Human Color Impressions Elicited by Well-ordered Color Signal Sequence with Minimum Distance

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Abstract

The effects of different color signal sequences with the same several colors in the human color impressions were examined. 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. In this study the degrees of pairs of terms applied to color (or color sequence) such as natural-unnatural, pale-deep, and dark-light 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. In addition, for both non-minimum and minimum sequences, the majority of subjects are impressed with light rather than dark. For pale-deep impressions, they are impressed with deep rather than pale. It seems that the impressions of natural-unnatural, pale-deep, and dark-light are independent. And we proposed a human color impression model using the route area indicated by both hue and saturation.

1 Introduction

There are many words in common use to describe the character and associative meanings of colors. Sivik and his coworkers (1997) have been using the Natural Color System (NCS) atlas and semantic differential techniques to study the references of pairs of terms frequently applied to color such as "warm-cold", "weak-strong", "beautiful-ugly", "active-passive", etc [1]. The whole color space has been sampled, and the work has been extended to cross-cultural comparisons. In later studies other connotations of colors have been studied, using a descriptive model of color combinations based on dimensions such as interval/contrast, chord/color content, and balance/tuning. Strong relationships have been shown to exist between these stimulus-describing variables and the semantic connotative dimensions. In four recent studies [2]-[5] each of the colors was presented singly and the subject was required to name the color with a monolexemic term as quick as possible. The entire set of colors was presented twice in different random sequences. However those for well-ordered color signal sequences with the minimum distance have not been examined.

In this paper therefore we tried to investigate some impressions for continuous color signal sequences [6]-[9]. Each of the colors was presented continuously and the subject was required to impress the color sequence.

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),…, (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),...,(r_7,g_7,b_7),(r_1,g_1,b_1),...,(r_7,g_7,b_7),(r_1,g_1,b_1),...,(r_7, g_7,b_7),(r_1,g_1,b_1),...,(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.

Table 1. Differences between non-minimum and minimum sequences. a) Non-minimum sequence. RGB values as additive primaries are randomly selected. The sum of the distances is 1371.2 (non-minimum distance). b) Minimum sequence. The sum of the distances is 1164.3 (minimum distance). Seven colors are No.1: violet, No.2: light orange, No.3: vivid magenta, No.4: pale greenish blue, No.5: purplish blue, No.6: vivid green, and No.7: cyan.

a) Non-minimum sequence

Selected order	RGB values *r*	*g*	*b*
No.1	117	76	209
No.2	230	143	43
No.3	243	38	122
No.4	181	202	235
No.5	35	23	133
No.6	0	243	30
No.7	46	220	179

b) Minimum sequence

Optimized order	RGB values *r*	*g*	*b*
No.3	243	38	122
No.2	230	143	43
No.6	0	243	30
No.7	46	220	179
No.4	181	202	235
No.1	117	76	209
No.5	35	23	133

2.3 Hopfield Networks and Traveling Salesman Problems

Hopfield [10] showed that the computation of a neural network is equivalent to the minimization of a certain cost function known as the energy of the network. A neuron is viewed as a computing element, which can assume one of two possible states 0 or 1. A typical neuron i has the threshold I_i , and an output value V_i . A neuron is connected to its neighbors through links. We assume that T_{ij} is the link from neuron j to neuron i , and that $T_{ij} = T_{ji}$. Furthermore, $T_{ii} = 0$ since the neurons do not have self-feedback. A neuron receives inputs from its neighbors, and computes an output as a function of the inputs, then sends the output value to its neighbors.

If the neural network has n neurons, the i th neuron determines its output value as follows:

1. Compute a weighted sum of the output values of its neighbors. This is given by $\Sigma_{j=1} T_{ij} V_j$.
2. Compare the weighted sum with its threshold I_i. The output value V_i of the neuron is given by the following update rule:

$$V_i = 1 \quad \text{if} \quad \Sigma_{j=1} T_{ij} V_j + I_i > 0$$
$$V_i = 0 \quad \text{if} \quad \Sigma_{j=1} T_{ij} V_j + I_i < 0 \qquad (1)$$
$$V_i = V_i \quad \text{otherwise.}$$

Hopfield [10] showed that the computation performed by a network of such elements is equivalent to finding a minimum of the following energy function:

$$E = -(1/2)\, \Sigma_{i=1} \Sigma_{j=1} T_{ij} V_i V_j - \Sigma_{i=1} I_i V_i \qquad (2)$$

To solve optimization problems with neural networks, one constructs a suitable energy function with minima that can be interpreted as solutions to the given problem. From the energy function, we determine the interconnections, respective link-weights, and thresholds of all neurons. Starting in any state, if we allow the neurons to change states, the network will finally settle at a minimum of the energy function.

Hopfield and Tank [11] proposed solving optimization problems using the neural network models using an analogy between the network's energy function and a cost function to be minimized. The traveling salesman problem (TSP) is historically among the first optimization problems to be solved using Hopfield neural network models.

In an instance of the traveling salesman problem (TSP), we are given a set of cities and a symmetric distance matrix that indicates the cost of direct travel from each city to every other city. The goal is to find the shortest circular tour, visiting each city exactly once, so as to minimize the total travel cost, which includes the cost of traveling from the last city back to the first city. In a seven-city problem, for instance, 1^{st}-2^{nd}-3^{rd}-4^{th}-5^{th}-6^{th}-7^{th} represents the travel plan that takes the salesman from 1^{st} to 2^{nd}, from 2^{nd} to 3^{rd}… from 6^{th} to 7^{th}, and finally from 7^{th} to 1^{st} again. The cost of this tour is hence the sum of the distances traversed in each travel segment. The number of possible tours is extremely large (n!/2n=360) even for problems containing a small number of cities.

The Hopfield network is well suited for this type of problem. The energy function that satisfies these conditions is not easy to construct. The energy function is

$$\begin{aligned} E = &(A/2)\, \Sigma_{x=1} \Sigma_{i=1} \Sigma_{j=1} V_{xi} V_{xj} \\ &+(B/2)\, \Sigma_{i=1} \Sigma_{x=1} \Sigma_{y=1} V_{xi} V_{yi} \\ &+(C/2)(\Sigma_{x=1} \Sigma_{i=1} V_{xi} - n)^2 \\ &+(D/2)\, \Sigma_{x=1} \Sigma_{y=1} \Sigma_{i=1} d_{xy} V_{xi} (V_{y(i+1)}+V_{y(i-1)}) \end{aligned} \qquad (3)$$

In the last term of this equation, if $i = 1$, then the quantity V_{y0} appears. If $i = n$, then the quantity $V_{y(n+1)}$ appears. These results establish the need for the definitions, $V_{x(n+1)} = V_{x1}$ and $V_{x0} = V_{xn}$, discussed previously. We first note that d_{xy} represents the distance between city X and city Y , and that $d_{xy} = d_{yx}$. Furthermore, the parameters, A, B, C, and D, are determined respectively.

3 Results and Discussion

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 with the minimum distance is found using Hopfield network (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

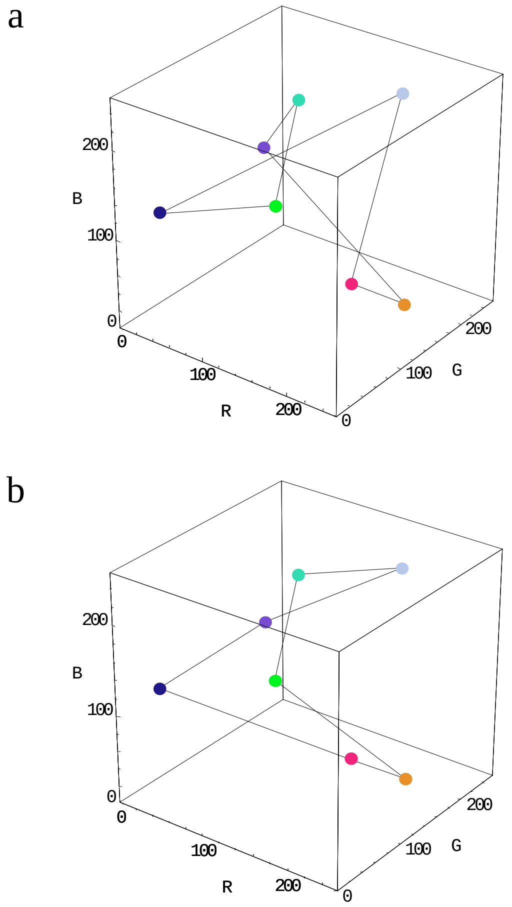

Fig.1a and b Seven colors and two routes in the RGB color space. Points show randomly selected seven color coordinates in Table 1. Lines show each route for a) *non-minimum* and b) *minimum* sequences with the same colors. In b, only one route with the minimum distance is obtained through the convergence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

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 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

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

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

Table 4. Differences between human color impressions "Dark-Light" elicited by a) non-minimum and b) minimum sequences. Numbers denote the number of subjects.

Display conditions (colors/sec)	a) Non-minimum		b) Minimum	
	Dark	Light	Dark	Light
1	8	24	6	26
2	6	26	6	26
3	6	26	8	24

Table 5. Differences between human color impressions "Pale-Deep" elicited by a) non-minimum and b) minimum sequences. Numbers denote the number of subjects.

Display conditions (colors/sec)	a) Non-minimum		b) Minimum	
	Pale	Deep	Pale	Deep
1	10	22	10	22
2	8	24	10	22
3	16	16	22	10

condition of 3 c/s.

In addition the references of pairs of terms frequently applied to color such as *pale-deep*, and *dark-light* were observed. Table 4 shows the difference between dark-light impressions elicited by the non-minimum and minimum sequences. The majority of subjects are impressed with *light* rather than *dark*. Table 5 also shows the difference between pale-deep impressions. They are impressed with *deep* rather than *pale*. There are the same characteristics, which the deep impressions are larger than the pale impressions for slower display frequencies (1 or 2 colors/s). For 3 c/s, however, pale impressions are equal to deep impressions in the non-minimum sequences. Pale impressions are over two times larger than deep impressions in the minimum sequences. It is shown that these characteristics are different only for higher display frequency. Total trend for pale-deep impressions is unclear.

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

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

Minimum 3 > Minimum 2 > Minimum 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 6 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

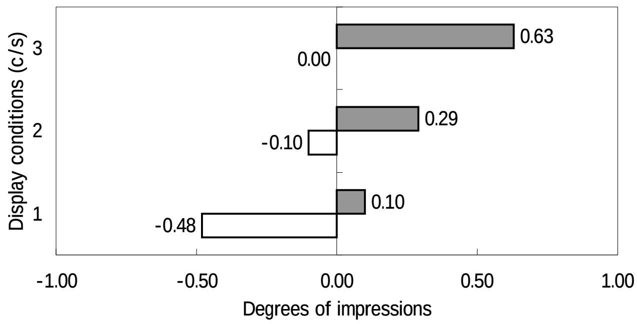

Fig.2 Differences between human color impressions "Natural-Unnatural" elicited by non-minimum and minimum sequences. Positive numbers denote the averaged degrees of natural impression and negative numbers denote that of unnatural impressions. The number of subjects is 42. Dotted area shows the degrees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

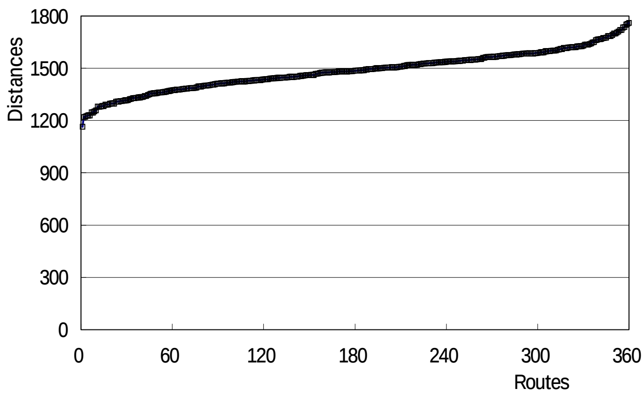

Fig.3 Relationship between possible routes and distances in a TSP seven-city tour. Abscissa shows 360 routes. Route is a function of distance. Ordinate shows the distance of each route. The 1st route has a minimum distance and the 360th route has a maximum distance. The route selected randomly is the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

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 [12]: 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 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 [13] based on Japanese Industrial standard [14].

4 Human Color Impression Model

We examine how a seven-color cyclic sequence affects human color impressions. In Fig.4a and b (see Fig.1), each hexagon is roughly corresponding to the hue circle (top view) indicated by both hue *h* and saturation *s* (except for lightness *l*) in HLS system. It is assumed that if *i)* the route is nearly the minimum, *ii)* each saturation *s* is large (each point is far away from achromatic colors as white and/or black), and *iii)* neighboring colors are not too close each other (No.1 and No.5 colors are very close on the hexagon), the route area is large (area in d is much larger than that in c). Namely the route area indicates the magnitude of naturalness (as a rainbow feeling) for color sequences. 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 (violet, indigo, blue, …, etc), and the seven-color cyclic sequences are also not continuous sequences with gradation, we can consider a human color impression model using the route area indicated by both hue and saturation. In this model, it implies that the subject has natural impressions when the route area is large, but on the other hand the subject has unnatural impressions when the route area is small

5 Conclusions

We examined how it affects human color impressions whether a several-color cyclic sequence has the minimum distance or not in the RGB color space. 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. It seems that the impressions of *natural-unnatural*, *pale-deep*, and *dark-light* are independent. Therefore we proposed a human color impression model which we can impress naturalness with increasing the route area.

Acknowledgements. The authors thank present and former members of our laboratory whose work and ideas have contributed to this project, including M. Matsuura, A. Kojima, Y. Sakai, S. Sato, M. Bando.

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Table 6. 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	RGB values			HLS values			Color names
order	*r*	*g*	*b*	*h*	*l*	*s*	
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	RGB values			HLS values			Color names
order	*r*	*g*	*b*	*h*	*l*	*s*	
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

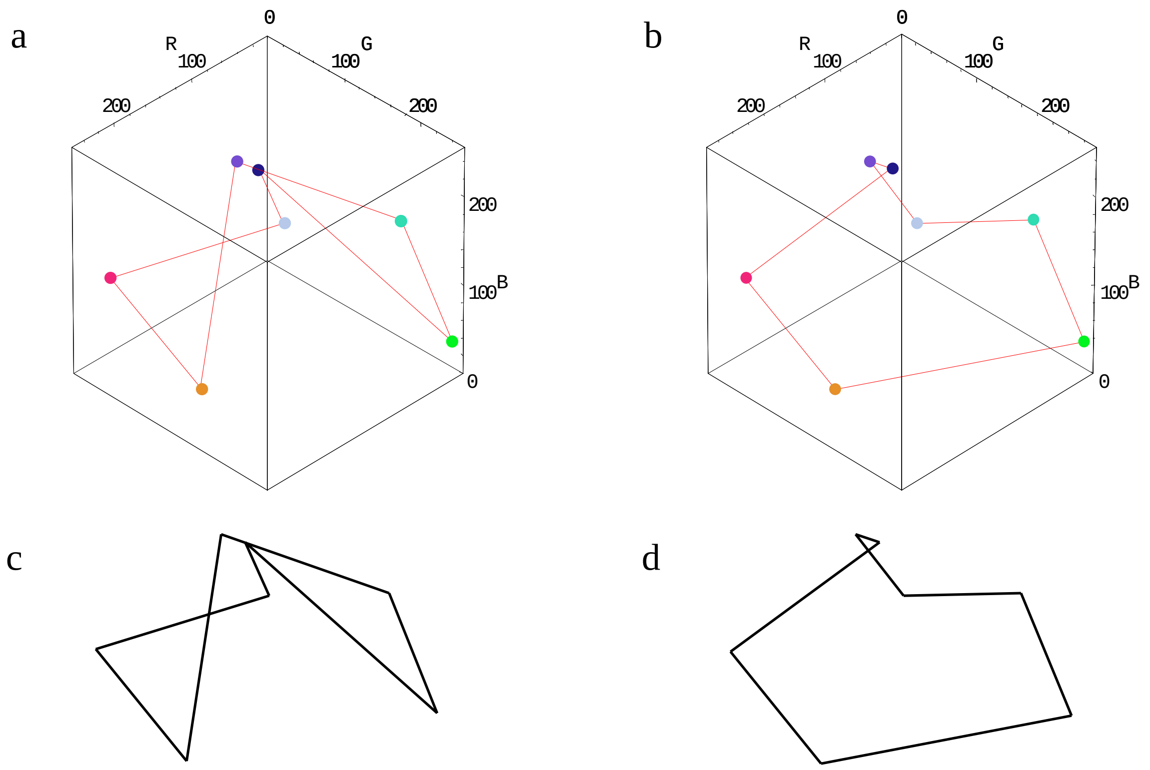

Fig.4a-d Two routes in the RBG color space (hexagonal diagram) and route area. a and b are the same routes as shown in Fig.1, but white and black are overlapped each other in the center. Six corners of the hexagon are named blue, cyan (blue green), green, yellow, red, and purple clockwise. c and d are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