Prediction of Color Appearance of Object Colors in a Complex Visual Field

Yoshinobu Nayatani
Kotaro Takahama*
Hiroaki Sobagaki*

Osaka Electro-Communication University
18-8, Hatsu-cho, Neyagawa, Osaka, 572, JAPAN

* Electrotechnical Laboratory, Life Electronics Research Center
3-11-46, Nakoji, Amagasaki, Hyogo, 661, JAPAN
Received January 27, 1995.

SUMMARY

Color appearance of object colors in a complex visual field is studied by a nonlinear color-appearance model of Nayatani et al. The experimental results by McCann et al. using a Color Mondrian are analyzed by the model. The analyses clarified that the experimental results are estimated well by introducing an incomplete adaptation mechanism to the nonlinear color-appearance model.

1. Introduction

A nonlinear color-appearance model was developed by the present authors for predicting the color appearance of object colors under various illuminations (various illuminants and adapting illuminances) on an achromatic background.¹⁻³ Further, the model gave the estimations correlating with the various experiments on the Helmholtz-Kohlrausch effect on object and pseudo-object colors.⁴ It also predicted well⁵ the G_0 function^{6,7} corresponding to the zero gray point by Evans and the discrimination of colorimetric purity at an achromatic point.^{8,9} However, all these studies were done for predicting the color appearance of object colors on a simple visual field. The simple visual field experiment means the color-appearance assessment of a single color stimulus presented on a uniform achromatic background. It is interesting to study whether the nonlinear color-appearance model can apply to a complex visual field experiment. For this reason, the following analyses were done on the color appearance of object colors on a complex visual field under various chromatic illuminations.

- (1) The results of a complex visual field experiment by McCann et al.¹⁰ were analyzed by using the nonlinear color-appearance model. The experiment was done using chromatic object colors on a Mondrian figure under various illuminations. It was confirmed that the model could predict the experimental results quite satisfactorily.
- (2) In the process of the analysis in item (1), a proposal was given to the nonlinear color-appearance model for applying it to an incomplete adaptation to chromatic test illumination.

- (3) Before conducting the analysis, all the colorimetric values on illuminants and object colors used in the experiment were estimated from the information described in the article by McCann et al.¹⁰

Based on the present study, it was clarified that the nonlinear color-appearance model could apply well to the chromatic-adaptation experiment on a practical complex visual field in addition to that on the simple visual field..

2. Formulation of the Nonlinear Color-Appearance Model

In this section, we introduce the nonlinear color-appearance model. The nonlinear color-appearance model uses the following basic three responses^{1,2} U_R , U_G , and U_B for predicting the color appearance of a test color on an achromatic background with tristimulus value Y_0 under a test illumination.

$$\begin{aligned} U_R &= \beta_1(R_0) \log[(R+1)/(Y_0\xi+1)], \\ U_G &= \beta_1(G_0) \log[(G+1)/(Y_0\eta+1)], \\ U_B &= \beta_2(B_0) \log[(B+1)/(Y_0\zeta+1)], \end{aligned} \quad (1)$$

where R , G , B are the relative tristimulus values of the test color in a fundamental-primary system, R_0 , G_0 , B_0 the effective adapting luminances also in the same fundamental-primary system, β_1 , β_2 the two kinds of monotonic increasing function with different slopes. The quantities ξ , η , ζ are related with the chromaticity coordinates x_0 , y_0 of the test illuminant, and they are given by eq.(2).

$$\begin{aligned}\xi &= (0.48105x_0 + 0.78841y_0 - 0.08081)/y_0, \\ \eta &= (-0.27200x_0 + 1.11962y_0 + 0.04570)/y_0, \quad (2) \\ \zeta &= 0.91822(1 - x_0 - y_0)/y_0.\end{aligned}$$

The quantities U_R , U_G and U_B correspond to the nonlinear output of the three kinds of cones corresponding to the color stimulus of the test color. The model further specifies the opponent-color responses given by eq. (3).

$$\begin{aligned}Q &= k_Q [(2/3)e(R)U_R + (1/3)e(G)U_G] + K, \\ T &= k_C e_s(\theta) [U_R - (12/11)U_G + (1/11)U_B], \quad (3) \\ P &= k_C e_s(\theta) [(1/9)U_R + (1/9)U_G - (2/9)U_B],\end{aligned}$$

where the coefficients $e(R)$ and $e(G)$ of the Q response are given by

$$\begin{aligned}e(R) &= 1.75 & \text{for } R \geq 20\xi \\ &= 1.00 & \text{for } R < 20\xi, \\ e(G) &= 1.75 & \text{for } G \geq 20\eta \\ &= 1.00 & \text{for } G < 20\eta\end{aligned} \quad (4)$$

and K is an additive constant.

The coefficient $e_s(\theta)$ in eq. (3) is the weighting function on chroma and hue initially introduced by Hunt.¹¹ The equation of $e_s(\theta)$ in the nonlinear color-appearance model is given in Appendix of the reference 1. Based on the responses Q , T , P , the formulations have been published for hue, brightness, colorfulness, lightness, and chroma.

3. Summary of the Experiment by McCann ET AL.

The scope of the present article is to confirm the applicability of the nonlinear color-appearance model to the prediction of the color appearance of object colors on a complex visual field. The experiment of McCann et al.¹⁰ is briefly summarized below. In addition, the colorimetric values of the experiment are derived, which are needed for testing the nonlinear color-appearance model.

A biseptum-matching method was used in the McCann experiment. One booth was illuminated by test illuminant with usually chromatic color, and it was used for test field. The other was always illuminated by a white illuminant and used for the comparison field. A Mondrian figure was displayed in the test field, and consisted of 18 colored areas with 17 object colors and a gray background. For reference, the area notation and the Munsell notation of each sample in the Mondrian figure used by McCann are shown in Fig.1. Five test illuminants were used, whose colors were white, green, orange, pink, and purple. The experiment on each test illuminant is called that of gray, red, blue, green, and yellow following the above order of illuminant color. The naming of the experiments is described later.

In the comparison field, colors of a Munsell book were displayed. In the experiment, each subject chose the Munsell color in the comparison field, which matched in color to each of object colors on the Mondrian figure of the test field. Three subjects participated in the experiments, and 5 repetitions were done for all the experiments. The results were given by taking the average of 15 observed data (3 subjects $\times$ 5 trials) to each test sample on the Mondrian figure under each test illuminant, and they were shown by Munsell notations.¹⁰ Their tristimulus values were not described.

To derive the tristimulus values, the spectral reflectance functions were estimated from the Munsell notations of the test and the matching colors given in the McCann experiment. In the estimation, the method developed by the present authors^{12,13} was used for deriving the spectral reflectance function corresponding to each Munsell notation. Based on the spectral irradiance values of each illuminant and the estimated spectral reflectance functions, the chromaticity coordinates of all the illuminants and the tristimulus values of all the test colors on the Mondrian figure in the test field were estimated for each test illuminant. Using the same procedure, the tristimulus values of each matching color under the white illuminant in the matching field were derived. The details are described below.

Before conducting the analysis of the McCann et al. data, the procedure used in their observation should be noted. In the McCann experiment, while the test sample in the test field was viewed by the left eye of each observer, his right eye adapted to dark. Then, while the matching sample of the comparison field was viewed by his right eye, his left eye adapted to dark. By observing the right and the left fields successively, finally the matching sample was determined to the test sample.

In this procedure, each eye of observer is adapted to dark about a half of the observation period, and a recovery of adaptation is expected during the period adapted to dark. This means that the effective adapting illuminance may be estimated at about $E/2$. However, the adapting illuminance E is always used to each field in the succeeding analyses, because the illuminance adaptation in photopic range proceeds rather rapidly.

3.1 Computation of Tristimulus Values

All the illuminants in both fields consisted of mixing three monochromatic lights. The wavelength of each monochromatic light was 450nm, 530nm, and 630nm with the same band width of 10nm, respectively.

By specifying $\lambda_1=450$ nm, $\lambda_2=530$ nm and $\lambda_3=630$ nm, the irradiance of each of the three monochromatic lights, $Ee(\lambda_i)$, with $i=1,2,3$, and the spectral reflectance of object color $\rho(\lambda_i)$, tristimulus values are given by eq.(5).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = k \sum_{i=1}^3 E_e(\lambda_i) \rho(\lambda_i) \begin{bmatrix} x(\lambda_i) \\ y(\lambda_i) \\ z(\lambda_i) \end{bmatrix}, \quad (5a)$$

where

$$k = 100 / \sum_{i=1}^3 E_e(\lambda_i) \bar{y}(\lambda_i) \quad (5b)$$

3.2 Illumination in Each Experiment

In each of the 5 experiments with different test illuminants, a specific sample was chosen from the 18 colors in the Mondrian figure. The sample chosen was different for different experiments. The 5 specific samples chosen are perceived as gray, red, blue, green and yellow colors under the white illuminant. Table 1 shows the samples and their Munsell notations in the third column. In all the 5 experiments, the irradiances of the three monochromatic lights were adjusted so that the radiances [$\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2}$] of the specific samples had the same values shown in eq.(6).

$$\begin{aligned} L_e(450) &= 1.6 \times 10^{-3}, L_e(530) = 3.2 \times 10^{-3}, \\ L_e(630) &= 5.8 \times 10^{-3} \end{aligned} \quad (6)$$

The naming of gray, red, blue, green, and yellow experiments shown in the first column of Table 1 corresponds to the perceived color of the specific sample in each experiment under the white illumination.

Though the chromaticity coordinates of the test illuminants are shown later, the following relations exist between the illuminant color and the name of the experiment. White test illuminant was used in gray experiment, green test illuminant in red experiment, orange test illuminant in blue experiment, pink test illuminant in green experiment, and purple test illuminant to yellow experiment. Test illuminant color was selected to be complementary to that of the specific sample in each experiment. This procedure makes the spectral radiances of the specific sample the same as shown in eq.(6) irrespective of the experiments.

By the above procedure, the relative spectral radiance distribution of the specific gray sample in the gray experiment under the white test illuminant is kept the same as that of the specific red sample in the red experiment under the green test illuminant. However the former is perceived an achromatic color, but the latter keeps the perception of red color due to the effect of chromatic adaptation.

Denoting the spectral reflectance function of each specific sample in each experiment was denoted by $\rho_r(\lambda)$, its irradiances were estimated by eq.(7) to each test illuminant,

$$E_e(\lambda_i) = \pi L_e(\lambda_i) / \rho_r(\lambda_i),$$

where $i=1,2,3$ and $\pi=3.1416$. (7)

The illuminance [lux] in each of the five experiments was estimated by

$$E = K_m \sum_{i=1}^3 E_e(\lambda_i) V(\lambda_i), \quad (8)$$

where $V(\lambda_i)$ is the value of the CIE 1924 relative spectral luminosity function at λ_i , and $K_m = 683 \text{ lm/W}$.

3.3 Spectral Reflectances of the Mondrian Samples

The spectral-reflectance values of all object colors on the Mondrian figure were estimated from their nominal Munsell notations in Fig. 1 and their x , y and Y values under illuminant C.^{12,13} Table 1 only shows the values of spectral reflectances at the 3 wavelengths to the 5 specific samples in the 5 experiments.

Table 1. Values of spectral reflectances of the five specific samples in the five experiments at 450 nm, 530 nm and 630 nm, respectively.

Experiment	Area	Munsell Renotation	$\rho_r(450)$	$\rho_r(530)$	$\rho_r(630)$
Gray	P	N6.75	0.3954	0.3954	0.3954
Red	G	10RP6/10	0.2524	0.1695	0.7211
Blue	H	2.5PB6/8	0.5829	0.3647	0.1976
Green	R	2.5G7/6	0.2756	0.5597	0.2361
Yellow	C	5Y8.5/10	0.1172	0.6610	0.8017

3.4 Specification of Test Illuminants

Using eqs.(6) and (7) and $\rho_r(\lambda)$ values in Table 1, the irradiances of the test illuminant in each experiment were derived and are shown in the columns 2 to 4 in Table 2. Further, the illuminance and the chromaticity coordinates of the test illumination in each experiment was derived from its irradiance values. The results are also shown in the columns 5 to 7 in Table 2.

Table 2. Values of irradiances, illuminances, and chromaticity coordinates estimated for the five test illuminants used in the McCann experiment.

Experiment	Irradiance ($\text{W} \cdot \text{m}^{-2}$)			Illuminance (lx)	Chromaticity	
	$E_e(450)$	$E_e(530)$	$E_e(630)$		x	y
Gray	$1.271 \cdot 10^{-2}$	$2.543 \cdot 10^{-2}$	$4.608 \cdot 10^{-2}$	23.64	0.3955	0.3595
Red	$1.992 \cdot 10^{-2}$	$5.931 \cdot 10^{-2}$	$2.527 \cdot 10^{-2}$	40.01	0.2536	0.4536
Blue	$0.862 \cdot 10^{-2}$	$2.757 \cdot 10^{-2}$	$9.221 \cdot 10^{-2}$	33.15	0.5066	0.3686
Green	$1.824 \cdot 10^{-2}$	$1.796 \cdot 10^{-2}$	$7.718 \cdot 10^{-2}$	25.02	0.4571	0.2853
Yellow	$4.289 \cdot 10^{-2}$	$1.521 \cdot 10^{-2}$	$2.273 \cdot 10^{-2}$	14.18	0.2446	0.1610

Fig. 1. The Color arrangement of the Mondrian figure used by McCann et al.¹⁰ The Munsell designation of each color area is shown in the figure. Each area is also identified by a capital letter for reference in this article.

Fig. 2. The chromaticity points of the five test illuminants used in the McCann experiment. The notations Gray, B, R, Y and G correspond to the names of the five kinds of experiments.

The chromaticity coordinates of the test illuminant in each experiment are shown in Fig.2. The notation at each chromaticity point in the figure corresponds to the experiment name. It is easily found that the red experiment corresponds to the green test illuminant, the yellow experiment to the purple test illuminant, and so on. The

chromatic illuminants used have intermediate saturations. Extremely saturated illuminant colors were not tested in the McCann experiment.

3.5 Colorimetric Information in Both Fields

The tristimulus values of each test color on the Mondrian figure under each test illuminant were computed by substituting its spectral-reflectance values already derived and the irradiance values of the component monochromatic lights of the corresponding test illuminant in Table 2 into eq.(5).

To the matching samples in the comparison field, their tristimulus values were determined by the following procedure. The illumination of the comparison field is always the same as that of the test field in the gray experiment found in Table 2. To the nominal Munsell notations of the matching samples in the comparison field, their colorimetric values were determined by using the procedure already described.

The tristimulus values of the test colors on the Mondrian figure are shown in Table 3 to each of the 5 experiments, and those of the matching colors in the comparison field are shown in Table 4 under the white illumination corresponding to each of the 5 experiments.

4. Analysis I

The chromaticities and illuminances of the illuminants used, and the tristimulus values of the test colors and the matching colors, were derived in the last section. On the basis of these colorimetric values, the responses Q, T, and P in the nonlinear color-appearance model were computed to the test colors used in the McCann experiment and to the corresponding matching colors. The background used in the computation was the achromatic sample with the tristimulus value $Y_0=20$, which was similar to the gray background with N5.75/ used in the McCann experiment. The normalized illuminance E_{0r} of the nonlinear color-appearance model was set at 3000 lx. In the computation, the adaptation of the test field was specified by the illuminance and the chromaticity coordinates of the test illuminant corresponding to each of the 5 experiments shown in Table 2. The adaptation of the comparison field was specified by the illuminance and the chromaticity coordinates of the white illuminant corresponding to the gray experiment in Table 2, and the same adaptation was used throughout all the experiments. The computed results of the responses Q, T, and P for the 5 experiments showed that the Q responses did not change appreciably by changing the adaptation from each test illuminant to the corresponding matching white illumination. By this reason, only the T, P responses were analyzed for each of the 5 different adapting conditions.

Table 3. Tristimulus values of the 18 test colors in the Mondrian figure for each of the five experiments.

Area		Experiment				
		Gray	Red	Blue	Green	Yellow
A	X	29.96	15.22	37.42	43.63	41.36
	Y	27.23	27.23	27.23	27.23	27.23
	Z	18.56	17.57	9.22	24.59	100.51
B	X	30.53	12.13	41.66	46.66	29.88
	Y	19.92	15.22	22.93	23.94	18.33
	Z	5.34	5.13	2.70	6.97	28.19
C	X	78.04	34.63	104.77	115.85	72.53
	Y	70.30	67.01	72.82	72.93	65.91
	Z	9.68	9.89	5.27	11.71	44.94
D	X	18.74	13.36	20.27	24.36	32.77
	Y	30.47	37.31	26.24	24.51	31.43
	Z	19.36	18.50	9.73	25.39	103.06
E	X	23.02	13.18	28.45	31.90	26.88
	Y	31.00	35.27	28.49	27.21	30.46
	Z	9.02	8.88	4.70	11.43	45.34
F	X	55.20	19.35	77.21	86.45	51.20
	Y	25.85	12.38	34.33	37.47	22.55
	Z	6.42	6.02	3.16	8.58	35.25
G	X	66.84	25.71	91.12	103.21	70.29
	Y	36.52	23.36	44.78	47.91	33.60
	Z	16.95	15.93	8.35	22.62	92.91
H	X	28.53	18.25	31.03	39.47	58.80
	Y	30.88	34.84	28.20	27.55	33.34
	Z	39.06	36.68	19.22	52.19	214.49
I	X	58.92	30.84	75.42	83.77	61.82
	Y	70.40	76.57	66.97	64.82	68.09
	Z	15.29	15.28	8.12	19.02	74.48
J	X	15.29	5.78	20.90	23.70	16.15
	Y	7.83	4.58	9.86	10.65	7.17
	Z	3.94	3.70	1.94	5.29	21.76
K	X	101.68	51.66	127.02	148.08	140.38
	Y	92.42	92.42	92.42	92.42	92.42
	Z	63.00	59.64	31.31	83.47	341.15
L	X	1.75	0.89	2.19	2.55	2.42
	Y	1.59	1.59	1.59	1.59	1.59
	Z	1.08	1.03	0.54	1.44	5.87
M	X	76.94	29.22	106.12	118.60	72.56
	Y	45.68	31.52	54.72	57.86	41.31
	Z	10.39	9.97	5.25	13.56	54.87
N	X	49.64	22.02	66.54	73.75	47.00
	Y	44.11	41.80	45.82	45.97	41.42
	Z	7.10	7.16	3.81	8.76	34.07
O	X	52.03	31.01	60.64	72.58	85.10
	Y	60.02	67.08	55.57	53.92	61.77
	Z	46.98	44.50	23.36	62.21	254.16
P	X	43.50	22.10	54.34	63.35	60.06
	Y	39.54	39.54	39.54	39.54	39.54
	Z	26.95	25.52	13.39	35.71	145.95
Q	X	57.16	28.24	71.17	84.33	84.88
	Y	44.33	41.29	46.07	47.05	45.02
	Z	41.87	39.34	20.61	55.95	229.89
R	X	30.40	19.07	35.73	41.12	42.53
	Y	44.16	51.90	39.48	37.36	44.35
	Z	19.67	19.00	10.02	25.48	102.61

In each experiment, the responses of the test and the matching colors were plotted in the T-P plane shown in each of Figs.3 to 7. In each figure, dots correspond to the test

Table 4. Tristimulus values of the Munsell colors in the comparison field matched with the 18 test colors in the Mondrian figure.

Area		Experiment				
		Gray	Red	Blue	Green	Yellow
A	X	34.58	27.17	34.25	24.86	23.40
	Y	30.01	29.69	29.40	19.91	19.81
	Z	17.51	18.97	18.25	13.80	19.83
B	X	33.62	23.98	51.89	36.75	19.59
	Y	20.23	19.95	31.00	20.99	12.06
	Z	3.54	6.01	4.64	4.44	2.70
C	X	78.73	78.29	76.66	81.06	67.11
	Y	70.49	80.95	60.80	60.53	60.54
	Z	6.24	11.44	5.64	9.84	11.45
D	X	19.04	34.03	22.62	26.61	25.81
	Y	30.40	43.17	30.30	30.63	31.16
	Z	21.58	25.55	17.56	26.31	31.60
E	X	25.51	31.18	27.56	29.05	24.59
	Y	30.83	44.77	30.72	30.44	30.52
	Z	7.44	10.56	6.66	10.21	13.52
F	X	53.51	41.27	53.51	53.51	36.57
	Y	25.20	22.66	25.20	25.20	16.02
	Z	4.64	7.02	4.64	4.64	2.37
G	X	66.63	51.06	66.05	75.16	63.01
	Y	36.13	32.59	35.69	37.99	35.56
	Z	14.55	15.34	12.35	13.57	22.74
H	X	28.52	40.35	30.41	23.75	24.64
	Y	30.88	44.45	30.25	20.09	20.27
	Z	39.06	43.91	28.26	33.45	39.14
I	X	52.64	47.54	67.91	62.77	53.51
	Y	61.00	61.33	70.41	60.80	60.32
	Z	7.67	8.79	9.15	7.30	17.73
J	X	24.06	19.23	28.60	28.60	14.54
	Y	13.52	12.35	14.48	14.48	7.71
	Z	5.40	5.13	4.64	4.64	5.56
K	X	90.92	78.28	91.68	80.16	70.19
	Y	77.28	76.68	77.45	61.13	59.65
	Z	49.23	50.99	47.44	39.52	50.98
L	X	2.22	2.78	2.78	2.78	2.78
	Y	2.02	2.53	2.53	2.53	2.53
	Z	1.38	1.73	1.73	1.73	1.73
M	X	76.94	55.86	61.89	83.61	57.17
	Y	45.68	43.78	32.98	46.64	32.29
	Z	10.39	12.24	4.10	7.44	6.02
N	X	54.23	38.89	55.63	60.56	58.29
	Y	44.03	44.26	44.18	44.09	43.96
	Z	7.79	7.33	4.96	5.90	8.71
O	X	56.14	49.64	58.46	62.33	44.49
	Y	60.13	59.35	59.39	59.13	43.22
	Z	50.33	42.71	43.49	52.56	45.69
P	X	34.25	42.54	34.25	36.97	35.01
	Y	29.40	41.97	29.40	30.10	30.13
	Z	18.25	28.73	18.25	20.36	28.27
Q	X	63.13	65.17	90.50	69.56	57.84
	Y	45.27	59.08	63.38	46.26	44.42
	Z	36.44	52.41	41.63	39.45	49.46
R	X	32.41	45.48	48.57	36.27	34.09
	Y	44.29	60.59	60.47	43.52	43.00
	Z	16.49	23.26	20.42	20.07	28.04

colors and open circles to the matching colors. Dot of each test color is connected by a straight line with the open circle of the corresponding matching color.

Fig. 3. The T and P values of the test colors (dots) under white illumination (the gray experiment) in the test field, and those of the matching colors (open circles) under the same white illumination in the comparison field. Each dot of a test color is connected by a straight line with the open circle of its corresponding matching color.

The predictability of the model is assessed by the degree of conformity between the test and the matching colors in the plane. The T, P responses of the gray experiment are shown in Fig.3. As the illuminant of the test field was the same as that of the comparison field in the gray experiment, it is expected that the Munsell notation of each test color is the same as that of its corresponding matching color in the McCann experiment. In other words, the same T, P values are expected between the test and the matching colors. However, some deviations are found in Fig.3 reflecting observational errors and the different color arrangement in both fields. The average deviation between the dots and the open circles is 3.50 in the T-P plane. The values of 3.5 corresponds to about 0.5 Munsell Chroma difference.

Figures 4 to 7 show the computed results to the red, the blue, the green, and the yellow experiments, respectively. The inspection of each figure clearly shows that the predicted points of matching colors (open circles) shifted in the direction of test illuminant hue from the points of test colors (dots). For example, in the green experiment (Fig.6) the test illuminant has a pink color. The T, P values of the matching color to the gray background under the test pink illuminant (the open circle with A in the figure) show its perceived color reddish, and they correspond to the actual observation. On the other hand, the corresponding predicted T, P values with dot to the gray background in the test field under the pink illumination is close to the origin of the T-P plane. This means that the background in the test field is perceived gray, but this is a prediction by the model to the tristimulus values of the background under the pink illumination.

Fig. 4. The T and P values of the test colors (dots) under green illumination (the red experiment) in the test field, and those of the matching colors (open circles) under white illumination in the comparison fields. Regarding the connecting lines between dots and open circles, see the caption of Fig. 3.

Fig. 5. The T and P values for orange illumination (the blue experiment). See the caption of Fig. 4 for notations.

Fig. 6. The T and P values for pink illumination (the green experiment). See the caption of Fig. 4 for notations.

Fig. 7. The T and P values for purple illumination (the yellow experiment). See the caption of Fig.4 for notations.

The prediction using the nonlinear color-appearance model under the test illumination is done by postulating the complete adaptation to the test pink-illuminant color in the test field. The predicted point of the matching color to the test background (the open circle with A in Fig.6), however, shifted from the origin to the reddish hue direction, though the experiment by McCann et al. showed the color match between the backgrounds in the test field and its matching color in the comparison field. This may suggest that the condition of complete adaptation to the test chromatic illuminant used in the nonlinear color-appearance model is inadequate for predicting the McCann experiment satisfactorily.

The above results suggest that the adapting point of the test chromatic illuminant may lie at an intermediate point between the test and the white illuminant. To confirm this, the T, P responses in the nonlinear color-appearance model were computed to the test colors under the test pink illuminant by keeping the adaptation to the white illuminant. In the confirmation, the adapting illuminance and the adapting chromaticity coordinates used in the test field are those corresponding to the gray experiment in Table 2. The tristimulus values of the test and the matching samples used are the same as those shown in Tables 3 and 4 for the green experiment. This situation corresponds to the condition that the observer adapted to daylight illumination looks at the object colors under the test pink illuminant in a small booth constituting a part of his visual field.

The T, P responses of the test colors estimated by keeping the adaptation to the white illuminant are shown by open triangles in Fig.8. The T, P responses of the matching colors (open circles) are found just in between the dots completely adapted to the pink test illuminant and the open triangles adapted to the white illuminant. The results clearly show that an incomplete adaptation to the test chromatic illuminant holds in the observing condition of the McCann experiment, which will be discussed later. To the other test chromatic illuminants, the results similar to Fig.8 were observed.

Fig. 8. The T and P responses for pink illumination (the green experiment). Dots correspond to the T and P responses of the test colors in the test field predicted by observers adapted completely to pink illumination [$k=1$ in Eq. (9)], and open triangles to those of the test colors under pink illumination but predicted by observers adapted to white illumination [$k=0$ in Eq. (9)]. Open circles are the T and P responses of the matching colors under white illumination in the comparison field. Dots and open circles are the same as those in Fig. 6. Each combination of dots, open circles, and open triangles connected by straight lines corresponds to each of the 18 test colors.

5. Introduction of Incomplete-Adaptation Mechanism to the Nonlinear Color-Appearance Model

5.1 Formulation of Incomplete Adaptation

As already stated, the results of the McCann experiment showed an incomplete adaptation to the test chromatic illuminant. For this reason a procedure for incomplete adaptation was introduced to the nonlinear color appearance model, and the experimental results by McCann et al. were predicted by the modified model. The coefficient of incomplete adaptation k ($0 \leq k \leq 1$) was introduced, and the effective adapting chromaticity coordinates ξ , η , ζ in the fundamental primary system were specified by eq.(9).

$$\begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} = k \begin{bmatrix} \xi_c \\ \eta_c \\ \zeta_c \end{bmatrix} + (1-k) \begin{bmatrix} \xi_w \\ \eta_w \\ \zeta_w \end{bmatrix}, \quad (9)$$

where ξ_c , η_c and ζ_c are the chromaticity coordinates of a test chromatic illuminant and ξ_w , η_w and ζ_w are those of the white illuminant. The values ξ , η , ζ are specified at an intermediate point between ξ_c , η_c , ζ_c and ξ_w , η_w , ζ_w . The effective adapting illuminance E , however, was set equal to each of the test illuminance E_c and the matching illuminance E_w .

It is given by

$$E=E_C \text{ for test illuminant, and} \quad (10)$$

$$E=E_W \text{ for matching white illuminant.}$$

In eq.(9), the condition of $k=1$ corresponds to the state of complete adaptation to the test chromatic illuminant. The condition of $k=0$ corresponds to that of the white-illuminant adaptation. A part of the predicted results for $k=1$ and $k=0$ were already shown by dots and open triangles in Fig.8, respectively.

In eq. (10), $E=E_C$ and $E=E_W$ are used, because the illuminance adaptation in the photopic range proceeds rather rapidly as compared with the adaptation to the change of illuminant color. This is confirmed by our daily experiences.

5.2 Analysis II

A prediction was done again to the McCann experiment by introducing eqs.(9) and (10) to the nonlinear color-appearance model. To each of various k values from 0 to 1, the values of ξ , η , ζ in eq.(9) were estimated. By substituting the estimated values of ξ , η , ζ and the test illuminance E_C in eq.(10) to the nonlinear color-appearance model, the T, P responses were computed to the test object colors under each of the 4 test chromatic illuminants. In the computations, the tristimulus values of the test colors used are the same as those shown in Table 3 irrespective of the k value used. As expected, the T, P responses of the matching colors are the same as those in Figs. 4 to 7. The average deviations on the 18 test colors were computed between the T, P values of the test colors under each test chromatic illuminant and those of corresponding matching colors under the white illuminant already derived in Analysis I.

In Fig.9, the average deviations of the 18 test colors ΔE are shown on the ordinates to various k values shown on the abscissa. As found from Fig.9, the average deviations have their minimum values at the intermediate values of k between 0.0 and 1.0. The minimum deviations are found at the k values close to 1.0 to the red experiment (green test illuminant) and the yellow experiment (purple test illuminant). On the other hand, the minimum deviations are found close to $k = 0.5$ to 0.6 in the green experiment (pink test illuminant) and the blue experiment (orange test illuminant). This facts may suggest that the degree of incomplete adaptation may be different for different test illuminant color.

The real line in Fig.9 shows the average of the four deviation curves with dashed lines on the four kinds of test chromatic illuminants. The best prediction or one minimum value of the average deviation curve is found at $k = 0.7$. At this k value, the average deviation ΔE is 7.59 for the red experiment, 4.49 for the blue experiment, 4.71 for the green

experiment, and 6.31 for the yellow experiment. The average of the four deviations is 5.78, which corresponds to a pretty good prediction considering the observational error of $\Delta E = 3.50$ at the gray experiment already described. In the succeeding analysis, we adopt $k = 0.7$.

Fig. 9. Average deviations ΔE between the T and P values of the 18 test colors under each of the 4 chromatic test illuminations for different k values, and those of the corresponding matching colors under white illumination. Dashed curves denoted by R, Y, G and B correspond to the chromatic test illuminations in the red, yellow, green and blue experiments, respectively. The real curve denoted by AV is the average of the four dashed curves for the four kinds of experiments with R, Y, G and B in the figure. The horizontal line denoted Gray corresponds to the average deviation ΔE between the T and P values of the 18 test colors under white illumination and those of the corresponding matching colors under the same white illumination shown in Fig. 3.

For this reason, the T, P responses corresponding to chroma and hue are compared between the test and the matching colors for $k=0.7$. The results are shown in Figs.10 to 13 to each of the four experiments. In each figure, the T, P responses of the matching colors are shown by open circles, and those of the test colors by dots for $k = 0.7$. The matching color corresponding to each of the test color is connected by a straight line between the two colors. By inspecting Figs.10 to 13, it is confirmed that the nonlinear color-appearance model modified for incomplete adaptation can predict the experimental color matches between the test and the comparison fields to each of the four test chromatic illuminants fairly well. The significant large deviations

found in Figs.4 to 7 are appreciably improved as found from Figs.10 to 13.

Fig. 10. The T and P values of the test colors (dots) under green illumination (the red experiment) in the test field for the incomplete-adaptation coefficient $k=0.7$, and those of the matching colors (open circles) under white illumination in the comparison field. regarding the connecting lines between dots and open circles, see the caption of Fig. 3.

Fig. 11. The T and P values for orange illumination (the blue experiment) with $k=0.7$. See the caption of Fig. 10 for notations.

Fig. 12. The T and P values for pink illumination (the green experiment) with $k=0.7$. See the caption of Fig. 10 for notations.

Fig. 13. The T and P values for purple illumination (the yellow experiment) with $k=0.7$. See the caption of Fig. 10 for notations.

6. Conclusion

To confirm the applicability of the nonlinear color-appearance model to predict the color-appearance of object colors in a complex field under various illuminations, the results of the McCann experiment were analyzed by using the model. The following conclusions and information were obtained from the analyses.

- (1) The nonlinear color-appearance model predicted the McCann experiment on the color appearance of object colors on the Mondrian figure under four kinds of chromatic illuminants sufficiently well. In the process, the following points were made clear.
 - a) The method for estimating the colorimetric values was made clear on the illuminants and the test and the matching colors used in the experiment.

- b) The results of the McCann experiment showed a certain incomplete adaptation to each of the test chromatic illuminants probably due to the procedure of observation described at the end of the introduction in Chapter 3 and the low illuminance levels used in the experiment. Considering these factors, a method was proposed to introduce the effect of incomplete adaptation to the nonlinear color-appearance model. Using the method, the degree of incomplete adaptation in the McCann experiment was estimated by using the adaptation coefficient k , and the results of the McCann experiment were predicted fairly well by using a specified k value.

- (2) The analyses in the present article clarified that the experiment by McCann et al. was very well done with careful precautions.

Acknowledgment

The authors wish to thank Messers. T. Izumi and M. Nakajima, the former students of the Osaka Electro-Communication University, for their assistances in typing a part of the present article.

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