Human Color Impression Model for Well-Ordered Color Signal Sequence with Minimum Distance

Naotoshi Sugano, Youichi Matsushita
Department of Electronic Engineering, Tamagawa University
Machida, Tokyo, Japan
sugano@eng.tamagawa.ac.jp

Abstract

We examine how a seven-color cyclic sequence affects human color impressions. In order to investigate different effects of two sequences, we consider hexagonal diagram that is a projection of RGB color space from white to black. The hexagonal diagram is roughly corresponding to the hue circle indicated by both hue and saturation in HLS system. It is assumed that if *i)* the projected route is nearly the minimum, *ii)* each saturation is large, and *iii)* neighboring colors are not too close each other, the projected route area is large. Namely the route area indicates the magnitude of naturalness (as a rainbow feeling) 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 seven colors in this study are not distributed as rainbow colors, and the seven-color cyclic sequences are also not continuous sequences with gradation, we can propose a human color impression model using the route area indicated by both hue and saturation. In this model, the subject has natural impressions when the route area is large, but the subject has unnatural impressions when the route area is small.

1. Introduction

The effects of different color signal sequences with the same several colors in the human color impressions were examined in previous study [2]-[7]. Whether a several-color cyclic sequence has a minimum distance or not in the RGB color space was applied for subjects in an analysis of color sensations. There are many words in common use to describe the character and associative meanings of colors [1]. The degrees of pairs of terms applied to color sequence such as natural-unnatural were investigated. The word natural as a human color impression is, for example, calm, flowing, relaxed, etc., and the word unnatural is intense, tight, unpleasant, etc. in this case. As the results, the well-ordered color signal sequences with the minimum distance (minimum sequences) showed natural degrees. The random-ordered color signal sequences not having the minimum distance (non-minimum sequences) showed unnatural degrees. We adopted two word (natural and unnatural) based on a questionnaire for 31 subjects although there are many words in common use to describe the character and associative meanings of colors.

In this study we proposed a human color impression model using the projected route area indicated by both hue and saturation.

2. Methods

2.1 Color Signal Sequences

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

2.2 Experiments

The subjects were 73 (male: 70, female: 3) undergraduate students who volunteered for the experiments. The subjects sat in a chair, and were continuously required to watch the display. The clock intervals for a color signal sequence were 1/3, 1/2, and 1s. One trial (sequence) was composed of the same seven colors shown in Table 1a and b, and the seven colors were repeated during about 30s. For example, a seven-color cyclic sequence is $(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),\ldots,(r_7,g_7,b_7),(r_1,g_1,b_1),(r_2,g_2,b_2)$ if the clock interval is 1s. The experiments were performed in the isolated area to restrict visual cues to the display.

3. Experimental Results

Fig.1a and b show two of possible tours (360) in the three dimensional RGB color space. One (circuitous) route is selected randomly (Fig.1a), another route

Table 1a and b. Differences between each component of non-minimum and minimum sequences. Each component is red r, green g, and blue b of RGB values or hue h, lightness l, and saturation s of HLS values. The shaded numbers show pairs of close components. In this case, a threshold for each component is about 10% of maximum value (255). Hue angle h is indicated in degrees.

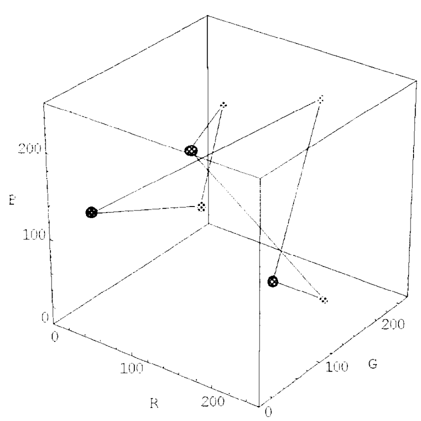
a) Non-minimum sequence (d=1371.2)

Selected order	RGB values r	g	b	HLS values h	l	s	Color names
No.1	117	76	209	258	.56	.52	Violet
No.2	230	143	43	32	.54	.73	Light orange
No.3	243	38	122	335	.55	.80	Vivid magenta
No.4	181	202	235	217	.82	.21	Pale greenish blue
No.5	35	23	133	247	.31	.43	Purplish blue
No.6	0	243	30	127	.48	.95	Vivid green
No.7	46	220	179	166	.52	.68	Cyan

b) Minimum sequence (d=1164.3)

Optimized order	RGB values r	g	b	HLS values h	l	s	Color names
No.3	243	38	122	335	.55	.80	Vivid magenta
No.2	230	143	43	32	.54	.73	Light orange
No.6	0	243	30	127	.48	.95	Vivid green
No.7	46	220	179	166	.52	.68	Cyan
No.4	181	202	235	217	.82	.21	Pale greenish blue
No.1	117	76	209	258	.56	.52	Violet
No.5	35	23	133	247	.31	.43	Purplish blue

a



b

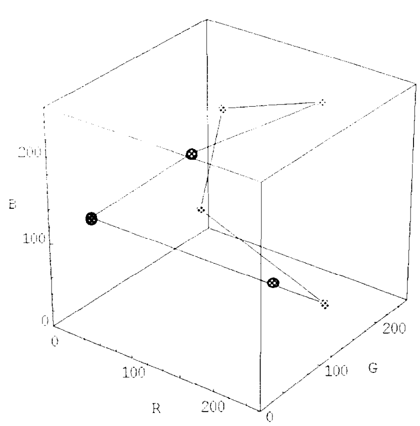


Fig.1a and b Seven colors and two routes in the RGB color space. Points show randomly selected seven color coordinates in Table 1. Lines show each route for a) *non-minimum* and b) *minimum* sequences with the same colors. In b, only one route with the minimum distance is obtained through the convergence of Hopfield network for a 7-city TSP

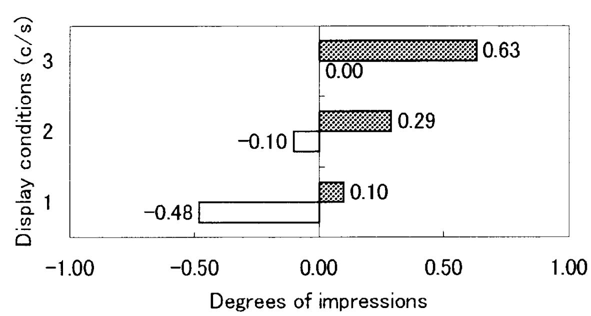


Fig.2 Differences between human color impressions "Natural-Unnatural" elicited by non-minimum and minimum sequences. Positive numbers denote the averaged degrees of natural impression and negative numbers denote that of unnatural impressions. The number of subjects is 42. Dotted area shows the degrees of impression for minimum sequences. White area shows the degrees of impression for non-minimum sequences.

with the minimum distance is found using Hopfield network [2]-[7] (Fig.1b). Two 7-city TSP tours are obviously different. A complex route in a and a simple route in b are visually recognized. Therefore whether the color impression for such a color signal sequence could be expressed by simple adjectives (adverbs) or not were examined. In early experiments (the clock interval of 1s was only used), 31 subjects answer many impressions freely for two sequences. That is, the subjects are required linguistic expressions. For instance, their answers are *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, unpleasant, etc.* for a questionnaire. It is possible to use simple adjectives (or adverbs) as the impressions for such the color signal sequences. Thus their impressions were analyzed in order to show a difference of two sequences.

Table 2. A classification of human color impressions elicited by non-minimum and minimum sequences. Simple impressive words expressed by subjects were classified into "natural", "unnatural", "unknown", and other impressions. Natural (N): *agreeable, calm, fair, flowing, natural, pleasant, quiet, regularly, relaxed, smooth, etc.*, Unnatural (UN): *busy, disagreeable, fidgety, flickeringly, glitter, intense, irregularly, noisy, pit-a-pat, severe, tight, tired, unpleasant, etc.*, Unknown (UK): *bad, good, nothing, unknown, etc.*, and Other (O): *dark, deep, fast, light, etc.* Non-minimum shows color signal sequences without minimum distance and Minimum shows color signal sequences with minimum distance. Numbers denote the number of subjects. In this case, one color per second was fixed.

Sequences	N	UN	UK	O
Non-minimum	0	20	5	6
Minimum	13	5	3	10

Table 3. Differences between human color impressions "Natural (N) - Unnatural (UN)" elicited by a) non-minimum and b) minimum sequences. Numbers denote the number of subjects.

Display conditions (colors/sec)	a) Non-minimum N	a) Non-minimum UN	b) Minimum N	b) Minimum UN
1	11	31	23	19
2	19	23	27	15
3	16	16	26	6

Table 2 shows a classification of human color impressions elicited by non-minimum and minimum sequences. Simple impressive words of subjects are classified into *natural*, *unnatural*, *unknown*, and other impressions. In the non-minimum sequences, they do not have only natural impressions. Unnatural impressions of non-minimum sequences are four times greater than the same impressions of minimum signal sequences. Unknown impressions of non-minimum sequences are larger than those of minimum sequences. These impressions are small minority. Other impressions of non-minimum are smaller than those of minimum sequences. As a result of Table 2, the non-minimum sequences evoke unnatural impressions, but do not evoke natural impressions. On the other hand, the minimum sequences evoke natural impressions rather than unnatural impressions. It seems that the impressions for two sequences are opposite in this experiment.

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

Table 3 shows only the difference between human color impressions for "natural-unnatural" in two color signal sequences. The subjects were required to determine whether the natural impression for each color signal sequence is suitable or not. That is a straight choice between two things. In the non-minimum sequences, natural impressions are smaller than unnatural impressions except for 3 colors/sec. In the minimum sequences, natural impressions are larger than unnatural impressions. It seems that with increasing the display frequency the percentages of natural impressions are increasing, although first 10 subjects do not try tasks in a display condition of 3 c/s.

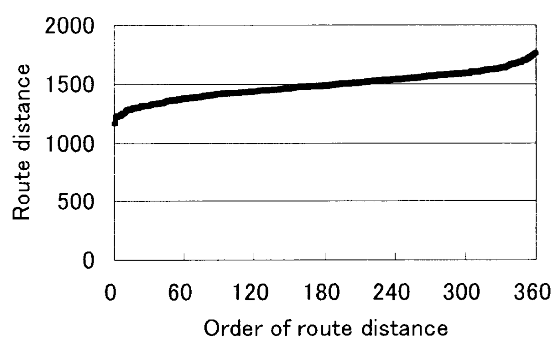


Fig.3 Relationship between possible routes and distances in a seven-city TSP tour. Abscissa shows order of 360 route distances. Route is a function of distance. Ordinate shows the distance of each route. The 1st route has a minimum distance and the 360th route has a maximum distance. The route selected randomly is the 59th.

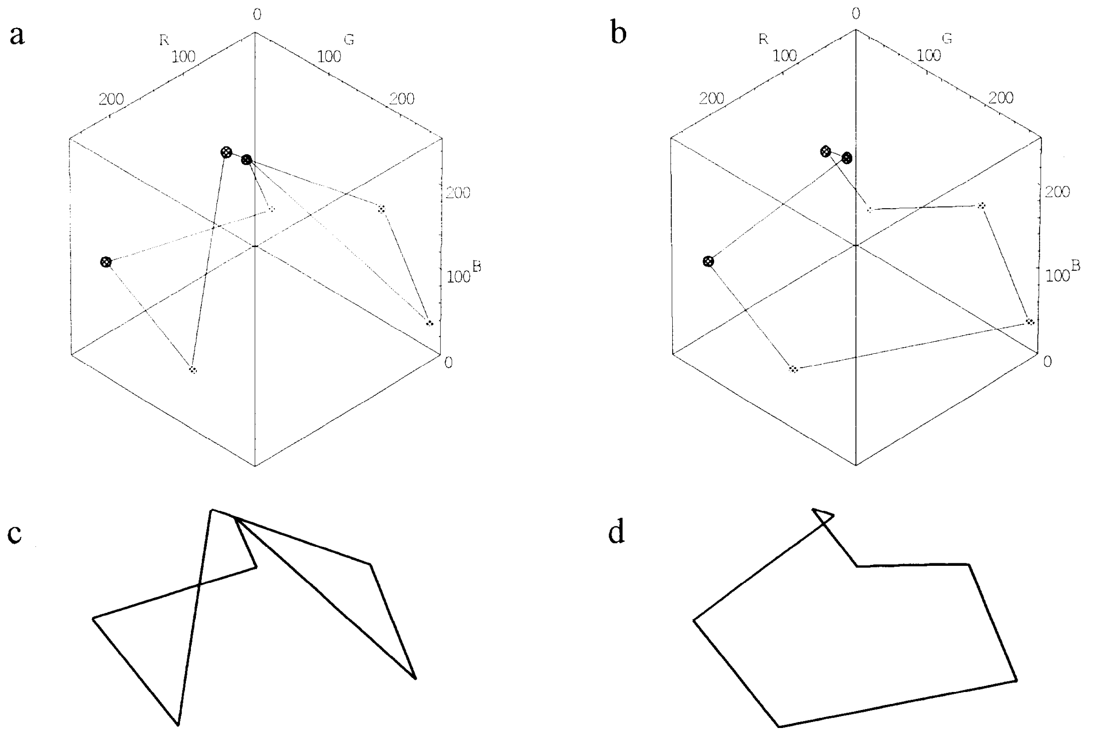


Fig.4a-d Two routes in the RGB color space (hexagonal diagram) and route area. a and b are the same routes as shown in Fig.1, but white and black are overlapped each other in the center. Six corners of the hexagon are named blue, cyan (blue green), green, yellow, red, and purple clockwise. c and d are each route area on the hexagon.

How well does the word *natural* suit the color sequences? Therefore the natural (or unnatural) degree was defined in this study. If a subject chooses word *natural*, then natural degree is positive one (+1) and if a subject chooses word *unnatural*, then unnatural degree is negative one (−1). These averages were calculated. Fig.2 indicates how many percent of subjects think that the word *natural* suits each color signal sequences (corresponding to Table 3). The unnatural degree for each non-minimum sequence satisfies the following relation (numbers denote display conditions in c/s):

Non-min 1 >Non-min 2 > Non-min 3

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

Min 3 > Min 2 > Min 1

In spite of display conditions, human color impression shows the natural degree for the minimum sequences, and the unnatural degree for the non-minimum sequences.

Fig.3 shows route vs. distance characteristic plots. We found that non-minimum sequence ordered randomly is the 59th route. The difference of distance between minimum (1st) route and non-minimum (59th) route is about a quarter of the difference of distance between minimum and maximum. The minimum is about 60% of maximum.

In the RGB system, we examine the differences between components of a non-minimum and a minimum sequence. In Table 1 the shaded numbers show pairs of close components. Here we define that a threshold for each component is about 10% of maximum value (255). For example, if a difference between neighboring numbers is less than equal to 26.0, the numbers are shaded. At the non-minimum distance, there are only two pairs: (r_2 = 230, r_3 = 243) and (r_6 = 243, r_7 = 220). At the minimum distance, there are seven pairs: (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 color No.1 and color No.5, such the pair does not exist. It is clear that the number of pairs of close components in the minimum sequence is more than that in the non-minimum sequence. Namely it implies that the number of pairs of close components effects total distance. In the HLS system, also, hue angles h are sorted orderly except for No.5. This is similar to the order of rainbow color which is composed of that of wave length [8]: 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, violet is purple blue.

Which route is similar to the order of rainbow

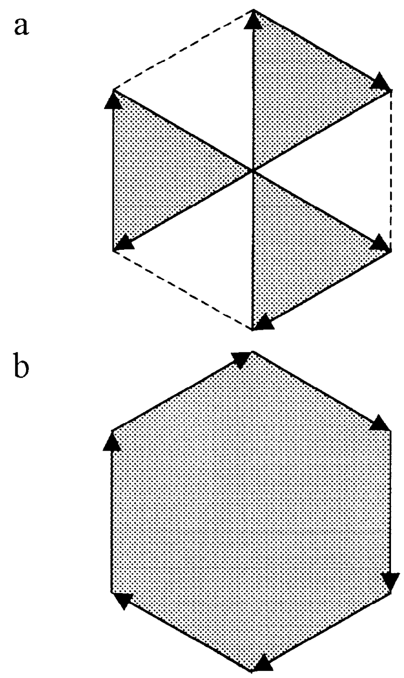


Fig.5a and b Two routes and route areas of fundamental six colors. In a, order of complimentary colors is used. In b, order is blue, cyan (blue green), green, yellow, red, and purple clockwise.

color? It is the 3rd route shown in Fig.3. A difference between the 1st route minimized and the 3rd route is in the position of No.1 and No.5. If we substitute No.1 for No.5, and vice versa, seven hues are completely equal to the order of wavelength. But the sum of the distances increases a little. 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*) in our fuzzy color naming system [9] based on Japanese Industrial standard [10].

4. Human Color Impression Model

We examine how a seven-color cyclic sequence affects human color impressions. In order to investigate different effects of two sequences, here we consider hexagonal diagram that is a projection of RGB color space from white (black) to black (white). The hexagonal diagram in Fig.4a and b (see Fig.1) is roughly corresponding to the hue circle (top view) indicated by both hue and saturation (except for lightness) in HLS system. It is assumed that 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 each other (on the hexagon), the projected route area is large. Namely the route area indicates the magnitude of naturalness (as a rainbow feeling) 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. In spite of seven colors in this study are not distributed as rainbow colors (violet, indigo, blue, green, yellow, orange, and red), and the seven-color cyclic sequences are also not continuous sequences with gradation, we can propose a human color impression model using the route area indicated by both hue and saturation. In this model, the subject has natural impressions when the route area is large (Fig.4d), but the subject has unnatural impressions when the route area is small (Fig.4c).

5. Modeling Results

In the hexagonal diagram (Fig.5) we consider two routes and route areas of human color impression model with fundamental six colors (at 6 corners). Each color has maximum saturation and the projected neighboring colors are widely spread in this specific case. For instance, non-minimum route (blue, cyan, red, purple, green, yellow) in Fig.5a is including order of complimentary colors. But this is not maximum route. Minimum route (blue, cyan, green, yellow, red, purple) in Fig.5b is clockwise order in hexagon. If sides are 1 the ratio of non-minimum distance to minimum distance is equal to 1.5 and the ratio of non-minimum route area to minimum route area is 0.5. The distances are only calculated in RGB color space, but not in HLS color space because hue is angle in degree. However hue, lightness, and saturation in HLS system are available to analysis of color sensation. In this study hue and saturation rather than lightness are important. There is no difference between projected routes in RGB system and HLS system. For randomly selected seven colors the projected routes in RGB system is not equal to those in HLS system. But there is not so large difference.

In the simulation results of fundamental six colors (Fig.6), relationship between order of projected routes and route areas shows a decreasing trend with some fluctuations. This trend indicates logarithmic approximation from minimum route (the 1st order of projected distance) to maximum route (the 60th order). These fluctuations are getting bigger for increasing the order. With small fluctuations the distances of three-dimensional route are directly proportional to those of the projected route.

In the simulation results of randomly selected seven colors (Fig.7), with increasing route distance, route areas diminish having much fluctuations. The result of randomly selected seven colors is nearly equal to that of fundamental six colors. With large fluctuations the distances of three-dimensional route are directly proportional to those of the projected route. The fundamental six colors and randomly selected seven colors are obviously different, however, these trends show similar characteristics.

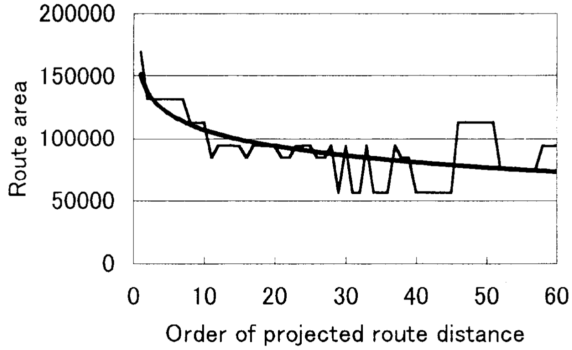


Fig.6 Simulation results of fundamental six colors. Relationship between possible routes and distances in a six-city TSP tour. Abscissa shows order of 360 route distances. Ordinate shows the route area.

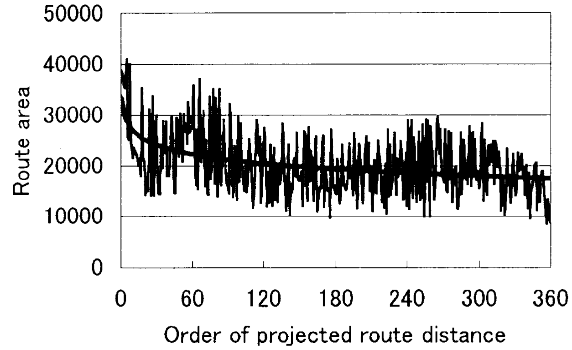


Fig.7 Simulation results of seven colors in the psychological experiments. Corresponding to Fig.1

6. Conclusions

In this paper we proposed a human color impression model that indicates a degree of naturalness using the projected route area. These simulation results suggest one of human color impressions. That is, if route distance is the minimum or nearly minimum human color impression becomes "natural" and if not that becomes "unnatural". Such a degree of naturalness can be not explained by only route distance, but can be almost explained by the projected route area on hexagonal diagram. It implies that in human color sensation there is a deep relationship between naturalness and route area composed of hue and saturation. In this model with fundamental six colors it suggests that rainbow color feelings are correlated with high naturalness.

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