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Effect of Color Signal Sequence with Minimum Distance on Human Color Impression Model

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Abstract: *We examine how a seven-color cyclic sequence affects human color impression. In order to investigate the different effects of two sequences, we consider a hexagonal diagram that is a projection of RGB color space from white to black. The hexagonal diagram corresponds roughly to the hue circle indicated by both hue and saturation in the HLS system. If i) the projected route is approximately the minimum, ii) each saturation is large, and iii) neighboring colors are not too close each other, the projected route area is assumed to be large. In other words, the projected route area indicates the magnitude of naturalness (as in rainbows) for color sequences. The minimum sequence is similar to the order of colors in rainbows. On the other hand, the non-minimum sequence is completely different. Although the seven colors used in the present study are not distributed as in rainbows, and the seven-color cyclic sequences are not continuous sequences having gradation, we propose a human color impression model using the projected route area indicated by both hue and saturation. In the proposed model, the subject has natural impressions when the route area is large and unnatural impressions when the route area is small.*

Keywords *color signal sequence, minimum distance, human color impression, natural-unnatural, RGB color space, route area, HLS system, human color impression model*

1. Introduction

The effects of different color signal sequences of the several colors on human color impression were examined in a previous study [7], [10]. Determination of whether a several-color cyclic sequence has a minimum distance in RGB color space was investigated for subjects in an analysis of color sensations. Several words are commonly used to describe the character and associative meanings of colors [4]. The degrees of pairs of terms applied to color sequence such as natural-unnatural were investigated herein. The word "natural" as a human color impression invokes expressions such as calm, flowing, and relaxed, whereas the word "unnatural" invokes expressions such as intense, tight, and unpleasant. Well-ordered color signal sequences having a minimum distance (minimum sequences) were found to elicit responses of a degree of naturalness. In contrast, random-ordered color signal sequences having no minimum distance (non-minimum sequences) were found to elicit responses of a degree of unnaturalness. We adopted two words, natural and unnatural, based on the questionnaire given to 31 subjects. Two words *natural* and *complex* (or *unnatural*) were also described in ref. [2].

In the present study, first we explain our previous experiments of human color impression [7], [10]. Secondly we propose a human color impression model using the projected route area based on the experiments. This model will provide color sequences for emotional control and similar application.

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2. Methods [7], [10]

2.1 Color Signal Sequences

A system of the three primary colors, red, green, and blue (RGB) presented in a cubic color space was used in the previous study. In this space, we randomly selected seven color coordinates: (r_1,g_1,b_1), (r_2,g_2,b_2),..., (r_7,g_7,b_7), and prepared non-minimum sequences as a seven-color cyclic sequence *i)* (see Table 1a). The minimum distance of coordinates could be computed using Hopfield networks (as three-dimensional traveling salesman problems). The minimum sequences having the same colors were also prepared as another seven-color cyclic sequence *ii)* (see Table 1b). In Table 1, RGB values ranged from 0 to 255. The sum of the distances is 1371.2 in one cycle of non-minimum sequence *i)* (Table 1a) and 1164.3 in one cycle of minimum sequence *ii)* (Table 1b). The distance of minimum sequence is clearly smaller than that of non-minimum sequence.

2.2 Experiments

Table 1. Differences between each component of a) non-minimum and b) minimum sequences. Components are red r, green g, and blue b for RGB values or hue h, lightness l, and saturation s for HLS values. The maximum value is 255 for RGB values. Hue angle h is indicated in degrees. Distance d is the total of seven distances in the RGB values.

a) Non-minimum sequence (d=1371.2)

Selected order	RGB values r	g	b	HLS values h	l	s	Color
No.1	117	76	209	258	0.56	0.52	Violet
No.2	230	143	43	32	0.54	0.73	Light orange
No.3	243	38	122	335	0.55	0.80	Vivid magenta
No.4	181	202	235	217	0.82	0.21	Pale greenish blue
No.5	35	23	133	247	0.31	0.43	Purplish blue
No.6	0	243	30	127	0.48	0.95	Vivid green
No.7	46	220	179	166	0.52	0.68	Cyan

b) Minimum sequence (d=1164.3)

Optimized order	RGB values r	g	b	HLS values h	l	s
No.3	243	38	122	335	0.55	0.80
No.2	230	143	43	32	0.54	0.73
No.6	0	243	30	127	0.48	0.95
No.7	46	220	179	166	0.52	0.68
No.4	181	202	235	217	0.82	0.21
No.1	117	76	209	258	0.56	0.52
No.5	35	23	133	247	0.31	0.43

Table 2. Differences between human color impressions "natural-unnatural" elicited by a) non-minimum and b) minimum sequences. Numbers with square are the total of three display conditions.

Display conditions (colors/sec)	a) Non-minimum sequences: Natural % of subjects	Natural No. of subjects	Unnatural % of subjects	Unnatural No. of subjects	Degree of impression	b) Minimum sequences: Natural % of subjects	Natural No. of subjects	Unnatural % of subjects	Unnatural No. of subjects	Degree of impression
1	26.2	11	73.8	31	-0.48	54.8	23	45.2	19	0.10
2	45.2	19	54.8	23	-0.10	64.3	27	35.7	15	0.29
3	50.0	16	50.0	16	-0.00	81.3	26	18.7	6	0.63
Average	40.5	46	59.5	70	-0.58	66.8	76	33.2	40	1.02

A total of 73 undergraduate students (70 male and three female) volunteered for the experiments in the previous study [7], [10]. The subjects sat in a chair and were required to watch a display continuously. The clock intervals for a color signal sequence were 1/3s, 1/2s, and 1s. One trial (sequence) consisted of the same seven colors shown in Tables 1a and b, and these seven colors were repeated after approximately 30s. For example, for a clock interval of 1 s, a seven-color cyclic sequence is $(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),(r_2,g_2,b_2)$. The experiments were performed in an isolated area in order to restrict visual cues to the display.

2.3 Equipment

A Panasonic 17" CRT display was used for presenting the stimulus pattern. The display resolution was 1024× 768 pixels/75Hz.

3. Experimental Results [7], [10]

Figures 1a and b show two possible tours (360) in the three-dimensional RGB color space. One (circuitous) route is selected randomly (Fig.1a), another route is selected based on the minimum distance using Hopfield network (Fig.1b) [7], [10]. The two seven-city TSP tours are obviously different. A complex route in a, and a simple route in b, are visually recognizable. Therefore, we examined whether the color impression for such a color signal sequence could be expressed by simple adjectives (or adverbs).

In early experiments (the clock interval of 1 s was used), 31 subjects reported their impressions freely for two sequences. That is, the subjects were required to provide linguistic expressions. For instance, responses to a questionnaire included *agreeable, bad, busy, calm, dark, deep, disagreeable, fair, fast, fidgety, flickeringly, flowing, glitter, good, intense, irregularly, light, loose, natural, noisy, nothing, pit-a-pat, pleasant, quiet, regularly, relaxed, severe, smooth, tight, tired, unknown,* and *unpleasant*. Thus, the use of simple adjectives (or adverbs) to convey the impression made by such color signal sequences is possible. These impressions were analyzed in order to determine differences between two sequences.

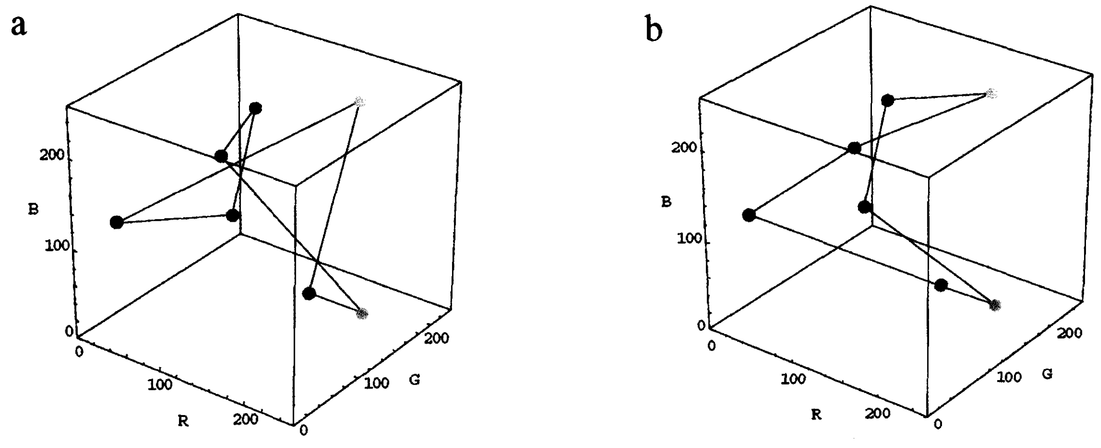


Fig.1. Seven colors and two routes in RGB color space. Points show the seven randomly selected color coordinates listed in Table 1. Lines indicate each route for a) *non-minimum* and b) *minimum* sequences of the same colors. In Fig.1b, only one route having the minimum distance is obtained through the convergence of the Hopfield network for a seven-city TSP tour.

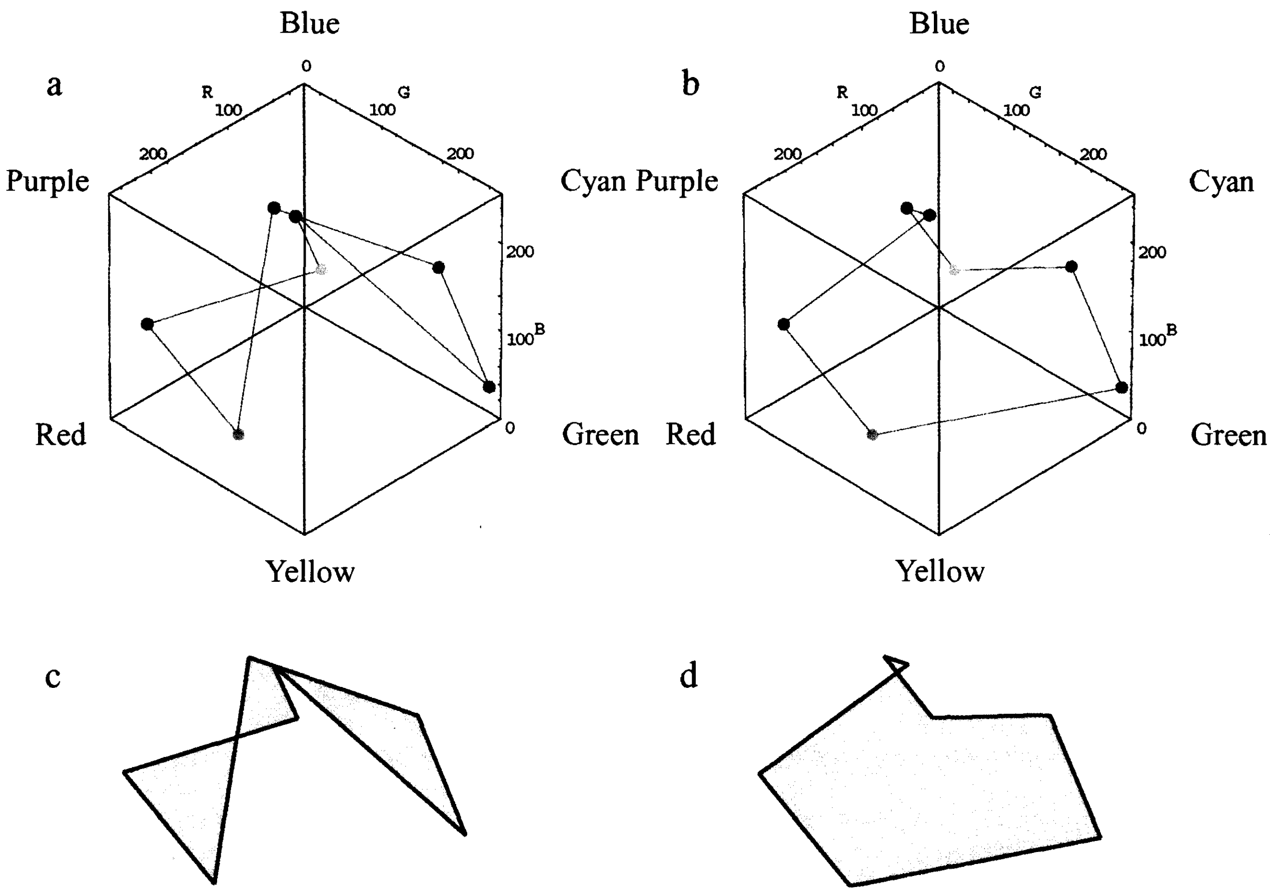


Fig.2. Two routes in the RGB color space (hexagonal diagram) and projected route area. Fig.2a and b are the same routes shown in Fig.1, but white and black overlap each other in the center. The six corners of the hexagon are labeled, moving clockwise, blue, cyan (blue green), green, yellow, red, and purple. The shaded regions in Fig.2c and d show the projected route areas on the respective hexagons.

A classification of human color impressions

Simple words describing impression expressed by subjects were classified into "natural", "unnatural", "unknown", and "other" impressions. Natural: *agreeable, calm, fair, flowing, loose, natural, pleasant, quiet, regularly, relaxed, smooth,* etc., Unnatural: *busy, disagreeable, fidgety, flickeringly, glitter, intense, irregularly, noisy, pit-a-pat, severe, tight, tired, unpleasant,* etc., Unknown: *bad, good, nothing, unknown,* etc., and Other: *dark, deep, fast, light,* etc. Two main words *natural* and *complex* (or *unnatural*) based on ref. [2] were used in previous study [7], [10]. Unknown and other impressions are not related with words *natural* and *unnatural.* Other impressions are color-related words and speed-related words in this case.

The non-minimum sequences did not evoke natural impressions alone. Unnatural impressions of non-minimum sequences are four times more numerous than the same impressions of minimum signal sequences. Unknown impressions of non-minimum sequences are more numerous than those of minimum sequences, which are few in number. Other impressions of non-minimum sequences are fewer in number than those of minimum sequences. The non-minimum sequences evoke unnatural impressions and do not evoke natural impressions. In contrast, minimum sequences evoke natural impressions rather than unnatural impressions. It seems that the impressions produced by two individual sequences appear to have the opposite effect.

Next, experiments were performed in order to examine the references of pairs of terms applied to color (sequence), such as *natural-unnatural.*

Table 2 shows only the difference between human color impressions for "natural-unnatural" for two color signal sequences. The subjects were required to determine whether the natural impression for each color signal sequence was suitable. In the non-minimum sequences, natural impressions are fewer in number than unnatural impressions, except for the 3-colors/sec display condition. In the minimum sequences, natural impressions are more numerous than unnatural impressions. Increasing the display frequency appears to increase the percentage of natural impressions, although the first 10 subjects do not perform tasks under the display condition of 3 c/s.

How well does the word *natural* suit color sequences?

In order to address this question, the degree of naturalness (or unnaturalness) was defined in the present study. If a subject selects the word *natural,* then the degree of naturalness is positive (+1), whereas if subject selects the word *unnatural,* the degree of unnaturalness is negative (−1). These averages were calculated, and Table 2 indicates the percentage of subjects for which the word *natural* suits each color signal sequences. Positive numbers denote the average degree of natural impression, and negative numbers denote that of unnatural impression. The degree of unnaturalness for each non-minimum sequence satisfies the following relation (numbers denote display conditions in c/s):

Non-minimum 1 > Non-minimum 2 > Non-minimum 3

The degree of naturalness for each minimum sequence satisfies the following relation (numbers denote display conditions in c/s):

Minimum 3 > Minimum 2 > Minimum 1

Irrespective of display condition, human color impression shows a degree of naturalness for the minimum sequences, and a degree of unnaturalness for the non-minimum sequences. In Table 2 the total degree of impression is 1.02 for the minimum sequences and −0.58 for the non-minimum sequences.

We examined relationship between route and distance obtained for the previous experiment. The 59th route for the non-minimum sequence was found to be ordered randomly. The difference in distance between the minimum (1st) route and the non-minimum (59th) route is approximately one-quarter of the difference in distance between the minimum and the maximum. The minimum is approximately 60% of the maximum [7], [10].

Pairs of close components in the minimum sequence

In the RGB system, we examined the differences between components of a non-minimum sequence and those of a minimum sequence. In Table 1 the underlined numbers indicate pairs of close components. Here, we define that a threshold for each component is approximately 10% of the maximum value (255). For example, if a difference between neighboring numbers is less than or equal to 26.0, the numbers are underlined. At the non-minimum distance, only two such pairs exist: (r_2 = 230, r_3 = 243) and (r_6 = 243, r_7 = 220). At the minimum distance, seven pairs exist: (r_3 = 243, r_2 = 230), (g_6 = 243, g_7 = 220), (g_7 = 220, g_4 = 202), (g_5 = 23, g_3 = 38), (b_2 = 43, b_6 = 30), (b_4 = 235, b_1 = 209), and (b_5 = 133, b_3 = 122). In this case, only for colors No.1 and No.5, such a pair does not exist. The number of pairs of close components in the minimum sequence is clearly more than that in the non-minimum sequence. This, implies that the number of pairs of close components affects total distance. Moreover, in the HLS system, hue angles h are sorted in order, except in the case of No.5. This sorting is similar to the order of rainbow colors which are composed of the following wavelengths [3]: violet (400-430nm), indigo (440-460nm), blue (470nm), green (505nm), yellow (575nm), orange (590-620nm), red (>630nm), where orange is yellow red, indigo is dull blue, and violet is purple blue.

Which route is most similar to the order of rainbow colors?

The most similar route is the 3rd route. A difference between the 1st route minimized and the 3rd route lies in the positions of No.1 and No.5. By substituting No.1 for No.5, and vice versa, we find that the order of the seven hues is identical to the order of wavelengths. However, the sum of the distances increases slightly (Fig.3 of previous paper [10]). The HLS values (*h, l, s*) are transformed from RGB values (*r, g, b*), and the color names are translated from RGB values (*r, g, b*) into our fuzzy color naming system [5], which is based on the Japanese Industrial standard [1].

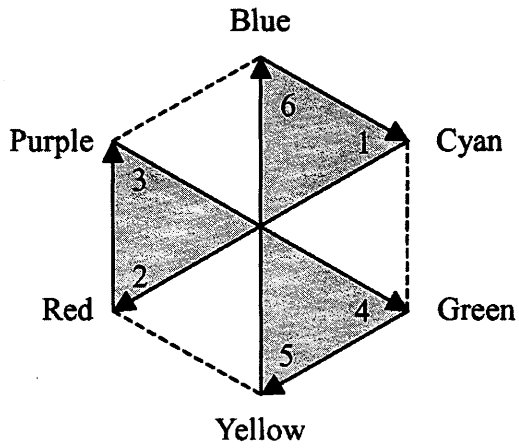
4. Human Color Impression Model

We examine how a seven-color cyclic sequence affects human color impression. In order to investigate different effects of two sequences, we consider a hexagonal diagram that is a projection of RGB color space from white (black) to black (white). The hexagonal diagram in Figs.3a and b (see Fig.1) corresponds roughly to the hue circle (top view) indicated by both hue and saturation (except for lightness) in the HLS system. If *i)* the projected route is nearly the minimum, *ii)* each saturation is large (each point is far away from the center), and *iii)* neighboring colors are not too close to each other (on the hexagon), the projected route area is assumed to be large. The route area indicates the magnitude of naturalness (as a rainbow effect) for color sequences. The minimum sequence is similar to the order of rainbow colors. On the other hand, the non-minimum sequence is completely different from the order of rainbow colors. Although the seven colors used in the previous study are not distributed as rainbow colors (violet, indigo, blue, green, yellow, orange, and red), and the seven-color cyclic sequences are not continuous sequences having gradation, we propose a human color impression model using the route area indicated by both hue and saturation. This model [8], [9], invokes natural impressions when the route area is large (Fig.2d) and unnatural impressions when the route area is small (Fig.2c).

5. Modeling Results

In the hexagonal diagram (Fig.3), we consider two projected routes and projected route areas of the human color impression model using six fundamental colors (at the six corners). Each color has maximum saturation, and the projected neighboring colors are widely spread in this case. For instance, the non-minimum route (blue, cyan, red, purple, green, yellow, and blue again), shown in Fig.3a, includes order of complimentary colors. But this is not so for the maximum route. The minimum route (blue, cyan, green, yellow, red, purple, and blue again), shown in Fig.3b, runs in the hexagon. If the sides are of unit length, the ratio R_d of non-minimum projected route distance d_n to minimum projected route distance d_m is equal to 1.5, and the ratio R_a of non-minimum route area a_n to minimum route area a_m is

a



b

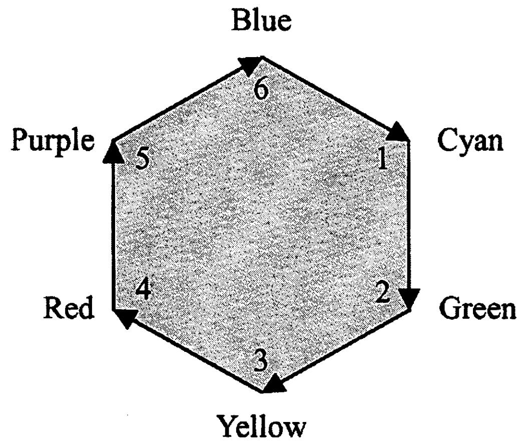


Fig.3. Two projected routes and projected route areas for six fundamental colors. In Fig.3a, the order (No.1-2, No.3-4, and No.5-6) of complimentary colors is used. In Fig.3b, the order (No.1~No.6), moving clockwise, is blue, cyan, green, yellow, red, purple and blue again. The shaded regions show the projected route areas.

0.5. We also calculate the ratios of seven randomly -selected colors in Fig.2:

$$R_d = d_n / d_m = 1090.5 / 834.5 = 1.3$$

$$R_a = a_n / a_m = 15286.5 / 38747.5 = 0.39$$

The distances are only calculated in RGB color space, and not in HLS color space, because hue represents the angle in degrees. However, hue, lightness, and saturation in the HLS system are available for analysis of color sensation. In the present study, hue and saturation, rather than lightness, are important. No difference exists between the projected routes in the RGB system and those in the HLS system. For seven randomly-selected colors the projected routes in the RGB system are not identical to those in the HLS system. However, the difference is not large.

In the simulation results for six fundamental colors (Fig.4), the relationship between order of projected routes and route areas shows a decreasing trend having

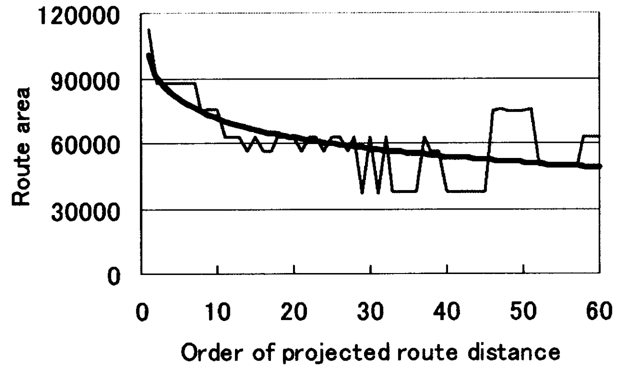


Fig.4. Simulation results of six fundamental colors. Relationship between possible routes and distances in a six-city TSP tour. The abscissa shows the order of 60 route distances from the minimum route (1st order) to the maximum route (60th order), and the ordinate shows the route area. See the minimum projected route distance and the maximum route area in Fig.3b.

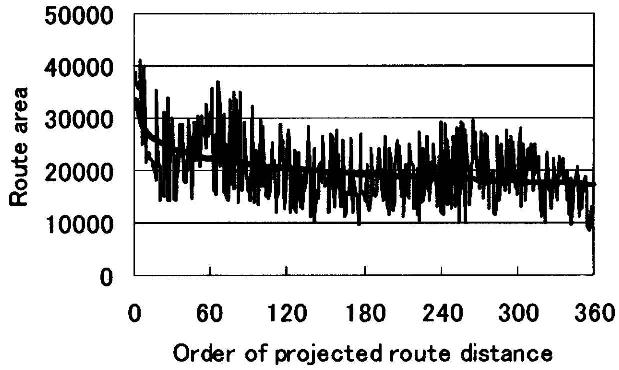


Fig.5. Simulation results of seven colors in the psychological experiments, corresponding to Fig.1. The abscissa shows the order of 360 route distances, and the ordinate shows the route area. The route areas of Fig.4 are approximately three times larger than these route areas.

fluctuations. This trend indicates logarithmic approximation from the minimum route (1st order of projected distance) to the maximum route (60th order of projected distance). These fluctuations become larger for increasing order. Ignoring small fluctuations, the distances of the three-dimensional route are directly proportional to those of the projected route.

The simulation results for seven randomly-selected colors (Fig.5) indicate that as route distance increases, route area diminishes, and numerous fluctuations occur. The result for seven randomly-selected colors is nearly equal to that for six fundamental colors. The distances of three-dimensional route are directly proportional to those of the projected route, and large fluctuations occur. Although the results for six fundamental colors and those for seven randomly-selected colors differ, their trends have similar characteristics [8], [9].

The route area of six fundamental colors in Fig.4 is approximately three times larger than that of seven randomly selected colors in Fig.5 (compare also the hexagon of Fig.2b and the route area of Fig.2d).

6. Conclusions

In the present paper we proposed a human color impression model that indicates the degree of perceived naturalness using the projected route area. These simulation results suggest that if route distance is minimum, or nearly minimum, human color impression becomes “natural”, otherwise human color impression becomes “unnatural”. Although, such a degree of naturalness can not be explained by route distance alone, the projected route area on hexagonal diagram provides a good approximation. This implies that in human color sensation, a deep relationship exists between naturalness and route area, which is composed of hue and saturation.

The proposed model of six fundamental colors suggests that the impression of a rainbow of color correlates highly with naturalness [2].

This model will provide a design of suitable color sequences for control of feeling and emotion (for example, in the theater), because of we can control our feeling and emotion using single color effects (of illumination) [6].

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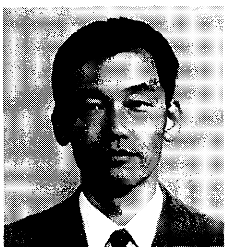

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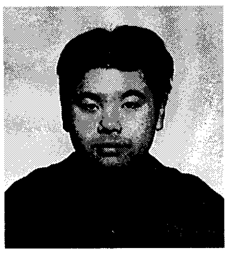

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