Upper-limit luminance for the surface-color mode appearance

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A series of experiments were carried out to reveal determinants for the mode of color appearance by measuring the upper-limit luminance of a color chip for the surface-color mode. We used a CRT color monitor to present test and surround stimuli in the surface-color mode. The stimuli were composed of a three-by-three array of color chips on a gray background with a white frame. The observer increased the luminance of a center test color until it just ceased to appear in the surface-color mode. Our results show that this upper-limit luminance was different among test colors, but their brightnesses, calculated from the luminance and brightness/luminance values, were almost the same and were slightly below the brightness of the white frame. The existence of the surrounding color chips affected the results, but their sizes and spatial arrangements did not. When all of the luminances of the surrounds changed equally, the upper-limit luminances of the test colors for the surface-color mode appearance changed by the same ratio. This result indicates that the brightness of a target was a determinant for selecting the mode of color appearance and that the brightest surround stimulus acted as a cue for determining the judgment. © 2000 Optical Society of America [S0740-3232(00)02211-0]

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1. INTRODUCTION

We can perceive an object as self-luminous even when it does not physically emit light. It has been reported that a black paper appears to glow when it is illuminated by a spotlight in a completely dark environment.[1] The black paper reflects only some of the light impinging on it. When the intensity of the reflected light is increased, the black paper, which first appeared to be a surface, gradually appears as if it is emitting light.[2] Such a phenomenon is referred to as changing the mode of color appearance.[3] In the case of the black paper, the mode of color appearance changes gradually from the surface-color to the aperture-color mode.

In the surface-color mode, a color appears as an attribute of the surface. Most colors seen in our daily lives can be classified into this mode. In the aperture-color mode, on the other hand, a color appears as an attribute of the light coming through an aperture, or the object appears to glow. Uchikawa *et al.*[4] conducted a color-naming experiment using colored papers in both modes. They reported that the results depended on the mode of color appearance. Some color chips were perceived as being a different color depending on the mode of color appearance. Several studies have been conducted to measure the luminosity threshold where a stimulus began to appear self-luminous after being in the surface-color mode.[5–11] A stimulus whose intensity is above the luminosity threshold is perceived as being in the aperture-color mode.

Ullman[5] measured the minimum intensity required for a light source to be detected in a stimulus consisting of papers: The intensity of the light source should be sufficiently higher than that of the surround. He discussed the following possible factors: the highest intensity in the scene, absolute intensity value, local and global contrast, comparison with the average intensity, and lightness computation. However, he mentioned that none of these factors could decisively explain the phenomenon of detecting a light source.

Evans[6] and Evans and Swenholt[7] focused on grayness, which was a property specific to the surface-color mode. Evans defined the G_0 color as the stimulus that contained no grayness. He measured luminances of the G_0 color for stimuli of different colors and purities when the surround was a uniform gray background. He reported that the G_0 color depended on the purity and the dominant wavelength of the colored lights. It is likely that the G_0 color corresponds to the appearance at the state of transition from the surface-color to the aperture-color mode. Evans seemed to measure the luminosity threshold with the G_0 color criterion for many differently colored lights.

Bonato and Gilchrist[8] reported that a target began to appear self-luminous when its luminance became 1.7 times higher than that of a surface that would be perceived as white in the scene. It was not important whether the white surface was actually presented to the observer. Their results indicated that luminosity threshold is determined by the relative condition of the surround. Gilchrist *et al.*[9] further investigated this point with the anchoring theory. In this theory, the lightness of a target is determined in relation to the anchor, which is set according to the stimulus condition. They discussed how the observer determined the anchor in the scene. They also pointed out that not only the intensity of the stimulus but also the area and the stimulus configuration are important factors in determining the perception of luminosity.

Speigle and Brainard[10] surrounded the stimulus with a colored paper array in a natural scene. A target was illuminated with a spotlight colorimeter, which changed only the luminance of the target while maintaining its chromaticity. The subject adjusted the luminance of the target so that the target appeared self-luminous. Speigle and Brainard reported that luminosity threshold depended both on the ambient illumination and on the chromaticity of a target.

Petrov *et al.*[1] adopted the fluorescent appearance and the surface appearance of the patch to estimate the perceived illumination. They conducted the experiment with a monitor and three-dimensional scenes. They reported that the observer's settings were not stable and that the surround information was helpful in stabilizing the results. Three colors (red, green, and blue) were used as the target. The results, however, were not given quantitatively.

Koida and Uchikawa[12] measured the ratio of the surface-color component to the aperture-color component in a colored light with variable luminances surrounded by a uniform gray background. They reported that the aperture-color component of equal-luminance colored lights was proportional to the brightness/luminance (B/L) ratios of those colored lights. Uchikawa *et al.*[13] showed that the luminous efficiency functions obtained by brightness matching and those obtained by luminosity threshold were similar.

These previous studies measured the condition required for a stimulus to appear self-luminous, or in the aperture-color mode, under different experimental conditions. However, they did not reveal the determinants of such an appearance. Recently computer monitors and color printers have become more advanced, and it has become important to reproduce color appearance accurately across different medias. Several color-appearance models have been proposed to predict color appearance under several observation situations.[14,15] To predict color appearance in a useful manner, we should note that two physically identically colored lights can be perceived differently depending on their mode of color appearance.[4]

To clarify the determinants of the surface-color mode perception, we measured the luminance of a test stimulus of various chromaticities when the test stimulus no longer appeared to be in the complete surface-color mode. We refer to this luminance as the upper-limit luminance. It is known that there are two visual dimensions corresponding to the intensity of a colored light: luminance and brightness.[16] If it is assumed that a stimulus is perceived as being in the aperture-color mode when the visual system evaluates its luminance to be greater than the maximum luminance permitted for a surface under the illumination, the upper-limit luminance of the stimulus will be the same regardless of the chromaticities of the test colors. But if the visual system uses brightness as a criterion, the luminance at the upper limit for the surface-color mode would change according to the chromaticity of the stimulus. Its chromatic dependency would show chromatic characteristics similar to those of brightness. The results presented in this paper will clarify the mechanism by which the visual system judges the mode of color appearance.

In experiment 1 we measured the upper-limit luminance of test colors with various chromaticities. In experiment 2 we measured the B/L ratio of the test colors. The brightness of the test color was measured with the direct brightness-matching method to match the brightness of the test with that of the reference stimulus, which had constant luminance. In experiments 3 and 4 we investigated the effects of the surround stimuli on the mode of appearance.

2. EXPERIMENT 1: MEASUREMENT OF THE UPPER-LIMIT LUMINANCE

A. Method

1. *Apparatus*

An experimental booth was composed of two small rooms. The observer sat in one room that was illuminated by a D_{65} fluorescent lamp. The illuminance of the room was 90 lx at the position of the observer. The stimulus was displayed on a CRT monitor, which was located in the other room. A viewing window of 14 cm × 8 cm with a shutter was placed at the border of two rooms. The observer saw the stimulus binocularly at a distance of 120 cm. The luminance of the test stimulus could be changed with a trackball controlled by the observer.

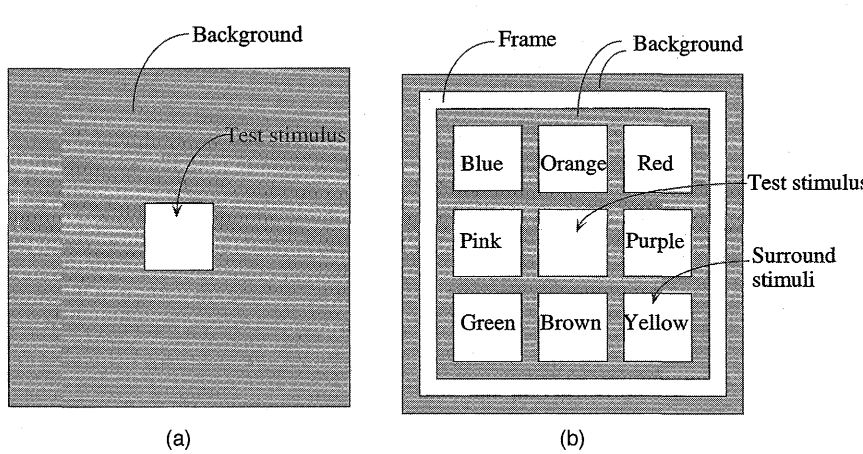

Fig. 1. Schematic representation of the stimuli used in experiment 1. (a) No-surround condition, (b) Array-surround condition. In the no-surround condition, only a test color was presented on the achromatic background, and in the array-surround condition, the stimulus was composed of a three-by-three array of 2-deg simulated color chips with a white frame on an achromatic background. The test patch was located at the center of the array.

2. Stimulus

The test and surround stimuli, background, and frame were simulated color chips on the monitor as shown in Fig. 1. The stimuli appeared as flat colored papers. The test stimulus, surrounding stimuli, and frame were placed on the achromatic background. The luminances and chromaticities of these stimuli are listed in Table 1. We selected 16 chromaticities for test colors as shown in Fig. 2. The numbers of the colors within the figure were based on the results of experiment 1, and we shall refer to the stimuli with these numbers throughout the paper.

Two surround conditions were used; the no-surround condition and the array-surround condition, as shown in Figs. 1(a) and 1(b), respectively. In the no-surround condition, a square test stimulus subtending 2 deg was located at the center of a uniform background. Three luminance levels of the background were used, as given in Table 1.

In the array-surround condition, eight color chips and a white frame were placed on the background, as shown in Fig. 1(b). A three-by-three array configuration was used, with the test stimulus at the center. Each color chip was a 2-deg square and was separated from an adjacent chip by an interval of 0.5 deg. A white frame, with a width of 0.5 deg, surrounded the array and was separated from the nearest chip by 0.5 deg.

3. Procedure

Before the experiment started, the observer was shown a complete surface and a complete luminous appearance of the test stimulus. The observer was then told to adjust the luminance of the test stimulus until it started to change its appearance from the complete surface-color mode. We call this luminance the upper-limit luminance for the surface-color mode. This criterion is similar to criteria adopted in the preceding studies,[8,10,11] but we did not refer explicitly to the appearance of luminosity when instructing the observer.

After adapting to the D_{65} fluorescent lamp for 3 min, the observer opened the shutter. In each trial, the observer changed the luminance of the test stimulus and then set the upper-limit luminance for the surface-color mode by pressing the button. The next trial started after 2 s. A session was composed of 16 trials, in which different test colors were presented in a random order. We conducted five sessions for each experimental condition.

4. Observers

Four males (31, 24, 24, and 23 years old) and a female (25 years old) with normal color vision participated in the experiments. All had previously participated in psychophysical experiments.

Table 1. Chromaticities of the Colors Used in the Experiment As the Surround Stimuli and Three Achromatic Colors in the Background

Variable	Luminance (cd/m²)	x	y
Surround Stimulus			
Blue	2.66	0.188	0.171
Orange	11.2	0.519	0.376
Red	4.97	0.491	0.325
Pink	15.9	0.385	0.294
Purple	7.02	0.325	0.252
Green	3.03	0.266	0.397
Brown	3.20	0.410	0.349
Yellow	25.5	0.453	0.444
Frame			
White	36.1	0.333	0.356
Background			
Black	0.54	0.219	0.183
Gray	9.31	0.323	0.346
White	35.6	0.332	0.356

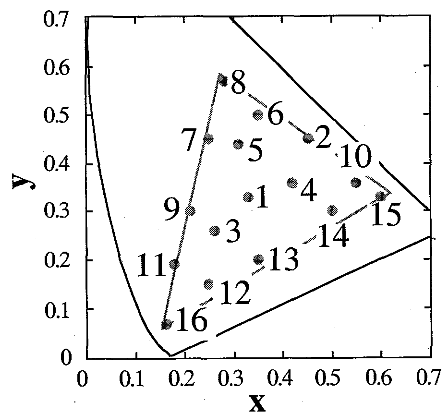

Fig. 2. Chromaticities used in the experiments as a test color. Each test color is referred to by a number within the figure. The triangle shows the gamut of the CRT color monitor.

B. Results and Discussion

When the luminance of the test stimulus was sufficiently low compared with the surround, it was perceived in the surface-color mode. With increasing luminance the test stimulus changed its appearance from the surface-color to the aperture-color mode. In the aperture-color mode, the observer perceived a colored light being emitted from the test stimulus area. Between these two modes, the test stimulus appeared partly in the surface-color mode and partly in the aperture-color mode.

Figures 3(a) and 3(b) show mean luminances across all observers for the no-surround condition and the array-surround condition, respectively. The abscissa denotes the test stimulus number, as labeled within Fig. 2. The ordinate represents the upper-limit luminance. Circles, squares, and triangles indicate results of the black, gray, and white backgrounds, respectively. The mean standard deviation across observers was 0.096 in log units for the no-surround condition and 0.087 in log units for the array-surround condition. The maximum and the minimum standard deviations among the test colors were 0.145 and 0.044 in log units for test colors number 12 and 14, respectively, in the array-surround condition.

As shown in Fig. 3, the upper-limit luminances for the surface-color mode were found to be different among test colors. In the no-surround condition, the luminances were also different among the background conditions. Luminances for the white background were highest, and those of the black background were lowest.

Petrov *et al.*[11] reported that, as more trials were conducted, a lower luminance setting was required to make the stimulus appear luminous. This tendency, however, was not observed in our experiments.

In the array-surround condition, shown in Fig. 3(b), the upper-limit luminances for the black and the gray backgrounds were almost identical. Those for the white background were the highest. The differences, however, were smaller in the array-surround condition than in the no-surround condition. The difference between the two conditions was the existence of surround colors. Therefore the surround color chips might work as a cue for judging the surface-color mode perception.

Petrov *et al.*[11] used red, green, and blue as test colors to measure the luminosity threshold. Since their results are not shown quantitatively with physical dimensions, such as luminance, we unfortunately cannot compare their results directly with ours.

Speigle and Brainard[10] conducted a similar experiment, in which they used colored papers as surrounds and measured the luminance when a target appeared luminous. Their results showed chromaticity dependence, but their luminances were lower than our results. However, in some conditions the luminance of the white in the scene was almost the same as in our experiment. This difference might be due to the different experimental conditions. Speigle and Brainard's experiments were conducted in an illuminated room, and the observer could see not only the stimulus but also many items in the room.

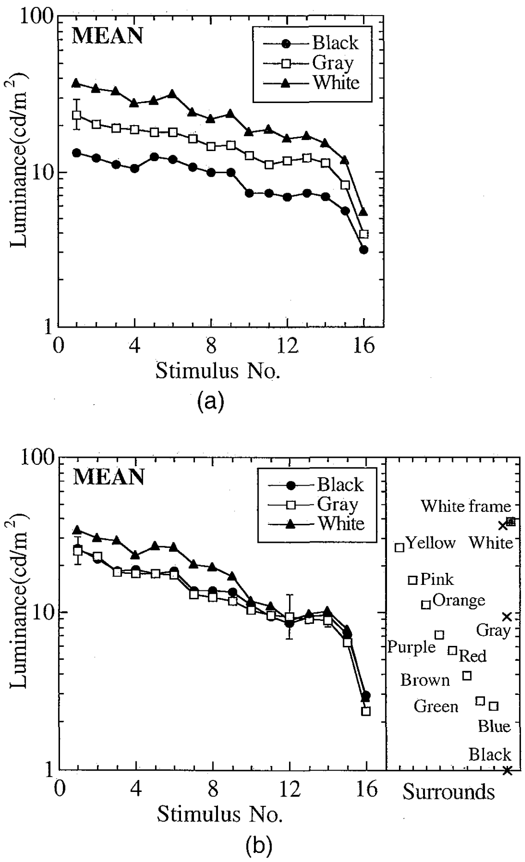

Fig. 3. Mean upper-limit luminances for the surface-color mode obtained in experiment 1 across all observers. (a) No-surround condition, (b) array-surround condition. Circles, black background; squares, gray background; triangles, white background. The abscissa indicates the test color numbers defined in Fig. 2, and the ordinate indicates the luminance in candelas per square meter. The mean standard deviation across test colors and observers is shown by stimulus number 1 with the gray background. Maximum and minimum standard deviations are shown by stimulus numbers 12 and 14, respectively, with the gray background. The right-hand panel shows the luminances of the surround stimuli.

Bonato and Gilchrist[8] reported that the test stimulus was perceived to be luminous when the luminance was 1.7 times higher than that of a perceived white in the scene. In our results, however, the luminances of all test colors at their limits for the surface-color mode were lower than that of white. In their experiments, Bonato and Gilchrist used an articulated array and achromatic stimuli. Such differences might account for the different results between the two studies.

It would also be possible to explain these discrepancies by the difference between the criteria used in the experiments. In the previous two studies, the luminosity threshold was measured when the test stimulus appeared to be luminous. Evans[6] described the transition in the appearance of the test color as follows. When the intensity of the stimulus is increased, the grayness included in the stimulus first decreases until the grayness diminishes to a certain point. Then it starts to appear self-luminous through the appearance of fluorescence. Bonato and Gilchrist[8] measured the luminosity threshold using a psychometric function obtained from the observer's response when the target appeared luminous. We, on the other hand, measured the upper limit for the surface-color mode directly. It seems that the perception of luminosity is not necessarily accompanied by its judgment when our criterion is used. This might explain why our luminance results were lower than those of Bonato and Gilchrist.

It has been reported that the effects of lightness contrast are larger in a CRT-simulated experiment than in an experiment using actual papers.[17] The difference in the devices used to display the stimuli might also cause these differences in luminance from the results of Bonato and Gilchrist. We previously tested the array-surround condition with the actual color papers used in our previous experiments.[18] The surround stimuli were made of color papers while the test stimulus was presented with a color monitor, observed through an aperture of a gray background paper. The results of that experiment were very similar to those of experiment 1. Therefore the types of devices used in the experiments were not the main factor accounting for our differences.

Our results indicate that the limit for the surface-color mode can be measured with our experimental method and have the same precision in comparison with similar results reported elsewhere.[19] The upper-limit luminances of the surface-color mode were different because of the chromaticity of the test color. More-saturated test colors, such as blue and green, had a lower luminance limit for the surface-color mode than less-saturated test colors, such as white and yellow. These results are consistent with those reported by Evans.[6] He showed that the more-saturated colors needed a lower intensity in order to be perceived as being self-luminous.

It was reported in previous studies that the luminance of equally bright colored lights decreased as their saturation increased.[20] It was also reported that equiluminant colored lights changed their appearance from the surface-color to the aperture-color mode as their purity increased.[12,13] The chromatic dependence observed in our experiment (in which the upper-limit luminances differed according to chromaticity) might be explained by brightness. Therefore in experiment 2 we investigated the influence of brightness on the mode of color appearance.

3. EXPERIMENT 2: EFFECTS OF BRIGHTNESS ON THE MODE OF APPEARANCE

A. Method

1. *Apparatus and Stimulus*

The apparatus was identical to that of experiment 1. The stimulus consisted of two 2-deg squares, separated by 0.5 deg, on a uniform background as shown in Fig. 4. Two background conditions, white and gray, were tested. The upper square was a white reference, and the lower square was the test color.

The mean luminance of the reference white was 26.9 cd/m^2. The luminance value, chosen as 80% of the white obtained in the array-surrounding condition of experiment 1, ensured that the brightness matching was conducted in the surface-color mode.

2. *Procedure*

First the observer adapted to the D_{65} fluorescent lamp in the booth for 3 min. In the experimental session the observer adjusted the luminance of the test color so that it became as bright as the white reference. We verified that the observer perceived the white reference in the surface-color mode. Sixteen test colors were presented in a random order in each of five sessions. The same observers as in experiment 1 participated in experiment 2.

B. Results and Discussion

B/L was defined by the ratio of luminance B of the reference stimulus to the adjusted luminance L of the test stimulus when they appeared equally bright. In Fig. 5, squares and triangles indicate mean log (B/L) across observers for the gray and white backgrounds, respectively. Log (B/L) values increase as the stimulus number increases. Here it becomes possible to calculate the equivalent luminance of each test color at the limit of the surface-color mode. The equivalent luminance yields the same brightness as that of the white reference and can be obtained by the product of the upper-limit luminance and the B/L of a test color, shown in the left panel of Fig. 6.

In Fig. 6, the equivalent luminance, or brightness, was almost the same for all test colors except No. 16. The differences between the background conditions became smaller. These results indicate that brightness is a determinant for the mode perception. There might be some threshold level of brightness when the surface-color mode perception reaches its limit, and it may be that a surround stimulus worked as a cue for setting the threshold.

The equivalent luminances of the surround colors are shown in the right-hand panel of Fig. 6. As shown in the figure, the equivalent luminances of all the test colors do not exceed the maximum value of the surround stimuli in both background conditions. The big differences that were observed in the no-background conditions are no longer significant when the results are compared on the brightness scale. This means that the differences in the

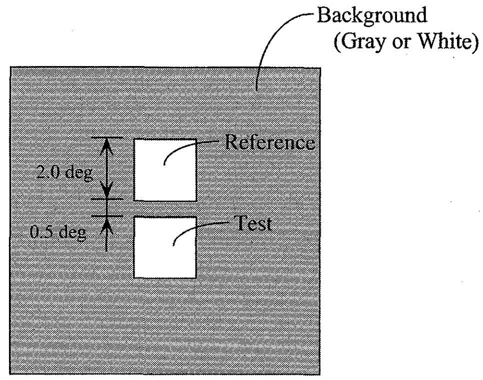

Fig. 4. Schematic diagram of the stimulus used in experiment 2. See text for details.

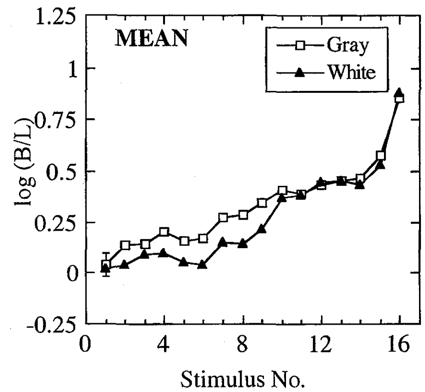

Fig. 5. Mean B/L (on a log scale) obtained from experiment 2 for all observers for each test color. Squares, gray background; triangles, white background. The mean standard deviation across test colors was calculated for each observer, and its average value is shown in the figure.

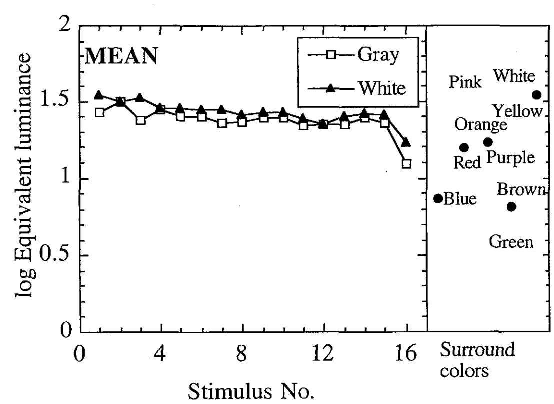

Fig. 6. Mean equivalent luminance of each test color obtained in experiments 1 and 2 for all observers. The ordinate indicates the equivalent luminance of an equally bright white reference on a log scale. Squares, gray background; triangles, white background. The abscissa indicates the test color number defined in Fig. 2.

mean luminances of the surrounding stimuli are no longer the determinant for the surface-color mode perception. This result indicates that the brightest surrounding stimulus works as a determining cue for mode perception in setting the upper limit of the surface-color mode.

4. EXPERIMENT 3: EFFECTS OF SIZE AND ARRANGEMENT OF THE SURROUND STIMULI

A. Method

1. *Apparatus and Stimulus*

We tested three surround stimulus conditions: (1) replacement condition, (2) size-change condition, and (3) interval-change condition. In the replacement condition, one of the surround colors was exchanged with the white of the frame. The total number of colors showed to the observer was the same except for their spatial distribution. Pink and green were replaced by the white in the frame in each session. In the size-change condition, we varied the sizes of the square surround chips to be 0.5, 1.0, and 1.5 deg. The width of the frame and the separation between surround color chips were 0.5 deg. Their relative positions were identical to those of experiment 1. In the interval-change condition, the spacings between the color chips were 0.1, 0.5, or 1.0 deg. In conditions (2) and (3), the test stimulus was a 1-deg square.

2. *Procedure*

The procedure in experiment 3 was the same as in experiment 1. The same five observers participated in experiment 3.

B. Results and Discussion

Figures 7(a), 7(b), and 7(c) show the results of experiment 3 in the replacement condition, the size-change condition, and the interval-change condition, respectively.

As shown in Fig. 7, the upper-limit luminances were almost the same as those obtained in experiment 1, suggesting that the differences in the size, separation, and arrangement of the surrounding colors were not the main factors in the judgment of the surface-color mode.

One of the possible influences of the surrounds on the test stimulus is chromatic induction. It has been reported that the effect of the induction depended on the distance between the surround color and the test color.[21] If the mode of appearance is judged by the grayness of the test stimulus, as Evans pointed out, the influence of blackness induction[22] should be taken into consideration. Such effects, however, were not observed in our experiments. The results were almost the same regardless of the interval between the test and the surround color chips. The gray background always surrounded the test stimulus. Therefore the effects of induction, if present, would be quite similar for all interval conditions.

The instruction to the observer was to pay attention not only to the test stimulus but also to the entire display while adjusting the luminance of the test color. Assuming that the judgment of the mode perception had been based on the information from all stimuli, it should not be surprising that the results for all conditions were almost the same.

5. EXPERIMENT 4: EFFECTS OF THE INTENSITY OF THE SURROUNDS

A. Method

The method was the same as that in experiment 1 except for the luminances of the surround stimuli. All the luminances of the surround stimuli changed proportionally. The mean luminances were 19.8, 13.2, and 5.3 cd/m^2, corresponding to 150%, 100%, and 40% of the luminances in

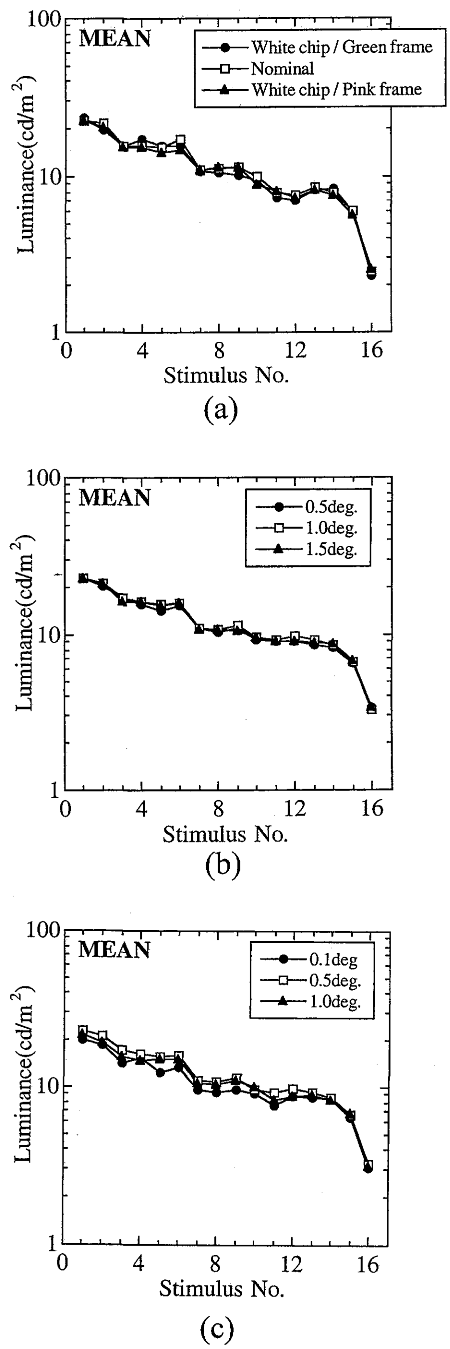

Fig. 7. Mean upper-limit luminances for the surface-color mode across all observers obtained in experiment 3. Results are from (a) the replacement condition, (b) the size-change condition, and (c) the interval-change condition. The abscissa indicates the test color numbers defined in Fig. 2, and the ordinate indicates the luminance in candelas per square meter. See text for the explanation of the symbols for each panel and for details.

experiment 1. The same five observers participated in experiment 4 as in the earlier experiments.

B. Results and Discussion

Figure 8 shows the upper-limit luminance of the test stimulus in experiment 4. It shows that the upper-limit luminance of the surface-color mode increased when the luminance of all the surrounding stimuli increased. We obtained a ratio of the change in luminance of each test color by dividing the luminance obtained in the 150% and 40% conditions by that in the nominal condition, or the 100% condition. The ratios were almost identical among all test colors in both experimental conditions. The mean values were 51% ± 3% and 131% ± 5% for each condition. The luminance changes of the test color were smaller than the changes of the surrounds.

Equivalent luminances of the tests and the surrounds are shown in Fig. 9. They were almost constant across test colors and did not exceed the maximum value of the surrounds. This result supports the previous finding that the brightest surround works as a determining cue during judgment of the surface-color mode perception.

Some observers reported that the luminance difference in the surrounds could be perceived as if the illumination intensity on all of the stimuli were changing. In this case, the smaller change of the upper-limit luminance would be due to the improper evaluation of the illumination intensity.

6. GENERAL DISCUSSION

We found that the upper-limit luminance for the surface-color mode was different for different test colors. Brightness, on the other hand, was almost equal for all test colors. The upper-limit luminances were different depending on the luminance of the background when only the test color was presented. On the other hand, the differences among the background levels were not so significant when many colors were presented at the same time. The spatial arrangement of the stimuli did not affect the results. This chromaticity dependence of the upper-limit luminance is consistent with previous studies that used color stimuli.[6,7,10] Our finding that brightness is a determinant for the mode of color appearance can account for this chromatic dependence.

In a natural scene, a white surface is brighter than all other colors under the same illumination. The visual system might compare the brightness of an object with that of a white surface to judge the mode of color appearance. An object that is brighter than a white surface might be perceived as being in the aperture-color mode. This notion is explained by "equivalent-brightness reflectance" defined as the ratio of the equivalent luminance of the test color to that of the white surface. When the equivalent-brightness reflectance of a surface exceeds 100%, the surface is no longer perceived to be in the surface-color mode. The equivalent-brightness reflectances are shown in Fig. 10. We used the luminance of a $BaSO_4$ plate to represent the brightness of the white surface, as was done in our previous study.[18]

As shown by the solid curves in Fig. 10, the equivalent-brightness reflectances are less than 100% for all test colors. These results would indicate that the observer perceives the limit for the surface-color mode before the brightness of the test color exceeds that of the white. One possible explanation for this discrepancy could be a "real white" surface. Real white is supposed to reflect all lights falling on it, but it does not always exist in the scene. The observer might set the limit of the surface color to that of the white frame in our experiments. The modified equivalent-brightness reflectances, obtained by substituting real white with that of the white frame, are shown in Fig. 10 by dotted curves. They are still smaller than 100%. The criteria used in the present experiments would have some relationship to this discrepancy. If we adopted a different criterion, such as the lower limit for the aperture-color mode or the midpoint between the upper limit for the surface-color mode and the lower limit for the aperture-color mode, the equivalent-brightness reflectance would increase to 100% or more.

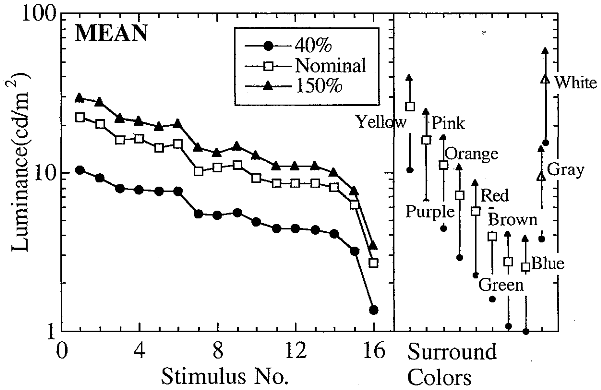

Fig. 8. Mean upper-limit luminances for the surface-color mode across all observers obtained in experiment 4. Circles, decrement condition; squares, nominal condition; triangles, increment conditions. The abscissa indicates the test color numbers defined in Fig. 2, and the ordinate indicates the luminance in candelas per square meter. The right-hand panel shows the luminances of the surround stimuli in each condition.

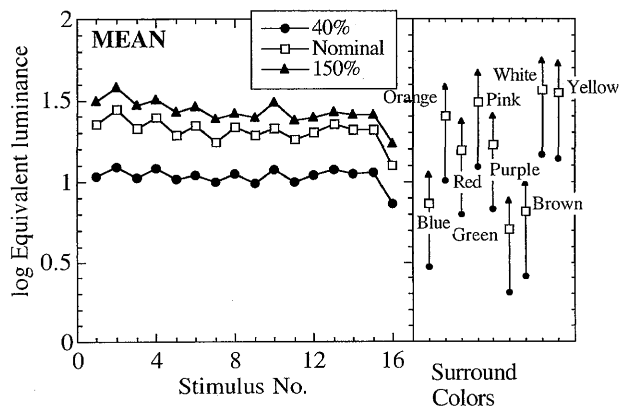

Fig. 9. Mean equivalent luminance of each test color at the limit of the surface-color mode for all subjects obtained in experiments 2 and 4. The ordinate indicates the brightness of the equivalent bright white reference at the upper limit for the surface-color mode on a log scale. Circles, decrement condition; squares, nominal condition; triangles, increment condition. The abscissa indicates the test color number. The equivalent luminance of the surround colors in each condition is shown in the right-hand panel.

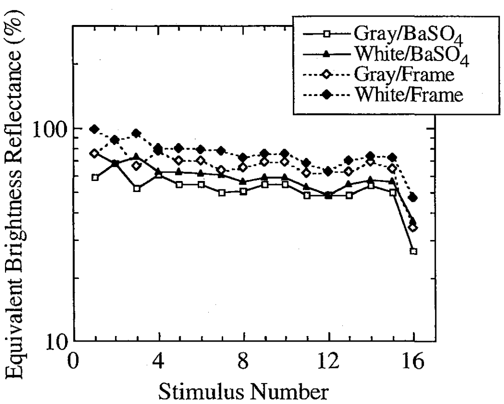

Fig. 10. Equivalent-brightness reflectance at the limit of the surface-color mode from experiments 1 and 2. Squares with solid curve correspond to a gray background; triangles with solid curve correspond to a white background and are the equivalent reflectances to $BaSO_4$. Open diamonds with dotted curve correspond to a gray background; solid diamonds with dotted curve correspond to a white background and are the equivalent reflectances of the white frame. The abscissa indicates the test color numbers defined in Fig. 2.

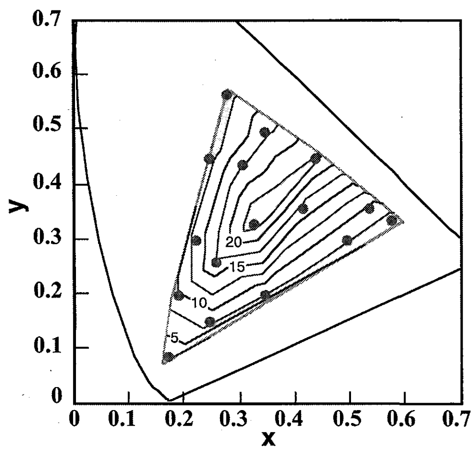

Fig. 11. Constant-luminance loci of the limit of the surface-color mode in the 1931 CIE *x,y* chromaticity diagram, calculated from the results in a gray background of the array-surround condition in experiment 1. Connected lines indicate the constant luminance locus in 2.5 cd/m^2 steps. The numbers shown at each locus indicate the luminance value in candelas per square meter.

Besides the notion that brightness reflectance determines the mode of appearance, the anchoring theory[9,23] might provide another strategy for judging the mode of appearance. In our experimental setup, white worked as an anchor. It is not clear, however, whether white always plays the special role of an anchor among all colors. The brightest stimulus of any color could work as an anchor. Considering that we can correctly judge the lightness of the objects in a natural scene that does not contain any white surface, we might get some information from the scene that can work as the anchor. Further studies need to be conducted to clarify this point.

If white plays a role, how does the visual system find a white surface in the visual scene and set it as a determining cue? Here it becomes necessary to consider the color-constancy problem[24] to explain how the visual system specifies the color white. If white works as a determinant, it becomes necessary to specify white from all colors in the scene by discounting the illuminant chromaticity. It is known that the surround color chips work to discount the illumination chromaticity.[25] In our experiment, the surround stimuli might work to estimate the intensity and chromaticity of the illumination, in addition to giving the observer a cue for judging the mode appearance.

If the visual system might know how much brighter a colored surface could be, or its optimal color, the visual system might use that information to judge the mode of appearance. We calculated constant-luminance loci for the upper limit of the surface-color mode from the results of the array-surround condition in experiment 1; these loci are shown in Fig. 11. The chromaticities used to interpolate the constant-luminance loci, indicated by circles, are similar to those of the optimal color.[19] They also have chromatic characteristics similar to the constant-B/L loci.[20] We cannot conclude from these analyses whether the visual system knows the optimal color and uses it for mode perception.

The equivalent-illuminant model proposed by Speigle and Brainard[10] is similar to this notion, stating that white is found through an estimate of the illuminant in the scene and that the judgment of luminosity is related to the optimal color under the estimated equivalent illumination.

Optimal color is determined solely by the ideal spectral reflectance. It is interesting that such a physical model shows a tendency similar to that of the psychophysical data. As the optimal-color locus changes according to the illumination, it is necessary to specify the intensity and chromaticity of the illumination even if the visual system knows the optimal color. Some previous studies reported the relationship between the mode appearance and the perception of the illumination,[9,11,25,26] but its mechanism is still under investigation.

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