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Effect of Route Complexity of Spatial Color Sequence on Human Color Impression and its Fuzzy Model

Naotoshi SUGANO, Yuuichirou NEGISHI, and Toshihiro ISHIHARA

Department of Intelligent Information Systems, Tamagawa University

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Abstract: *We examine how a toroidal sequence of the six fundamental colors affects human color impression. In order to investigate the different effects of spatial color sequences, we consider a hexagonal diagram that is a projection of RGB color space. The hexagonal diagram corresponds roughly to the hue circle indicated by both hue and saturation. The toroidal sequence is similar to the hue circle. 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, whereas the non-minimum sequence is completely different. Therefore, we propose a simple fuzzy model of human color impression using the projected route area assisted by route complexity. The complexity is defined by the ratio of the square of envelope route distance to route area. The relationship between route complexity and the number of subjects for projected route area is investigated. We clarified that the majority (approximately over 26%) of subjects of nearly all ages have natural impressions when the minimum route area is large, and propose a simple fuzzy model of the human color impression. This model provides the natural (or unnatural) order of spatial color sequences of several colors.*

Keywords *Spatial color sequence, Human color impression, Natural impression, Unnatural impression, RGB color space, Route area, Envelope route, Route complexity, Fuzzy model.*

Introduction

Various effects of temporal color sequences of several colors on human color impression and its model were examined in previous studies [8], [9]. These effects were investigated for subjects in an analysis of color sensation to determine whether a several-color cyclic sequence has a minimum distance in RGB color space. Several terms are commonly used to describe the character and associative meanings of colors [4]. The degrees of pairs of terms applied to color sequences, such as natural-unnatural, were investigated herein. Two terms, natural and complex (or unnatural), were also described in Reference [2].

The various effects of spatial color sequences of six colors on human color impression and its model were also examined in a recent study [10], [12]. Although four different groups of six colors (Type A: six fundamental colors; Type B: five fundamental colors and orange; Type C: six intermediate colors; Type D: six magenta-blue relevant colors) were used, subjects preferring the minimum sequence made up the largest group (approximately 20-50%), when considering the natural color sequence.

In the present study, we introduce a tournament task in our experiments of human color impression and compare human color impression and the fuzzy model of human color impression using the projected route area (or envelope route) based on the experiments. This model provides spatial color sequences for emotional control, color coordination and similar applications.

6-1-1 Tamagawagakuen, Machida, Tokyo, 194-8610 Japan
Phone number: +81-42-739-8402
Fax number: +81-42-739-8858
Email: sugano@eng.tamagawa.ac.jp

Table 1. Subjects participating in the experiment.

No. of subjects	male	female	age
215	130	85	4-82

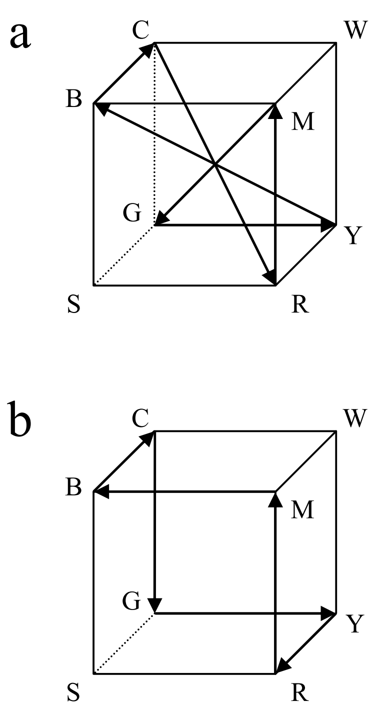

Fig. 1. Two typical routes (*a*: non-minimum route and *b*: minimum route) of six fundamental colors in RGB color space.

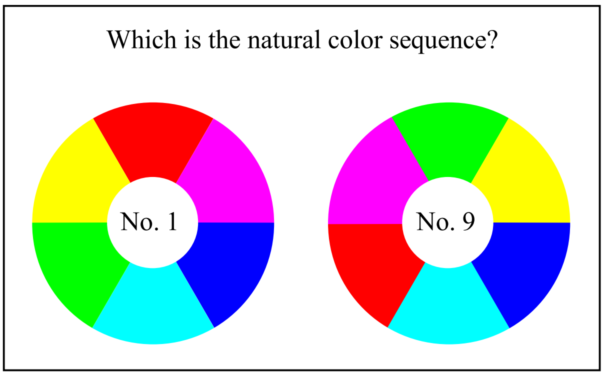

Fig. 2. Two toroidal color sequences in the schematic GUI used for the questionnaire.

Methods

A. Color Sequences

A system of the three primary colors, red, green, and blue (RGB), is presented in a cubic color space. The system of three primary colors is used in the present study. As Fig. 1 shows, blue, cyan, green, yellow, red, magenta, white, and black are abbreviated as *B*, *C*, *G*, *Y*, *R*, *M*, *W*, and *S*, respectively. For example, we selected six fundamental color coordinates: (r_1, g_1, b_1), (r_2, g_2, b_2), …, (r_6, g_6, b_6), where r_n, g_n, and b_n are red, green, and blue components, respectively, of the n^{th} color. It is possible to compute the minimum distance of coordinates. Ten sequences consisted of the same six fundamental colors (*B*, *C*, *G*, *Y*, *R*, and *M*) were presented.

In Fig. 2, we prepared a graphical user interface (GUI) for use in a simple questionnaire related to the presentation of the six fundamental colors as spatial color sequences [9]. The minimum cyclic route is blue, cyan, green, yellow, red, magenta, and blue again. In a cubic color space (Fig. 1), RGB values range from 0 to 255. For example, the sum of the RGB distances is 2,090 for the non-minimum route (*B*, *C*, *R*, *M*, *G*, *Y*, and *B*) in *a* and 1,530 for the minimum route (*B*, *C*, *G*, *Y*, *R*, *M*, and *B*) in *b*. The distance of the minimum route is clearly smaller than that of the non-minimum route. Sixty routes can diminish to twelve routes, because these routes are based on a regular hexagon with six fundamental colors (See Fig. 5). Namely, there are several projected routes with the same shape.

B. Experiments

A total of 215 undergraduate, graduate students, employees, and participants of a university festival volunteered for the experiments of the present study (See Table 1). The subjects sat in a chair and were required to watch a display continuously. Different sequences consisting of six colors, denoted No.1 through No.10, as shown in Fig. 3, were presented in an isolated area in order to restrict visual cues to the display.

Using a graphical user interface (GUI), the subjects compared two (out of the ten) typical sequences in a questionnaire, as shown in Fig. 2. The subjects were asked to determine which color sequence gave the more natural impression.

Figure 3 shows a tournament task of ten numbered routes (No.1 through No.10, excluding the two sequences shown by dashed lines), which involves two six fundamental color sequences. The two sequences shown by dashed lined are omitted in order to reduce the complexity of the task in this case. The route numbers in Fig. 3 do not correspond to the sequence numbers (No.1 and No.9 in Fig. 2). Numbers are randomly selected from ten routes. Therefore, one suitable color sequence for which the subject reports a natural impression is chosen from among the ten sequences (See Fig. 3) for the nine trials.

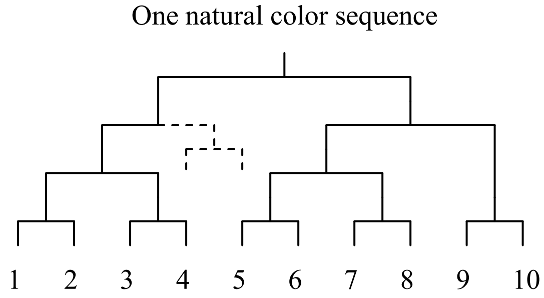

Fig. 3. Tournament method of ten typical routes used to acquire one "natural" color sequence. The two sequences shown by dashed lines were not performed.

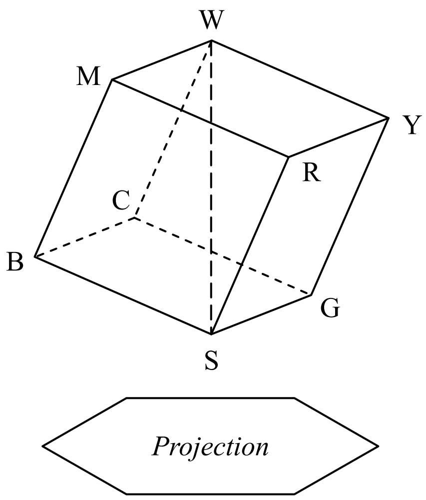

Fig. 4. RGB color space and hexagonal projection.

C. Equipment

A Sharp 11.3" Liquid Crystal Display was used to present the stimulus pattern. The display resolution was 1024 x 768 pixels / 60 Hz.

Experimental Results

In order to investigate the effects of these sequences, we consider a hexagonal diagram that is a projection of RGB color space from white (black) to black (white) in Fig. 4.

Using a graphical user interface (GUI) for this experiment (as shown in Fig. 2), we examined whether the subject selects the minimum route (color sequence) or not, when the subject has natural impression. The minimum cyclic route is blue, cyan, green, yellow, red, magenta, and blue again, as shown in Fig. 1*b* and Fig. 5*b*. Six sets (*B*, *C*, *G*, *Y*, *R*, *M*), (*M*, *B*, *C*, *G*, *Y*, *R*), (*R*, *M*, *B*, *C*, *G*, *Y*), (*Y*, *R*, *M*, *B*, *C*, *G*), (*G*, *Y*, *R*, *M*, *B*, *C*), and (*C*, *G*, *Y*, *R*, *M*, *B*) are treated as the same minimum sequence.

Table 2 summarizes the characteristics of inputs and the responses of 215 subjects. Table 2 lists both *a*) input and output and *b*) pre-processed input. The numbers in the first column do not correspond to those in Fig. 3. The projected route distance and area are listed in Table 2*a* (2nd and 3rd columns). In Table 2*a* (5th column), the minimum sequence (No.1) was preferred by the greatest number of subjects (more than 26%). With respect to the projected route, in particular, the distances of sequences No.3, No.5, and No.10, envelopes are recomputed in Table 2*b* (2nd column). If the sides of the hexagon are of unit length, then the envelope route distance and route area (calculated with unit length) are computed as in Table 2*b* (2nd and 4th columns). In addition, if the area of the hexagon is of unit area ($\Delta = 3\sqrt{3}/2$), then the area is computed as in Table 2*b* (3rd column). The route area ranges from $\Delta/3$ to Δ.

Next we define route *complexity c* as follows [1]:

$$c = \frac{d^2}{a} \tag{1}$$

where d is the envelope route distance and a is the route area. For example, for a circle, $c = (2\pi r)^2/\pi r^2 = 4\pi = 12.6$. For the minimum sequence of six fundamental colors (Fig. 5*b* and Fig. 6, No.1), $c = 13.9$ is equal to that of six intermediate colors reported in a previous paper [10], [12]. Because these color sequences are regular hexagons, the complexity is computed by envelope and area in Table 2*b* (1st column). In this table, if the areas are the same, then the order having the lowest complexity is selected as natural.

In Fig. 5, the hexagonal diagram corresponds roughly to the hue circle (top view) indicated by both hue and saturation (except for lightness) in the HLS system. The numbers (1 to 6) denote the order of each color, corresponding to the arrows from the previous color to the present color in the sequences. For example, the projected minimum route is formed by (blue, cyan, green, yellow, red, magenta, and blue again) and the projected minimum route area is the area (dotted region) enclosed by route (*B*, *C*, *G*, *Y*, *R*, *M*, and *B*) in Fig. 5*b*.

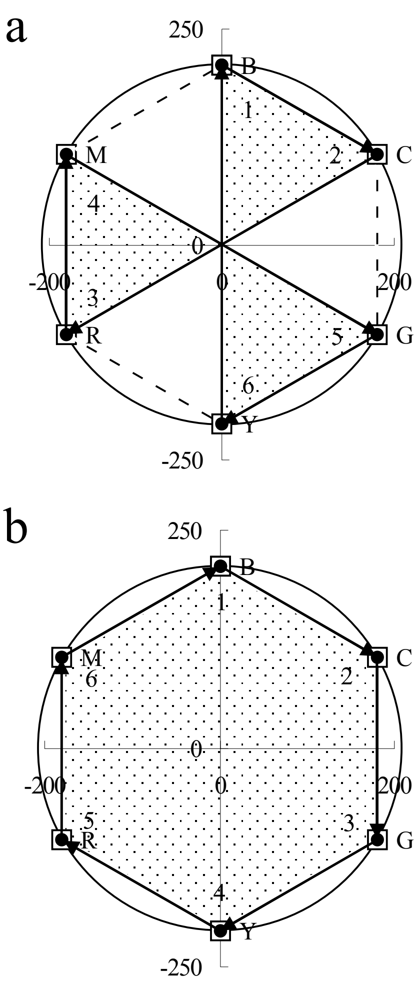

Fig. 5. Two projected routes (with arrows) and projected route areas (dotted regions) for six fundamental colors. *a*: No.9, *b*: No.1.

For instance, the projected minimum route indicates a hexagon (with filled points) of route (*B*, *C*, *G*, *Y*, *R*, *M*, and *B*).

Here, we consider two specific projected routes and projected route areas to make 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, magenta, green, yellow, and blue again), No.9 shown in Fig. 5*a* and Fig. 6, has the order of complimentary colors. However, this is not so for the maximum route. The minimum route (blue, cyan, green, yellow, red, magenta, and blue again), No.1 shown in Fig. 5*b* and Fig. 6, runs in a hexagon. The order of movement is clockwise. The dotted regions show the projected route areas. If the sides are of unit length (See Table 2*b*, 4th column), the ratio of non-minimum projected route distance to minimum projected route distance is 9.0/6.0 = 1.5, and the ratio of non-minimum route area to minimum route area is 1.3/2.6 = 0.5. However, these are not simple relationships [10], [12].

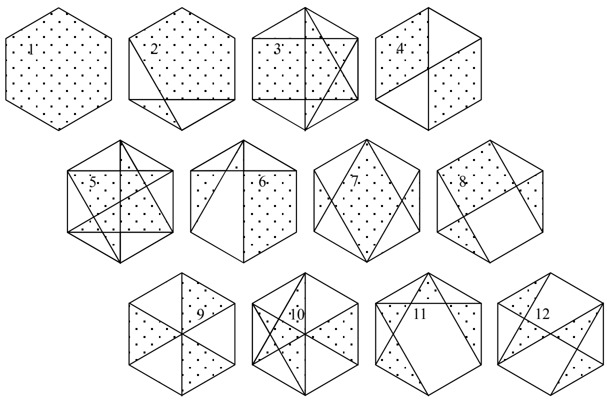

Fig. 6. Twelve typical routes and the route areas (dotted areas) for the six fundamental color sequences. Input sequences No.6 and No.7 were not performed in the experiments.

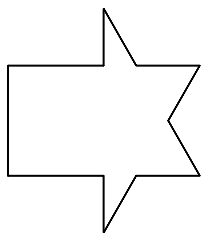

Fig. 7. Projected envelope route of sequence No.3.

In addition, we examined whether the color impression for such a spatial color sequence could be expressed by a simple adjective "natural". Twelve projections of 60 possible tours in three-dimensional RGB color space are shown in Fig. 6. In Fig. 6, the order of projected route areas is from No.1 (maximum as wide) to No.12 (minimum as narrow). The order of route complexity is from No.1 (minimum as simple) to No.12 (maximum as complex). The shape of No.3 is complex, but the route complexity (c = 32.2) of No.3 is lower than that (c = 37.0) of No.4. However, the area of No.4 is equal to that of No.3. The envelopes are recomputed, excluding cross cut lines, in three routes (No.3, No.5, and No.10, See Fig. 7). When the sizes of two areas are the same, the route complexities are compared in this case (See Table 2).

Figure 7 shows the envelope of the No.3 route used to calculate the route complexity. We have to compute the envelope of the route distance, especially for three routes of No.3, No.5, and No.10, in this study (See Table 2*b*).

Table 2. Summarizing characteristics of input sequences and responses.

a) Input and output					*b*) Pre-processed input			
							Route *area*	
No.	RGB route distance	Projected route distance	Projected route *area*	Number of subjects	Route *complexity*	Envelope route distance	Hexagonal ratio *r*	Area with unit length
1	1530	1247.6	112320	57	13.9	6.00	1	2.60
2	1741	1552.2	87360	19	27.6	7.46	7/9	2.02
3	2139	2064.3	74880	14	32.2	7.46	2/3	1.73
4	1903	1663.6	74880	28	37.0	8.00	2/3	1.73
5	2326	2272.3	62400	10	42.0	7.77	5/9	1.44
6	1928	1760.0	62400	-	49.6	8.46	5/9	1.44
7	1953	1856.3	62400	-	55.1	8.93	5/9	1.44
8	1928	1760.0	56160	24	55.6	8.46	1/2	1.30
9	2090	1871.4	56160	21	62.4	9.00	1/2	1.30
10	2301	2176.0	49920	13	68.4	8.89	4/9	1.15
11	1953	1856.3	37440	10	69.7	7.77	1/3	0.87
12	2115	1968.0	37440	19	103.4	9.46	1/3	0.87

There are no data for the number of subjects for sequences No.6 or No.7. Route area calculated with unit length = hexagonal ratio r x regular hexagonal area Δ ($= 3\sqrt{3}/2$).

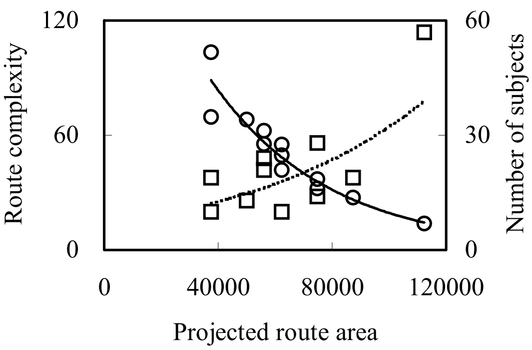

Fig. 8 Route complexity (circle) and number of subjects (square) for projected route area in six fundamental color sequences.

Figure 8 shows the relationship between route complexity and the number of subjects for the projected route area in six fundamental color sequences. These trends indicate an exponential approximation (dotted curve). The responses of subjects show a roughly exponential trend (solid curve) to the route area in Fig. 8. This is not such a good fit to the dotted curve (upper-right). The results for six colors indicate that as the route area increases, the route complexity (solid curve with circles) diminishes and the number of subjects increases (dotted curve with squares). The characteristics of color sequences for which subjects report a "natural" color impression were clarified to be minimum complexity (simple) and maximum route area (wide).

The degree β of naturalness relates route area a

for similar hexagons of different size, and the degree γ of unnaturalness relates route complexity c for similar hexagons of different size. These relationships are as follows:

$$\beta \approx \omega_1 a \tag{2}$$

$$\gamma \approx \omega_2 c \tag{3}$$

where ω_1 and ω_2 are unknown constants. Namely, the natural color sequence is evaluated by projected route area, rather than by route complexity, because the route complexities of the sequences with the six colors are exactly the same for different sizes of regular hexagons (similarity).

Fuzzy Model

In Fig. 9, we create a simple fuzzy model of natural human color impression using projected route area together with the assisting complexity of six fundamental color sequences (lower trace). Medium-sized route area and medium-sized envelope route distance do not correspond to each other. However, maximum (wide) route area corresponds to minimum (short) envelope route distance, and minimum (narrow) route area corresponds to maximum (long) envelope route distance (Fig. 10).

If the RGB route distance is a candidate input for a simple fuzzy system, we cannot compute the route complexity [1] because of the three dimensionality. In the pre-process, (Fig. 9, top trace) using both projected envelope route and projected route area, we can adopt route complexity. However, it is not possible to use route complexity alone because route complexity is simply a ratio and does not change for different route area sizes (e.g. similarity) in the general model we consider herein.

Although the values of route complexity used in the study do not actually exist, those of RGB route distance, projected route distance, envelope route distance, and route area do exist. Therefore, together with assisting route complexity, fuzzy rules of human color impression (HCI) i are constructed by projected route area a in Fig. 9 (bottom-left). Fuzzy rules are as follows:

$$IF\ a\ is\ Small\ \&\ Medium, THEN\ i\ is\ Unnatural \tag{4}$$

$$IF\ a\ is\ Large, THEN\ i\ is\ Natural \tag{5}$$

The area a is the input, and human color impression (HCI) i is the output. “Small & Medium” and “Large” are fuzzy values for a, and are expressed by fuzzy sets of trapezoid and triangle. When an actual input is given, the output is calculated by means of fuzzy inference. Now, let the input be $a = a'$. From Eq. 2, the triangular membership function f_1 to the route area a' gives the degree of naturalness:

$$\beta = f_1(a') \tag{6}$$

From Eqs. 1 and 3, trapezoidal membership function f_2 to the route area a' gives the degree of unnaturalness:

$$\gamma = f_2(a') \tag{7}$$

$$\beta + \gamma = 1 \tag{8}$$

$$f_1(a) = \{ \begin{array}{ll} b(a - a_0), & \Delta \ge a \ge a_0 \\ 0, & a_0 > a > 0 \end{array} \tag{9}$$

$$f_2(a) = \{ \begin{array}{ll} -b(a - \Delta), & \Delta \ge a \ge a_0 \\ 1, & a_0 > a > 0 \end{array} \tag{10}$$

where the constant $a_0 = 2\Delta/3$ is between $\Delta/3$ (minimum area) and Δ (maximum area) and the constant b shows the inclination in Fig. 9.

Modeling Results

Figure 10 shows a summary of the relationship in Table 2, these orders for route area and envelope distance of six fundamental color sequences are sorted by complexity size. The twelve-route complexity is computed in Table 2, and the RGB route distance is composed of ten levels, where the maximum distance of the RGB route distance is ordered in the fifth trace and does not exist in lower traces. The envelope route distance is of nine levels, and the route area is of only seven levels, which is the same size in some case. In No.5-No.7, each route area is $5\Delta/9$. Therefore, No.6 and No.7 are omitted in the present experiment. Excluding the RGB route, we can separate the upper traces (1-3) in Fig. 10, middle and lower traces (3-12). This corresponds to “small and medium” and “large” membership functions on the route area.

In the previous simulation results for six fundamental colors [10], [12], the relationship between the order of RGB routes and route areas shows a decreasing trend having fluctuations. These fluctuations become larger for increasing order. That is, a mixture of the relationship in Fig. 10 causes the fluctuations.

We thought that the route area indicates the magnitude of naturalness (as a rainbow effect) for color sequences in our model. The minimum sequence is similar to the order of rainbow colors, which are composed of the following wavelengths [14]: violet (400-430nm), indigo (440-460nm), blue (470nm), green (505nm), yellow (575nm), orange (590-620nm), and red (> 630nm), where orange is yellow-red, indigo is dull blue, and violet is purple-blue. On the other hand, the non-minimum sequence is completely different from the order of rainbow colors.

Although the six colors used in the previous study [10], [11], [12] are not distributed as rainbow colors (violet, indigo, blue, green, yellow, orange, and red) and the six-color cyclic sequences are not continuous sequences having gradation, we propose a simple fuzzy model of human color impression using the route area indicated by both hue and saturation. This model [6], [7], [9] invokes natural impressions when the route area is large and unnatural impressions when the route area is small or medium-sized (Fig. 9).

In the present study, we clarified that the majority of subjects chose large projected route area as the minimum sequence, when reporting a "natural color sequence". When the number of colors increases, such a simple fuzzy system is useful [13].

Conclusions

In the present paper, we proposed a simple fuzzy model of human color impression that indicates the degree of perceived naturalness using the projected route area with assisting route complexity. These simulation results suggest that if the area of the projected route is the maximum, or nearly maximum, then human color impression becomes "natural", otherwise human color impression becomes "unnatural". Route complexity has an inverse relationship to the projected route area.

This fuzzy model will also provide a toroidal design of suitable colors (as spatial information) for controlling feelings or emotions (for example, when used in signboards, tile floors, or gardening) and of color signal sequences (as temporal information) [5], [8] based on single-color effects [3].

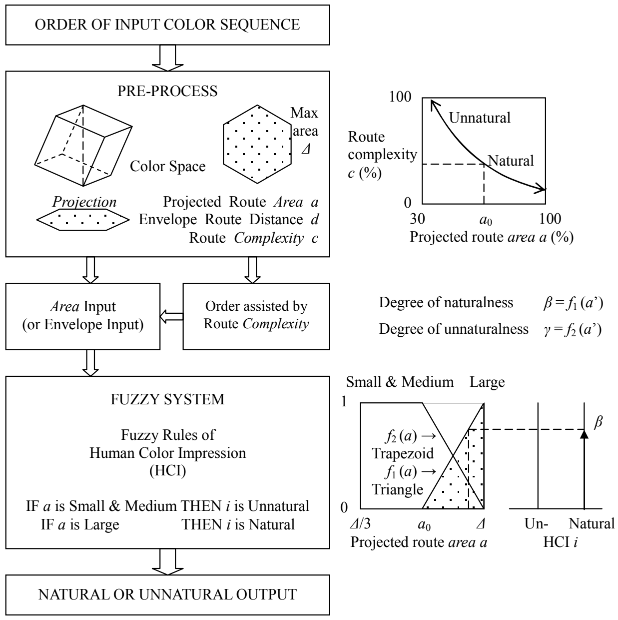

Fig. 9 Simple fuzzy model of human color impression (HCI) and determination of naturalness for six fundamental color sequences.

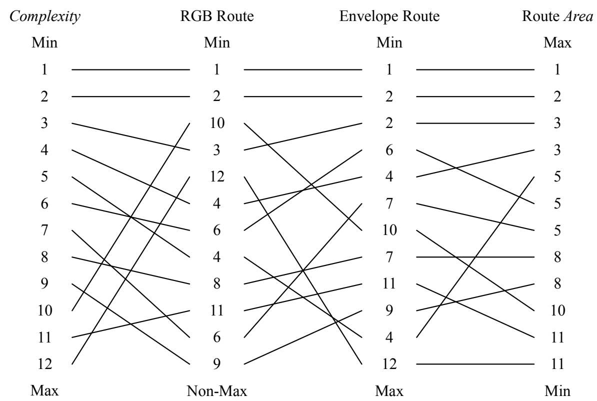

Fig. 10 Relationship between each order of route complexity (twelve levels of twelve routes), RGB route distance (ten levels of twelve routes), envelope route distance (nine levels of twelve routes), and route area (seven levels of twelve routes) of six fundamental color sequences. The orders of sequences correspond to those in Table 2.

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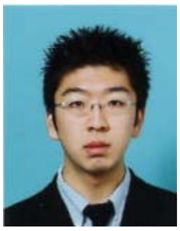
Naotoshi SUGANO

He received Doctor of Engineering from Tamagawa University, Tokyo in 1979. He joined with Tamagawa University in 1979. From 1981 to 1982, he was a Visiting Fellow at National Institutes of Health, Maryland. He is currently a Professor at Tamagawa University. His main research interests include color information processing using fuzzy set theory and Kansei information processing for human interface. He is a member of Institute of Electrical and Electronic Engineers, Institute of Electronics, Information and Communication Engineers, Japan Society for Fuzzy Theory and Systems, Japan Society of KANSEI Engineering, Biomedical Fuzzy Systems Association, and Architectural Institute of Japan.



Yuuichirou NEGISHI

He received Bachelor of Engineering from Tamagawa University, Tokyo in 2004. He joined with Naito Densei co. ltd. in 2004. He is a system engineer. His main research interests include color information processing and Kansei information processing for human interface.

Toshihiro ISHIHARA

He received Master of Engineering from Tamagawa University, Tokyo in 1990. He joined with Fuji Heavy Industries ltd. in 1990. From 1990 to 1999, he was a system engineer. He is currently a system engineer at C-TECH co. ltd. His main research interests include color information processing and Kansei information processing for human interface.