Characteristics of grouping colors for figure segregation on a multicolored background

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A figure is segregated from its background when the colored elements belonging to the figure are grouped together. We investigated the range of color distribution conditions in which a figure could be segregated from its background using the color distribution differences. The stimulus was a multicolored texture composed of randomly shaped pieces. It was divided into two regions: a test region and a background region. The pieces in these two regions had different color distributions in the OSA Uniform Color Space. In our experiments, the subject segregated the figure of the test region using two different procedures. Since the Euclidean distance in the OSA Uniform Color Space corresponds to perceived color difference, if segregation thresholds are determined by only color difference, the thresholds should be independent of position and direction in the color space. In the results, however, the thresholds did depend on position and direction in the OSA Uniform Color Space. This suggests that color difference is not the only factor in figure segregation by color. Moreover, the threshold dependence on position and direction is influenced by the distances in the cone-opponent space whose axes are normalized by discrimination thresholds, suggesting that figure segregation threshold is determined by similar factors in the cone-opponent space for color discrimination. The analysis of the results by categorical color naming suggests that categorical color perception may affect figure segregation only slightly.

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1. INTRODUCTION

One important function of visual perception is the detection or discrimination of an object from its background, and color is an important signal for detection and discrimination. The characteristics of color discrimination and detection have been fully investigated using a uniform field, and mechanisms relevant to color detection such as the three cardinal mechanisms [1,2] have been clarified. In addition, several recent studies have used a nonuniform field with chromaticity and luminance variations to investigate color vision properties in the natural environment. In such experiments, the observer, for example, detected a sine-wave grating embedded in spatiotemporal random noise [3] or discriminated a square region in a multicolored texture by luminance or chromaticity differences [4,5]. These investigations revealed some chromatic mechanisms that underlie detection and discrimination on chromatically nonuniform fields as described below.

For example, Li and Lennie [4] showed that when the stimulus varied only in the plane made by a chromatic axis and an achromatic axis, texture segmentation, a kind of discrimination task, required only two mechanisms tuned to the cardinal directions [2]. However, when chromatic variations were made in the isoluminant plane, at least four mechanisms tuned to the cardinal and other intermediate directions were required. They also found large individual differences in the effects of chromatic variations for the isoluminant stimuli, which is consistent with previous studies [2,6,7]. Their study indicates that higher-order chromatic mechanisms may play an important role for texture segmentation. Li and Lennie [5] reported that achromatic noise did not disrupt chromatic segmentation of multicolored textures, whereas chromatic noise was effective in disrupting luminance segmentation. This suggests that the visual system is asymmetric in discounting chromatic and achromatic variations. As described above, chromatic properties of mechanisms contributing to segmentation of multicolored regions have been clarified to some extent.

Meanwhile, figure segregation from the background, not just detection and discrimination, might be another important visual function. Figure segregation is different from detection and discrimination in that figure segregation requires form processing to extract the form of a figure in addition to mere detection. It has been widely believed that form processing is based mainly on luminance information (rather than chromatic information), because, for example, the visual system is poor at segregating an isoluminant figure from its ground [8], and the chromatic mechanisms are more sensitive to low-spatial-frequency components than to high-spatial-frequency components [9]. On the other hand, Mollon [10] stated that figure segregation by grouping colors in a nonuniform field was an important function of our color vision. Moreover, Mullen and Beaudot [11] found that an observer could discriminate two shapes that were isoluminant with their background at the hyperacuity level, indicating that the chromatic response can play an important role for form processing. However, the characteristics of the mechanism underlying form processing by chromatic information have barely been investigated and remain unclear.

Comparing figure segregation with texture segmentation, figure segregation should depend on higher-spatial-frequency components to extract local orientations of the figure contour [11], while texture segmentation depends on analysis of the lower-spatial-frequency components [4]. In addition, the local orientations should be globally integrated to create a shape of the figure in figure segregation. Therefore, chromatic processing different from that underlying texture segmentation might be involved in figure segregation by color, leading to a difference in chromatic characteristics derived from a figure segregation task compared with a texture segmentation task.

The visual system can segregate a figure from its multicolored background by grouping pieces of colors. A group of colors in a certain region of a color space should be distinguished from another group of colors in order for a figure to be segregated. In this study, we aim to investigate the range of color distribution conditions for a figure and its background that allow segregation of the figure from the background. Knowing these chromatic conditions might help us to understand the chromatic mechanism underlying figure processing by color. One of the possible factors to determine whether a figure can be segregated from its background is difference of color appearance. This is quite a simple idea: a figure can be segregated when the color appearance difference between the figure and its background is larger than a certain value. We can investigate the relationship between figure segregation and color appearance difference by using the OSA Uniform Color Scales (OSA-UCS) [12], a uniform color space created on the basis of color appearance difference. First, we measure the color difference needed to segregate a figure in terms of the OSA-UCS in order to examine whether color appearance can explain figure segregation performance. Then we also test whether other chromatic factors could contribute to figure segregation.

2. EXPERIMENT 1

In Experiment 1, we tested the effect of varying the distance between the centers of the spherical color distributions of a figure and its background on segregation of the figure.

A. Apparatus and Stimulus

The stimulus was presented on a CRT monitor (Nanao T766, 75 Hz) controlled by a PC (Power Macintosh G4, 450 MHz). The subject binocularly viewed the stimulus at a distance of 57 cm. His head was fixed by a chin rest.

We used the samples of the OSA-UCS as stimuli. The appearance of the samples on the monitor simulated illumination by a D65 fluorescent lamp (Toshiba FL20S, D-EDL-D65). The OSA-UCS has 424 samples, and color differences of all pairs of neighboring colors are equal. This color difference is defined as 2 OSA color-difference units. We increased the number of color samples by linear interpolation with 0.25 OSA color difference, because 2 OSA color-difference units is too large for our experiment. The OSA-UCS has three axes (L, j, and g), and the origin $(L,j,g)=(0,0,0)$ is gray. Lightness increases along the L axis, redness increases (and greenness decreases) along the j axis, and blueness increases (and yellowness decreases) along the g axis.

Figure 1(a) shows an example of the stimulus. The size of the texture was 16 deg × 16 deg. The texture consisted of 40 × 40 small, multicolored, octagonal pieces. The vertices of each octagon were made by moving four vertices and four midpoints of a 0.4 deg × 0.4 deg square within circles whose centers were at original positions and radii were 0.2 deg. Three vertices were shared with each of the adjustment pieces. The size of each piece was approximately 0.4 deg × 0.4 deg with a 0.1 deg gap. A gray background with a luminance of 11.1 cd/m^2 and a CIE1931 (x,y) chromaticity of (0.311, 0.329) surrounded the texture stimulus. The stimulus was divided into two regions, the test region and the background region. The (L, j, g) coordinates of the pieces in the test and background regions were uniformly distributed in spheres in the OSA-UCS [Fig. 1(b)]. These two spherical distributions of the test and background regions were of the same radius but of different center positions.

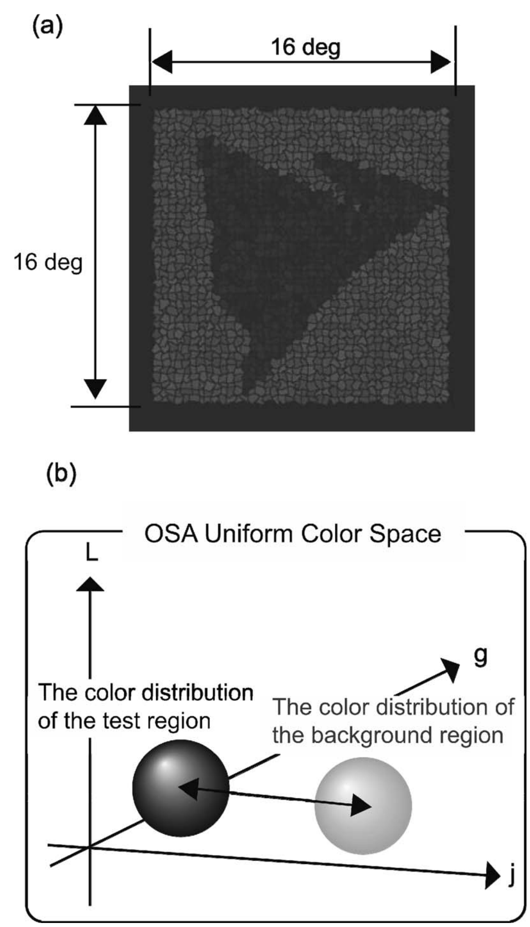


Fig. 1. (a) Stimulus used in Experiment 1 (color versions were used in the actual experiments but are shown here in grayscale). This stimulus consists of 40 × 40 small pieces. The region near the center is the test region, and the region surrounding the test region is the background region. (b) Diagram of two color distributions of the test and background regions in the OSA-UCS.

B. Procedure

The center of the background color distribution was fixed at (L,j,g)=(2,2,2) in the OSA-UCS. The luminance of the center of the background color distribution was 43.5 cd/m^2, and the CIE1931 (x,y) chromaticity coordinate was (0.309, 0.371). This color was perceived as yellowish green brighter than the gray background. The center of the test color distribution varied from that of the background distribution up to 2.0 of the OSA color-difference unit in 0.25 steps in four directions, +j, −j, +g, and −g. The radii of the background and test distributions were set equal at 0.5, 1.0, 1.5, and 2.0 OSA color-difference units. The number of chromaticities that could be assigned to the pieces increased with the radius.

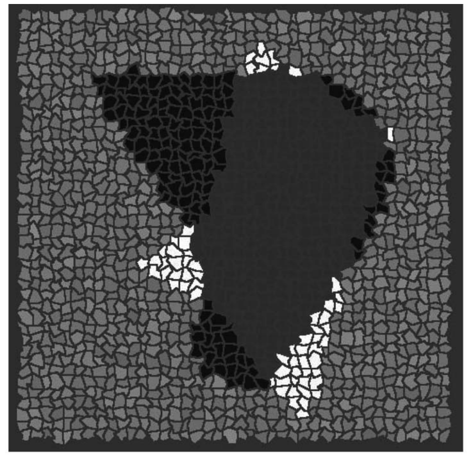
The subject adapted to the gray background for 3 min before a session started. In each trial, the shapes of the test region were randomly determined by the computer in the same way as the shape of each piece based on an 8 deg × 8 deg square, and the color of each piece was randomly selected from the color distribution it belonged to. The stimulus was steadily presented during a trial. The subject traced the perceived contour of the test region with a mouse pointer, though he drew a random shape when the color distributions of the test and background regions were identical. Twenty trials were carried out for each experimental condition.

C. Subjects

Three subjects, DK (male, age 23), TS (male, age 24) and TN (male, age 24), participated in Experiment 1. All had normal color vision as assessed by the Ishihara color blindness plates and the 100 Hue test.

D. Analysis

We defined a disagreement index (DI) to evaluate the difference in shape between the test figure and the drawing made by the subject. Figure 2 shows an example of a subject's drawing. In Fig. 2, the test region is shown with dark gray and white pieces, and the background region is shown with black and light gray pieces. The subject drew the outline of the dark gray and black regions. The black pieces are included in the subject's drawing but not in the test region, while the white pieces are included in the test region but not in the subject's drawing. We named the region of black pieces "error region B," and the region of white pieces "error region T." The number of pieces included in error regions increases and the distance between an error piece and the contour of the test region tends to become larger as the difference in shape between the subject's drawing and the test region becomes larger. Meanwhile, the larger the number of pieces in the test region and the subject's drawing region, the larger the number of error pieces tends to be even if the shape difference between the subject's drawing and the test region was small, because the large number of pieces leads to long contours of the regions, and even a slight displacement between the contours of the two shapes yields many error pieces as a result of the long contours. Therefore, we used three kinds of values to define the DI; the number of error pieces, the distance between the error pieces and the contours of the test region, and the number of pieces in test region and the subject's drawing.



	in subject's response	not in subject's response
test region		error region T
background region	error region B	

Fig. 2. A subject's response in Experiment 1. The pieces in the test region are shown in dark gray and white, and those in the background region are shown in black and light gray, respectively. The dark gray and black pieces lie within the contour of the subject's drawing. The area of black pieces is referred to as the error region B, and the area of white pieces is called the error region T.

The DI was defined as shown in Eq. (1). Here, N_t and N_r are the numbers of pieces in the test region and in the subject's drawing, respectively. D_t is defined for each error piece in the error region t as the shortest distance of all distances between centers of the most external pieces in the test region and the error piece t (these distances were normalized by the average distance between adjacent piece centers). D_b is defined for each piece in the error region b in the same manner as D_t:

$$DI = \frac{\Sigma D_t^2}{N_t} + \frac{\Sigma D_b^2}{N_r}. \quad (1)$$

Figure 3 shows DI as a function of the shift distance of the test distribution from the background distribution. Each panel corresponds to a magnitude of the radius. The symbols indicate the shift directions +j, −j, +g, and −g. Error bars represent standard errors of the DI. The values for zero shift distance represent a baseline, since the test region is not visible. In all radius conditions, DI approaches zero as the shift distance increases, indicating that the subject succeeded in drawing the test figure when the test and the background appeared clearly different.

We chose an arbitrary value of 1.0 for DI as our criterion for whether the subject's drawing was correct. DIs were calculated for all trials so that the percentage of correct responses was obtained. The shift distance of 50% correct response was defined as the threshold by fitting a logistic function to the correct response data with the maximum-likelihood method. Although the value of 1.0

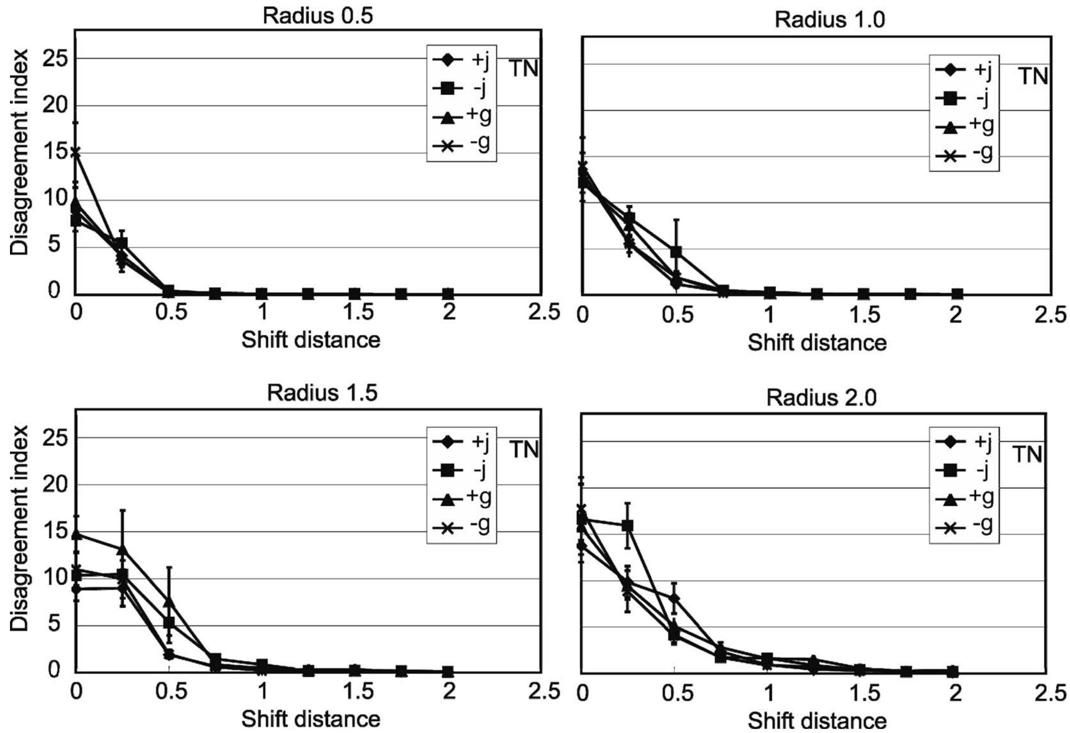


Fig. 3. DIs (see text) as functions of the shift distance for subject TN. DI approaches 0 as the between-center distance increases.

for DI was arbitrarily chosen as the correct-response criterion, we confirmed that using values of 0.5 and 1.5 yields similar results.

E. Thresholds

Figure 4 shows the thresholds of the shift distance for each subject in Experiment 1. The abscissa represents the radius of the color distributions. The bar patterns represent the directions of the test color distribution shifts. Error bars represent the standard errors of the thresholds derived from the maximum-likelihood method.

The threshold increases linearly with the radius in all the directions. There is a main effect of radius ($p<0.001$ for all subjects according to the chi-squared test). The thresholds are different for different shift directions. There is a main effect of the shift direction ($p<0.001$ for subjects TN and TS but $p<0.1$ for subject DK). All subjects show the smallest thresholds in the −g direction for most radii. For subject TS the thresholds in the +g direction are higher than the other three directions except in the 0.5 radius condition. For subject TN the thresholds in −j and +g are higher than in the other two directions. The threshold differences in different directions seem to be constant across all radii for each subject. There are no interactions between radius and direction for subjects TN and DK.

If the distance thresholds were determined only by color difference between the test and background color distributions as measured by distance in the perceptually uniform OSA-UCS space, then the thresholds should be equal in all directions. Therefore, it is likely that color difference is not the only factor contributing to figure segregation (although alternatively the OSA-UCS might not be perfectly uniform in general or for each individual subject). One possible additional factor is categorical color difference: it seems that color categories vary more in the −g direction than in the +g direction at the background color distribution used in Experiment 1. The effect of categorical color perception on figure segregation is investigated in Experiment 3.

Test and background color distributions overlapped in all radius conditions at the threshold distance. The size of the overlapping area can be considered as a measure of noise tending to prevent segregation of the test region, and the nonoverlapping area can be considered as the signal. Figure 5(a) shows the percent correct responses as functions of the shift distance in four radius conditions for subject TN. The results were averaged across all shift directions. The thresholds at 50% are different across the four radius conditions. Figure 5(b) shows the same percent correct responses as functions of the ratio of signal volume in the test distribution sphere that does not overlap the background distribution to the signal volume of the whole distribution. All these functions, except for the radius 0.5, can be described by a single function, in which percent correct is approximately linear with volume ratio for small shift distances. The results for the other subjects showed the same tendency. We found that the distance threshold was determined by the signal volume ratio.

Some individual differences exist for the thresholds in the ±j and ±g directions (Fig. 4). Li and Lennie [4] reported that there were large individual differences in color-difference threshold for texture segmentation of the stimuli defined in the isoluminant plane. They also reported that the results of experiments that explored higher-level chromatic mechanisms [2,6,7] had larger individual differences than results from typical color studies such as color discrimination on a uniform stimulus. Individual differences in our results might be due to the multicolored stimuli as in Li and Lennie's study, since the

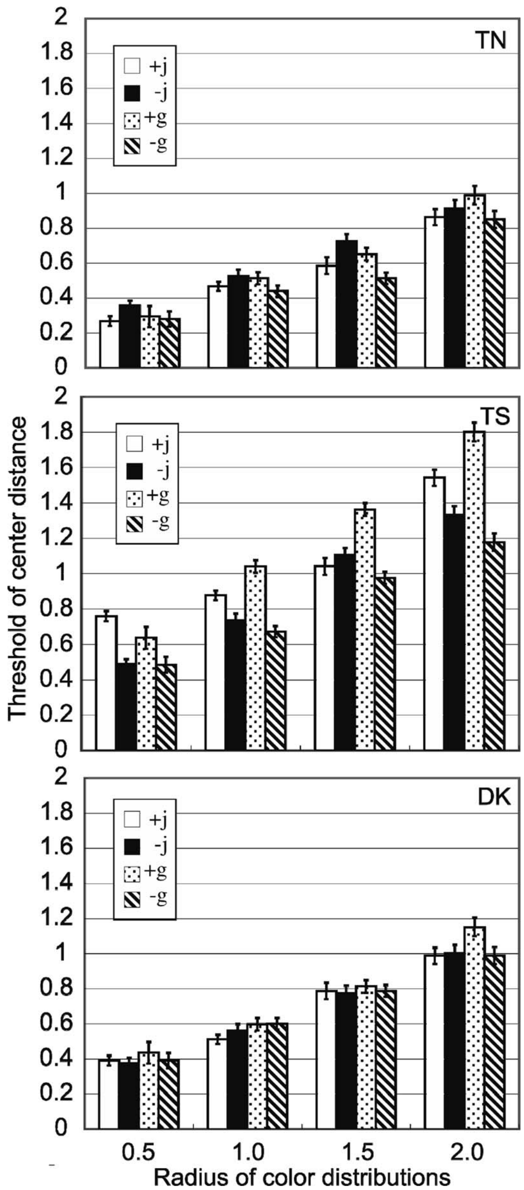


Fig. 4. Thresholds for all experimental conditions in Experiment 1. The horizontal axis represents the radius of color distributions. The bar patterns represent the shift directions of the test color distribution. Each panel corresponds to a different subject's result. Error bars are standard errors of thresholds estimated from the logistic analysis.

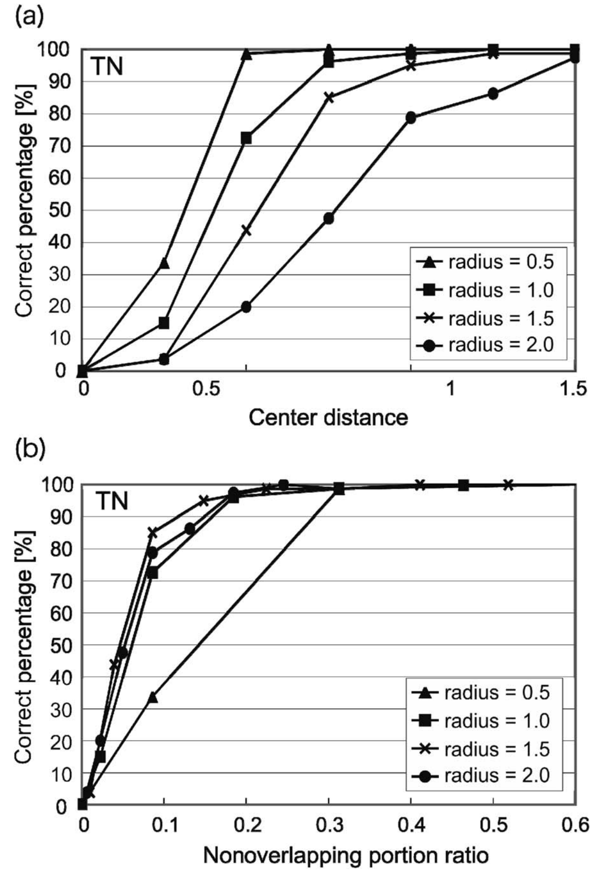


Fig. 5. (a) Correct percentages for four color distribution radii as functions of the center distance between test and background distributions. Each symbol corresponds to a distribution radius. These correct percentages are averaged over four (±j and ±g) shift directions. (b) Percent correct for four distribution radii as functions of nonoverlapping ratio of test color distribution (see text for detail).

shift between test and background color distributions was defined in the isolightness plane.

3. EXPERIMENT 2

In Experiment 2 we investigated effects of the location of the distributions of the test and background regions in the OSA-UCS.

A. Stimulus

We wanted to investigate the chromatic properties of figure segregation. However, there might be a problem in the task of Experiment 1 in relation to this purpose: the subject's judgment might be based on the local edge of the test region, not on the global perceived shape of it. Accordingly, we adopted a new procedure and stimulus in Experiment 2, in which the subject is more likely to base his response on the global shape of the test figure.

The stimulus consisted of two squares in Experiment 2. Figure 6 shows an example of the stimulus. The size of each square was 8 deg × 8 deg (30 × 30 pieces). The other configurations were the same as in Experiment 1. The shapes of the test regions were decided in the same man-

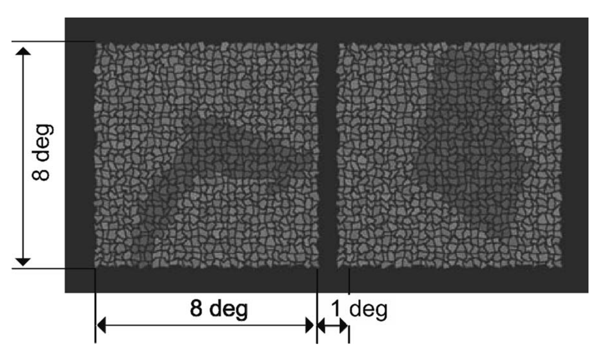


Fig. 6. Stimulus used in Experiment 2 (colored in the experiment but shown here in grayscale). Each square consists of 30 × 30 pieces. The region with a random figure near the center of each square is the test region, and the region surrounding the test region is the background region.

ner as in Experiment 1. When the shapes of the two test regions were different, the two shapes were selected so that the DI (defined in Experiment 1) between them was from 4 to 6. Therefore, the size difference between them was also not so large, though the sizes of the test regions varied with trials to some extent.

B. Procedure

The background color distribution positions were set at (L,j,g)=(0,2,2), (0,2,−2), and (0,−2,2). The luminances of the centers were 31.2, 30.5, and 28.5 cd/m^2, and their CIE1931 (x,y) chromaticity coordinates were (0.312, 0.380), (0.367, 0.354), and (0.266, 0.302), respectively. The center of the test color distribution shifted from that of the background in 0.25 steps up to 2.0 OSA units in four directions, +j, −j, +g, and −g. The radii of the test and background distributions were fixed at 2.0 OSA units. However, the shift directions −j and +g for the background distribution (L,j,g)=(0,−2,2) were not tested, because the test distributions shifted in those directions protrude beyond the OSA-UCS limit.

Figure 7 shows the sequence of the stimulus presentation in a trial. The subject saw a fixation point at the center of the gray background. After the subject pressed a button, the two stimuli were successively presented for 507 ms each interleaved by a gray background for 507 ms. Either in the first or in the second presentation, the right and the left test regions differed from one another. According to the two-alternative forced-choice procedure, the subject indicated which interval had the different test figures. The subject could freely move his eyes during the stimulus presentation. Fifty trials were carried out for an experimental condition. The subject conducted 10,350 trials in total.

C. Subject

The same three subjects (DK, TS, and TN) participated in Experiment 2.

D. Results

The threshold was defined as the shift distance corresponding to 75% correct responses with the logistic analysis. Figure 8 shows the thresholds for all subjects. The positions of the background color distribution are shown on the horizontal axis. The bar patterns show the shift directions of the test color distribution. Error bars represent the standard errors of the thresholds derived from the logistic analysis.

A chi-squared test showed that there are main effects of the shift direction for the background distributions (L,j,g)=(0,2,2) ($p<0.01$) when the results for all subjects are averaged (though there are main effects of the shift direction only for subject TS when the statistical analysis is done for each subject's results). This indicates that the thresholds are different between shift directions as in Experiment 1. However, there is no interaction between shift direction and background distribution position both for the summed results of all subjects and for each subject individually except for the position (L,j,g) =(0,−2,2) according to a chi-squared test, suggesting that the positions of the color distributions had little effect on determining the thresholds.

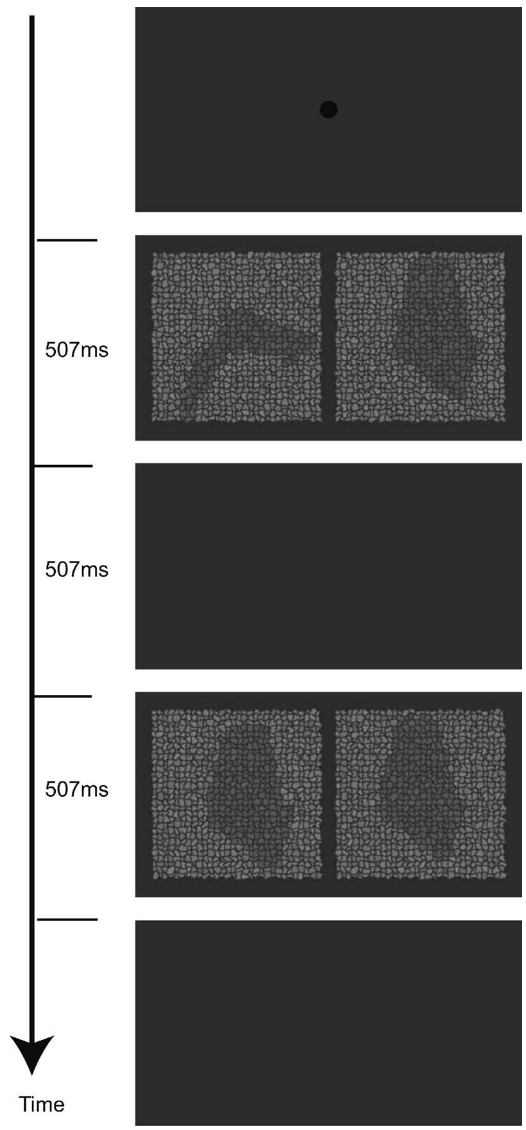


Fig. 7. Procedure for a trial in Experiment 2. After the subject pressed a button, two stimuli presented for 507 ms separated by a 507 ms gray interval. Either of the two stimuli had different test figures in the right and left squares. The subject indicated which stimulus had different test figures.

Recently, many studies examined color discrimination or detection to reveal chromatic mechanisms using stimuli whose colors were defined in the cone-opponent spaces. Sankeralli and Mullen [13] and Krauskopf and Gegenfurtner [14], for example, investigated color discrimination from a reference color to different color directions. They obtained the threshold contour in the isoluminant cone-opponent color plane. The contour traced out ellipses whose major axes were on the lines from the gray origin (the adaptation color) to the reference colors. They suggested that there were discriminators tuned to different directions in the cone-opponent plane.

Here, we analyze the figure segregation thresholds in the cone-opponent space to investigate their behaviors in the cone-opponent space as in previous color discrimination studies. Figure 9(a) shows the plots of the OSA color samples on the L=0 plane, near the contours of the three background color distributions in the isoluminant cone-

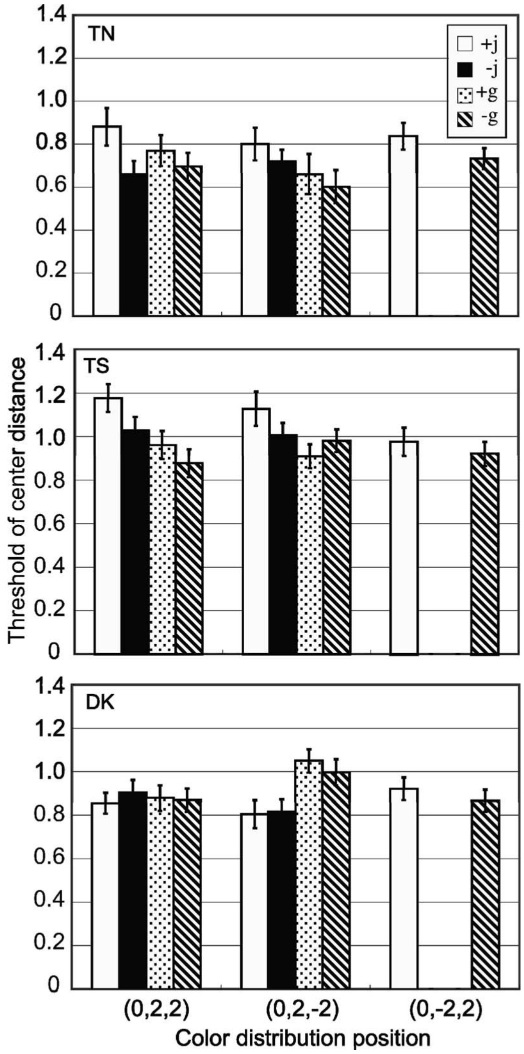


Fig. 8. Thresholds for all experimental conditions in Experiment 2. The horizontal axis represents color distribution positions. The bar patterns represent shift directions. Each panel corresponds to one subject's result. Error bars are standard errors of thresholds estimated from the logistic analysis.

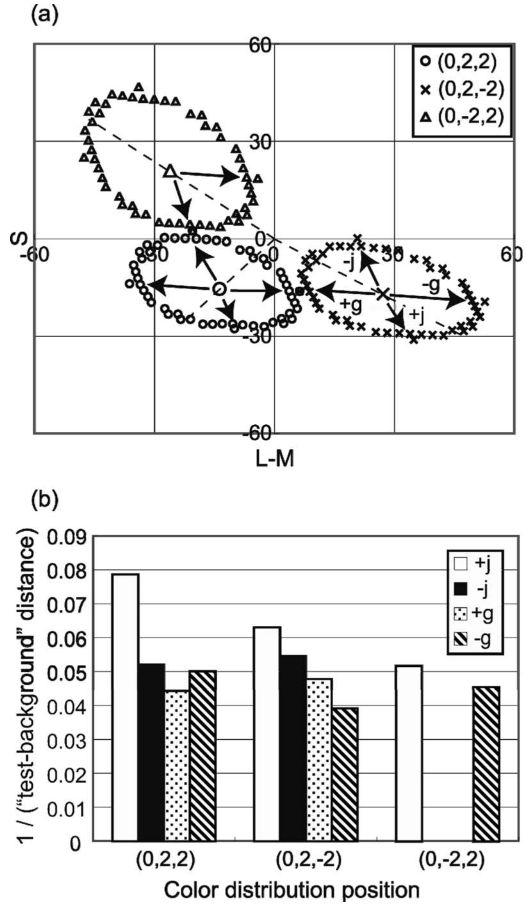


Fig. 9. (a) OSA color samples near the contours of three background color distributions in Experiment 2 plotted in the isoluminant cone-opponent plane. Each symbol corresponds to one color distribution. The large plot at the center of each color distribution represents the center sample of the distribution. The arrows from the center sample represent ±j and ±g shift directions. Dashed lines are drawn from the origin to the center samples. (b) Reciprocals of distances of 2 OSA units from the center samples ±j and ±g directions in cone-opponent plane. The horizontal axis represents color distribution positions. The bar patterns represent shift directions.

opponent plane [15,16]. These cone excitation values were calculated by multiplying the spectral distribution of the OSA samples simulated on the CRT and the cone fundamentals of Smith and Pokorny [17]. The horizontal and vertical axes represent L–M and S, respectively. The origin is the gray background used in the experiments. Each axis is normalized by the average of detection thresholds of subject TN from the origin in the + and − directions measured in a separate experiment, in which the subject detected the uniform square region on the gray background. We use only the cone-opponent space normalized by the detection thresholds of subject TN to analyze each subject's results in this paper. A large symbol at the center of the plots of each color distribution represents the center sample of the color distribution. The arrows show the shift directions (±j and ±g) of the test distributions in Experiment 2. The dashed lines represent the directions from the origin to the center of color distribution. It turned out that the arrows, namely, the shift directions used in Experiment 2, are approximately symmetric to the dashed line in each color distribution in Fig. 9(a).

As mentioned above, previous studies [13,14] indicated that color discrimination thresholds from a reference color that is different from the color the subject adapted to tended to make an ellipse whose major axis was on the line from the adaptation color to the reference color. This means that color discrimination thresholds in different directions symmetric to the major axis are nearly equal. Therefore, it is expected that the figure segregation thresholds for ±j and ±g directions should be nearly equal in the cone-opponent plane if figure segregation thresholds behave similarly to color discrimination thresholds, because the ±j and ±g directions are symmetrical to the line from the gray background color and the background distribution center in the cone-opponent space as shown in Fig. 9(a). If this is the case, the reciprocals of the shift distances of 1 OSA unit in the ±j and ±g directions on the cone-opponent plane should be proportional to the thresholds in the OSA-UCS.

Figure 9(b) shows the reciprocals of the distances of 2 OSA-units in the ±j and ±g directions in the cone-opponent plane for the three background distributions. The position of the background color distribution is shown along the horizontal axis, and the bar patterns indicate the directions. The relationship between the distance reciprocals and the directions looks similar to the results for subjects TN and TS in Experiment 2 (Fig. 8). Even the asymmetry between the +j and −j data can be traced to a corresponding asymmetry in the mapping between the two spaces.

Figure 10 shows the relationship between the distance reciprocals and the thresholds of Experiment 2. The abscissa represents the distance reciprocal, and the ordinate represents the threshold. The correlation coefficients for subjects TN and TS are 0.73 and 0.82, respectively. This suggests that the distance in the cone-opponent space influenced figure segregation thresholds even with OSA-UCS distance held constant and that the chromatic mechanism similar to those for color discrimination or detection might mediate figure segregation. The amplitudes of the threshold variations by shift directions, however, are smaller than expected from Fig. 9(b). This might be due to the large influence of the overlapping portion of the test and background color distributions on the thresholds as described in Experiment 1. The correlation coefficient for subject DK, however, is −0.50, indicating that his results were not explained by the distance in the cone-opponent space. One possible reason for this negative correlation is that the cone-opponent space used for the analysis was normalized by subject TN's detection thresholds. Subject DK's results might have a positive correlation if the results were analyzed in the cone-opponent space normalized by his thresholds. In addition, his results might have been more strongly affected by the overlap in color distributions, which may cause thresholds for the different shift directions to be similar to one another, than the other subjects' results, though there is no result supporting this explanation.

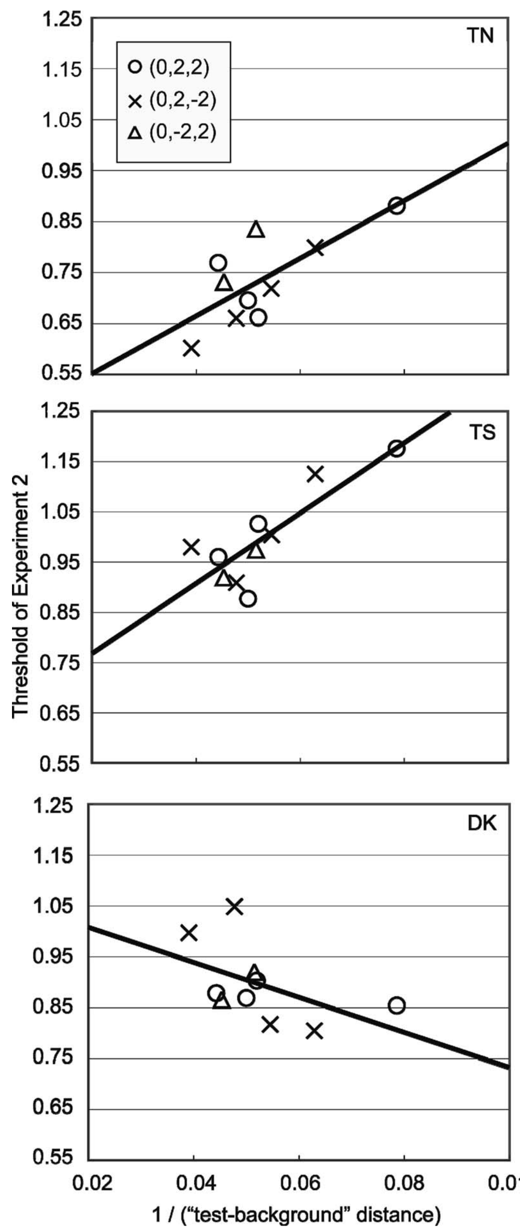


Fig. 10. Thresholds of Experiment 2 as functions of the reciprocal of shift distances of 2 OSA units in the cone-opponent plane. Symbols represent the color distribution positions. The straight line is the result of a linear regression analysis by the least-squares method. Each panel corresponds to one subject's result.

If the segregation thresholds correlate with the distances in the cone-opponent space, the distance in the cone-opponent space should help to explain the threshold differences due to the color distribution positions and color directions. We derived a modified color-difference measure, d_o', that incorporated both the OSA-UCS distance and the cone-opponent space distance in each case:

$$d_o' = d_o \frac{\alpha(d_c - d_{cm}) + d_{cm}}{d_{cm}},$$

where d_o is 2.0, the original distance in the OSA-UCS; d_c is the distance in the cone-opponent space corresponding to d_o; d_{cm} is the mean of the d_c values for all positions and directions; and α is a free parameter common to all positions and directions. $\alpha=0$ means no modification of an OSA distance, and $\alpha=1$ means that d_o' is completely proportional to d_c. The constant α was calculated so that the coefficient of variation of the segregation thresholds defined in terms of d_o' was minimized for each subject. The threshold values of d_o' for subject TS are shown in Fig. 11. The threshold variation in Fig. 11 appears to be less than that seen in Fig. 8. The calculated α values are 0.44, 0.37, and −0.27; the coefficients of variation of the modified

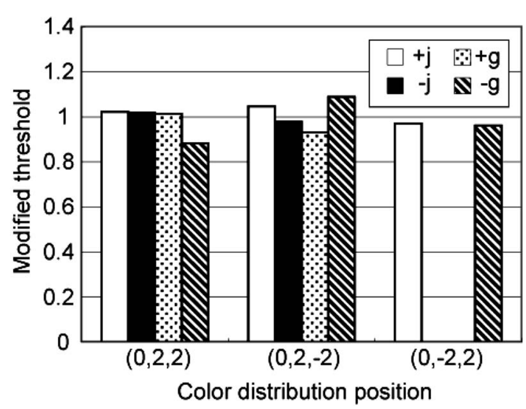


Fig. 11. Threshold values of d_o', a modified color-difference measure, for subject TS in Experiment 2 (see text).

thresholds are 0.082, 0.060, and 0.070; and those of the original thresholds are 0.118, 0.095, and 0.085 for subjects TN, TS, and DK, respectively: the variations of the modified thresholds are less than those of the original thresholds (note that α is negative only for subject DK as expected from the negative correlation in Fig. 10). That is, the distance in the cone-opponent space helps to reduce variations of the segregation thresholds as expected.

Though it was suggested that the distance in the OSA-UCS could help to explain the variation of the figure segregation thresholds to some extent, could the thresholds be simply equal in the cone-opponent space? Figure 12 shows the thresholds of subject TS defined by distance in the cone-opponent space. As is clear from Fig. 12, the thresholds in the cone-opponent space cannot be equal. Also, the other subjects' thresholds cannot be equal in the cone-opponent space. Our results suggest that the distance in the cone-opponent space influenced the figure segregation thresholds but cannot explain all of the threshold differences between the shift directions and positions. We used the cone-opponent space normalized by the detection thresholds of subject TN for analysis of the other subjects' results. This may cause variations of figure segregation thresholds plotted in the cone-opponent space. However, we believe that the main cause of the threshold variation is not that a subject's results were not analyzed in the space normalized by each subject's detection threshold, because subject TN's thresholds also had variations even in the space normalized by his own thresholds. The other factors, such as the effect of distribution overlapping, which should make the thresholds in different directions in the OSA-UCS equal (this leads to the threshold difference in the cone-opponent space), might reduce the correlation between the thresholds and the reciprocal distance in the cone-opponent space.

The position (L,j,g)=(0,2,2) corresponds to the background color distribution position of Experiment 1 except for lightness. The differences in the threshold across the directions for the position (L,j,g)=(0,2,2) are not the same as those of radius 2.0 in Experiment 1, while the distances in the cone-opponent space corresponding to a single OSA unit in different directions are also different between the experiments due to the lightness difference. The correlation coefficient between the thresholds of Experiment 1 and the distance reciprocals in the cone-opponent space is 0.25 for TN, −0.03 for TS, and −0.46 for DK: the correlation coefficients are generally lower than those in Experiment 2. There are many differences between Experiments 1 and 2, which could yield the observed difference in the correlation coefficients. For example, the use of only one background color distribution in Experiment 1 may reduce the correlation if the correlation happens to be small for the background distribution used. In that case, the correlation may increase when the thresholds are measured for many background color distributions. In addition, the procedure used in Experiment 1 could generate stronger chromatic and contrast adaptation than that in Experiment 2, since the background color distribution was always identical in Experiment 1. It is also possible that the difference in the stimulus size and the subject's task between Experiment 1 and 2 caused these differences. However, we cannot conclude which factor yielded the correlation difference between Experiments 1 and 2 from our results. More controlled experiments would be necessary to discern these possibilities.

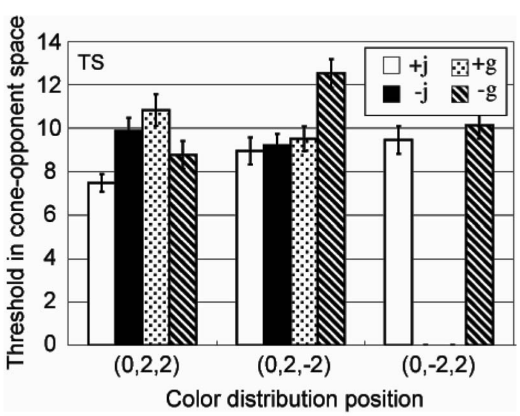


Fig. 12. Thresholds of subject TS in Experiment 2 expressed as distances in the cone-opponent plane.

4. EXPERIMENT 3

Yokoi and Uchikawa [18] reported that heterochromatic stimuli could be segregated on the basis of basic color categories in a color search task. This means that categorical color difference could be one of the possible chromatic factors that affect figure segregation. In Experiment 3, we measured perceived color categories of the colors used in the stimulus of Experiment 2 with the categorical color naming method [19,20] in order to examine the relationship between the color categories and the thresholds of figure segregation measured in Experiment 2.

A. Stimulus

The stimulus was an 8 deg × 8 deg square composed of 30 × 30 pieces. The test region was a central 8 deg × 8 deg square region of 30 × 30 pieces, and the remaining area constituted the background region.

B. Procedure

We used the same three color distributions of the background region as in Experiment 2. The color of each piece in the background region was selected from one of those color distributions. All test pieces had an identical color in a given trial. For each background color distribution, the test color was selected from either the background color distribution or the test color distributions whose shift distance in four (±j, ±g) directions was 1 OSA color-difference unit used in Experiment 2. The number of colors we used as test colors was 500, the total number of colors included in the three background color distributions and ten test color distributions [shift directions ±j and ±g for the background distributions (L,j,g)=(0,2,2) and (0,2,−2), and +j and −g for the background color distribution (0,2,−2)] in Experiment 2.

We used the category-rating-estimation method [21] to measure the categorical color appearance. The subject named a test color using a maximum of three basic color categories [22] based on which color category appeared most similar to the test color. The observation time was not restricted. Three trials were repeated for a test color.

C. Subject

The same three subjects participated in Experiment 3.

D. Results

A color category was given 6 points if it was the only category used by the subject, 4 or 2 points if it was the first or second category when the subject used two categories, and 3, 2, or 1 point if it was the first, second, or third category when the subject used three categories. The total number of points for a test color was 18, since each test color was named three times. We defined a category transition index (CTI) as shown in Eq. (2) for each shift direction and each background color distribution to examine to what extent perceived color category changes between the background and test color distributions. Here, w_{bi} is the ratio of a category's points to the total category points calculated for all colors in the background color distribution, and w_{ti} is the total category points for each test color distribution. A large CTI means that the difference of category assignment between samples in the background and test distributions is large. We compared CTI with the thresholds measured in Experiment 2. If color category contributes to figure segregation by color, then the correlation between CTI and the threshold should be negative:

$$CTI = \sum_{i=1}^{11} (w_{bi} - w_{ti})^2. \tag{2}$$

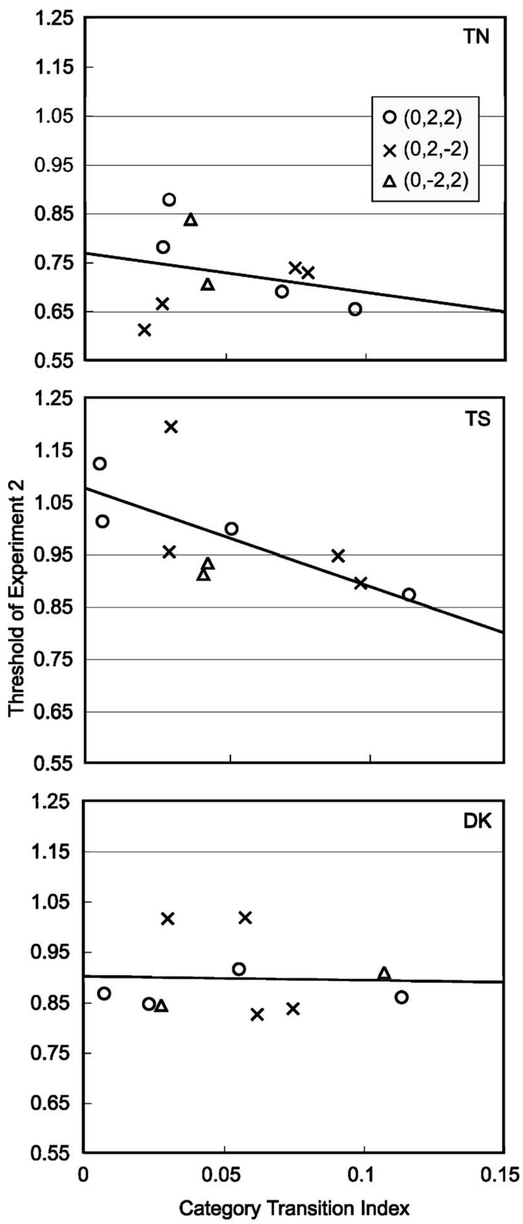


Fig. 13. Thresholds of Experiment 2 as functions of CTI (see text) calculated from the results of Experiment 3. Symbols represent the color distribution positions. The straight line is a linear regression solution using the least-squares method. Each panel corresponds to one subject's result.

Figure 13 shows the thresholds in Experiment 2 as a function of the CTI. Each symbol corresponds to the results of each background color distribution, and the different plots for each symbol are the results of different test shift directions from the background color distribution. The solid line is a linear regression line fitted using the least-squares method. The regression lines show negative correlation coefficients (correlation coefficients for the subjects TN, DK, and TS are −0.23, −0.07, and −0.66, respectively) for all subjects' results. This could suggest that color category changes may serve as a cue for figure segregation, but the correlations are not statistically significant for any of the subjects. Moreover, the results for subject DK show almost zero correlation between the CTI and threshold. It seems that there are individual differences in terms of how categorical color perception influences figure segregation.

5. GENERAL DISCUSSION

We first investigated whether the performance of figure segregation by color distribution difference can be well described in the OSA-UCS, a uniform color space based on color difference, and then investigated whether factors other than the color appearance difference could affect figure segregation. In Experiments 1 and 2, we measured the color-difference thresholds in the OSA-UCS to achieve figure segregation. The results showed that the thresholds varied slightly across directions despite using stimuli chosen from the OSA-UCS. This suggests that the difference of color appearance is not the only determining factor in figure segregation performance but that other factors should be involved as well. If the OSA-UCS is truly uniform for color appearance, our results also may suggest that the uniformity of a color space is different for different tasks such as color appearance and figure segregation. We also showed in Experiment 1 that threshold differences between radius conditions depended on the volume ratio of the nonoverlapping color distribution portion. The factor with the greatest effect on the segregation threshold was not color difference but volume ratio. Thus the influence of other chromatic factors that could induce threshold differences among shift directions might be diminished by the volume ratio, just as external noise generally obscures the influence of variations in internal noise.

Next we focused on the distance in the cone-opponent space as one of the possible parameters affecting the figure segregation thresholds and analyzed the thresholds of Experiment 2 in the cone-opponent space. The results show that the figure segregation thresholds correlate significantly with the reciprocals of the distances in the cone-opponent space corresponding to an OSA unit distance in different directions in the OSA-UCS, suggesting that the distance in the cone-opponent space could influence thresholds of figure segregation by color. There should be many processes between the cone-opponent mechanism and the higher-level mechanism mediating color appearance. Therefore, considering the effect of distance in the cone-opponent space on figure segregation thresholds, our results may suggest that figure segregation is influenced by mechanisms at sites near the cone-opponent mechanism such as multiple channels underlying the color discrimination [3,4]. However, our results do not clarify the precise characteristics of the figure segregation mechanism in the cone-opponent space such as the number of channels tuned to different directions in the color space and their tuning widths. The difference of the chromatic properties between color discrimination and figure segregation is also still unclear. To investigate these characteristics, experiments in which the stimulus was defined in the cone-opponent space will be necessary.

In addition, we examined whether categorical color perception could influence figure segregation in Experiment 3. In the results, the CTI—an index of color category change between the test and background distributions—only weakly correlates with the figure segregation thresholds, suggesting that the effect of color category on figure segregation is not strong. Yokoi and Uchikawa [18] found that search time for a target color increased more when the color category of the target was the same as the color of most distractors than when the color categories of test and distractor differed. This indicates that heterochromatic stimuli can be segregated by categorical color perception. Their target was a color in a basic color category, whereas our multicolored target figure was composed of pieces whose colors belong to many basic categories. The effect of categorical color perception might be weak when the task is the integration of many colors with different color categories.

The uniformity of the OSA-UCS is an important consideration in describing the relationship between figure segregation and color difference in our results. One of the possible factors disrupting the uniformity is the interpolation used to create small color differences in our experiments. Because the linear interpolation we used may not be the best interpolation method, other interpolation methods such as a spline interpolation might improve the uniformity of small color difference to a certain degree. We checked how much the spline interpolation changed the positions of interpolated colors in the color space spanned by the CIE1931 chromatic diagram and the luminance axis. In the results, the difference between colors interpolated with those two interpolation methods are within 5% against the difference corresponding to 2 OSA units in the range we used. Accordingly, the use of other interpolation methods might not greatly affect the results, although they might slightly improve the precision of interpolation and the uniformity of the OSA-UCS. In addition, the OSA-UCS might not be originally uniform. The OSA-UCS was built so that Euclidean distances in the space corresponded to differences in color appearance perceived by humans. Though Indow [23] showed that the uniformity of the OSA-UCS is reasonably good, the perceived color difference of an OSA sample pair could be different between subjects. The nonuniformity of OSA-UCS must exist, and it must affect figure segregation thresholds more or less. However, we believe that the nonuniformity is not the only cause of threshold variation but that other factors such as distance in the cone-opponent space should have a large effect on threshold variation, because this same factor influenced the thresholds in a similar manner for multiple subjects. To confirm the uniformity for each subject, separate experiments must be run for each subject to check whether the OSA-UCS is uniform in terms of color appearance for each subject. After that, the relationship between figure segregation and color appearance can be discussed more persuasively.

There could be other possible chromatic factors affecting figure segregation thresholds. One of them is the contrast adaptation produced by repeated presentations of stimuli with the same background [6,7]. The threshold dependencies on color-shift directions were different between Experiment 1 and 2, although their background colors were almost identical except for lightness. The background color distributions used in Experiment 2 could have caused weaker contrast adaptation than in Experiment 1. We expected the thresholds to increase in the direction from the gray to the greenish background distribution because of contrast adaptation [6,7]. However, considering that the directions of $\pm$j, $\pm$g in the isoluminant cone-opponent plane are symmetrical about the line from the gray to the distribution center $(L,j,g)=(0,2,2)$ [Fig. 9(a)], contrast adaptation should have a similar effect on the results for the $\pm$j, $\pm$g directions. Thus contrast adaptation might not be able to explain the difference between the results of Experiments 1 and 2. The stronger chromatic adaptation in Experiment 1 could also influence the thresholds. Krauskopf and Gegenfurtner [14] reported that the color discrimination thresholds from the adaptation color along the $S-(L+M)$ direction were proportional to the S-cone excitation of the adaptation color, while the thresholds along the L–M direction are independent of L- and M-cone excitations for the adaptation color. Therefore we expected lower thresholds for the $\pm$j directions in Experiment 1. It was not evident, however, that the threshold differences between Experiments 1 and 2 obeyed this expectation. We speculate that the difference between the results of Experiments 1 and 2 might be caused by the difference in the correspondence between the OSA-UCS and cone-opponent space due to the difference between background color distributions in Experiments 1 and 2.

The generality of our findings on chromatic properties of the figure segregation mechanism may be limited. For example, the test regions we used had random shapes, which had different spatial-frequency components. Thus the results for different shapes might show different tendencies reflecting the chromatic properties for the respective components. It is necessary to examine the effects of spatial-frequency and shape difference on the chromatic characteristics of figure segregation.

In conclusion, though figure segregation is determined primarily by the nonoverlapping volume ratio of the color distributions when the test and background color distributions overlap, the figure segregation thresholds are different between shift directions. This suggests that figure segregation may not be well explained by differences in color appearance. In addition, the distances in the cone-opponent space could help account for the threshold differences, suggesting that a mechanism whose chromatic properties are well described in the cone-opponent space may be involved in figure segregation. Our experiments also suggest that a color category change might only weakly influence figure segregation.

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