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OPTICAL REVIEW Vol. 7, No. 2 (2000)

OPTICAL REVIEW Vol. 7, No. 2 (2000) 177–185

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(Received September 10, 1999; Accepted February 1, 2000)

We can perceive a surface through another surface. This perception is called transparency. It is known that transparency can be perceived even if the stimulus conditions are not consistent with physical conditions for a real transparent surface. In this study, we measured the ranges of luminance and chromaticity of the overlapping area of two crossed layers at which a surface was perceived as chromatically-uniform transparent. As the results, the luminance range of the overlapping area existed around or near the luminance of the inducing area. The upper and lower limits of the luminance range were higher for the dark background than for the light background. Moreover, the chromatic range existed around the additive color-mixture line between two chromaticities of the inducing areas for both dark and light backgrounds. This indicates that the perceptual transparency mechanism would divide the color of an additive color mixture into the original colors that exist in the inducing areas. We noticed that the perceptual appearance of the stimulus changed greatly depending on the luminances of the overlapping area and the background. These differences in perceptual appearance would be a factor explaining individual difference and deciding the luminance conditions for transparency.

Key words: transparency, additive-color mixture, chromatic condition, luminance condition, visual system

1. Introduction

There are two kinds of surfaces in visual scenes: opaque and transparent surfaces.[1] An opaque surface completely occludes other surfaces, whereas a transparent surface does not. In the latter case, other surfaces can be seen through the overlapping area of a transparent surface. The visual system is believed to utilize visual dimensions of a physical image such as luminance, color, texture, motion and binocular disparity, to segregate opaque and transparent surfaces in a visual scene. For the transparent surface, the overlapping area is divided into two or more surfaces although it is physically uniform. This suggests that transparency occurs in the visual system, and that the surface perception mechanism may be determined by investigating transparency.

Several research projects have studied the luminance condition for transparency. Achromatic transparency depends on the luminance and the figure of an overlapping area. Metelli[2,3] and Metelli *et al.*[4] showed that transparency could occur when lights from two surfaces were additively mixed in the overlapping area. They proposed a simple algebraic model, called the episcotister (a disk with a sector cut out) model, based on the observation of a rotating episcotister. Beck[5,6] and Beck and colleagues.[7,8] proposed a filter model based on the physical transmittance of the surface. Beck's model was a subtractive color-mixture model. Masin[9–13] proposed a weighted-average model that depended on the differences of luminance between adjacent areas. Although these models are not greatly different in their predictions, they are based on different rules.[14,15] Some researches suggested the importance of the Gestalt law of similarity in achromatic transparency.[16,17]

Most previous studies focused on achromatic transparency. However chromatic transparency is also important to understand the perceptual transparency mechanism. For chromatic transparency, the overlapping area has a single chromaticity, but perceptually it is split into two differently colored layers. Oyama and Nakahara[18] investigated the effects of hue for transparency using a cross figure with two horizontal green arms, two vertical red arms and a central square. When the central square was the average chromaticity of the red and the green, transparency could be perceived. De Weert[19] reported that observers could read overlapping pairs of words most legibly when the transparent overlapping areas had a chromaticity of additive color-mixture of two non-overlapping areas of the words. D'Zmura *et al.*[20] showed that the chromatic change with equiluminance, which could not be generated by the episcotister or the filter models, yielded transparency. These previous studies pointed out some important chromatic rules for transparency. It is worthwhile to fully investigate chromatic transparency in addition to achromatic transparency.

In this study, we further investigated the chromatic perceptual transparency mechanism. We measured the entire ranges of luminance and chromaticity necessary for the overlapping area of two surfaces to be perceived as transparent.

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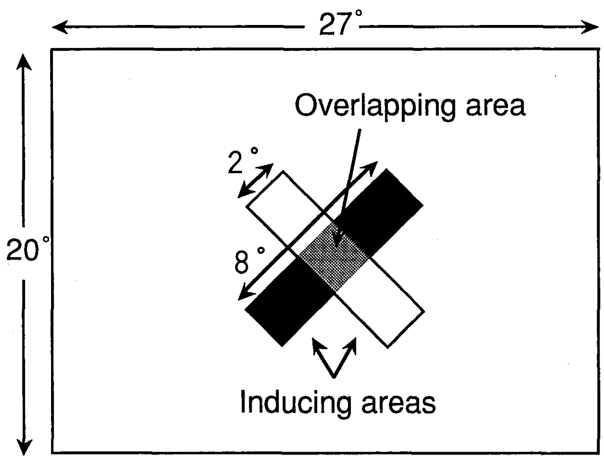

Fig. 1. The cross pattern used in this experiment. It appears that two rectangles are overlapped at the center of the cross pattern.

2. General Methods

2.1 Stimulus

We used a cross pattern, as shown in Fig. 1, as the stimulus in the experiments. This pattern satisfied a figural condition that there must be at least four different intensity regions to yield transparency.[12] It was reported that there was no difference in induced brightness of the center area by this type of oblique cross-pattern.[21] We defined the center, where two rectangles were crossed, as the overlapping area, and the outer portions of the rectangles as the inducing areas. The overlapping area and the rectangles subtended 2×2 deg and 2×8 deg, respectively. The subject could adjust the luminance of the overlapping area.

The stimulus was presented on a 13-inch color CRT monitor. The background of the stimulus subtended 20×27 deg. The subject binocularly observed the stimulus at a distance of 40 cm from the CRT in a dimly illuminated room.

2.2 Procedure

The subject adapted for 3 min to a D_{65} light stimulus of 30 cd m^{-2}, 20×27 deg. Then, s/he started adjusting luminance of the overlapping area so that s/he perceived a transparent surface in the area. In preliminary observations, we found that the overlapping area had some range of luminance to be seen as transparent; therefore, we separately measured the upper and the lower limits of the luminance range. When the overlapping area had higher luminance than the upper-limit luminance, it appeared to glowing like a light and was no longer transparent. When the overlapping area had lower luminance than the lower-limit luminance, it appeared to be a dark hole. After the adjustment, the subject reported which rectangle was perceived in front as transparent at the overlapping area.

We noticed that there were two kinds of transparent appearances for our cross pattern stimulus. For both appearances, the subject perceived two surfaces at the overlapping area of the stimulus: a transparent surface was seen in front and an opaque surface behind. However, depending on the chromaticity of the overlapping area it appeared that both transparent and opaque surfaces were chromatically uniform or that the transparent surface or the opaque surface was not chromatically uniform. In the latter case each rectangle surface consisted of two colors: a color in the inducing area and a different color in the overlapping area. We call the former case of transparency "chromatically-uniform transparency" and the latter case "chromatically-non-uniform transparency." Chromatically-non-uniform transparency has not been described as a criterion of transparency in previous studies. With respect to the perception of a transparent surface, both appearances would be satisfied with the definition of transparency. In this study, we employed a criterion of chromatically-uniform transparency, since the purpose of our study is to investigate chromatic transparency. Transparent and opaque surfaces must be seen as chromatically uniform in order to satisfy the present criterion.

In the next trial, a different chromaticity was selected in the overlapping area. The stimulus was presented after adaptation to the D_{65} white for 5 s. When the subject could not achieve the transparency criterion at any luminance, s/he said "no." To cancel the chromatic adaptation effect, two chromaticities, R and G, of the inducing areas were alternated at each trial.

We used only a combination of chromaticities of the inducing areas in one session. Different chromaticities in the overlapping area were presented in random order in a session, which session consisted of 15 or 23 trials. All chromaticites of the overlapping area were presented in two successive sessions. Several sessions for different backgrounds and two types of limits were run in a day. For each stimulus condition, the measurements were repeated 5 times. A total of 40 sessions were run for each subject.

In Experiment 1, we also measured unique-yellow points on the dark and the light backgrounds for each subject. Unique-yellow is neither reddish nor greenish. So, we assumed there would be some changes for the transparency when the overlapping area had the unique-yellow. For this measurement, only the overlapping area was presented on the background. The subject adjusted the chromaticity of the overlapping area on the additive-mixture line so that these points appeared neither reddish nor greenish. Only YI measured unique-white points in addition to unique-yellow points. These measurements were repeated 5 times for each individual condition.

2.3 Subjects

We employed four subjects YI (24, female), KU (45, male), YY (30, male) and KM (24, male) in the first condition of Experiment 1 and Experiment 2. Only YI participated in the rest of the experiments. They had normal color vision.

3. Experiment 1: Luminance and Chromaticity Ranges for Transparency

3.1 *Stimulus*

We examined three chromaticity combinations of the inducing areas; (1) red (R) ($x=0.615, y=0.340$) and green (G) ($x=0.273, y=0.593$), (2) red (R) and bluish green (BG) ($x=0.213, y=0.325$), and (3) green (G) and purple (P) ($x=0.335, y=0.184$). The luminance of the inducing areas was fixed at 10 cd m^{-2}. In condition (1), the chromaticity of the overlapping area was selected from 15 chromaticities on the additive color mixture line of two inducing chromaticities, and 18 chromaticities were selected on the lines that connected the D_{65} white with chromaticities on the additive color mixture line. For subject YI, 9 more chromaticities were added. In conditions (2) and (3), in addition to 15 chromaticities on the additive color-mixture line, 24 and 22 chromaticities were selected, respectively. The background was either dark or light. Those were 0.16 cd m^{-2} and 60 cd m^{-2} of the D_{65} white, respectively. The light background was appeared as white to the subject.

3.2 *Results*

Figure 2 shows the luminance range of the overlapping area obtained in condition (1). The chromaticities of the overlapping area were on the additive color mixture line between the R and the G inducing areas. The ordinate represents luminance (cd m^{-2}). The abscissa indicates k value as defined in the equation below.

$$k=(x_O-x_G)/(x_R-x_G), \quad \text{or} \quad (y_O-y_G)/(y_R-y_G)$$

Here, (x_R, y_R), (x_G, y_G) and (x_O, y_O) represent the CIE1931 (x, y) chromaticity coordinates for R, G and the overlapping area. The k value shows relative chromaticity of the overlapping area on the CIE 1931 (x, y) chromaticity diagram. $k=0$ and 1 mean the G and R points, re-

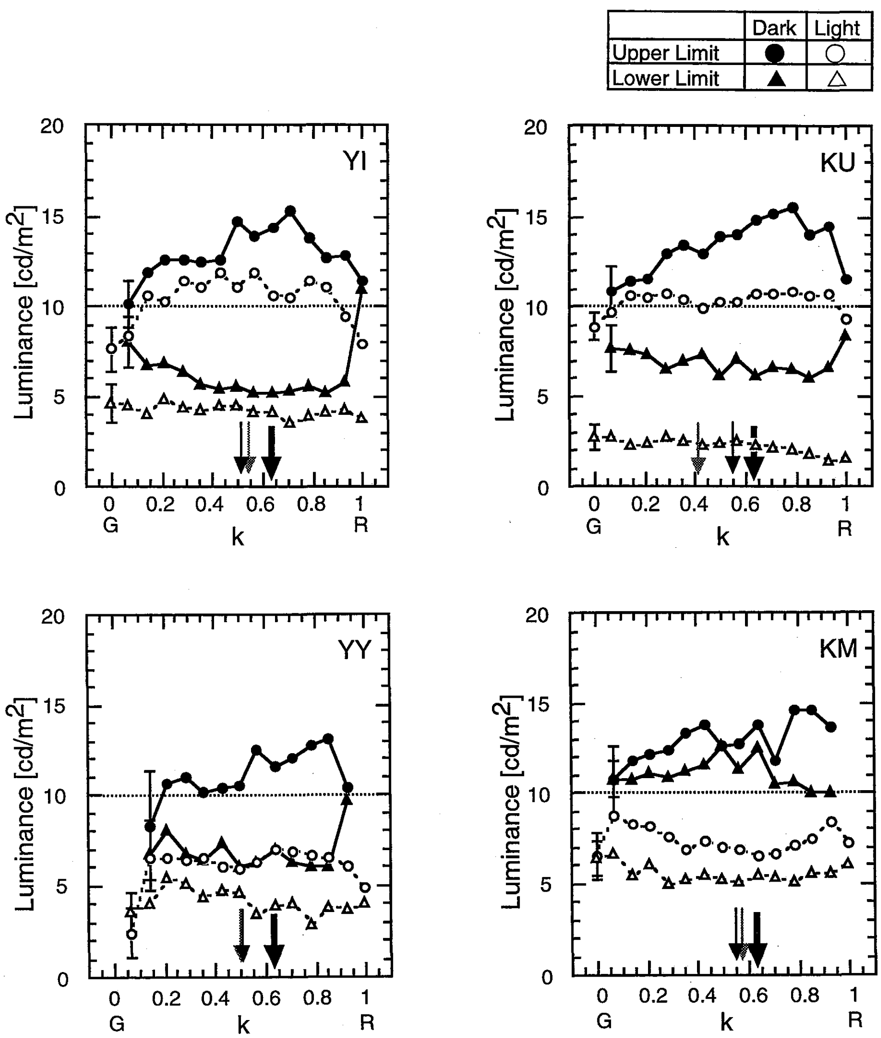

Fig. 2. Luminance ranges of the overlapping area for transparency perception for red and green inducing areas. Black and open symbols denote results for the dark background and the light background of the D_{65} white (60 cd m^2), respectively. Circle and triangle symbols represent the upper and the lower limits of the luminance range. Bold arrow represents the chromaticity given by additive mixture of two inducing chromaticities. Solid and dashed arrows indicate the individual unique yellow points for the dark and the light backgrounds, respectively. The four panels show results obtained from four subjects, YI, KU, YY and KM.

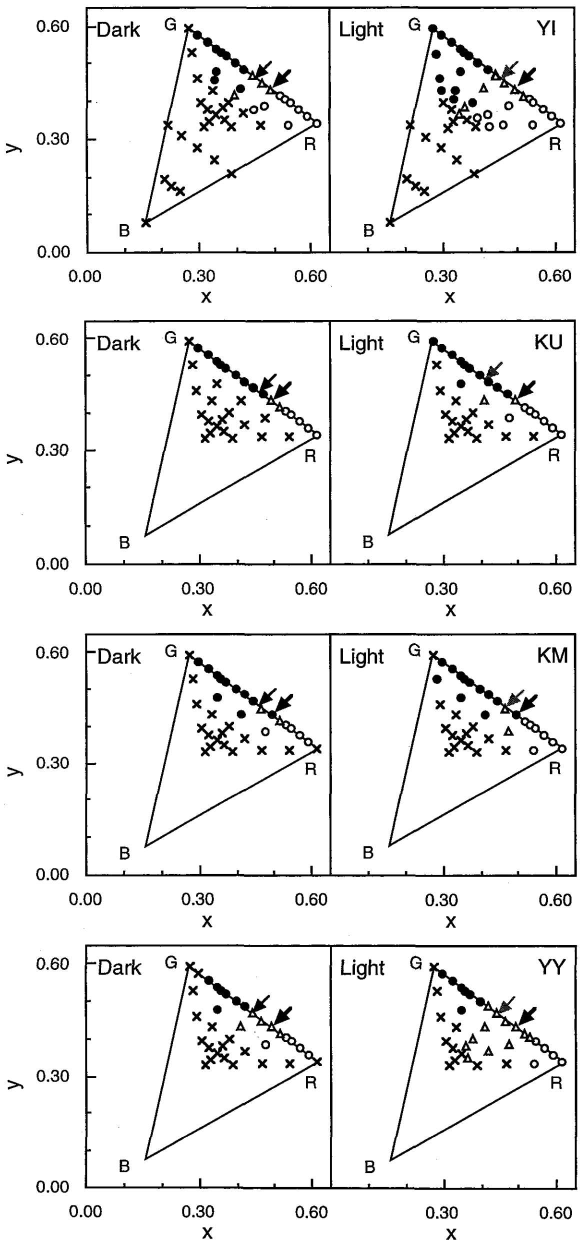

Fig. 3. Chromatic ranges for transparency perception and colors perceived in front. The symbols denote the color of the rectangle perceived in front: ●, green; △, both; ○, red and ×, no. Thin arrow in each panel indicates a chromaticity of the unique yellow for individuals. Bold arrow represents the chromaticity of additive color-mixture of two inducing chromaticities.

spectively.

Closed and open symbols represent the dark and the light background conditions, respectively. Circular and triangular symbols denote the upper and the lower limits of the luminance range, respectively. The error bars in each panel indicate mean standard deviations for the corresponding conditions. The subject could perceive transparency in the overlapping area in the range between the circles and triangles.

A bold arrow in each panel indicates the chromaticity

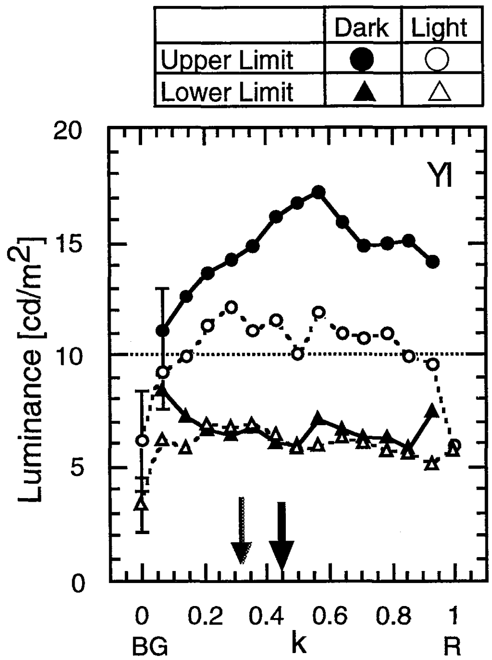

Fig. 4. Luminance ranges of the overlapping area for transparency for red and bluish green inducing areas. Bold arrow represents the chromaticity given by additive mixture of two inducing chromaticities. Solid and dashed arrows indicate the individual unique-white points for the dark and the light backgrounds, respectively.

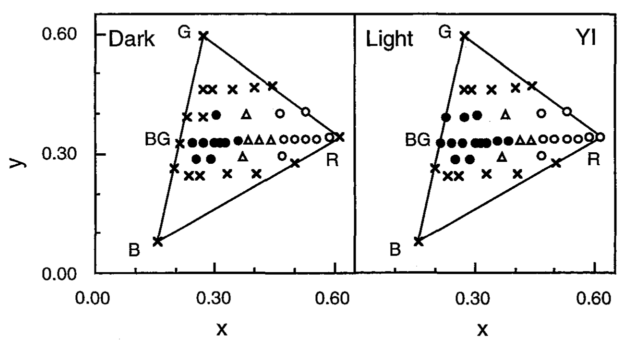

Fig. 5. Chromatic ranges for transparency and colors perceived in front. The symbols denote the color of the rectangle perceived in front: ●, bluish green; △, both; ○, red and ×, no.

given by additive-mixture of two inducing chromaticities. Solid and dashed arrows indicate the individual unique yellow points for the dark and the light backgrounds, respectively.

Figure 3 shows the chromatic range for transparency. The results for the dark and the light backgrounds are shown in the left and the right sides of one panel, respectively. Closed and open circles denote a rectangle that was perceived in front as transparent in the overlapping area. An open triangle shows that the subject could see either rectangle in front. Their positions were alternated spontaneously or intentionally. At the chromaticities shown by × symbols no transparency was perceived.

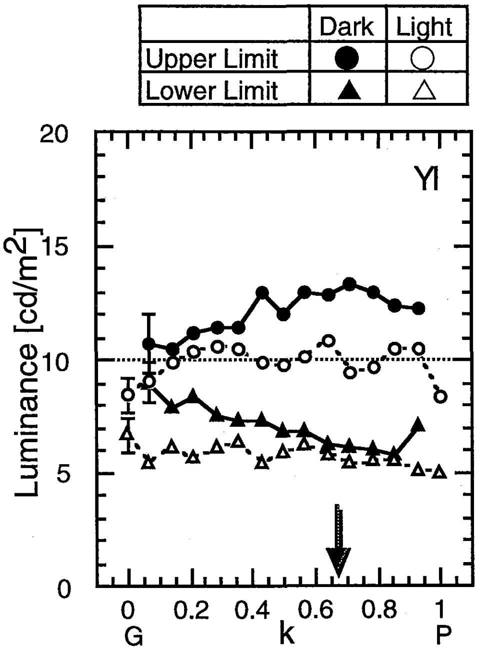

Fig. 6. Luminance ranges of the overlapping area for transparency for green and purple inducing areas. Bold arrow represents the chromaticity given by additive mixture of two inducing chromaticities. Solid and dashed arrows indicate the individual unique-white points for the dark and the light backgrounds, respectively.

The thin arrow and the bold arrow in each panel indicate the chromaticities of the individual unique-yellow and the additive-mixture of the two inducing chromaticities, respectively.

Figures 4 and 5 show the results for condition (2), and Figs. 6 and 7 show those for condition (3). In Figs. 4 and 6, the bold arrows in each panel indicate the chromaticity given by additive-mixture of two inducing chromaticities like the arrow in Fig. 2. Solid and dashed arrows indicate the individual unique white points for the dark and the light backgrounds, respectively. Under these stimulus conditions, the chromaticity that appeared neither two colors of the inducing areas corresponded to white.

In Figs. 2, 4 and 6, it was found that there was the luminance range of the overlapping area to see transparency both for the dark and light backgrounds. The luminance range tended to be wider when the chromaticity of the overlapping area was at about the middle position on the additive color-mixture line than when the chromaticity of the overlapping area was close to the R and the G points. It was also found that the upper and lower limits of luminance ranges were different between these two background conditions, being higher for the dark background than for the light.

In Fig. 2 it is obvious that the upper and lower limits were also somewhat different among subjects. For the dark background, the subjects YI, KU and YY could perceive transparency when the overlapping area was equal to and lower than 10 cd m^{-2}, equal to the luminance of

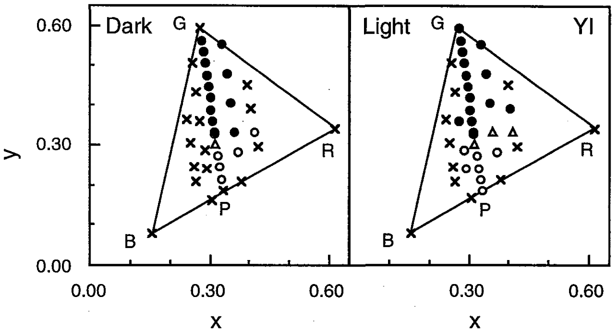

Fig. 7. Chromatic ranges for transparency and colors perceived in front. The symbols denote the color of the rectangle perceived in front: ●, green; △, both; ○, purple and ×, no.

the inducing area. However, KM did not perceive transparency in this condition. For the light background, the upper limits of YI and KU came to the level of 10 cd m^{-2}, but those of YY and KM were below this.

In Figs. 3, 5 and 7 it is shown that the chromatic range located around the additive color-mixture line between two chromaticities of inducing areas. The chromatic range for the light background was a little wider than that for the dark background.

4. Experiment 2: Luminance Range for Achromatic Transparency

4.1 Stimulus and Procedure

In Experiment 2 we examined the luminance range for achromatic transparency in order to compare with that for chromatic transparency obtained in Experiment 1. The stimulus conditions were the same as in Experiment 1 except that the overlapping area and the inducing areas had the same chromaticity; either red (R), green (G) or white (D_{65}). These chromaticities were the same as used in Experiment 1. The procedure and the subjects were also the same as in Experiment 1.

4.2 Results

Figure 8 shows luminance ranges of the overlapping area for achromatic transparency. These luminance ranges were almost the same for all chromatic conditions of the stimulus. Since all inducing areas were of the same chromaticity and luminance, either rectangle could be perceived in front. The transparent rectangle appeared slightly brighter than the other rectangle perceived behind.

In Fig. 8, the luminance ranges of YI and KU and that for the dark background of YY spread on both sides across 10 cd m^{-2}. Because the overlapping area had the same chromaticity as the inducing areas, the stimulus pattern became uniform when the luminance of the overlapping area was 10 cd m^{-2}, so that no transparent surface was seen. Except the data around 10 cd m^{-2}, the luminance ranges were similar to those in Fig. 2. For KM, the luminance range existed at the upper side for the dark background and the lower side for the light background. The individual differences were similar to those

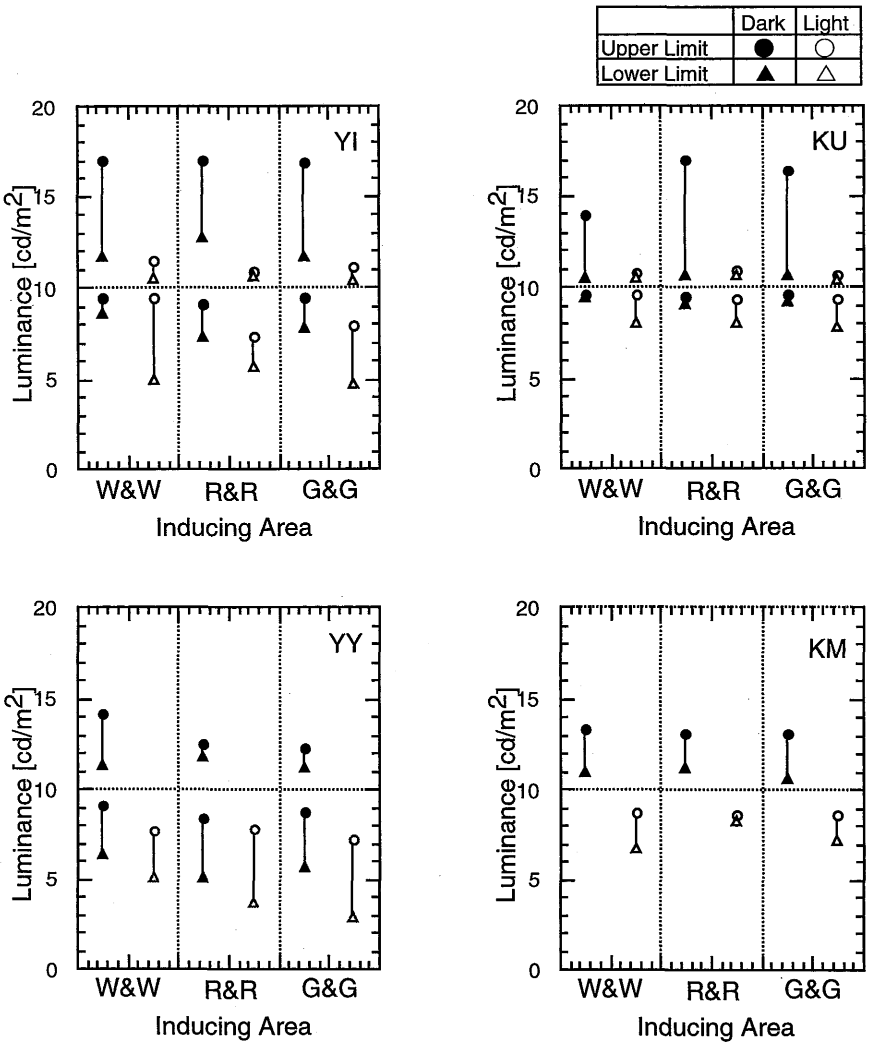

Fig. 8. Luminance ranges of the overlapping area for achromatic transparency perception. The abscissa indicates the color of the inducing areas, W&W, R&R, G&G. Symbols are the same as Fig. 2. For dark background: ●, Upper Limit; ▲, Lower Limit. For light background: ○, Upper Limit; △, Lower Limit.

obtained for the chromatic transparency in Fig. 2. This will be discussed later.

6. Discussion

6.1 Luminance Conditions for Transparency

In Figs. 2, 4 and 6, the luminance range of the overlapping area was found to include the equal luminance level with the inducing areas (10 cd m^{-2}) for some conditions. However, the perceptual appearance of the stimulus changed to a great extent when the luminance of the overlapping area crossed 10 cd m^{-2}. With the luminance higher than 10 cd m^{-2} for the dark background, one of two rectangles was perceived as a perfectly transparent surface. The subject had a strong impression of transparency. However, with the luminance of the overlapping area lower than 10 cd m^{-2} for the dark background, a somewhat dark field like a shadow appeared in the overlapping area through the frontal transparent surface, although two inducing colors could be seen in the overlapping area.

For the light background when the overlapping area had the luminance lower than 10 cd m^{-2}, a perfectly transparent surface appeared. Similar shadow appearance was perceived when the overlapping area had the luminance higher than 10 cd m^{-2}.

Similar appearance change also occurred for achromatic transparency in Experiment 2. That is, there was the luminance range of the overlapping area for perfect transparency and non-perfect transparency.

This difference of the perceptual appearance of the stimulus would cause the individual difference of the judgement criterion. This would be the main reason for some individual differences in the present results. In some cases, YY for the dark background and YI and KU for both backgrounds, these non-perfect transparencies were judged to be "transparent." In other cases, YY for the light background and KM for both backgrounds, the non-perfect transparencies were judged to be "no transparent." Although there is a difference of judgement criterion among subjects and among stimulus conditions, all subjects had the common impression of the perceptual appearance of the stimulus under these conditions.

In Fig. 2, the luminance range was narrowest when the chromaticity of the overlapping area was close to either end of the additive color-mixture line. Some subjects could not perceive transparency when the overlapping area had the same chromaticity as the inducing area. This indicates that it is necessary for transparency that the overlapping area has the chromaticity of an additive mixture of two inducing chromaticities.

On the contrary, the luminance range was widest, except for KM, when the chromaticity of the overlapping area was at about the middle position on the additive color-mixture line. On this position, transparency could occur easily because the chromaticness of the overlapping area was easily divided into two inducing chromaticnesses. The chromaticity of the widest range did not correspond to either the unique-yellow chromaticity or the chromaticity given by the additive mixture of two inducing chromaticities.

We should consider why the luminance ranges for perfect transparency were not equal between the two backgrounds. The subject reported that when the background was brighter than the inducing areas, the stimulus appeared as if the transparent sheet were placed on a light box. When the background was darker, the stimulus appeared as if it was a colored light coming through an aperture in the dark space or an illuminated surface by a colored illuminant. We assume that this appearance difference is the main factor accounting for above question.

The perceptual appearances of the stimulus on the dark and the light backgrounds might be partly related to the conditions of additive and subtractive color-mixture. If the stimulus appears as the colored light on the dark background, it would be reasonable to suppose that two rectangles are added in the overlapping area so that the overlapping area has higher luminance than the inducing areas. On the other hand, if the stimulus appears as the colored filter on the light background, it would be supposed that subtractive color-mixture occurs in the overlapping area so that luminance of the overlapping area is lower than that of the inducing areas. Although the chromaticity condition for transparency obtained in this study did not meet the subtractive condition, the luminance condition for transparency partly corresponded to the physical color-mixture, including the subtractive and the additive conditions.

6.2 *Chromatic Conditions for Transparency*

In Figs. 3, 5 and 7 we found that transparency occurred when the overlapping area had the chromaticity on the additive-color mixture line between the two inducing chromaticities. This implies that the perceptual transparency mechanism divides the color of an additive color mixture into the original colors existing in the inducing areas.

An additively-mixtured color can be created by optically superimposing a colored light onto another light. For example, when red and green colored lights are presented simultaneously to a retinal location, the sensation of yellow is provoked in this location. In order to yield the original green color of one rectangle perceived behind, the red color of another rectangle perceived in front should be subtracted from the yellow of the overlapping area. The process that subtracts one color from another would occur in the visual system for transparency.

It is well known that color appearance depends on the spatial structure of the image as a whole. If conditions for transparency other than chromatic condition are satisfied, this cross pattern could be recognized as the overlap of two rectangles. Therefore, the visual system would try to estimate whether the color appearance inside a rectangle was uniform. Color sensation is encoded by relative activation of three L-, M- and S-cones. The summation between cone-activations of two colors leads to an additive color-mixture. In the present stimulus, this process can be represented by the following equation.

$$(L, M, S)_O = r(L, M, S)_{R1} + s(L, M, S)_{R2}$$

Here, $(L, M, S)_O$ represents the relative cone-activation in the overlapping area, $(L, M, S)_{R1}$ and $(L, M, S)_{R2}$ represent the relative cone-activation in one of two rectangles, respectively. Two small letters, r and s represent the rate of mixture of two rectangle colors. According to the cone-activation in each area, the reverse process, that is, the subtraction process would occur in the visual system. This subtraction process can be represented by the following equation.

$$(L, M, S)_O - r(L, M, S)_{R1} = s(L, M, S)_{R2}$$

If the relative cone-activation in one rectangle is subtracted from that of an additively-mixtured color in the overlapping area, after the subtraction the relative cone-activation in another rectangle should be left in the overlapping area. If this assumption is true, it is very useful that the overlapping area has the color of an additive mixture of two rectangle colors.

In Figs. 3, 5 and 7, the chromatic ranges for transparency spread around the additive color-mixture line. According to the above assumption, transparency should occur only when the chromaticity of the overlapping area had the chromaticity on the additive color-mixture line between two inducing chromaticities. However, the visual system has the threshold of the chromatic discrimination. If the relative cone-activation that was left in the overlapping area after the subtraction was almost the same as that in another rectangle perceived behind, we could not discriminate the chromatic difference. Therefore, the visual system would judge the rest of the color in the overlapping area as the same color as the rectangle perceived behind. Moreover, in order to try to be consistent with the figural recognition, the visual system would allow the ability of this chromatic discrimination to be lower than the previous experimental data for the chromatic discrimination.[22]

If this subtraction depends on the relative cone-activation, this process would occur in the lower visual areas. However, it is considered that figural recognition is achieved in higher visual areas. Thus, we considered that the information about the relative cone-activation would stream over higher visual areas. Some subjects needed time to perceive transparency after the presentation of the stimulus. This time would be used to compare figural and chromatic information in higher visual areas and to assign the color of the overlapping area to the two original colors of the rectangles.

In Fig. 3 the rectangle with a chromaticity closer to the overlapping area was perceived as the front transparent surface. Thus, the chromaticity of the overlapping area determined which rectangle was the front transparent surface. However, there were some ranges of chromaticities of the overlapping area with that both rectangles were alternately perceived in front. These chromaticities existed between the individual unique-yellow and the chromaticity given by additive mixture of two inducing chromaticities. The unique-yellow would have the same amount of red and green responses. The additive-mixture chromaticity has physically the same amount of red and green components. For these reasons, the overlapping area could easily spread into either inducing area. Under these conditions, the subject's attention could control which rectangle was perceived in front.

It was found that the chromatic range was wider for the light background than for the dark background. For the dark background, the luminance range of the overlapping area was higher. This means that color difference between the overlapping area and the inducing areas was more evident for the dark background than for the light background. This difference in color-difference appearance might be a cause of the range difference between the backgrounds.

6.3 Comparison between Our Experimental Results and Metelli's Model

Figure 9(a) shows a figure used to explain Metelli's model in which a transparent circular sheet is put on the border of two colored background surfaces. Metelli's transparency model has two constraints for relationships between the luminances of the four areas:

$$\{(p-q)/(A-B)\}=\alpha, \qquad 0<\alpha<1$$
$$[(Aq-Bp)/\{(A+q)-(B+p)\}]=t, \qquad 0<t<m$$

Here, p, q, A and B represent the luminance of each area in Fig. 9(a). The letter α shows a portion of a sector angle of Metelli's episcotister, and t shows the luminance reflected from the surface of the episcotister. The letter m represents the maximum possible luminance of t. The m should be equal to that of the white the subject perceives in the stimulus. The first equation indicates that the luminous difference of two areas in the circle must be smaller than that of the backgrounds. The second equation means the reflectance range of an episcotister surface in Metelli's model.

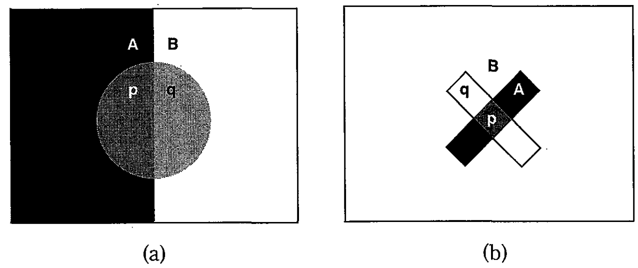

Fig. 9. The conventional labeling of the stimulus. (a) The pattern used to explain the episcotister model by Metelli. The conventional labeling of the four-intensity areas. (b) The conventional labeling of the present stimulus correspond to those in the Metelli's figure.

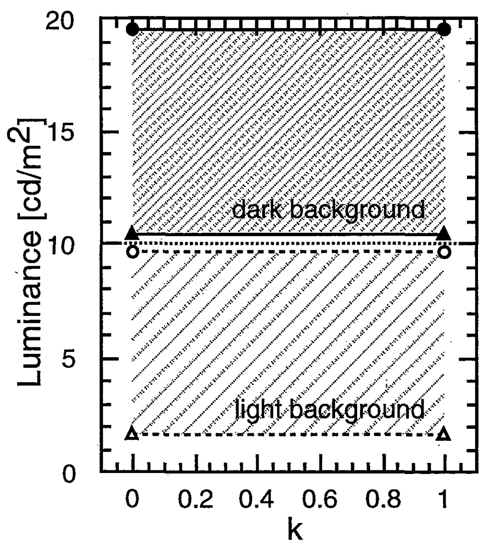

Fig. 10. The ranges predicted by Metelli's model. Symbols are the same as in Fig. 2. Dark shaded portion is the prediction for the dark background. Bright shaded portion is the prediction for the light background.

The areas of the present stimulus correspond to those in Metelli's figure as shown in Fig. 9(b). In our stimulus, one of the inducing areas should correspond to one of Metelli's backgrounds. In the present experiments $A=10$ cd m^{-2}, $q=10$ cd m^{-2}, and $B=0$ cd m^{-2} (dark background) or 60 cd m^{-2} (light background). According to Metelli's constraints, the following relations are predicted:

$$10<p<20 \text{ cd m}^{-2} \text{ for the dark background}$$
$$1.67<p<10 \text{ cd m}^{-2} \text{ for the light background}$$

Here, the higher limit (20 cd m^{-2}) for the dark background is obtained for m=infinity. Shaded regions in Fig. 10 show these ranges.

Our present results did not satisfy the luminance ranges predicted by Metelli's model. Even for the achromatic stimulus in our experiments, the results were not the same as Metelli's prediction. In that prediction only the luminance ranges for the subject KM were included. It seems that Metelli's model predicts only the perfect transparency, but does not include non-perfect transparency, which was found in the present investigation.

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