Hiroyuki Shinoda

School of Architecture
Faculty of Engineering
Kyoto University
Kyoto 606-01
Japan

Keiji Uchikawa

Department of Intelligence Science
Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku
Yokohama 227
Japan

Mitsuo Ikeda

School of Architecture
Faculty of Engineering
Kyoto University
Kyoto 606-01
Japan

Categorized Color Space on CRT in the Aperture and the Surface Color Mode

The study was made for structure of categorized color space in the aperture and the surface color modes. The color appearances of two modes were reproduced on a CRT display with or without a surround configuration. Subjects made categorical color naming with 11 basic color terms. The (x,y,L) color space divided with these terms showed structural difference between the two modes. This result indicates that color is categorized by only chromaticity in the aperture color mode but by luminance and chromaticity in the surface color mode. © *1993 John Wiley & Sons, Inc.*

INTRODUCTION

When light reflecting from a surface causes a sensation of color, the visual system normally treats the color as an attribute of the surface (perception of surface color). We also perceive the color as an attribute of light itself (perception of aperture color) if some specific conditions are fulfilled. If a reflecting color chip is spot-lighted with a hidden light source, we perceive an aperture color over the chip. In a self-luminous display a stimulus appears a surface color if it is surrounded by brighter stimuli. We use the term "color mode" to distinguish these two different color appearances: the aperture color mode and the surface color mode.

While most colorimetric experiments are carried out with aperture color, most of the colors we perceive in everyday life are of surface color mode. There arises a question whether the psychometric laws established with aperture colors are also valid with surface colors. It was well known that an aperture color appears different from a surface color even when their colorimetric values, namely, chromaticity and luminance, are equated. These issues about mode of appearance have been treated mostly among color scientists, but in the recent years the issues are becoming practical problems among engineers because of the development of various media for color representation.

Attempts have been made to characterize perceived brightness as a function of stimulus luminance under various surrounding conditions.[1–3] These studies indicated that perceived brightness differs depending on color mode. It changed more gradually in the aperture color mode with dark surround than in the surface color mode with luminous surround. Uchikawa, Uchikawa, and

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Boynton[4] have made categorical color naming for the OSA color samples and showed that the centroid of each category had lower lightness value in the aperture color mode than in the surface color mode. The result indicates that color chips look brighter in the aperture color mode. Okajima *et al.*[5] reported that B/L ratio is higher in the surface color mode than in the aperture color mode. The fact implies that the contribution of chromaticness to brightness is larger in the surface color mode than in the aperture color mode. It had also been found that colorfulness is reduced in the aperture color mode.[6–9]

Color can be perceived discretely as well as continuously. Brightness, colorfulness, and hue are continuous attributes of color, while color terms are discrete specification of colors. An assignment of a color term to an observed color is categorization of the color. Colors are also memorized through categorical process.[10,11] Berlin and Kay proposed 11 basic color terms which are common in all developed languages through comparative studies of languages.[12] In English they are white, gray, black, blue, green, yellow, orange, brown, red, pink, and purple. It was also demonstrated in psychophysical experiments[13] that the 11 basic color terms meet the following criterion:

(1) to be used consistently within each subject;
(2) to be used by common consent among all subjects;
(3) to require shorter response time when named.

While color specialists can treat colors with their colorimetric values and by various color-order systems, most people communicate colors through color terms in everyday life. In traffic signals, traffic signs, route maps, and diagrams of a network of railroads or buses, information is coded by colors. Thus messages are frequently communicated through color codes. On these occasions, it is required to select color codes carefully in order to communicate information correctly.[14] In various observation conditions, colors do not always appear similarly to all people, and colors used in the codes for transmitting information to people should be selected in accordance with an ability of the visual system to treat colors roughly or to categorize colors. Therefore categorical color perception should be studied in utilizing colors.

The aim of this research is to study how colors are categorized in the aperture and the surface color mode. We study zones of categorized colors at the chromaticity diagram when colors are perceived as aperture or surface colors on a CRT display.

EXPERIMENT

Apparatus and Stimuli

A 13-in. Apple Color High-Resolution RGB Monitor served as the CRT display for presenting stimuli and was driven by a Macintosh II with 8-bit video board. The computer was also used to record subjects' responses. The experiment was carried out in a dark booth. A partition with a window was placed between the subject and the CRT display, and the subject viewed only the screen position of the display when seated 130-cm apart from it. The test stimulus was a square form with a 5-cm side giving the subject the visual angle of about a 2° arc. The stimulus was placed at the center of the screen. When the test stimulus was presented alone with dark surround, it was perceived as an aperture color. When the test stimulus was presented simultaneously with a gray surround stimulus of 16×22 cm^2, it was perceived as a surface color. In this case the stimuli appeared as a colored patch on a gray board. The gray surround had the luminance of 29.6 cd/m^2 and the chromaticity, $x = 0.333$, $y = 0.335$.

With a CRT display the available colors are limited within a triangle with apexes of R, G, B phosphors, with chromaticity coordinates (0.623,0.346), (0.262,0.603), and (0.152,0.065). Colors at intersecting points of grids with 0.025 steps in both x and y coordinates were prepared as test stimuli. Six different luminance levels, 2, 5, 10, 20, 30, and 40 cd/m^2 were employed. A total of 939 and 802 test stimuli were prepared for aperture colors and surface colors, respectively.

Test color stimuli were produced on the CRT display by monitoring RGB phosphor intensities, which were preliminarily calibrated to the luminances and chromaticities of test stimuli.[15] In our color-generating system the relation was different if there was a gray surround[16] and we were forced to prepare two sets of calibrations, one for the no-surround condition (the aperture color mode) and the other for the surround condition (the surface color mode).

Subjects

Three male subjects, HS (24 years old), YU (24), and KU (39), participated in the experiment. All subjects had normal color vision tested with the Ishihara test and the 100-hue test.

Procedure

After a few minutes of dark adaptation a subject pressed a mouse button to generate a stimulus on the CRT display. He could observe it as long as he wanted. After the observation, which normally lasted for a few seconds, the subject pressed the mouse button to replace the test stimulus with a list of 11 color terms (white, gray, black, blue, green, yellow, orange, brown, red, pink, and purple). He clicked a color term according to his perception of the test stimulus. Then the next test stimulus presentation followed.

One session consisted of 94 or 93 observations for the aperture color mode and 80 or 81 for the surface color mode. All stimuli were named twice. They were presented first in a random order and in the reverse order for the second presentation.

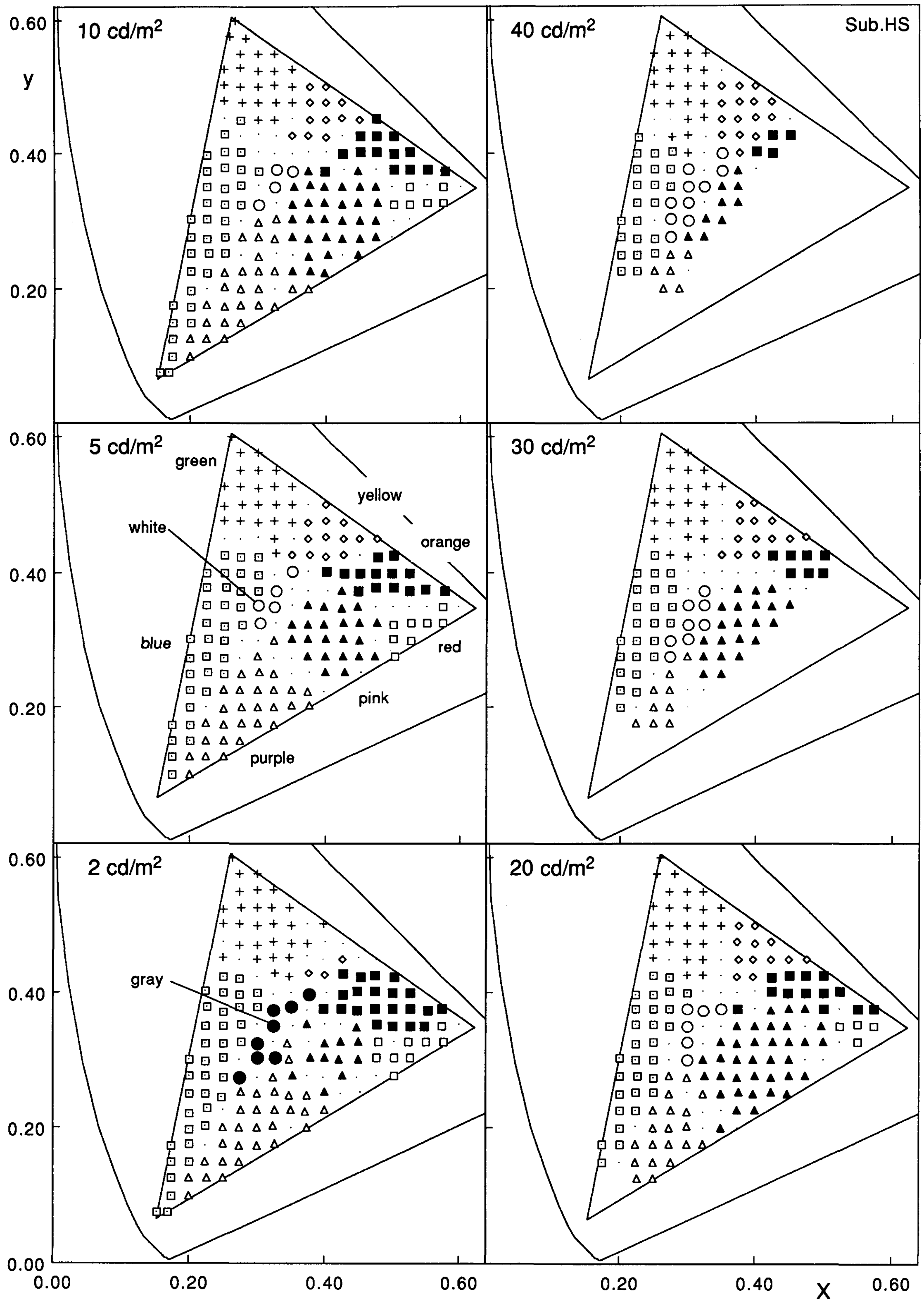

FIG. 1. The categorized colors on CRT for aperture color. Each diagram corresponds to a luminance. Various symbols denote the stimuli named consistently with the same term at both presentations: ○, white; ●, gray; ⊡, blue; +, green; ◇, yellow; ■, orange, □, red; ▲, pink; △, purple. The dots denote the stimuli named inconsistently. Subject, HS.

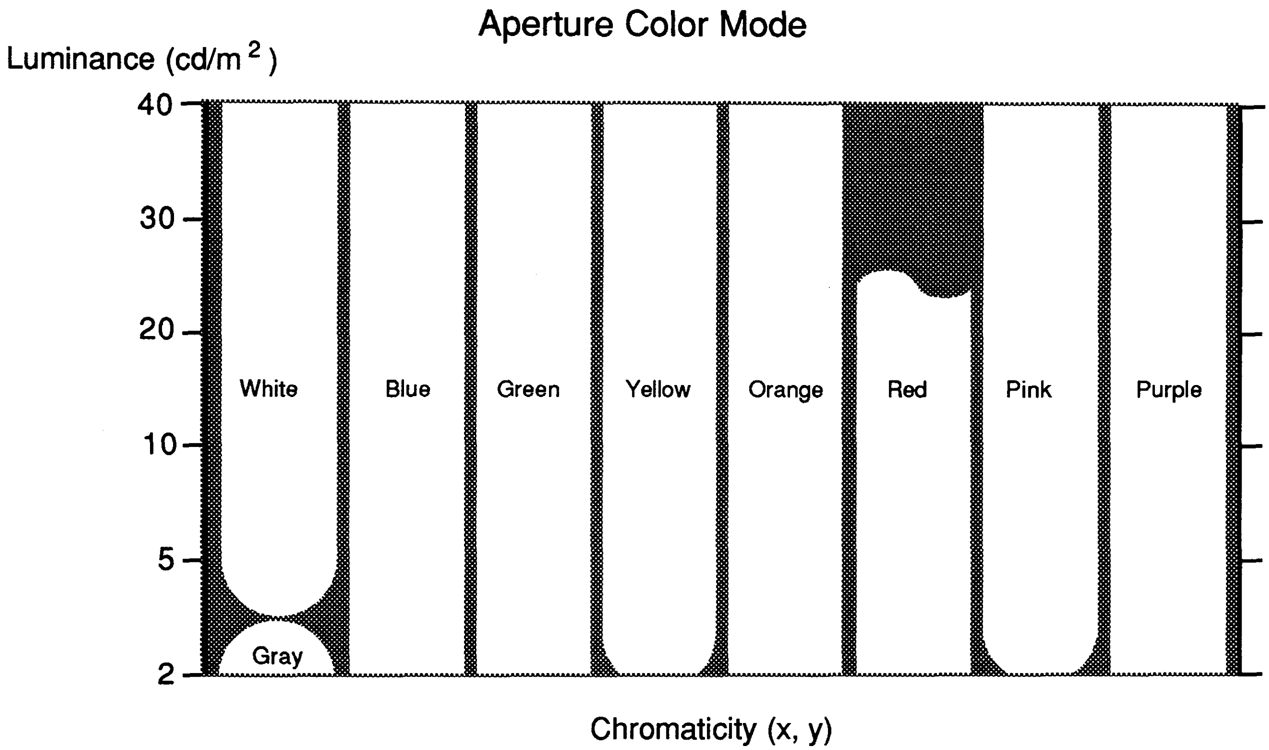

FIG. 2. The (x,y,L) color space categorized by subject HS in the aperture color mode. Blank area above the wavy end of the red category indicates that the data were not obtained at 30 and 40 cd/m^2.

RESULTS AND DISCUSSION

Figure 1 shows the results of color naming made by subject HS for stimuli of the aperture color mode. Each chromaticity diagram corresponds to a certain luminance level. The stimuli named by a same color term for both presentations are represented by a certain symbol such as □ for red, + for green, and so on, while those named by two different color terms are shown by dots (•). Some saturated stimuli could not be reproduced on our CRT display at high luminances and they are shown by blanks inside the triangle. It is clear that most of the stimuli were named consistently and they form clusters implying that colors are categorized. At the borders between two categories, however, stimuli were inconsistently named as indicated by dots. The subject divided stimuli of constant luminance into specific categories and border regions on the chromaticity diagrams.

Subject HS divided the (x,y,L) color space (L standing for luminance) into nine categories for the aperture color mode: white (○), gray (●), blue (⊡), green (+), yellow (◇), orange (■), red (□), pink (▲) and purple (△). The black (■) and brown (◆) are lacking among 11 assigned categories. For luminance levels above 2 cd/m^2, the term white (○), is used, while at 2 cd/m^2 the term gray replaced white. The regions of yellow and pink are slightly smaller at this luminance level compared to others. In spite of these differences the results are relatively similar among different luminances.

The categorized color space in the aperture color mode can be illustrated as in Fig. 2, where the (x,y,L) color space in Fig. 1 is transferred to a two-dimensional expression with luminance (L) along the vertical direction and various chromaticities (x,y) along the horizontal direction. As pointed out in Fig. 1, the behavior of the red category was not decided at 30 and 40 cd/m^2 since the apparatus was unable to produce stimuli in the right corner of the triangle with those luminances. The area corresponding to these stimuli was left blank in Fig. 2. Aperture colors seem to have columnar structure along the L axis in the categorized (x,y,L) color space and thus aperture colors are classified two-dimensionally (x and y). The color categorization depends merely on the chromaticity coordinates in the aperture color mode. All other subjects showed similar trends.

Figure 3 shows the results for the surface color mode obtained from the same subject HS as for Fig. 1. For achromatic colors the term black (■) was used at 2 cd/m^2, gray (●) at 5, 10, and 20 cd/m^2 and white (○) at 30 and 40 cd/m^2. Regions of yellow (◇), orange (■), and pink (▲) do not exist at 2 and 5 cd/m^2. Region of brown (◆) disappears at 20, 30, and 40 cd/m^2. The color terms vary depending on luminance in the surface color mode differing from the aperture color mode.

The results of Fig. 3 are also summarized in Fig. 4, which shows more complications compared to Fig. 2. The horizontal arrow indicates the luminance level of the surrounding gray. The most complicated part is seen at the brown region. The same brown category at low luminance shifts to orange in a more reddish region as the luminance

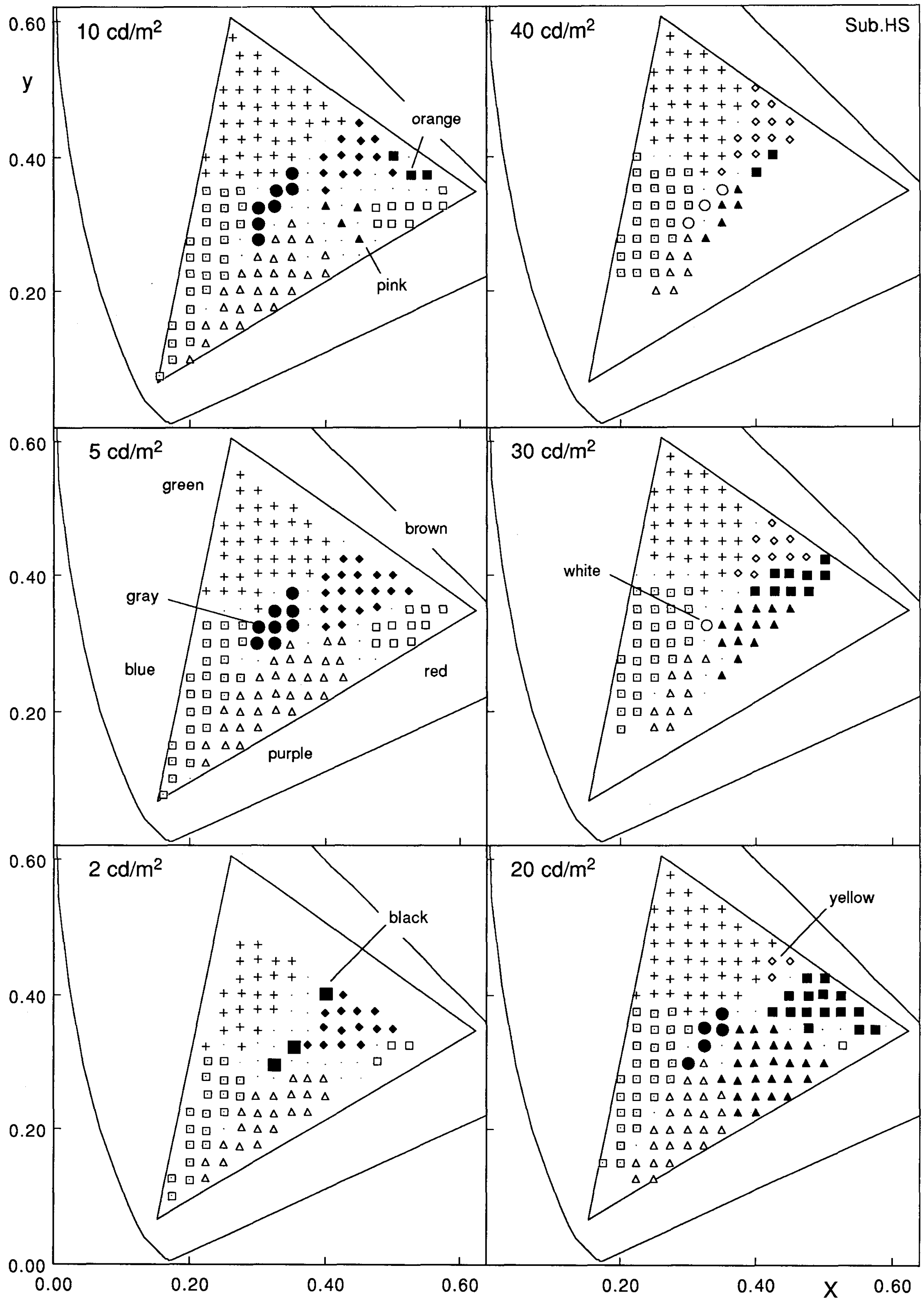

FIG. 3. The same as Fig. 1, but for surface color. Symbols are ○, white; ●, gray; ■, black; ⊡, blue; +, green, ◇, yellow; ■, orange; ◆, brown; □, red; ▲, pink; △, purple. Subject, HS.

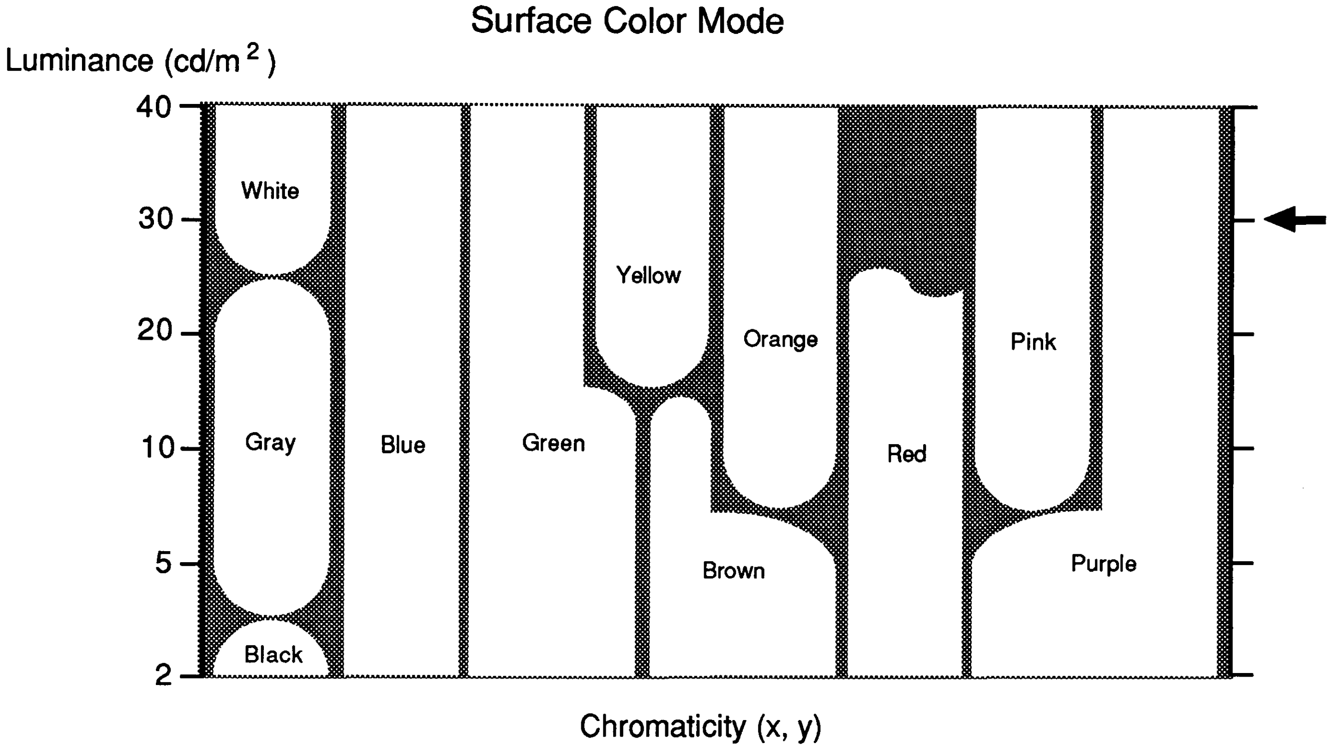

FIG. 4. The (x,y,L) color space categorized by subject HS in the surface color mode. The horizontal arrow shows the surround luminance. Blank area above the wavy end of the red category indicates that the data were not obtained at 30 and 40 cd/m^2.

is increased, while it shifts to yellow in a more greenish region. This figure indicates that colors are classified three-dimensionally (x, y, and L) rather than two-dimensionally in the surface color mode. The color categorization depends not only on chromaticity but also on luminance. Hence, we cannot know what color term is used from only the chromaticity coordinates. The luminance level must be accounted for also.

Color terms seemed to have different information in the aperture and the surface color mode.[17] Color terms convey information of two-dimensional "chromaticity" in the aperture color mode, but three-dimensional "color" including brightness in the surface color mode. This suggests that the color appearance changes more largely with luminance in the surface color mode than in the aperture color mode. This conforms to the phenomenon of rapid change of color appearance with luminance observed near surround luminance level.[3,18,19] The large change of appearance in surface color is thought to be due to blackness induction by surround of higher luminance.

Figure 5 shows the results from subject YU for the luminance levels of 5 and 20 cd/m^2 only, for the aperture color mode (left) and the surface color mode (right). It is interesting to notice that this subject did not use the term red (□) for these conditions. In fact, he never used the term for any other condition as well. We suppose for YU the red category was located outside the triangle. As in other subjects the left two diagrams are relatively similar and aperture colors were similarly classified at 5 and 20 cd/m^2. The right two diagrams show differences. Yellow (◇), orange (■), and pink (▲) do not exist at 5 cd/m^2. Brown (◆) does not exist at 20 cd/m^2. In the surface color mode the category regions vary with luminance, although in the aperture color mode they are invariant, as already pointed out for the subject HS.

The comparison of the left and right diagrams in Fig. 5 shows changes of color term accompanied with change of mode. The bottom two diagrams are quite different. Figures 6 and 7 are prepared from these diagrams to illustrate the difference for several category regions at 5 cd/m^2. In Fig. 6 the outlines of regions of orange and pink in the aperture color mode are shown by dashed lines and those of brown and purple in the surface color mode by solid lines. The stimuli named orange and pink in the aperture color mode were named brown and purple, respectively, in the surface color mode. In Fig. 7 the similar comparison was made for yellow in the aperture color mode (dashed line) and for green and brown in the surface color mode (solid lines). Notice that there exists a boundary region between the brown and the green region where the subject responded with both the terms brown and green. The stimuli called yellow in the aperture color mode are now called green or brown in the surface color mode. These figures indicate that an aperture color and a surface color are often classified into different categories even when their colorimetric values are equal. On the other hand, the difference observed between the top two diagrams of Fig. 5 is smaller than that of the bottom two

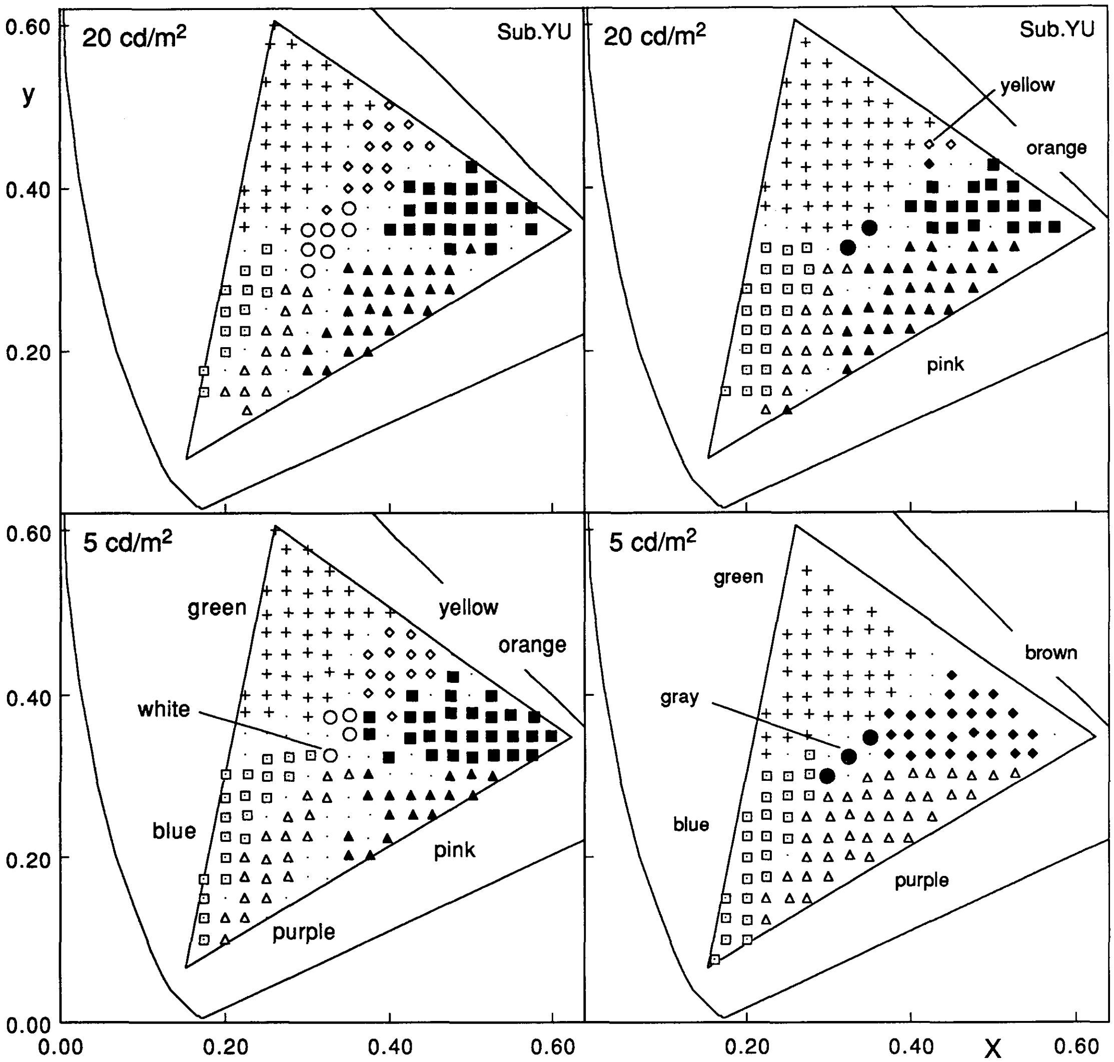

FIG. 5. Categorized colors for the stimuli of 5 and 20 cd/m^2: left diagrams, aperture colors; right diagrams, surface colors. Subject YU.

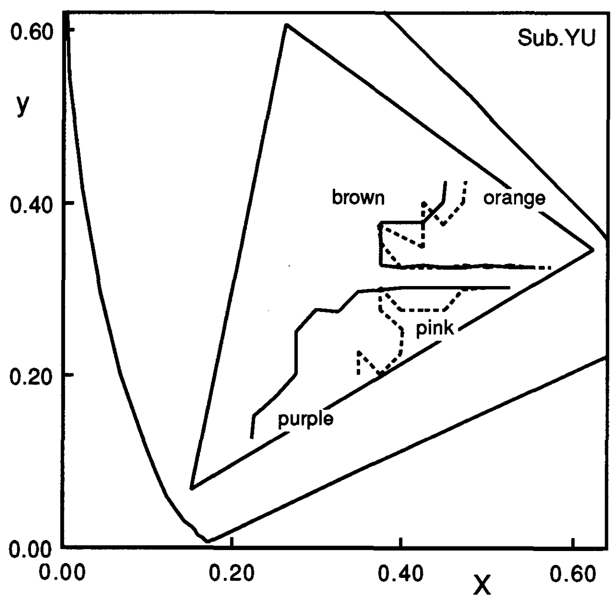

FIG. 6. Comparisons between the category regions of orange and pink in the surface color mode and those of brown and purple in the aperture color mode: dashed lines, orange and pink; solid lines, brown and purple. L = 5 cd/m^2. Subject YU.

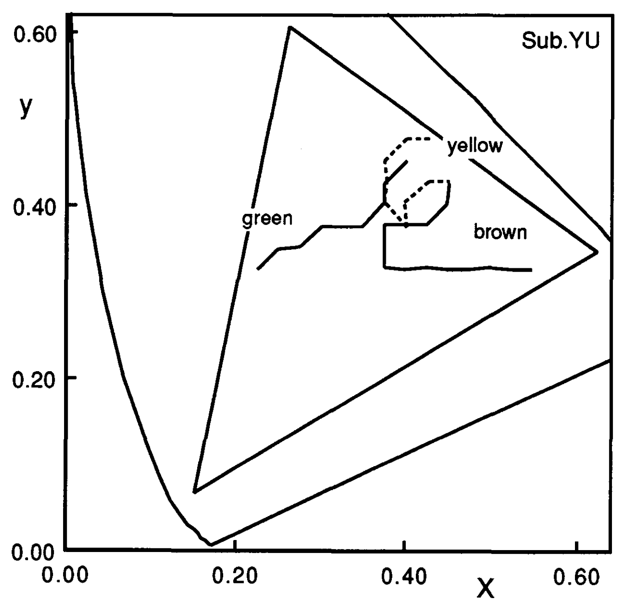

FIG. 7. Comparison between the category region of yellow in aperture color mode and those of green and brown in surface color mode: dashed line, yellow; solid lines, green and brown. L = 5 cd/m^2. Subject YU.

diagrams. This is probably because test stimuli changed their appearance gradually from surface color to aperture color with luminance increase. In fact at the luminance of 40 cd/m^2 in gray surrounding condition all subjects perceived highly saturated test stimuli as surfaces covered with fluorescent paint. In this luminance level the test stimuli were brighter than the gray surround of 30 cd/m^2. Hence, it is expected that test stimuli change their appearance gradually from surface color to aperture color with luminance increase.[20]

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