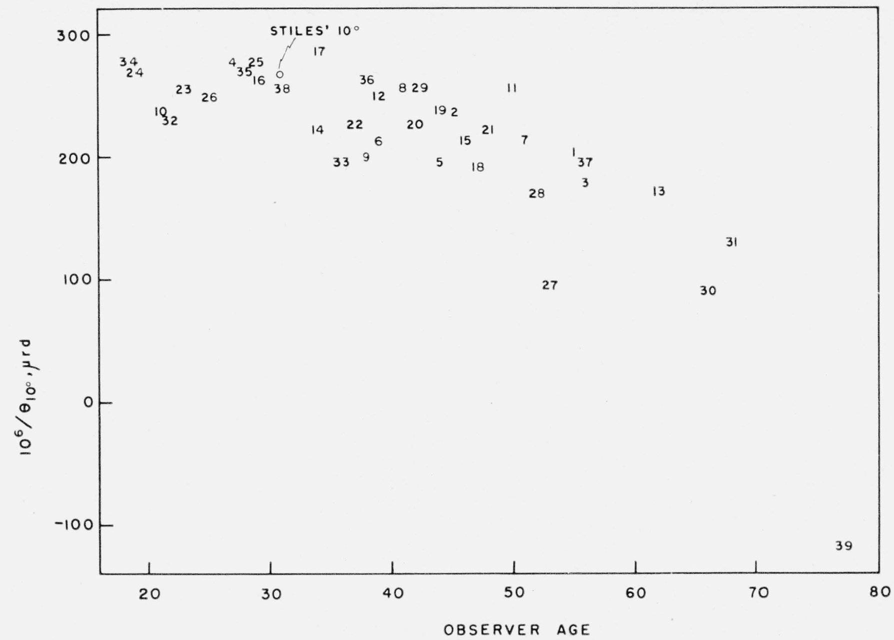

FIGURE 4. *Reciprocal color temperature of source required in a 10° field by 39 observers to produce red-green balance between the Granville grays plotted against observer age.*

Note that older observers require lower reciprocal color temperatures. This result is ascribed to the known increase in lens pigmentation with age.

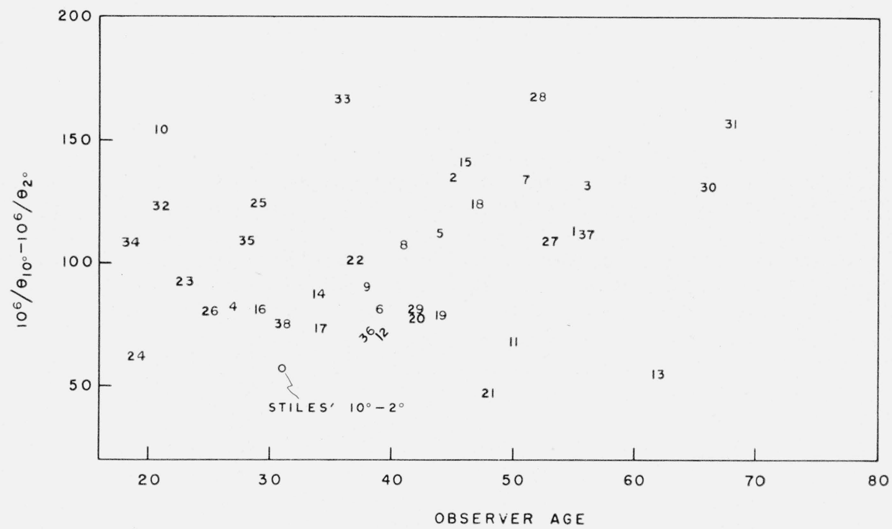

FIGURE 5. *Difference between the reciprocal color temperatures required for 10° and 2° fields by 39 observers to produce red-green balance between the Granville grays.*

On the assumption that the spectral sensitivities, apart from macular pigmentation, of the receptors are invariant over the whole central 10° of the retina, this difference is a measure of the amount of macular pigmentation. Note that there is no evidence of change in amount of macular pigmentation with age.

shown in table 6. According to this classification, all four color-mixture functions fall into the red-red group of very lightly pigmented observers with the CIE the most heavily pigmented and the Stiles' 10° the least.

5. Conclusions

The reciprocal color temperature of the source required to produce red-green balance between the Granville grays has been found to vary widely from one observer of normal color vision to another, and determination of this value of reciprocal color temperature for any one observer serves to characterize his color vision in an approximate but useful way. The value of reciprocal color temperature required in a 10° field for red-green balance of the Granville grays is dependent on the amount of yellow pigmentation in the lens of the observer's eye, and is tentatively taken as a measure of this pigmenta-

Table 6. *Classification of observers into five groups according to indicated ocular pigmentation as shown by their description of the simplex gray relative to the complex gray for source C, and alternatively by the color temperature and reciprocal color temperature of source required to make neither gray redder or greener than the other*

Observer group	Simplex relative to complex		Color temperature of source at match point	Reciprocal color temperature of source at match point
	10°	2°		
red-red	red	red	$\Theta_{10^\circ}<\Theta_{2^\circ}<6{,}750^\circ$	$148<10^6/\Theta_{2^\circ}<10^6/\Theta_{10^\circ}$
red-match	red	match	$\Theta_{10^\circ}<6{,}750^\circ=\Theta_{2^\circ}$	$10^6/\Theta_{2^\circ}=148<10^6/\Theta_{10^\circ}$
red-green	red	green	$\Theta_{10^\circ}<6{,}750^\circ<\Theta_{2^\circ}$	$10^6/\Theta_{2^\circ}<148<10^6/\Theta_{10^\circ}$
match-green	match	green	$\Theta_{10^\circ}=6{,}750^\circ<\Theta_{2^\circ}$	$10^6/\Theta_{2^\circ}<148=10^6/\Theta_{10^\circ}$
green-green	green	green	$6{,}750^\circ<\Theta_{10^\circ}<\Theta_{2^\circ}$	$10^6/\Theta_{2^\circ}<10^\circ/\Theta_{10^\circ}<148$

tion. Similarly, the value of reciprocal color temperature required in a 2° field for red-green balance of the Granville grays is dependent both on lens pigment and on macular pigment, and the difference in these two values (value for 2° field minus value for 10° field) is tentatively taken as a measure of the macular pigmentation of the observer.

The tentative measure of lens pigmentation afforded by the Granville grays correlates well with the age of the observer, but the tentative measure of macular pigmentation shows no correlation with age. Neither measure shows significant correlation with eye color or hair color, but a tendency, significant at about the 15 percent level of confidence, was found for female observers to have less pigmented eyes than male observers of the same age.

The reciprocal color temperatures of source required by four sets of color-mixture functions for red-green balance of the Granville grays have been computed and found to be higher than the average value for 39 actual observers with normal color vision. Of the three sets of color-mixture functions intended to refer to 2°-field observation, the 1931 CIE standard observer agrees best. These data thus afford no basis for supplanting the 1931 CIE standard observer either with the Judd "i" color-mixture functions or the 1955 Stiles' 2° color-mixture functions for a pilot group of 10 observers.

With respect to these observations on the Granville grays, the Stiles' 1955 data for 2° viewing does not fulfill the requirement recommended in 1955 by the CIE [1] that any revision of the "standard observer for colorimetry should represent average normal vision, adjusted as for an observer 30 years of age", but the data for 10° viewing are fairly satisfactory in this regard.

6. References

[1] Comm. Internationale de L'Éclairage, Compt. rend., Zurich, p. II, sec. 1.3.1. (1955).

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