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FUNDAMENTAL PROBLEMS IN COLOR VISION. II. HUE, LIGHTNESS, AND SATURATION OF SELECTIVE SAMPLES IN CHROMATIC ILLUMINATION

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That the limits of color constancy are reached in everyday experience is shown by the fact that colors of objects do not remain constant in different illuminants and when various conditions of viewing are changed. Thus a suit of clothes which is a good bluish gray in the lamplight of the store may be a saturated blue in daylight. Changes in color which escape the layman are easily detected by experts engaged in matching and grading objects by their colors.

The belief is widely held that changes in object colors in strongly chromatic illuminants, when the whole retina is stimulated by homogeneous light, are either wholly inexplicable or unamenable to the laws governing normal color vision. The conflicting hypotheses advanced for the facts of constancy and conversion have not contributed to a clearer understanding of the phenomena or their underlying mechanisms. The application of laboratory controls to the phenomena of color conversion has resulted in the formulation of principles valid for non-selective samples in various illuminants.[1] As most

[1] D. B. Judd, Surface color, *J.O.S.A.*, 1935, 25, 44; H. Helson, Tri-dimensional analysis and the non-film modes of color appearance, *J.O.S.A.*, 1937, 27, 59, and Fundamental problems in color vision. I. The principle governing changes in hue, saturation, and lightness of non-selective samples in chromatic illumination, this *Journal*, 1938, 23, 439–476.

objects have chromatic daylight colors, that is, possess spectrally selective reflectance, the question arises: "Do the laws for non-selective samples hold for selective ones as well?" The present paper deals, therefore, with the facts and principles of changes in hue, lightness, and saturation of selective samples in spectrally homogeneous and mixed illuminants.

Procedure and Experimental Controls

As a full account of the apparatus and technique of experimentation has already appeared in a previous publication of this *Journal*[2] we shall limit ourselves to the most essential facts. For univocal answers to the questions which have concerned us it was necessary to use illuminants of known spectral energy distributions, stimuli and backgrounds of known spectral reflectance, and subjects (S) trained to report on hue, lightness, and saturation with fair consistency.[3] The following arrangements contributed to these ends:

The source of illumination was a 500-watt Mazda lamp equivalent to a black body radiator of 2848° K. when operated at 103 volts. This source lamp reproduces 'Illuminant *A*' recommended by the International Commission on Illumination.[4] It was used chiefly in conjunction with spectrally selective filters to give strongly chromatic illumination. Some observations, however, were taken without any filter as representative of weakly chromatic illumination and these were supplemented by observation with a Palo Daylight lamp which gives illumination that is nearly achromatic or 'white.' Observations were made in a light-tight booth to guard against stray light which can materially affect results.

The transmissions of the filters for 2848° K., the trilinear coördinates of the illuminants,[5] the illumination on the sample plane, with and without filters interposed, the hues of the illuminants, and their after-image complementaries are given in Table 1. From this table it will be seen that transmissions of the filters, and hence the illumination on the samples, differed by a factor of 60 for each intensity of source which we employed. This range of illuminations was counterbalanced by deliberate change in source intensity by a factor of 96, that is, by varying the amount of light from the source it was possible to produce 96-fold change in illumination with each filter. Actual intensities from the source were 135, 72, 4.5, and 1.4 foot-candles on the sample plane and when multiplied by the transmissions of the filters as given in Table 1 we have

[2] H. Helson, *ibid.*

[3] We are grateful to Dr. Deane B. Judd of the National Bureau of Standards for advice on experimental techniques, aid in measurement of spectral reflectances and transmissions, and for his unfailing interest in the progress of the work in all its stages. We trust that our debt to him has been repaid at least in part by some of the results of our experiments which he has built into the theory and formulæ which appear under his own name.

[4] *Cf.* D. B. Judd, The 1931 standard observer and coördinate system for colorimetry, *J.O.S.A.*, 1935, 25, 24-35.

[5] For definitions of various terms especially from colorimetry see Judd, *ibid.*, and Helson, *ibid.*

the illumination on the samples for each source-filter combination. These products are given in Table 1 for the main case, *viz.*, 72 f.c. on the sample plane.

The hues of the illuminants, as revealed by reports on the colors of the lightest non-selective samples, were not all unitary, that is, they require more than one hue-name to describe them.[6] It should be noted that we have indicated in Table 1 the hues of the after-image complementaries to the illuminant hues *because our results are explicable only in terms of after-image hues and not in terms of mixture complementarism.* The former complementaries differ from the latter in that they contain more red and blue (purple) than the latter.[7]

TABLE 1

TRANSMISSIONS OF THE CHROMATIC FILTERS, ILLUMINATION ON THE SAMPLE PLANE, TRILINEAR COORDINATES OF THE ILLUMINANTS, HUES OF THE ILLUMINANTS, AND THEIR AFTER-IMAGE HUES

	No Filter	Red	Yellow	Green	Blue
Transmission for 2848° K.	1.000	0.052	0.362	0.038	0.006
Foot-candles on samples	72.00	3.70	26.00	2.70	0.44
Trilinear coördinates	r g	r g	r g	r g	r g
	.543 .424	.958 .042	.705 .295	.372 .613	.237 .351
Hue of illuminant	Y of low saturation	yR	rY	yG	rB
After-image hue	Indeterminate low saturation	bG	B	bR	Y

The color stimuli consisted of 15 Munsell selective samples, 50 × 50 mm as given in Tables 2 and 5, and three non-selective samples identical with our black, gray and white backgrounds, making 18 stimuli in all. Spectral reflectance curves of the 15 Munsell samples were determined at the National Bureau of Standards and the trilinear coördinates of each sample in each illuminant were calculated. These data are re-

[6] The yR illuminant is in effect spectrally homogeneous even though it is yellowish-red because all of the samples illuminated by it fall closely on the same part of the spectrum locus when plotted in the color mixture diagram. The reddish-yellow, yellowish-green, and reddish-blue illuminants do not plot on the spectrum locus and are therefore equivalent to non-homogeneous lights. In laying claim to the use of homogeneous illuminants we shall have only the first in mind. It should be remembered that purity of stimulus does not give unitary hues always—in fact the reverse is true as only three psychologically unitary hues have been found in the spectrum—G, Y, and B, all reds in the spectrum having a yellow component. For most recent determination of spectral unitaries, see F. L. Dimmick and M. R. Hubbard, The spectral location of psychologically unique yellow, green and blue, *Am. J. Psychol.*, 1939, 52, 242–254.

[7] A. Tschermak, Licht und Farbensinn, *Handb. d. norm. u. pathol. Physiol.*, Berlin, 1929, XII/1, Receptionsorgane 11, pp. 474 f.; also T. Karwoski, Variation toward purple in the visual after-image, *Amer. J. Psychol.*, 1929, 41, 625–636.

served for a later article but the reflectance of each sample for each illuminant is given in Tables 2 and 5. Since the lightness of a sample is directly dependent upon its reflectance this value is of prime importance.

The Ss in these experiments numbered 21. Sixteen observed during the first year of experimentation and 5 observed during the major variations carried on during the second year, two of the five having observed in both years' work. Ss were trained to report on hue, lightness, and saturation in daylight by the use of the Munsell color book, after which their reports in the color booth were accepted at their face value. Reports on hue were made in terms of a sixteen-fold classification, R, yR, RY, rY, Y, gY, YG, yG, G, bG, BG, gB, B, rB, RB, bR, the small letters denoting minor components in binary hues. The abbreviations are self-evident for the hues and the achromatic series was denoted by A 10/0, A 5/0 and A 0/0 for white, gray, and black. The Munsell notation was used wherein the number in the numerator refers to lightness and the one in the denominator to saturation. Maximum saturation or lightness was denoted by 10 and minimum by 0. Thus a black would be denoted by A 0/0 and a yellowish-red of medium saturation and lightness by yR 5.0/5.0.

Each S adapted to the illuminant for 15 minutes before the samples were exposed. S was instructed to glance about the field without fixating too long on any one sample as steady fixation often caused the samples to change in color. Under our conditions the whole retina was stimulated with chromatic illumination. The total range of conditions investigated in this study and the number of observations on which our conclusions are based can be gained from the following: 18 samples were reported on by 5 Ss (whose results we shall concentrate on in the present report) in 25 different illuminants (incandescent, yR, rY, yG, rB and mixtures of the chromatic illuminants with the lamp light), with three backgrounds (white, gray and black) in four intensities of each illuminant (high, medium, low, and very low), resulting in a total of 27,000 ($18 \times 5 \times 25 \times 3 \times 4$) reports on hue, lightness, and saturation.

General Characteristics of Colors in Strongly Chromatic Illuminants

When we view a number of differently colored papers in illumination having a continuous spectrum, we see a variety of colors in every sense of the word. The reds stand out from the greens while the blues and yellows appear in their individuality also. Various degrees of lightness and saturation add to the variety of hues in the field. Multiplicity of colors characterizes the ordinary conditions of vision. The colors are solid as the glance falls upon them and they stand out from their background. They are one with the objects to which they belong. Some colors are more pleasing than others and the affective value of any color can be isolated more or less from the rest. Or if we regard the colors as a whole both the color-qualities as such and their affective values seem to adhere to the objects.

If, however, we change the illuminant from daylight to any strongly chromatic illuminant, the experience changes in very radical fashion. Objects and their colors lose their individuality to a great extent. A single hue and mood pervade the field. There is a peculiar luminous quality to everything that is seen. Colors retreat into the plane of the background, some even appearing within or behind it. The observer seems bathed in the illuminant hue. Wherever one looks he is conscious of the illuminant hue even though differences in color are visible. The colors have become softer and filmier. Demarcation between samples and background is not sharp and contours almost disappear. Variety, individuality, and thingness give way to a single predominating color tone wherein objects seem fused. The affective value of the daylight plane has changed to include three-dimensional space. Affective tone is stronger than in ordinary light and one is more conscious of the effect of color on feeling and mood than in normal surroundings.

One of the most striking differences between daylight hues and those seen in strongly chromatic illuminants is the loss in saturation which the latter have undergone. It is most pronounced in those samples having a daylight hue like that of the illuminant and seems paradoxical at first. In spite of the fact that 'red' samples, to take this hue as an example, reflect a greater fraction of homogeneous red light than daylight, and similarly for samples of other hues, they have a very much less saturated color in strongly chromatic red illumination owing to the desensitization of the eye to light of the illuminant hue.[8] Two factors are at work: strong stimulation by certain spectral energies to produce a given hue and retinal adaptation to neutralize this effect. Thus it is possible for samples having

[8] For this reason when maximum values are given for the saturation of illuminant hues it does not mean that the samples are as saturated as possible or even as saturated as in daylight. Both A. Gelb, Die Farbenkonstanz der Sehdinge, *Handb. d. norm. u. pathol. Physiol.*, Berlin, 1929, XII/1, Receptionsorgane 11, pp. 624 ff., and D. Katz, Die Erscheinungsweisen der Farben und ihre Beeinflussung durch die individuelle Erfahrung, *Z. F. Psychol.*, 1911, Erg. Bd. 7, pp. 270 ff., have found that samples having the illuminant hue are less saturated than in daylight illumination. But the complementary hues are fully as saturated at their best as any seen in daylight.

a daylight hue different from that of the illuminant to be more saturated than samples like the illuminant—for example, a daylight white (having higher reflectance) is redder than daylight reds in red illumination. On the other hand, the after-image hues are more saturated, stronger, and deeper than the illuminant hues and appear equally well in any samples regardless of daylight hue provided reflectance is sufficiently low for the illuminant.

The after-effects of exposure to strongly chromatic illumination are also striking. Immediately after the illuminant is changed from strongly chromatic to daylight, colors are greatly desaturated for many seconds, especially those having the hue of the chromatic illuminant. This 'after-desaturation' was greatest with the yR and rB illuminants and least with the yG and rY. This finding is in harmony with the fact that the red and blue-violet portions of the spectrum show greater fatigability than the yellow and green regions even though their saturation is greater.[9] Since the yR and rB illuminants plot farthest from the daylight point in the color mixture diagram we expect them to have the greatest chromatic effects and after-effects.

Hue, Lightness, and Saturation in Chromatic Illuminants

In attempting to formulate principles governing color conversion it is necessary to use an average, median or some other typical S as the object of predictions owing to individual differences in color vision. Unanimity of report on colors is not found even under optimal daylight conditions and so it cannot be expected when observations are much more difficult as in chromatic illumination. The chief types of variation in

[9] According to D. McL. Purdy, On the saturations and chromatic thresholds of the spectral colors, *Brit. J. Psychol.*, 1930–31, 21, 303, violet requires minimal intensity for maximal saturation, red is next, and greenish-yellow (565 mμ) needs maximal intensity for full saturation. He points out that the highly saturated colors require the minimal *time* to desaturate and lose their saturation first as intensity is raised—findings which we have corroborated under entirely different conditions in our after-desaturation effect and in the return to daylight hue with admixture of lamp light—red and blue requiring less than yellow, the exception of green being discussed below.

report found in chromatic illuminants which have also been reported among Ss with so-called normal color vision in daylight [10] are as follows:

(1) Samples which have unitary hues for the majority of Ss have binary hues for the remaining Ss—for example, Y 5/7 reported Y by 10 Ss was seen as gY by 6 others.

(2) Components of binary hues may be given different emphases: thus the sample P 3/6 was called RB by 5 Ss, rB by 6, and bR by 5.

(3) Minor components of binary hues may be on either side of the major component. The sample 7/6 which was called R by 13 Ss was seen as yR by 2 and bR by one S.

(4) Less agreement exists regarding unitary hues (hues supposed to be unitary) than with respect to binary hues as would be expected from the above. But binary hues are seldom seen as unitary since the tendency is to add components rather than to miss them.

By using illuminants of known composition and papers of known spectral reflectance and by excluding such sources of error as arise from stray light, insufficient adaptation, and inexperience in naming colors, the general principles governing conversion emerge concretely and clearly through the individual differences in color vision.

Consideration of the data in Table 2 for the median *S* reveals certain regularities. If we arrange the samples in order of decreasing reflectance for each illuminant we find first reports of illuminant hue or mixtures of daylight and illuminant hues in the case of the less homogeneous illuminants (rY and yG), secondly, reports of achromaticity, which may not be present in all cases, and thirdly, on white and gray grounds, after-image hues with the darkest samples. Taking the yR illuminant as an example, on white ground the first 10 samples are R or YR, the next sample is A, and the remaining 7 samples are, with one exception, GB; on gray ground, the first 12 samples are RY, the next two are YG and Y, and the remaining four are GB or G; on black ground, all the

[10] H. Helson, Color tolerances as affected by changes in composition and intensity of illumination and reflectance of background, *Amer. J. Psychol.*, 1939, 52, 406–410.

TABLE 2

HUE (H), LIGHTNESS (L), AND SATURATION (S) FOR THE MEDIAN S, AND APPARENT REFLECTANCE (A) OF 18 MUNSELL SAMPLES (M), IN yR, rY, yG, AND rB, ILLUMINANTS ON WHITE, GRAY AND BLACK BACKGROUNDS

Yellowish-Red Illumination							
M	*A*	White		Gray		Black	
		H	*L/S*	*H*	*L/S*	*H*	*L/S*
A 10/0	.800	R	9.0/4.0	RY	8.0/7.5	yR	8.0/9.0
R 7/6	.781	yR	9.0/3.0	RY	8.0/7.0	yR	7.5/9.0
R 5/10	.706	yR	8.0/3.5	yR	8.0/7.0	yR	7.5/9.0
Y 7/8	.577	RY	8.0/3.0	yR	7.5/6.0	yR	6.5/9.0
pB 7/4	.428	yR	7.0/2.5	RY	7.0/4.5	R	6.0/8.0
B 7/4	.381	rY	6.0/1.0	rY	6.0/5.0	R	5.5/8.0
P 5/6	.359	yR	6.0/2.0	RY	6.0/5.0	R	5.5/8.0
G 7/7	.329	R	5.0/1.0	rY	6.0/4.0	yR	5.0/7.0
YR 4/5	.297	yR	4.5/1.0	RY	5.0/4.0	yR	4.5/7.0
R 3/7	.276	R	4.5/1.0	RY	5.0/4.0	R	4.5/7.0
Y 5/7	.272	A	4.5/0.0	rY	5.0/4.0	R	4.5/7.0
A 5/0	.240	R	4.0/0.4	yR	5.0/1.5	R	4.5/3.5
B 5/6	.161	gB	3.0/1.0	YG	3.0/0.5	R	3.0/5.0
P 3/6	.153	gB	3.5/1.0	Y	3.0/0.7	bR	3.0/5.0
G 5/7	.087	GB	1.0/4.0	gB	2.0/2.0	yR	2.0/2.0
G 3/4	.072	GB	1.0/7.0	GB	2.0/2.0	yR	1.5/2.0
B 3/5	.064	bG	2.0/7.0	BG	1.5/2.0	yR	1.5/2.0
A 0/0	.030	gB	2.5/9.0	G	2.5/9.0	A	0.0/0.0

Reddish-Yellow Illumination							
M	*A*	White		Gray		Black	
		H	*L/S*	*H*	*L/S*	*H*	*L/S*
A 10/0	.800	Y	9.0/4.5	Y	8.5/9.0	Y	9.0/8.0
R 7/6	.618	RY	8.0/5.0	rY	7.5/7.0	rY	8.0/7.5
Y 7/8	.588	gY	8.0/4.0	Y	8.0/7.0	Y	8.0/7.0
B 7/4	.445	yG	7.0/5.0	YG	8.0/5.5	YG	7.0/5.5
G 7/7	.428	yG	7.0/7.0	yG	7.5/7.0	yG	7.0/5.0
pB 7/4	.405	gY	7.0/3.0	gY	5.0/4.5	gY	7.0/5.0
R 5/10	.404	yR	7.0/8.0	yR	7.0/9.0	RY	7.0/8.5
Y 5/7	.288	rY	5.0/1.0	gY	5.0/3.5	yG	6.0/5.0
P 5/6	.273	bR	5.0/3.5	RY	5.0/3.5	rY	6.0/4.0
YR 4/5	.246	bR	4.5/3.5	rY	5.0/3.5	rY	5.5/4.0
A 5/0	.240	gY	4.5/0.5	Y	5.0/1.5	Y	6.0/2.0
B 5/6	.185	bG	3.0/0.5	yG	3.0/3.0	yG	5.0/4.0
G 5/7	.171	bG	4.0/8.0	G	5.0/9.0	G	5.0/8.5
R 3/7	.151	bR	4.5/9.0	bR	5.0/8.5	yR	5.0/7.0
P 3/6	.119	bR	3.0/5.0	yR	3.0/4.0	RY	4.5/4.0
G 3/4	.078	rB	2.0/2.5	rB	2.0/2.0	G	3.0/2.0
B 3/5	.072	rB	2.0/2.5	rB	2.0/2.0	yG	3.0/3.0
A 0/0	.030	rB	1.0/2.0	RB	1.0/3.0	A	0.0/0.0

TABLE 2—*Continued*

Yellowish-Green Illumination

M	*A*	White		Gray		Black	
		H	*L/S*	*H*	*L/S*	*H*	*L/S*
A 10/0	.800	G	8.5/3.0	gY	9.0/9.0	gY	8.5/7.0
G 7/7	.596	yG	8.0/3.0	YG	8.0/5.0	yG	7.5/6.0
B 7/4	.581	yG	8.0/3.0	yG	8.0/5.0	yG	7.5/6.0
pB 7/4	.485	G	7.0/3.0	yG	6.5/6.0	yG	7.0/6.0
Y 7/8	.455	rY	6.5/4.5	Y	6.5/5.0	gY	7.0/4.5
G 5/7	.377	yG	5.0/2.5	yG	6.0/7.0	yG	6.0/7.0
R 7/6	.357	Y	5.5/2.5	Y	6.0/3.0	YG	6.0/4.0
B 5/6	.324	bG	5.0/3.0	bG	5.0/7.5	G	5.0/7.0
A 5/0	.240	A	5.0/0.0	gY	5.0/2.0	yG	5.0/2.0
P 5/6	.235	rB	5.0/2.0	YG	5.0/0.5	yG	5.0/5.0
Y 5/7	.221	RY	5.0/4.0	rY	5.0/4.0	yG	5.0/3.0
B 3/5	.133	rB	3.0/4.0	B	3.0/1.0	G	4.0/7.0
R 5/10	.110	bR	3.0/5.0	bR	4.0/4.0	gY	4.0/2.0
YR 4/5	.110	bR	3.0/4.5	yR	4.0/4.0	Y	4.0/2.0
G 3/4	.107	rB	3.5/4.5	rB	4.0/2.0	G	4.0/2.0
P 3/6	.097	rB	3.0/4.5	rB	3.0/3.0	G	3.0/2.0
R 3/7	.049	RB	1.5/7.0	bR	2.5/7.5	RY	2.0/1.5
A 0/0	.030	RB	2.0/5.0	RB	2.0/9.0	A	0.0/0.0

Reddish-Blue Illumination

M	*A*	White		Gray		Black	
		H	*L/S*	*H*	*L/S*	*H*	*L/S*
A 10/0	.800	B	9.0/3.5	B	9.0/6.0	B	8.5/7.5
B 7/4	.642	B	8.0/6.0	B	8.5/6.0	B	8.0/6.0
pB 7/4	.600	B	8.0/5.0	B	8.5/7.0	B	8.0/6.0
G 7/7	.493	gB	7.0/4.5	B	7.0/6.0	B	7.5/5.0
B 5/6	.472	gB	7.0/3.5	B	7.5/7.0	B	7.5/8.0
R 7/6	.346	rB	6.0/6.0	RB	6.0/5.0	rB	6.5/6.0
P 5/6	.310	rB	6.0/6.0	rB	6.5/7.0	rB	6.0/8.0
G 5/7	.267	G	6.0/7.0	G	6.0/7.0	BG	5.5/6.5
A 5/0	.240	A	5.0/0.0	A	5.5/0.0	B	5.0/5.0
B 3/5	.217	B	5.0/0.5	BG	5.0/1.0	B	5.0/6.5
Y 7/8	.159	rY	3.0/3.5	rY	4.0/3.0	RB	4.0/1.5
P 3/6	.153	RB	5.0/6.5	rB	4.0/7.5	RB	4.0/8.0
R 5/10	.110	bR	3.0/1.5	bR	3.5/3.0	RB	3.0/6.0
Y 5/7	.097	yR	3.0/1.5	rY	3.0/2.0	bR	3.0/2.0
G 3/4	.093	Y	3.0/0.5	yG	3.0/1.5	B	3.0/1.5
YR 4/5	.069	RY	2.0/1.0	yR	3.0/3.0	bR	2.0/2.5
R 3/7	.048	yR	2.0/1.5	R	2.0/2.0	bR	2.0/3.0
A 0/0	.030	yR	1.0/0.5	RY	1.0/1.0	A	0.0/0.0

samples, with only two exceptions, are R or YR, one of the exceptions being bR (the b is an after-image component), the other, A, coincides with expectation. Similarly with the other illuminants: on white ground lighter samples have either the illuminant hue or a hue representing a mixture of daylight and illuminant hue if the illuminant is not fairly homogeneous, darker samples have the after-image hue and samples of intermediate reflectance either are achromatic or have hues of low saturation.[11] The hues are similar on gray ground but for the fact there are fewer after-image and more illuminant hues. On black ground we find practically no after-image hues, illuminant hues appearing almost exclusively.

The relation of the hues of samples in strongly chromatic illuminants to their daylight hues appears from Table 2. Some measure of constancy is present as some of the samples have at least one component of their daylight hue even in the homogeneous illuminant (yR). Daylight hue by itself is not sufficient for predictions of constancy. Whatever constancy is found is as much a function of reflectance of sample for the chromatic illuminant as the commonly supposed factor of hue. The *lightness* of a sample furnishes a better clue to its behavior under different conditions than does its hue. This explains why a sample whose daylight hue is different from that of the illuminant may have a more saturated illuminant hue than one whose daylight hue is like that of the illuminant —*e.g.*, pB 7/4 is a more saturated red in red illumination on black ground than R 3/7 owing to its higher lightness; similarly R 7/6 is a more saturated green in green illumination on black ground with a value of 4.0 than G 3/4 with a value of 2.0. A 10/0 always has the highest saturation in all illuminants because of its highest lightness. Samples having the hue of the illuminant will retain this hue provided they are of *high* reflectance in the illuminant. Samples having hues complementary to the illuminant will remain complementary in an illuminant provided their reflectance is *low* in it. Achromatic samples will remain achromatic in chromatic illuminants

[11] These are the samples most difficult to predict as samples with small saturations are liable to change, shifting from illuminant to after-image hue and back.

only if their reflectance happens to be near 'adaptation reflectance,' otherwise they will take either the illuminant or after-image hues. Color constancy is thus seen to occur for different reasons which can all be subsumed under the general principle of color conversion which we shall state after discussing the relations of lightness and saturation.

From Table 2 it is seen that the relations of lightness and saturation are different on the three backgrounds and seem anomalous at first sight. On white and gray backgrounds, decrease in lightness is correlated first with decreasing and later with increasing saturation, while on the black background lightness and saturation are positively correlated throughout. Both of these cases are in turn at variance with the classical account of the saturation-intensity relation according to which maximum saturation is found with stimulus intensities of *intermediate* value.[12] How explain both our own findings and the facts which have been taken for granted in the literature and in textbooks for years? The answer lies in the relation of sample reflectance to 'adaptation reflectance' and the dependence of the latter on background reflectance. To these we now turn in our theory of conversion.

The theory of conversion makes use of the experimental facts so far discussed and but one assumption in addition. We assume that in every viewing situation there is established a level of adaptation corresponding to a certain lightness level such that samples having reflectances yielding this lightness appear either achromatic or a desaturated purple. Samples having reflectances higher than 'adaptation reflectance' will take the hue of the illuminant, samples below adaptation reflectance take the after-image hue and samples near adaptation reflectance are either achromatic or desaturated.[13] The

[12] F. Hillebrand, Purkinjesches Phänomenon und Eigenhelligkeit, *Z. f. Psychol. u. Physiol. d. Sinnesorgane*, Abt. 11, 1920, 51, 46–95.

[13] This theory has developed out of the work at Bryn Mawr and from previous work of the senior author with D. B. Judd. The fundamental facts appeared in a study by Helson and Judd, A study in photopic adaptation, this *Journal*, 1932, 15, 380–398, and in other studies referred to above by Judd and Helson. A mathematical formulation of the theory by Judd stated in the next paragraph in colorimetric terms will appear in *J.O.S.A.* A preliminary account by Judd appears in: Hue, saturation and lightness of surface colors with chromatic illumination, *ibid.*, 1939, 29, 260.

present work with selective samples proves the validity of this formulation as well as the earlier work with non-selective samples.

The concept of adaptation level must not be regarded too simply. Only for non-selective samples are hue, saturation, and lightness simply a function of the reflectance of the sample (for the chromatic illuminants) relative to adaptation reflectance. For selective samples adaptation reflectance supplies a basic value in the definition of achromatic point on the triangular mixture diagram with reference to which hue and saturation are indicated. Adaptation reflectance has been shown to be a function of the reflectances of all samples in the field of vision, predominant weight being given to the background reflectance. The achromatic point, which we must determine anew for each sample of different spectral reflectance, depends chiefly upon the spectral character of the illuminant, upon the relation between adaptation reflectance and reflectance of the sample for the particular illuminant, and upon general level of illumination, to mention only the most important factors. Saturation may be regarded as a function of the distance of the sample point in the trilinear diagram from the achromatic point. Hue may be regarded as a function of the direction of the vector drawn from the achromatic point to the sample point.

The principle of conversion has related hue and saturation with lightness and we must now answer the question: "What determines the lightness of samples in various illuminants?" Reports in Table 2 bring out the almost perfect correlation existing between reflectance of samples for an illuminant and lightness. With changes of reflectance of a sample in different illuminants go changes in its lightness. Position of a sample in the reflectance column determines its position in the lightness column within the limits of experimental error. If lightness is a function of reflectance for an illuminant and as reflectance does not depend upon background, we should expect lightness values to remain practically constant with changing backgrounds.[14] Average lightness values for all illuminants and intensities are 4.62 for white background, and 4.85 for both gray and black backgrounds (Table 3). We have here the basis for the well-known 'brightness-constancy.'

Influence of Background on Hue, Lightness, and Saturation

That hue and saturation depend as much upon background lightness as upon composition of illuminant and spectral reflectance of sample appears from Table 2. For identical samples have different hues and saturations when placed on different grounds, *e.g.*, P 3/6 in red illumination is gB 3.5/1.0 on white ground, Y 3.0/0.7 on gray ground, and bR 2.0/2.0 on black ground; similarly, G 7/7 in blue illumination is gB 7.0/4.5 on white ground, B 7.0/6.0 on gray ground and B 7.5/5.0 on black ground. The hue of any sample is thus a function of the relation of its reflectance to adaptation reflectance, which depends largely on background. Owing to the close correlation between reflectance and lightness we may say, though with less accuracy, that hue is a function of position in the lightness-continuum taken with respect to adaptation lightness. As Helson[15] has previously said in writing of the effect of background on hue: "By its preponderating influence on adaptation level, the background can determine whether objects shall be tinged with illuminant hue, the contrasting hue, or shall lose in saturation to the point of achromaticity."

The effect of background on saturation is closely linked with its effect on hue. *On white ground dark samples are most saturated (in the complementary hue) while on black ground light samples are most saturated (in the hue of the illuminant).* This is explained by the dependence of hue and saturation on adaptation reflectance and the effect of background on adaptation level. Since some samples gain while others lose

[14] Due to lightness-contrast this statement is not, of course, strictly true if identical samples are compared on backgrounds of different reflectances simultaneously. We shall return to this point again below.

[15] *Cf.* footnote 10, p. 410.

in saturation on any given ground it is interesting to determine if there is a net gain on one ground over the others. From Table 3 it is seen that samples on black ground are on the average 1.14 saturation steps higher than on white ground and the average for gray is 0.73 step higher than on white ground. Higher saturations are found on the darker grounds in all illuminants, as Table 3 proves, with only one exception. The increase in saturation on darker grounds is due to increase in number of illuminant hues and in their saturations at the expense of the complementary hues.

Turning now to background and lightness we find that this dimension is least affected by background. The average values in Table 3 are practically identical for the three back-

TABLE 3

AVERAGE SATURATIONS AND LIGHTNESSES OF SAMPLES ON A 10/0, A 5/0 AND A 0/0 BACKGROUNDS IN FOUR ILLUMINANTS

Ill.	Saturation				Lightness			
	A 10/0	A 5/0	A 0/0	Av.	A 10/0	A 5/0	A 0/0	Av.
R	2.84	3.77	5.08	3.90	4.39	4.56	4.52	4.49
Y	4.20	4.58	4.59	4.46	4.97	5.10	5.42	5.16
G	3.53	4.10	3.92	3.85	4.65	5.01	4.81	4.49
B	2.56	3.62	4.13	3.44	4.44	4.70	4.64	4.59
Av.	3.29	4.02	4.43		4.62	4.85	4.85	

grounds, a fact which seems to contradict the well-known facts of lightness contrast. When *two* identical samples are compared simultaneously on white and black grounds the higher lightness of the one on black ground is easily seen. But when *many* samples are viewed on a half-white-half-black background the average lightness values will not be higher on the darker portion as Ss raise all lightness values for the samples on the lighter side! Under the conditions used in these experiments, that is, with samples on either white, gray, or black ground and with the lightness-range prescribed, Ss tended to assign the maximum value of 10 to the lightest sample in the field and ordered the remaining samples accordingly. In this way the lightness-inducing effect of darker grounds is lost in the reports and there results an appearance of even greater lightness constancy than is actually present.

But changes in intensity of illumination as well as changes in reflectance of background lighten or darken all samples simultaneously and the question arises: Do changes in general intensity affect lightness and saturation as much as changes in reflectance of background? Increase in general intensity from 1.4 f.c. to 135 f.c. increased average lightness from 4.50 to 4.96. Thus 96-fold change in intensity of illumination caused a change of only about one-half step in lightness so that lightness constancy is here about the same as with changes in reflectance of background. The case is different with saturation. This range of illumination intensities caused a change of only 0.75 saturation steps, on the average, whereas change in reflectance of background from 0.80 to 0.03 (about 27-fold change) resulted in an increase of 1.14 steps in saturation. If changes in general illumination were as effective as changes in reflectance of background, the 96-fold change in general intensity should have caused an increase of 4.9 steps instead of 0.75. Background lightness is thus seen to be about six times more effective than general intensity in effecting changes in saturation.

Determination of Adaptation Level

The determination of adaptation level is important for predictions involving color conversion. In assuming reflectance of background exercises preponderant influence in determining adaptation reflectance and its associated lightness, which we may call 'adaptation lightness' (L'), Judd,[16] and following him, Helson,[17] have taken adaptation reflectance to be the weighted geometric mean of background and sample reflectances according to the following formula:

$$A' = (\bar{A} \cdot A_0^3)^{1/4}, \tag{1}$$

where A' is adaptation reflectance, A_0 is reflectance of back-

[16] D. B. Judd, Hue, saturation and lightness of surface colors, *J.O.S.A.*, in press.
[17] *Cf.* footnote 1, p. 453.

ground, and $\bar{A}$ is the logarithmic average reflectance of all samples in the field of view. To predict lightness values in conformity with the 0–10 scale used in these experiments when reflectances range from 0.03 for darkest samples and background to 0.80 for lightest, Judd proposed the following formula by which reflectances transform into lightnesses:

$$L = \frac{1.03(10\,A - 0.3)(A' + 1)}{A' + A}, \qquad (2)$$

where A' is defined by formula (1) now and A is the apparent reflectance of the sample whose lightness is desired. To obtain adaptation lightness we substitute A' for A in formula (2) since we desire the lightness corresponding to adaptation reflectance or L'.

Formula (2) gave results in excellent agreement with the average lightness reported achromatic in a former study by Helson [18] with non-selective samples when $4/5A'$ was used in (2) in place of A'; but when applied even with this correction to the data of Table 2, it yielded values too high for adaptation lightness. Whereas adaptation lightness with only non-selective samples in the field was 7.1, 4.8, and 0.4 on the white, gray and black grounds, we find it to be 4.50, 3.81 and 0.00 in the present work with selective samples. Before making the changes in formula (1) necessary to make (2) satisfactory let us consider some of the differences between the former study and this one which account for the lower adaptation level we now find.

The chief differences between conditions in the present study and the earlier are to be found in the greater difficulty in judging saturations and hues of selective samples. Here we find greater individual differences among Ss and inversions in individual reports are more frequent. While plots of saturation as a function of lightness yield curves having the same general form found for non-selective samples, the scatter is much greater owing to longer fixation of samples and other factors which need to be correlated with measureable varia-

[18] *Ibid.*

bles. At the moment we can only 'allow' for them by introducing constants into the formulæ to accord with the experimental data.

There are, however, certain factors in the present conditions which are measureable and account, in part, for the lower adaptation lightness. Chief of these is the higher average reflectance of the samples in the present study as compared with that in the previous one. Whereas the logarithmic average reflectance of the non-selective samples was 0.14, here it is 0.22 for all samples in all illuminants. For a given reflectance of background the presence of a larger number of samples of higher reflectance will produce *more illuminant hues* and the situation is *as if* the reflectance of the background had been lowered, without this being the case, however. This means that the value of A' must be reduced if we are to derive values of L' in agreement with the findings of the present study.

We therefore change Judd's formula (1) as follows: we take the logarithmic average of $\bar{A}$ and A_0, giving unit weight to each, and then multiply this by the reducing factor 0.32. This gives:

$$A'' \equiv 0.32(\bar{A} \cdot A_0)^{1/2}. \qquad (3)$$

The use of A'' in formula (2) for L' yields adaptation lightnesses in good agreement with average observed adaptation lightness as shown in Table 4.[19] Owing to the inversions in

TABLE 4

AVERAGE LIGHTNESS OF SAMPLES REPORTED ACHROMATIC IN ALL ILLUMINANTS AND ADAPTATION LIGHTNESS AS CALCULATED FOR EACH BACKGROUND

Bckgd.	Observed L'	Calculated L' ($A'' = 0.32(\bar{A} \cdot A_0)^{\frac{1}{2}}$)
White	4.50	4.51
Gray	3.81	3.25
Black	0.00	0.00

the data average lightness for achromaticity was taken as the mean of the lightnesses of the two lowest contiguous satura-

[19] Calculations for L' are based on the following values derived from Table 2: logarithmic average reflectance of all samples in all illuminants, $\bar{A}$, is 0.22; A_0 is 0.80 for white ground, 0.24 for gray ground, and 0.03 for black ground. To solve for L' in formula (2) set $A = A''$.

tions on white and gray grounds and as zero on black ground because A 0/0 is achromatic on A 0/0 ground in every illuminant.[20]

The *A''* formulation for adaptation reflectance with its associated adaptation lightness still gives predominant weight to background reflectance in determining adaptation level but allows for special factors entering into these experiments.

Tolerance to Chromatic Illumination

The extent to which samples may be subjected to chromatic illuminants while retaining more or less of their daylight hues can be regarded as a measure of 'constancy.' Through the use of two apertures, one for filtered light and the other for lamp light of 2848° K., it was possible to mix varying amounts of these lights. Owing to the differences in transmission of our filters the addition of any given amount of lamp light to the filtered light resulted in different *percentages* of mixture: thus the use of 0.3 f.c. lamp light with the various filters gives the following percentages of lamp light in the mixtures when the illumination was 72 f.c. on sample plane without any filters: 8 percent in the yR, 1 percent in the rY, 5 percent in the yG, and 68 percent in the rB illuminations. The higher percentages in the yR and rB compensate for the greater chromaticity at lower intensities of wave-lengths at the ends of the spectrum. Thus in spite of the greater percentages of lamp light in the yR and rB illuminations the effects on hue are very much like those for the rY and yG.

Comparison of the hues reported in Table 2 with those given in Table 5 shows the effect of adding lamp light to the highly chromatic illuminants. A few examples will illustrate the general tendency: Y 7/8 which is RY in homogeneous yR illumination on white background is Y with the addition of the lamp light; G 3/4 under the same conditions changes from GB to bG, the added heterogeneous light reducing the B of the after-image hue; B 7/4 in yG illumination on white ground

[20] Adaptation reflectance turns out to be 0.026 on black ground but owing to formula (2) values less than 0.03 for A'' give negative values of L'. The small negative value in this case we take to be zero.

is yG but with the added lamp light it becomes gB, the yellow component of the illuminant disappearing while the green is reduced and the daylight hue becomes most prominent. The return to 'normal' is not a simple matter. Lightness and background reflectance come in to complicate matters. Thus G 3/4 in yG illumination on white ground is B, while G 7/7 is yG, the lighter sample holding the illuminant hue while the darker keeps the after-image hue.

The effect of background on constancy can be seen by following any one sample on the different backgrounds but in order to get a general idea of the facts let us deal in totals. Inspection of reports on black ground reveals fewer daylight hues than on white ground. Of the 180 reports on selective samples found in Table 5, 22 fail to contain at least one hue-component characteristic of the samples in daylight and of these 22, 12 occur on black ground as against 10 for both white and gray grounds. The fact that A 0/0 is A 0/0 with black ground in every illuminant is not an exception to our rule for it is the exception that proves the rule: A 0/0 being very near to adaptation reflectance on black ground, we expect it to be reported A 0/0 in homogeneous as well as mixed illuminations.

We come now to a consideration of the non-selective samples which we have left out of the discussion thus far. The statement is often found in the literature that "brightness constancy is greater than color constancy." This statement is extremely ambiguous as it stands for if taken in one way it is correct while taken in another it is incorrect. It is true that the lightness of both selective and non-selective samples undergoes less variation than hue with changes in composition and intensity of illumination and reflectance of background. It is not true that non-selective samples keep their achromaticity in chromatic illuminations better than selective samples do their hues. Exactly the reverse is the case because selective samples through their differential absorption of the components in the illuminant are able to emphasize certain wave-lengths and thereby their 'own hues' whereas non-selective samples, returning the energy of the illuminant indis-

TABLE 5

Hue, Lightness, and Saturation and Apparent Reflectance (A) of 18 Munsell Samples (M) in Four Chromatic Illuminants Mixed with 0.30 f.c. Lamp Light (2848° K.)

M	Yellowish-Red Illumination							Reddish-Yellow Illumination						
	A	White		Gray		Black		*A*	White		Gray		Black	
		H	*L/S*	*H*	*L/S*	*H*	*L/S*		*H*	*L/S*	*H*	*L/S*	*H*	*L/S*
R 3/7	.263	bR	5.0/3.0	yR	5.0/6.5	R	5.5/7.0	.151	bR	4.5/7.5	bR	4.5/7.0	yR	5.0/7.0
R 5/10	.671	yR	7.0/6.0	yR	7.0/7.0	yR	7.0/9.0	.402	yR	7.0/6.0	yR	7.0/8.0	yR	7.0/7.5
R 7/6	.759	RY	8.0/4.5	RY	7.5/7.5	yR	7.0/8.5	.616	yR	7.5/4.0	rY	7.5/7.0	rY	7.5/8.0
YR 4/5	.288	rY	5.0/2.0	rY	5.0/5.0	R	6.0/7.0	.245	yR	5.0/2.0	rY	5.0/3.0	Y	6.0/5.0
Y 5/7	.271	G	5.0/0.5	gY	5.0/3.0	yR	5.0/6.0	.288	A	5.0/0.0	yG	5.0/3.5	YG	5.0/5.0
Y 7/8	.573	Y	7.0/4.0	rY	6.5/6.0	yR	7.0/8.0	.588	yG	8.0/3.5	gY	7.0/6.0	Y	8.0/7.0
G 3/4	.074	bG	2.0/3.0	bG	2.0/1.0	bR	4.0/2.0	.079	B	2.0/3.0	B	3.0/3.0	yG	4.0/4.0
G 5/7	.100	bG	3.5/7.0	G	4.0/8.0	bG	5.0/5.5	.172	G	5.0/7.0	G	6.0/8.0	G	5.0/8.0
G 7/7	.343	bG	6.0/4.0	bG	6.0/5.0	bR	6.5/5.0	.429	yG	7.0/6.0	yG	6.5/5.5	yG	7.5/6.0
B 3/5	.067	gB	2.0/4.0	gB	2.0/4.0	rB	3.0/3.0	.073	B	2.0/3.5	B	2.5/2.0	G	3.0/3.0
B 5/6	.168	gB	3.5/3.0	B	5.0/3.0	RB	5.0/4.0	.185	BG	4.5/1.5	bG	5.0/4.0	yG	5.5/4.0
B 7/4	.391	gB	7.0/1.5	B	7.5/1.0	bR	7.0/5.0	.446	bG	7.0/5.0	yG	7.0/5.0	gY	7.5/5.0
P 3/6	.150	rB	2.5/2.0	bR	3.5/4.0	bR	4.0/6.0	.119	RB	4.0/5.0	bR	4.0/3.0	yR	5.0/4.5
P 5/6	.351	RB	6.0/2.5	bR	5.0/5.0	yR	7.0/7.0	.273	yR	5.0/2.5	bR	6.0/3.5	rY	6.0/4.0
pB 7/4	.429	rB	6.0/1.0	RB	7.5/4.0	bR	6.5/6.0	.405	gB	7.0/0.5	gY	6.5/2.0	gY	6.0/5.0
A 10/0	.800	R	9.0/0.5	R	8.0/3.0	R	7.0/7.5	.800	Y	9.0/3.0	Y	8.0/7.0	Y	8.0/8.0
A 5/0	.240	gB	4.0/0.5	R	4.5/1.0	bR	5.0/6.0	.240	RB	5.0/0.5	Y	5.0/0.5	Y	5.0/4.0
A 0/0	.030	BG	0.5/3.0	GB	1.0/2.0	A	0.0/0.0	.030	rD	1.0/4.0	B	0.5/0.5	A	0.0/0.0

TABLE 5—*Continued*

M	Yellowish-Green Illumination							Reddish-Blue Illumination							
	A	White		Gray		Black		*A*	White		Gray		Black	
		H	*L/S*	*H*	*L/S*	*H*	*L/S*		*H*	*L/S*	*H*	*L/S*	*H*	*L/S*
R 3/7	.054	RB	3.5/7.5	bR	3.0/6.0	yR	3.0/4.0	.072	R	3.0/3.0	R	3.0/7.0	R	4.0/6.0
R 5/10	.127	bR	4.0/7.5	bR	4.5/6.5	yR	5.0/6.0	.180	yR	4.0/7.0	bR	5.0/7.0	bR	5.5/7.0
R 7/6	.373	bR	7.0/3.5	rY	7.0/3.0	gY	7.0/4.5	.413	R	6.0/5.5	bR	7.0/5.5	bR	7.0/5.0
YR 4/5	.118	rY	4.5/4.0	rY	4.5/6.0	Y	5.0/4.0	.119	yR	4.0/6.0	RY	4.5/6.0	yR	4.5/6.0
Y 5/7	.225	rY	5.0/4.0	Y	5.0/4.5	gY	5.0/4.0	.166	rY	4.0/5.0	rY	4.0/6.0	RY	5.0/5.0
Y 7/8	.462	Y	7.0/5.0	Y	7.0/6.5	gY	7.0/6.0	.316	rY	6.0/7.0	rY	6.0/8.0	RY	6.0/6.0
G 3/4	.105	B	3.0/2.0	bG	4.0/0.5	G	4.0/5.0	.093	G	2.5/0.5	bG	3.0/4.0	B	4.0/1.0
G 5/7	.364	bG	6.5/6.0	G	6.0/7.0	G	6.0/7.5	.262	G	6.0/7.0	G	6.0/6.0	bG	6.0/7.0
G 7/7	.586	yG	8.0/4.0	yG	7.5/4.5	yG	7.0/6.0	.494	yG	7.0/5.0	bG	7.0/3.0	gB	8.0/3.0
B 3/5	.129	B	4.0/5.5	B	3.5/4.0	bG	4.0/7.0	.166	GB	5.0/6.0	gB	5.0/7.5	B	5.0/8.0
B 5/6	.138	gB	5.5/5.0	bG	6.5/7.0	G	6.0/6.5	.377	gB	6.0/7.0	gB	6.5/7.5	B	6.0/6.5
B 7/4	.573	gB	8.0/3.0	yG	8.0/3.5	yG	7.0/6.5	.584	B	8.0/5.0	B	8.0/4.0	B	8.0/5.0
P 3/6	.098	RB	3.5/6.0	rB	3.5/2.0	yG	3.0/0.5	.135	rB	4.0/5.0	rB	4.5/6.0	RB	4.5/8.0
P 5/6	.238	RY	5.0/0.5	bG	5.5/0.5	yG	5.0/4.0	.288	rB	5.0/5.0	rB	6.0/6.0	rB	6.0/5.5
pB 7/4	.481	gB	7.0/3.0	G	7.0/3.5	yG	7.0/5.5	.531	B	7.5/5.0	B	7.0/5.5	B	7.0/6.0
A 10/0	.800	YG	9.5/1.0	gY	8.0/3.0	gY	8.0/5.0	.800	A	10.0/0.0	rB	9.5/0.5	RB	8.0/4.0
A 5/0	.240	RB	5.0/1.0	A	5.0/0.0	yG	5.0/4.5	.240	A	5.0/0.0	A	5.0/0.0	rB	5.0/5.0
A 0/0	.030	rB	1.0/2.0	RB	1.0/0.5	A	0.0/0.0	.030	A	0.0/0.0	A	0.0/0.0	A	0.0/0.0

criminately, do not retain their achromaticity and are therefore more subject to conversion.[21] The non-selective samples in Table 5 are seen to lag behind the selective samples in returning to daylight hue. This is confirmed by adding 4.5 f.c. lamp light to the chromatic illuminants. While this amount of lamp light sufficed to bring back almost 100 percent of the selective samples to their daylight hues it was much less effective with the non-selective samples, 36 percent failing to become achromatic in it.

The quantitative determination of tolerance to chromatic illuminants, hence of constancy, is beset with the difficulty of drawing the line at which samples may be said to have their 'normal' hues. We have seen that with as little as 0.3 f.c. lamp light some return to daylight hues is noticeable (Table 5). If we take as our standard of tolerance the complete return of all samples to their daylight hues the amount of tolerance is enormously reduced for the lamp light required for this purpose is greater than the amount of chromatic in most cases.

For practically complete return of selective samples to daylight hues 4.5 f.c. lamp light was necessary. Owing to the differences in transmission of the four filters this gave the following percentages lamp light in the chromatic: 120 percent for the yR, 17 percent for the rY, 167 percent for the yG, and 1002 percent for the rB. Obviously the amount of lamp light admixture varies greatly for the different hues and brings out the fact that tolerance to chromatic components in an illuminant is least for the hues which have the greatest saturations.[22] With the exception of the yG the reciprocals of these percentages follow the order of intensities necessary for maximum saturation, violet and red requiring minimal intensities and yellow and green maximal. Had we used a graded series

[21] In line with this finding we recommend the use of non-selective samples to detect chromatic components in weakly chromatic illuminants. Non-selective samples furnish a more severe test of the achromaticity of an illuminant than do selective samples which have far greater constancy.

[22] In this connection the results for after-desaturation should be noted. *Cf.* also footnote 9.

of admixtures of lamp light to each of the chromatic illuminants the yG illuminant would not have emerged as an exception in all probability. On the other hand, the value for red would have been larger had our yR illuminant plotted in a longer-wave region of the spectrum (say 660 mμ) instead of at 630 mμ which is more yellowish-red. This would bring our results into perfect alignment with the facts of chromatic valence and the greater fatigability of the red and violet as opposed to the yellow and green hues.[23]

Some Theoretical Conclusions

The methods employed in the present series of studies have been characterized by stimulation of the *whole retina* with homogeneous and near-homogeneous illuminants. In this way we have duplicated the classic use of stimuli of known composition but we have gone farther in that we have varied the conditions of stimulation by enlarging the retinal area subject to these stimuli and by introducing differential intensities of stimulation between retinal regions. Our results prove the importance of field conditions in determining the color of local regions. This determination is wider than can be inferred from the classical work and theories based on it. Backgrounds differing only in lightness have been found to exert not only the classical lightness contrast but hue and saturation effects of even greater importance. We would expect, and confidently predict, that experiments employing small spectrally homogeneous patches of light will yield different results when background (surround in the retina) is changed from the classic dark field to light or chromatic field.

In a previous study in this series it was emphasized that underneath the *various color phenomena* a *single mechanism* must be functioning because effects formerly attributed to entirely different processes could be seen simultaneously if

[23] It should be pointed out that attitude of the S has a good deal to do with the amount of tolerance which will be found in any case. An S who is set to discover as many daylight hues as possible will seem to have greater tolerance for chromatic illuminants. Color workers, to whom small color differences are important, will show less tolerance than Ss with the other attitude. Quantitative measurements of tolerances will eventually have to provide for such differences in attitude.

the right conditions were provided. The principle of conversion states both the phenomenological or color facts and at the same time indicates the mechanism by which they are to be explained. Let us assume, as Troland has done in his presentation of the trichromatic theory,[24] that each intensity and composition of light beam reaching the eyes causes reaction in each of three retinal substances. Equal rates of the three result in achromaticity and hence determine adaptation level. A certain hue would correspond to a higher rate and the after-image hue to a lower rate. Actually both rate of reaction of processes in the retina and ratios of rates in different parts of the retina must be taken into consideration because higher saturations are found both with higher general intensities of illumination and with larger differential intensities within the visual field. High rates of reaction giving unit ratios among the three substances result in high adaptation level (white) while low unit ratios yield a low adaptation level (dark gray or black).

It is of minor importance whether we envisage these facts in terms of one color theory or another. On the basis of the Hering theory it is necessary to think of a given hue, which may arise as an illuminant hue or as a complementary hue, as being due in one case to ratios greater than unity and in the other case to ratios less than unity. This is awkward and so a trichromatic formulation seems at the moment preferable. Assuming now that hue is a resultant of the excitations of three color-cones or substances in the retina which respond in varying amount to various wave-lengths in the usual manner, we would expect these substances to mediate hues according to the rate at which they produce color materials through decomposition or some other physico-chemical change. Since rate of reaction depends on the concentration of reacting materials, as the reaction proceeds the concentration decreases and so does the rate. The faster each of these substances decomposes the greater its contribution to the resultant color but as a result less and less materials are available (up to a

[24] L. T. Troland, *The Principles of Psychophysiology*, 1930, Vol. 2, Sensation, 189 ff., especially 191–193.

certain point without replenishment) for further decomposition as stimulation continues. If one substance is used up more than the others, the latter make relatively more contribution to the seen color. With, for example, predominantly long-wave stimulation, one of the substances, the R-substance, will be stimulated more by the lighter parts of the field than the G- and V-substances and will contribute more to the resultant hue. But owing to the exhaustion of the R-substance darker parts of the field which do not send enough energy to the eye to maintain a higher rate of reaction than that of the G- and V-processes will appear not in R-hue but in GV-hue. The G- and V-substances having decomposed less than the R-substance are relatively more sensitive. The lessened sensitivity of the R-substance is therefore manifested either in lowered saturation of R-hues or in the appearance of after-image hues.

The relation of reactivity to intensity, both absolute and differential, explains why increase in intensity of the whole field results in more illuminant hues in lighter parts of the field. The background governs both absolute and differential intensities very largely and thus exercises its effects. Shifting adaptation level is explained by reference to establishment of unit ratios at various intensity levels. White and black may be regarded most simply as high and low unit ratios. For vision in daylight with its rich variety of colors we assume an adaptation level corresponding to unit ratios between the R-, G-, and V-processes. Added stimulation of one or the other of the three substances from local parts of the field gives rise to local colors. The induction of black in dark parts of the field is explained by the lower unit ratios in these regions.

No claim is made for the complete adequacy of the trichromatic theory or any other theory of color vision. A formulation is necessary in physiological terms which brings all parts of the visual field into intimate relations and takes into account the basic fact, which we have found in all our work, that the eye is a mechanism which responds in very important ways to differential stimulation. The theory of conversion recognizes these things and yet does not depend upon any particular theory of color vision since it springs directly from observation. Our application of the trichromatic theory to the phenomena of conversion has been merely for the purpose of illustrating how one of the classical theories can be made to explain new facts.

Summary

Experiments involving stimulation of the whole retina with homogeneous and near-homogeneous illuminants and differential intensities in various parts of the field show that certain hitherto neglected factors profoundly influence hue, lightness, and saturation in predictable ways. We can summarize briefly:

1. Hue, lightness, and saturation depend not only upon the composition and intensity of light from an object but fully as much upon the reflectance of background and other objects in the field of vision.
2. Through its effect on adaptation level the background may induce the illuminant hue or the after-image hue on the sample, depending upon the reflectance of the sample. Effects of backgrounds differing only in lightness are thus seen to be wider than classic laws imply, for hue and saturation are affected by reflectance of background as well as lightness.
3. Selective samples have greater constancy in chromatic illuminants than non-selective samples as the latter tend to be tinged more easily either with the hue of the illuminant or its complementary while the former tend to keep their daylight hue if their dominant wave-length is present even as a minor component in the illuminant.
4. The hue of selective samples in strongly chromatic illuminants which are not homogeneous tends to be a mixture of daylight hue and the hue resulting from conversion in homogeneous illuminants.
5. The effects of chromatic illuminants depend upon the distances of the illuminant points in the color mixture diagram from the white point. Illuminants having hues characteristic of the ends of the spectrum (red and blue-violet) give the greatest chromatic effects and after-effects.

6. Constancy of object color or tolerance to chromatic illumination is not predictable from the hues of sample and illuminant alone. It depends chiefly upon reflectance of sample and background, dominant wave-length of the illuminant, and attitude of the observer.

7. A revised formula was found necessary for adaptation reflectance to meet the conditions in the present study. It yields values of adaptation lightness in good agreement with observation.

8. The bearing of certain results in this study on previous work and theories has been pointed out and the importance of the eye as an organ that responds primarily to differential stimulation receives new confirmation.

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