Fuzzy Set Theoretical Analysis of Human Membership Values on the Color Triangle

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***Abstract*—The present study considers a fuzzy color system in which three membership functions are constructed on the RGB color triangle. This system can process a fuzzy input (as the membership values of subjects) to an RGB system and output the center of gravity of three weights associated with respective grades. Three membership functions are applied to the RGB color triangle relationship. By treating three membership functions of redness, greenness, and blueness on the RGB color triangle, an average color value can be easily obtained as the center of gravity of the fuzzy output. The differences between fuzzy input and inference output are described, and the relationship between the centers of gravity of fuzzy inputs and inference outputs for fuzzy inputs are shown in the present paper.**

***Index Terms*—fuzzy set theory, three additive primary colors, membership function, RGB system, color triangle, vague color, membership value, center of gravity**

I. INTRODUCTION

In the Natural Color System (NCS), a method similar to the fuzzy set theoretical method for obtaining hue expressions with vagueness has been reported by Sivik [2]. Using the fuzzy set theoretical method, in the recent study, a technique for acquiring tone expressions with vagueness on the NCS color triangle has been investigated by Sugano [3]. The triangular membership functions of achromatic colors and conical membership functions of chromatic colors were used as vagueness, which caused a gathering effect toward the center of the NCS tone triangle. In this previous study, fuzzy achromatic colors of triangular membership functions and fuzzy modified achromatic colors of conical membership functions were used on the NCS color triangle in a manner corresponding to the HLS (hue, lightness, and saturation) tone plane consisting of lightness and saturation. The vagueness effects of achromatic colors and modified achromatic colors (e.g., reddish, yellowish, greenish, and bluish achromatic colors) have been clarified [4].

A technique for obtaining expressions of the RGB color triangle using the fuzzy set theoretical method has been reported [5] and improved [6]. In the previous study, the relationship between input fuzzy sets with a plateau on the RGB triangle and fuzzy inputs of conical membership functions was examined. The RGB color triangle (plane) represents the hue and saturation of a color [8]. The six fundamental colors and white can be represented on the same color triangle (See Fig. 1). Vague colors on the RGB color triangle were clarified. In the present study, the membership value on the RGB triangular system are examined to determine the average color value as the center of gravity of the attribute information of vague colors. This fuzzy set theoretical approach is useful for vague color information processing, color-naming systems, and similar applications.

II. RGB COLOR TRIANGLE

Additive color mixing occurs when two or three beams of differently colored light combine. It has been found that mixing just three additive primary colors, red, green and blue, can produce the majority of colors. In general, a color can be described by certain quantities, called the tri-stimulus values, r for the red component, g for the green component, and b for the blue component, as follows:

$$color = r + g + b\,. \tag{1}$$

This is called the RGB color model. This concept allows colors to be represented by a planar diagram. The first step is to draw the red, green and blue components as the vertices of a color triangle, as in Fig. 1. The coordinates on the plane of the color triangle can specify various colors. The location given by the coordinates corresponds to the amounts of r, g and b that make up the color. The coordinates specifying the center of the color triangle represent the case in which the three primary colors are mixed in equal proportion and indicate the color white. Such representations are called chromaticity diagrams. The diagram represents hue and saturation but not lightness [8]. On the RGB color triangle, the percentages of redness, greenness, and blueness, where

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the total of the three attributes is equivalent to 100% (as shown in Table I), specify a color.

III. METHODS

A. Color Triangle Designs

The previous study [5], [6], considered a system of the three primary colors, red, green, and blue (RGB), presented on an RGB color triangle. As Fig. 1 shows, blue, cyan, green, yellow, red, magenta, and white are abbreviated as B, C, G, Y, R, M, and W, respectively. Six fundamental color coordinates, e.g., (r_1, g_1, b_1), (r_6, g_6, b_6), (r_{11}, g_{11}, b_{11}), …, were selected, where r_n, g_n, and b_n are the red, green, and blue components, respectively, of the n^{th} color.

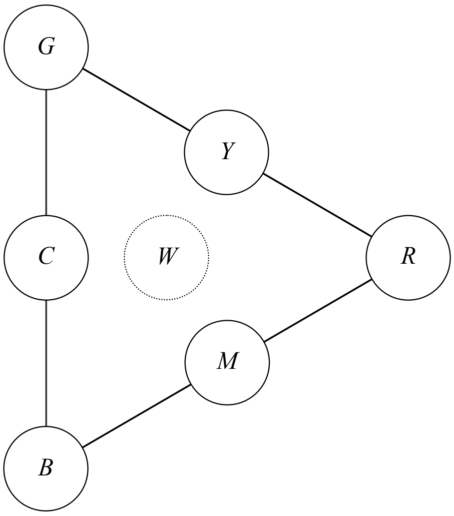

Figure 1. A color triangle: A point on the plane of the triangular system represents the hue and saturation of a color spaces.

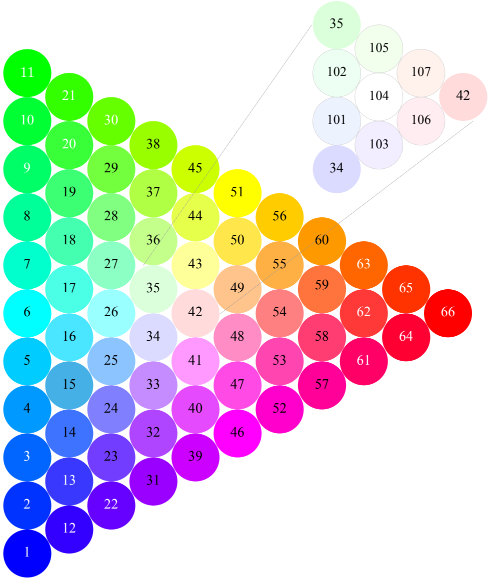

Figure 2. Sixty-six crisp color inputs (*fundamental type*) and white with six neighboring colors (*detail type*) on the color triangle. See Appendix A.

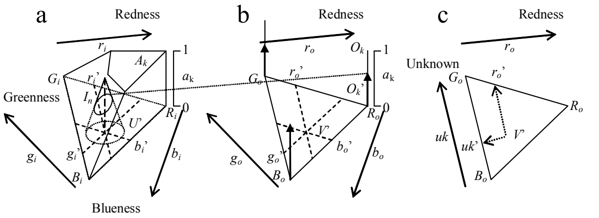

Figure 3. Fuzzy system using the membership function of input fuzzy sets A_k, output crisp sets O_k and conical fuzzy input I_n on the color triangle.

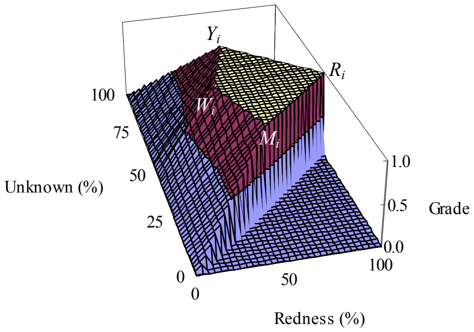

Figure 4. The membership function $\mu_1(r_i, uk)$ of input fuzzy set A_1 (*redness*) on the color triangle. This is corresponding to Fig. 3*a*.

Figure 2 corresponds to the schematic diagram shown in Fig. 1. The color names in Fig. 2 are No .1: blue, No .6: cyan, No. 11: green, No. 46: magenta, No. 51: yellow, and No. 66: red.

White (No. 104) is surrounded by six neighboring colors, as shown in the detail inset, and these seven colors (No. 101–No. 107) are surrounded by No. 34, No. 35, and No. 42. We try to examine the detail type which is extended from 66 colors (excluding to white) in the fundamental type to 496 colors (including to white). See Appendix A.

B. Fuzzy Rules

Figure 3 illustrates input fuzzy set, fuzzy input, output crisp set, and fuzzy output on the RGB color triangle, and crisp output on the graphical plane. The fuzzy rules are as follows (See Figs. 3 and 6):

$$R^1 : \mathit{if}\ U\ \mathit{is}\ A_1\ \mathit{then}\ V\ \mathit{is}\ O_1. \tag{2}$$

$$R^2 : \mathit{if}\ U\ \mathit{is}\ A_2\ \mathit{then}\ V\ \mathit{is}\ O_2. \tag{3}$$

$$R^3 : \mathit{if}\ U\ \mathit{is}\ A_3\ \mathit{then}\ V\ \mathit{is}\ O_3. \tag{4}$$

Rule R^k : *if* U *is* A_k, *then* V *is* O_k ($k = 1, 2, 3$), where k is the rule number corresponding to the components of r, g, and b, A_k is a fuzzy set of inputs, O_k is a crisp set of outputs, $U = (r_i, g_i, b_i)$ are input parameters (variable), and $V = (r_o, g_o, b_o)$ are output parameters. Here, U and V are fixed to these RGB parameters. A fuzzy set A_k of inputs shows a triangular pyramid-like shape with a plateau at corner points R_i, G_i, and B_i, and a crisp set O_k

of outputs of rule R^k is shown at corner points R_o, G_o, or B_o (a fuzzy set O_k' indicated by vertical arrows in Fig. 3*b*) on the color triangle, and the output is O_k if the input is A_k.

The fuzzy inference method is as follows. Let the inputs be $r_i = r_i'$, $g_i = g_i'$, and $b_i = b_i'$.

1) The input of rule R^k, grade $\alpha_k = A_k(U')$, where k = 1, 2, 3.

2) The output of rule R^k, output crisp set is shown as a vertical post.

3) $O_k' = \alpha_k O_k$, where O_k' is fuzzy sets (as vertical allows) and O_k is crisp sets (as vertical posts) in Fig. 3*b*. The complete inference results O' of rules R^1, R^2, and R^3.

$$O' = \alpha_1 O_1 \cup \alpha_2 O_2 \cup \alpha_3 O_3 = O_1' \cup O_2' \cup O_3'. \quad (5)$$

The output parameter, $V' = (r_o', g_o', b_o')$, corresponds to the coordinates of the central axis of the membership function of O'. In addition, in Fig. 3*c*, $V' = (r_o', uk')$ corresponds to a coordinates of the graphical system, where uk' (on the vertical axis) is calculated from g_o' and b_o'. uk' shows a value (as distance from B) on the line B-G.

An input fuzzy set A_1 of *redness* can be characterized by the following membership function:

$$\mu_1(r_i, uk) = r_i s; \quad r_i < \frac{1}{s}. \quad (6)$$

$$\mu_1(r_i, uk) = 1; \quad r_i \geq \frac{1}{s}. \quad (7)$$

where s is slope of projection and s ranges from 0.02 to 0.03 (See Fig. 6). The limitations of uk are as follows:

$$50 \geq uk \geq \frac{r_i}{2}. \quad (8)$$

$$50 < uk \leq -\frac{r_i}{2} + 100. \quad (9)$$

The membership functions of *greenness* and *blueness* are also described by similar equations.

C. Fuzzy Sets

Table I shows the membership value $\mu_k(r_i', g_i', b_i')$ of input fuzzy set A_k on the RGB color triangle. $\mu_k(r_i', g_i', b_i')$ is equal to $\mu_k(r_i', uk')$. The membership function μ_k was based on the values of seven colors (R, Y, G, C, B, M, and W).

In Fig. 4, the shape of membership function is shown by including to W_i (white). Top of the plateau is shown as diamond-like shape in this case. See also Table I and Fig. 6.

Figure 5*a* (left) illustrates twenty-one fuzzy inputs (I_1–I_6, I_{12}–I_{16}, I_{22}–I_{25}, I_{31}–I_{33}, I_{39}–I_{40}, and I_{46}) on the RGB color triangle as a triangle with color names (B, C, and M). The fuzzy inputs are formed by conical membership functions, and the membership functions are made to mutually overlap. The edge of the basal plane (circle) of the conical membership function passes through the centers of the overlapped circles.

Figure 5*b* (right) shows the arrangement of numbers corresponding to the conical membership functions of Fig. 5*a*, and the numbers are shown inside circles representing the top of the 0.5 level-set (bottom-right). The color names are No. 1: blue, No. 6: cyan, and No. 46: magenta.

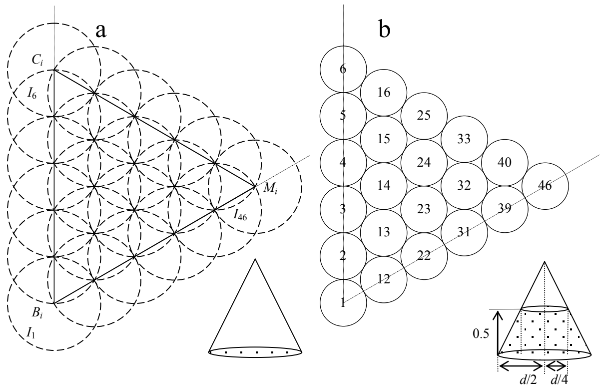

Figure 5. Fuzzy inputs on part of the RGB color triangle and top areas of 0.5 level-sets indicated by number. The diameter (d = 23.0%) of the basal plane (*circle*) of the cone indicated vagueness.

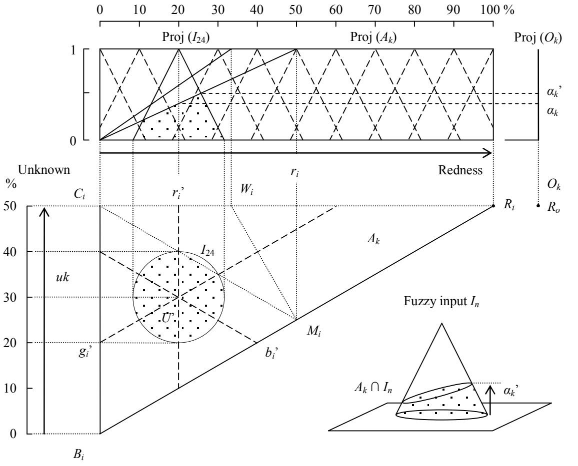

Figure 6. Membership functions of input fuzzy sets A_k on half of the RGB color triangle and one of sixty-six conical fuzzy inputs (*vague colors*).

TABLE I.
MEMBERSHIP VALUE OF INPUT FUZZY SET A_k ON THE COLOR TRIANGLE

Color	Color coordinate			Membership value μ_k		
	r_i'	g_i'	b_i'	k=1	k=2	k=3
B_i	0.0	0.0	100.0	0.00	0.00	1.00
C_i	0.0	50.0	50.0	0.00	1.00	1.00
G_i	0.0	100.0	0.0	0.00	1.00	0.00
M_i	50.0	0.0	50.0	1.00	0.00	1.00
Y_i	50.0	50.0	0.0	1.00	1.00	0.00
R_i	100.0	0.0	0.0	1.00	0.00	0.00
W_i	33.3	33.3	33.3	1.00	1.00	1.00

Figure 6 illustrates half of the RGB color triangle as a base of input fuzzy set A_k and one of the sixty-six conical fuzzy inputs (I_1–I_{66}) on the RGB color triangle. For k = 1 (as redness), sharp slant line (s = 0.03) shows a projection

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of line between C_i with membership value $\mu_k = 0$ and W_i with $\mu_k = 1$ and gentle slope line ($s = 0.02$) shows a projection of line between B_i with value $\mu_k = 0$ and M_i with value $\mu_k = 1$ (or between G_i with $\mu_k = 0$ and Y_i with $\mu_k = 1$ on the blind side). See also Table I and Fig. 4. The triangular membership function Proj(I_{24}) on the redness axis is one of eleven projections of the sixty-six fuzzy inputs (I_1–I_{66}) by the rays from the lower part, and the triangular membership function Proj(I_n) on the unknown axis is not used in the present study.

The intersection of input fuzzy set A_k for fuzzy input I_n is $A_k \cap I_n$. (See the dotted area at the bottom-right of Fig. 6.) Grade α_k' = height ($A_k \cap I_n$). If the input is crisp, α_k' becomes α_k. R_o is the new red as output. Proj(O_k) is a projection of an output crisp set at the corner point R_o (See Fig. 3*b*).

What happens if a vague color is input into the RGB system? The system considered in this study can translate input data U of vague color to output data V of simple color on the RGB color triangle. The fuzzy input on the RGB is constructed by the center $U' = (r_i', g_i', b_i') = (0, 0, 100)$ in % and the diameter d of the basal plane (circle) of the cone indicated vagueness.

TABLE II.
NUMBER OF SUBJECTS IN THE EXPERIMENT

Type	No. of subjects	Male	Female	Age
496	28	12	16	12-60

Semantic differential method is used. 496 is detail type.

IV. EXPERIMENTAL METHODS

For the experiment, 28 (in Table II) undergraduate students, graduate students, and participants in a university festival volunteered to participate as subjects for this study. The subjects sat in a chair and were requested to watch a display continuously.

Using the ensemble average of the fuzzy sets obtained from the red-relevant colors, green-relevant colors, blue-relevant colors, yellow-relevant colors, cyan-relevant colors, magenta-relevant colors, and white-relevant colors, then, the normalized membership values of subjects are computed [7].

In this study, using a graphical user interface (GUI) for the questionnaire, 28 subjects compared the differences between a target color (e.g. red) and neighboring colors of 495 colors in detail type (See Appendix A). In practice, the subjects watch only 120 colors (e.g. red) because the size of color of a circular shape is kept two degrees in sight. Seven groups of the red-relevant colors, green-relevant colors, blue-relevant colors, yellow-relevant colors, cyan-relevant colors, magenta-relevant colors, and white-relevant colors as the fuzzy sets are determined. The experiments were performed in an isolated area in order to restrict visual cues with regard to the display.

Equipment

HP Compaq 14.1" Liquid Crystal Display and Panasonic 12.1" Liquid Crystal Display were used to present the stimulus pattern. The display resolution was 1024×768 pixels/60Hz.

V. EXPERIMENTAL RESULTS AND DISCUSSION

Figures 7-9 show the experimental results for red-relevant colors, green-relevant colors, and blue-relevant colors on the coordinates (r_i', *uk*) in detail type (496 colors) using SD method. The membership values of 28 subjects are combined.

Figs. 10 and 11 show the intersection of input fuzzy set A_k for fuzzy input I_n ($A_k \cap I_n$). I_n is corresponding to a fuzzy set of red-relevant colors. See the dotted area at the bottom-right of Fig. 6. Grade α_k' = height ($A_k \cap I_n$).

Figure 12 is corresponding to Fig. 6 (lower part). Fig. 12 shows a top view of Fig. 7.

Figures 13-16 show the experimental results for cyan-relevant colors, magenta-relevant colors, yellow-relevant colors, and white-relevant colors on the coordinates (r_i', *uk*) in detail type (496 colors) using SD method. See Appendix A. The membership values of 28 subjects are combined.

It assumes that the fuzzy inputs on the RGB color triangle are constructed by the centers (r_i', g_i', b_i'). The center (R_i) of red-relevant colors is (100, 0, 0), the center (G_i) of green-relevant colors is (0, 100, 0), the center (B_i) of blue-relevant colors is (0, 0, 100), the center (Y_i) of yellow-relevant colors is (50, 50, 0), the center (C_i) of cyan-relevant colors is (0, 50, 50), and the center (M_i) of magenta-relevant colors is (50, 0, 50), which assume to fuzzy input I_n in Fig. 5*a*. The coordinates of centers and that of inference outputs are examined.

Red-relevant colors, green-relevant colors, and blue-relevant colors have a peak in Figs. 7-9 and a plateau peak in Figs. 13 and 14. Yellow-relevant colors are gathered round coordinate (50, 75) in Fig. 15. White-relevant colors are gathered about one coordinate (33.3, 50) in detail type (Fig. 16). See Appendix A. However, cyan-relevant and magenta-relevant colors have not sharp peak at coordinate (0, 50) in Fig. 13 and (50, 25) in Fig. 14.

The calculation of intersections between membership values (divided into red, green, blue, yellow, cyan, and magenta) and projection of membership function of input fuzzy set are performed. See Eqs.6–9. A fuzzy set of red-relevant colors is a subset of input fuzzy set of redness.

Table III is calculated from Figs. 7-9 and Figs. 13-16. The centers of gravity are equal to averages of fuzzy sets as the crisp inputs to the system.

Figure 17 illustrates a relationship between the redness value r_i and the unknown value *uk*. Filled circles indicate the centers of gravity for fuzzy inputs. A center (average) of fuzzy input is shown as a trend. Open circles indicate crisp inputs of colors (as target colors). Target color means the center of cone as vagueness in Figs. 3, 5, and 6. The differences between target colors (open circles) and the outputs (filled circles) are not so large. See Table III.

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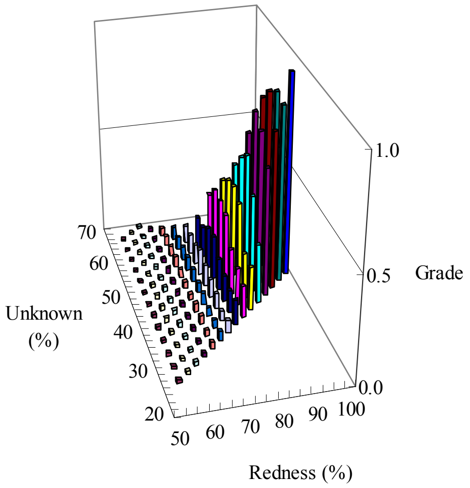


Figure 7. Membership values of red-relevant colors as fuzzy input.

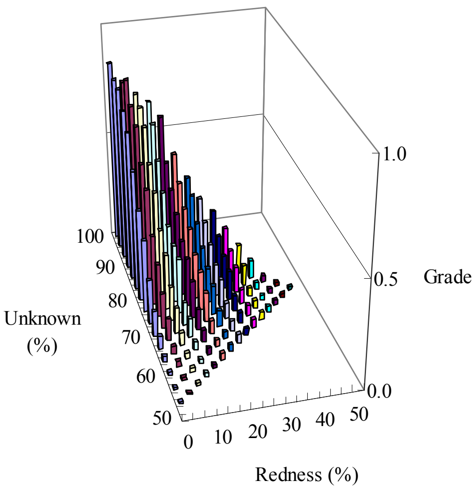


Figure 8. Membership values of green-relevant colors as fuzzy input.

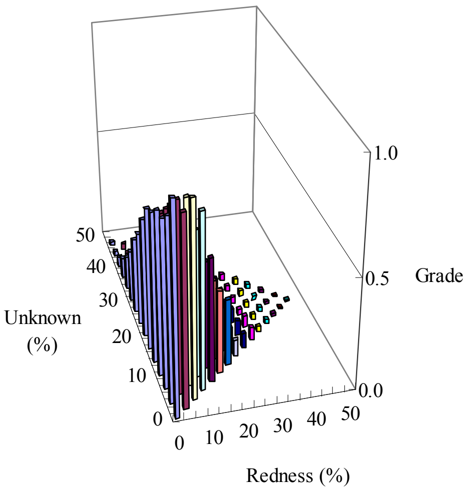


Figure 9. Membership values of blue-relevant colors as fuzzy input.

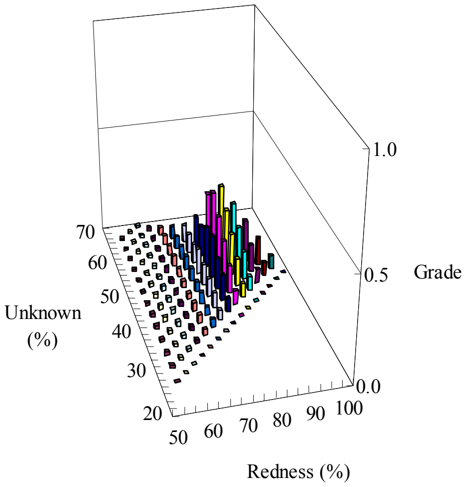


Figure 10. Intersection of the membership values of red-relevant colors and the membership function of input fuzzy set A_2 (*greenness*), α_2.

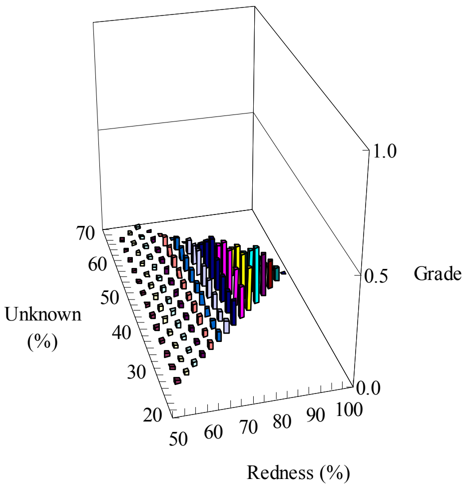


Figure 11. Intersection of the membership values of red-relevant colors and the membership function of input fuzzy set A_3 (*blueness*), α_3.

Unknown %	50			60			70			80			90			100 %	Redness
70				0.01													
			0.01		0.02												
		0.01		0.01		0.04											
65			0.01		0.02		0.06										
		0.01		0.01		0.05		0.09									
			0.01		0.02		0.06		0.15								
60		0.01		0.01		0.05		0.09		0.28							
			0.01		0.02		0.06		0.15		0.37						
		0.01		0.01		0.05		0.09		0.35		0.46					
55			0.01		0.03		0.07		0.20		0.41		0.62				
		0.01		0.02		0.04		0.12		0.35		0.54		0.80			
			0.01		0.02		0.06		0.20		0.43		0.76		0.84		
50		0.01		0.02		0.03		0.10		0.33		0.59		0.86		0.94	*R*
			0.02		0.02		0.05		0.15		0.40		0.72		0.82		
		0.01		0.02		0.03		0.09		0.21		0.45		0.73			
45			0.02		0.02		0.05		0.12		0.21		0.60				
		0.02		0.02		0.04		0.07		0.18		0.28					
			0.02		0.02		0.04		0.11		0.20						
40		0.02		0.02		0.04		0.05		0.15							
			0.02		0.02		0.04		0.12								
		0.01		0.02		0.03		0.06									
35			0.01		0.02		0.05										
		0.01		0.01		0.03											
			0.01		0.02												
30		0.01		0.02													
			0.01														
		0.01															
25																	
20																	

Figure 12. Membership values of red-relevant colors (red and neighboring colors) as fuzzy input.

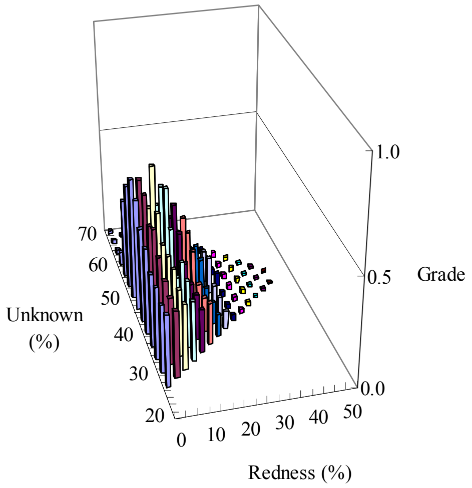


Figure 13. Membership values of cyan-relevant colors as fuzzy input.

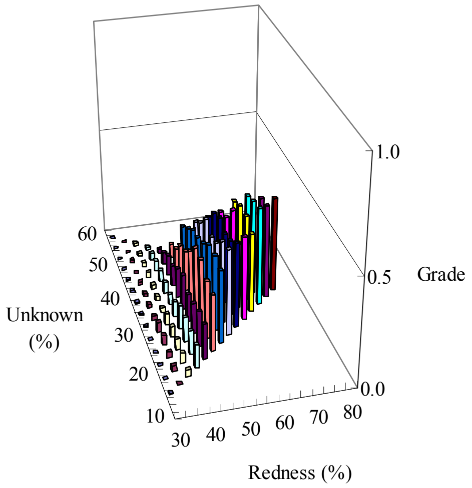


Figure 14. Membership values of magenta-relevant colors as fuzzy input.

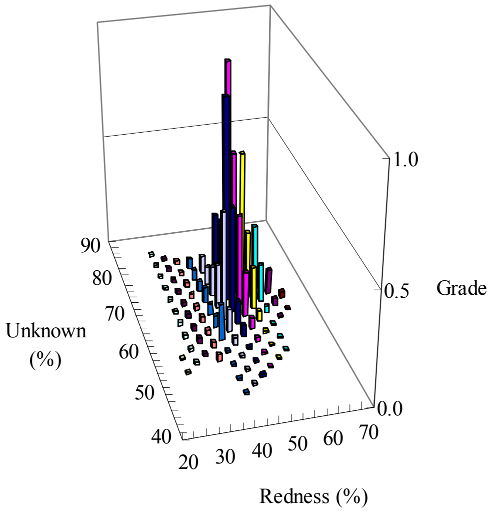


Figure 15. Membership values of yellow-relevant colors as fuzzy input.

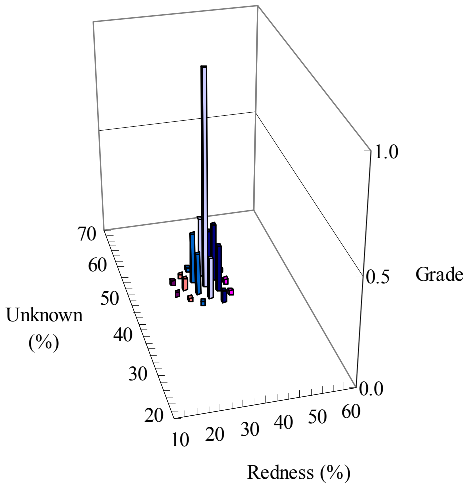


Figure 16. Membership values of white-relevant colors as fuzzy input.

TABLE III.
CRISP INPUTS AS CENTERS OF GRAVITY OF FUZZY INPUTS

Color	Color coordinate of crisp input				
	r_i’	uk’	r_i’	g_i’	b_i’
R	85.12	50.49	85.12	7.93	6.95
G	9.94	85.74	9.94	80.77	9.29
B	8.15	15.93	8.15	11.86	80.00
Y	47.74	69.61	47.74	45.74	6.52
C	8.63	45.45	8.63	41.14	50.24
M	54.49	35.43	54.49	8.19	37.33
W	33.40	50.41	33.40	33.71	32.89

Color coordinate (r_i’, g_i’, b_i’) is calculated from (r_i’, uk’).

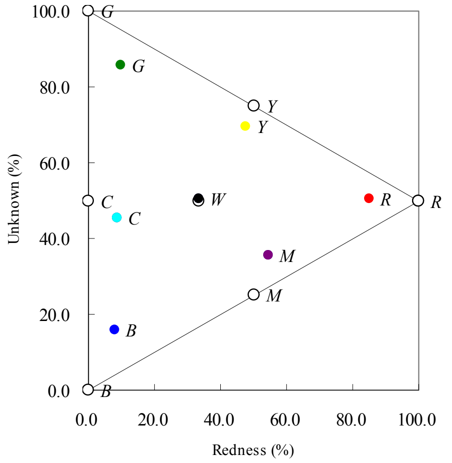


Figure 17. Centers of gravity of fuzzy inputs (*filled circles*). *W* is white (*large open circle*). See Table III.

TABLE IV.
INFERENCE RESULTS FOR CRISP INPUTS

Color	Grade for crisp input			Inference output		
	α_1	α_2	α_3	r_o’	g_o’	b_o’
R	1.00	0.16	0.14	77.07	12.22	10.71
G	0.20	1.00	0.19	14.36	72.22	13.42
B	0.16	0.24	1.00	11.64	16.94	71.42
Y	1.00	1.00	0.19	45.64	45.55	8.81
C	0.24	1.00	0.85	11.40	47.96	40.64
M	1.00	0.22	0.78	50.14	10.91	38.95
W	1.00	1.00	0.98	33.43	33.54	33.03

TABLE V.
INFERENCE RESULTS FOR FUZZY INPUTS

Color	Grade for fuzzy input			Inference output		
	α_1’	α_2’	α_3’	r_o’	g_o’	b_o’
R_f	1.00	0.33	0.27	62.50	20.63	16.88
G_f	0.40	1.00	0.40	22.22	55.56	22.22
B_f	0.33	0.42	1.00	18.86	24.00	57.14
Y_f	0.97	0.97	0.40	41.45	41.45	17.09
C_f	0.40	0.60	0.60	25.00	37.50	37.50
M_f	0.45	0.33	0.45	36.59	26.83	36.59
W_f	1.00	1.00	1.00	33.33	33.33	33.33

In Table IV the grades for crisp input is obtained from Table III, and the inference outputs for crisp inputs are calculated.

In Table V for instance the grades for fuzzy input *R* is obtained from Figs. 10 and 11, and the inference outputs for fuzzy inputs are calculated.

Figure 18 illustrates a relationship between the redness value r_o and the unknown value *uk*. In *a*, filled circles indicate the inference outputs for crisp inputs as the centers of gravity of fuzzy inputs. Open circles also indicate crisp inputs of colors (as target colors). In *b*, filled circles indicate the inference outputs for fuzzy inputs of colors, open circles also indicate crisp inputs of colors (as target colors). The outputs (filled circles) for fuzzy inputs are grouped at the center of the color triangle. The open and filled circles are clearly different in this case. The differences between target colors (open circles) and the outputs (filled circles) are so large. The differences in *a* are smaller than those in *b*. See Table IV and V in detail. The gathering effects exist [5]-[7]. The experimental results for GUI are shown in this paper.

Vague color inputs to the fuzzy system (Figs. 7-9), the system outputs crisp color in the RGB, and also outputs crisp color on the graphical plane (Fig. 18). These inference results for fuzzy 496 colors and fuzzy 66 colors are similar. These inference results for partition method [7] and semantic differential method ate also similar.

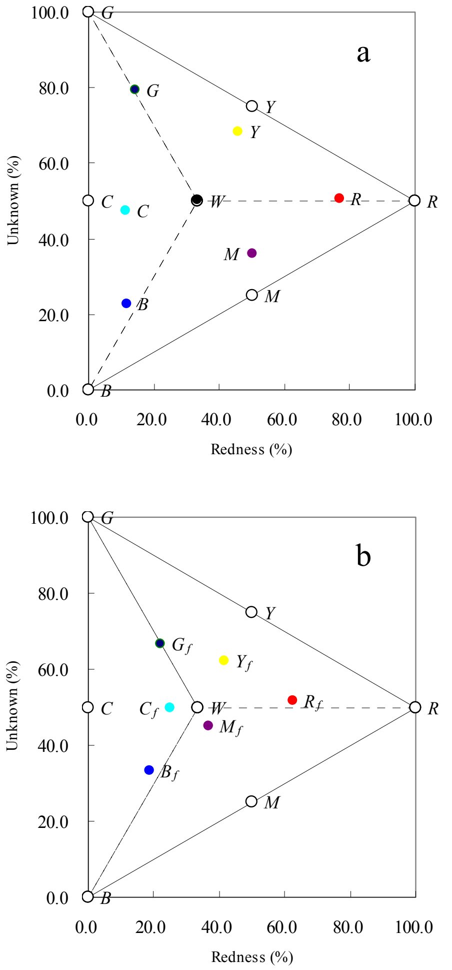


Figure 18. Inference outputs (*open circles*) for crisp inputs, inference outputs (*filled circles*) for crisp inputs as the centers of gravity of fuzzy inputs (*a*), and inference outputs (*filled circles*) for fuzzy inputs (*b*) on the RGB color triangle. Suffix *f* shows fuzzy inference output. *W* (*large open circles*) exists in the coordinate (33.3%, 50.0%). See Table IV for crisp inputs and Table V for fuzzy inputs.

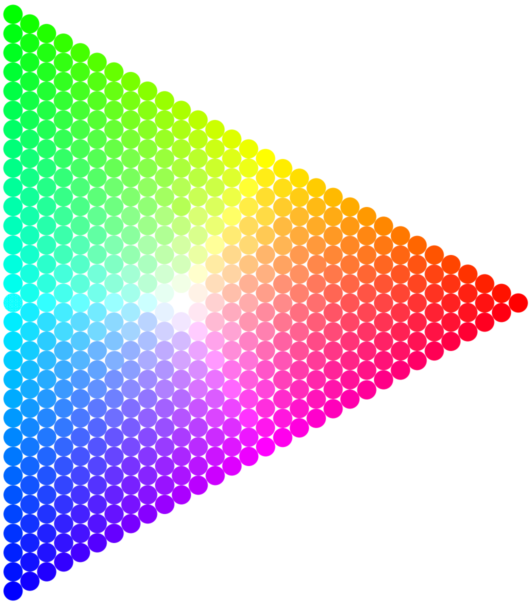
All the time people are in the environment with vagueness. Human beings are surrounded vague information. However the vagueness has not been shown in any color research. In this study RGB-relevant colors as a vague color are visualized for the first time. Using fuzzy set theoretical method vague data produce inference results similar to accurate results of the modified Munsell (Book of) Color, *R*: (*r*, *g*, *b*) = (54.57, 31.76, 13.67), *G*: (*r*, *g*, *b*) = (24.91, 42.13, 32.96), *B*: (*r*, *g*, *b*) = (18.16, 25.37, 56.47), *Y*: (*r*, *g*, *b*) = (46.34, 48.22, 5.44), and *S*: (*r*, *g*, *b*) = (31.13, 31.80, 37.07) in % [1]. Namely it implies that vague data cause real data. If huge data exist the accuracy will be high. This might be an answer for the question why human being can skillfully process vagueness.

VI. CONCLUSION

The present paper examined how vagueness is presented on the RGB color triangle using semantic differential methods and performed fuzzy set theoretical analysis. The subjects are asked the difference between fundamental color (as a target color) and neighboring colors (as a sample color) using semantic differential method. Each data and the ensemble average of those data are fuzzy sets. The results of experiments show a similar trend to that for the RGB tone triangle (unpublished results). Using the fuzzy inference for RGB data (as a fuzzy set), it is found that these results move to white direction as a center of RGB color triangle. The inference results of the cyan-relevant colors and the magenta-relevant colors show large vagueness in the present study. Stocking such a data the human-computer interaction will be going well with the environment.

APPENDIX A 496 CRISP COLOR INPUTS (*DETAIL TYPE*) ON THE COLOR TRIANLE

496 colors including white were used in experiments. Detail type (496 colors) is corresponding to fundamental type (66 colors).



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