Characteristics of color memory for natural scenes

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To study the characteristics of color memory for natural images, a memory-identification task was performed with differing color contrasts; three of the contrasts were defined by chromatic and luminance components of the image, and the others were defined with respect to the categorical colors. After observing a series of pictures successively, subjects identified the pictures using a confidence rating. Detection of increased contrasts tended to be harder than detection of decreased contrasts, suggesting that the chromaticness of pictures is enhanced in memory. Detecting changes within each color category was more difficult than across the categories. A multiple mechanism that processes color differences and categorical colors is briefly considered.

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1. INTRODUCTION

In our daily lives we use the memory of colors as one of the cues for seeking and identifying objects. In spite of its importance, the characteristics of color in a memorized image are incompletely understood, particularly for natural scenes. The aim of this study was to elucidate the nature of color memory in such complex colored images.

There has been a considerable amount of research into the importance of color in memory.[1–8] Some reports suggested that hue was retained correctly in memory even though saturation was increased.[1–4] Newhall *et al.*[2] compared the performance for successive matching and for simultaneous matching. They reported that successive memory matching yielded higher purity and luminance. Uchikawa and Ikeda[3] reported that discrimination between colors under successive comparison was half as good as that under simultaneous comparison. In research dealing specifically with memory color,[9–16] which is memory of color associated with a particular object, it was reported that the memorized color for familiar objects was more saturated than the colors of the real objects.

The categorical characteristics of color have also been considered as a basis of color perception and color memory.[17–19] In Uchikawa and Shinoda's experiment,[19] subjects tended to misidentify two different colors that happened to belong to the same color category and to distinguish two colors that were in different color categories. This property of categorical color may have a neurophysiological basis.[20]

It has been traditional to use a single-color stimulus to investigate the characteristics of color in memory in order to reduce the possibility of confounding effects caused by chromatic and spatial context in a scene, for instance, chromatic contrast and chromatic assimilation. However, this approach is not suitable for investigating the nature of color in memory for complex scenes, where there is a natural juxtaposition of multiple colored surfaces. There have been some studies of visual memory with complex pictures.[21–23] Gegenfurtner[22] and Wichmann *et al.*[23] reported that subjects' performance for color pictures in a memory-identification task was superior to that for black-and-white pictures. They suggested that color information could be useful for recognizing pictures. What remains unclear, however, is how color memory and categorical color perception influence the visual memory of colored scenes.

In the present study, we performed a memory-identification task for a variety of natural images with color contrasts as variables. The visual information included in a natural scene can be divided into chromatic and luminance components. To investigate how each of them may be influenced by visual memory, we manipulated chromatic and luminance contrasts, independently and together as variables, in experiment 1. In experiment 2 we defined three other kinds of color contrast to address the effects of categorical color perception. In experiment 3 we used simultaneous comparison to test subjects' performance of image-identification without memory. The results of experiment 1 show that subjects tended to misidentify the pictures as being the same as the memorized pictures in spite of the contrast of the pictures being higher than when they were memorized. This suggests that the chromaticness of a picture might be enhanced in visual memory. In experiment 2, subjects' performance was better with color manipulations in which the colors in an image were translated to color categories different from the original color categories than when the colors were within the same color categories. From the results of experiment 3, we were able to show that the effects found in the memory-identification task were indeed attributable to visual memory. As it was difficult to explain all of these findings by a single mechanism, we therefore speculated that visual memory for colored scenes involves multiple mechanisms based on categorical color perception and color differencing.

2. METHODS

A. Apparatus

The stimuli were presented on a 20-in. color CRT display (Sony Corp., GDM-2000TC, Japan) with a resolution of

600×400 pixels, which was controlled by a personal computer (Apple Computer, Power Macintosh 7600/132, U.S.A.)[24] with a full-color video board (ATI Technologies Inc., Xclaim VR 4Mb, Canada). The intensities of the phosphors of the CRT were calibrated with a spectroradiometer (Topcon, SR-1, Japan) to obtain the nonlinear relationship between digital values and luminance with each gun. The 1931 CIE (x, y) chromaticity coordinates for the R, G, B phosphors were (0.618, 0.347), (0.276, 0.604), and (0.152, 0.061), respectively. The homogeneity in luminance across the display was achieved; errors in the 1931 CIE (x, y, Y) coordinates for a simulated-color patch were <0.005 in (x, y) and $\leq \pm 5\%$ in Y. The display was viewed in a darkened booth. Viewing distance was 125 cm, at which the stimulus subtended 15×10 deg of visual angle.

B. Stimuli

The stimuli were pictures of natural scenes. These pictures were obtained from color photographic packages, whose color resolution was not less than 16 bits, that is, 65,500 colors. The experimenter selected pictures in advance so that they included various colors. Monochromatic images (e.g., images including only desert or sea), and artificial images (e.g., defocused or retouched images) were not used. Some examples are shown in Fig. 1. We did not categorize the content of the pictures. Gegenfurtner[22] and Wichmann *et al.*[23] used natural images and clustered them into four categories (green landscapes, flowers, rock formations, and man-made objects) in a memory-identification task. They reported that the performance in the identification was equally good for all the categories (almost 75% correct or higher). This suggests that the difference in the image contents would not affect the image identification. In the present experiments, such an effect was also minimized by using a variety of pictures. The pictures were shown only once to each subject during an experiment. In total, more than 5000 pictures were used in all of the experiments. The average luminance of the pictures was 18.9 cd/m^2, and the averaged chromaticity coordinates were (0.313, 0.329) in the 1931 CIE (x, y) coordinates [corresponding to (0.198, 0.468) in the 1976 CIE (u', v') coordinates].

We used chromatic, luminance, chromatic and luminance, and concentrated contrasts as the variables (the details of each definition are given in the following sections). These variables were calculated in a color space defined by the luminance axis and the 1976 CIE (u', v') uniform color space. The original distribution of chromaticity and luminance in each image was defined as 100% contrast, that is, the contrast value of the original image without any manipulation.[25] The contrast value of an experimental stimulus was calculated from the distance of chromaticities of each pixel in the 1976 CIE (u', v') color space. The ratio of distances is referred to as the index K, defined as $\Delta D/D_{\max}$, where $D_{\max}$ is the maximum distance from each pixel's chromaticity, luminance, or both to the origin defined in each contrast, and ΔD is obtained by manipulation of $D_{\max}$. The contrast is defined as $K \times 100\,[\%]$. Manipulations of the contrast values were achieved by changing the index value, that is, by manipulating ΔD.

1. *Chromatic Contrast*

The chromatic index was defined by the distances between the chromaticities of all pixels in a picture and the D65 white point W (0.198, 0.468) [Fig. 2(a)]. $C_{\max}$ is the maximum distance from W to the chromaticities of each pixel. The chromatic index K_{C} is defined as the ratio of $C_{\max}$ to ΔC; that is, $K_{\mathrm{C}} = \Delta C/C_{\max}$. The chromatic contrast is represented as $K_{\mathrm{C}} \times 100\,[\%]$. Changes in chromatic contrast were achieved by changing ΔC. The luminance value of each pixel was kept constant. An image with 0% chromatic contrast becomes a black-and-white image with the same pattern.

2. *Luminance Contrast*

The luminance index was defined for black-and-white images; chromaticity coordinates of all pixels in a picture were translated to D65 white. Luminance level of the pixels was kept constant. $L_{\max}$ is the maximum difference in luminance from each pixel to the averaged luminance $\mathrm{W_{AV}}$ [Fig. 2(b)]: The luminance index K_{L} is defined as the ratio of $L_{\max}$ to ΔL; that is, $K_{\mathrm{L}} = \Delta L/L_{\max}$. The luminance contrast is represented as $K_{\mathrm{L}} \times 100\,[\%]$. Changes in luminance contrast were achieved by changing ΔL.

3. *Chromatic–Luminance Contrast*

The chromatic-and-luminance index (CL index) was defined when both chromatic contrast and luminance contrast were changed together [Fig. 2(b)]. $CL_{\max}$ is the maximum distance from each chomaticity in color space to the averaged luminance with chromaticity coordinates the same as for D65 white. The CL index K_{CL} is defined as the ratio of $CL_{\max}$ to ΔCL; that is, $K_{\mathrm{CL}} = \Delta CL/CL_{\max}$. The chromatic contrast (CL contrast) is

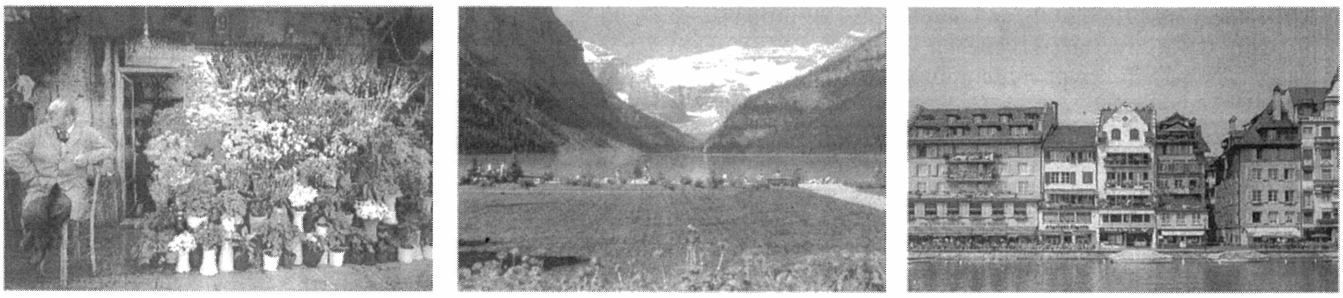


Fig. 1. Samples of natural scene pictures. These images have no change in color and luminance.

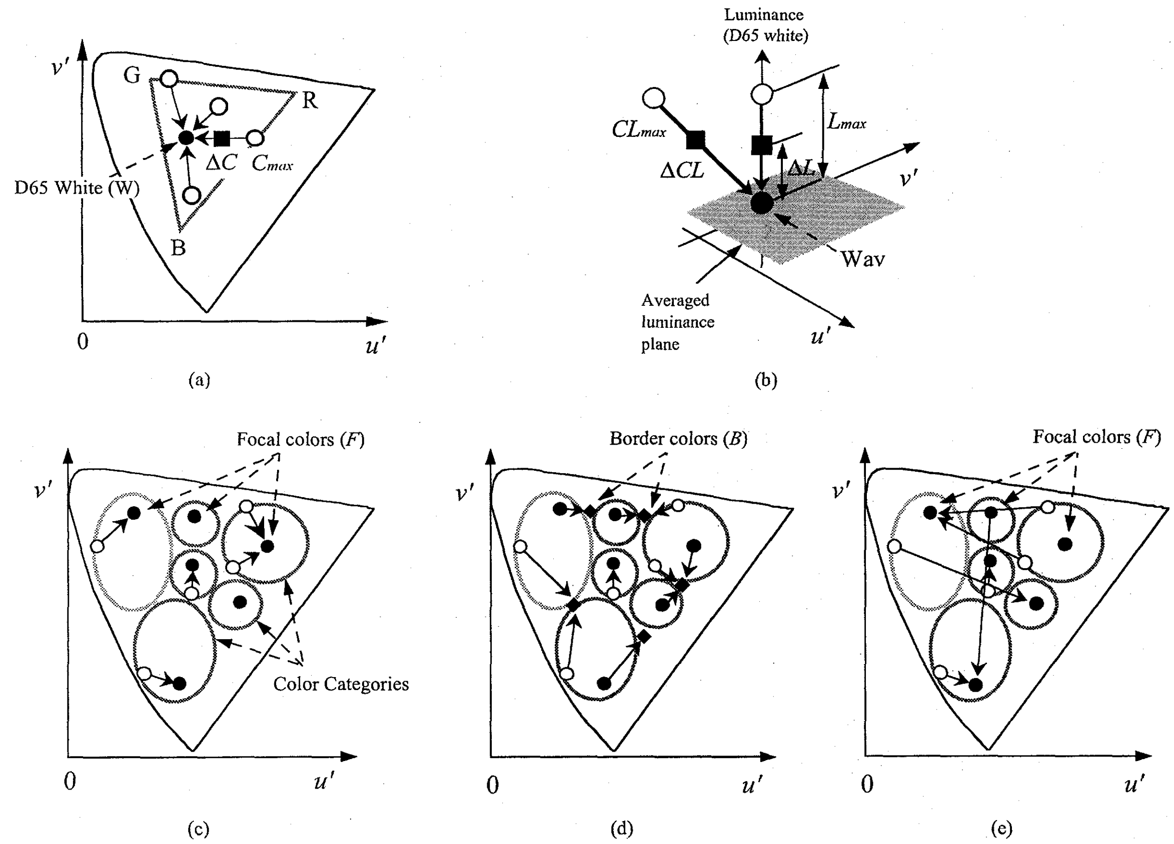


Fig. 2. Schematic explanation of definitions of the contrasts: (a) chromatic contrast, (b) luminance contrast and CL contrast, (c) focal concentrated contrast, (d) border concentrated contrast, and (e) nonborder concentrated contrast. For the luminance contrast, the chromaticities of all pixels were transformed to D65 white chromaticity to make a black-and-white image. For concentrated contrasts, categories in the middle of the diagram are the achromatic categories; the concentrations in the achromatic categories are invariant among the three kinds of concentrated contrasts.

represented as $K_{\mathrm{CL}} \times 100$ [%]. Changes in chromatic–luminance contrast were achieved by changing ΔCL.

We used the contrast values of 0%, 25%, 50%, 75%, and 100%. Since the screen would appear uniform gray with luminance contrast and CL contrast of 0%, we did not use this value. We therefore used the values of 10%, 25%, 50%, 75%, and 100% for luminance contrast and CL contrast. A picture with chromatic contrasts and CL contrast of 100% means that it underwent no change of chromaticity and luminance, that is, it coincided with the original picture; a picture of 100% luminance contrast had the same luminance values as the original picture. All combinations of these values were tested at each contrast: 25 (5×5) combinations multiplied by 3 conditions.

C. Concentrated Contrasts

Concentrated contrasts were defined with respected to the distribution of each of the 11 color categories. These color categories were obtained at nine luminance levels in a preliminary experiment (see Appendix A). The luminance distribution of an original picture was also clustered in the nine levels. A picture without any color manipulation is defined as a 100% concentrated-contrast picture. There was no significant difference in appearance with and without the luminance clustering. We used the following three kinds of concentrated color contrast, distinguished by the points at which the chromaticities in each color category were clustered [shown in Figs. 2(c)–2(e)].

1. Concentration toward Focal Colors

All colors in each color category were concentrated toward a focal color of that category, shown in Fig. 2(c); $F_{\max}$ is the maximum distance from the chromaticity (C) of each color in the color category to its focal color (F). ΔF is obtained by manipulation of $F_{\max}$. The index K_{F} of concentration toward focal colors was defined as $K_{\mathrm{F}} = \Delta F / F_{\max}$. The focal concentrated contrast is represented as $K_{\mathrm{F}} \times 100$ [%]. Changes in the contrast were achieved by changing ΔF. We refer to this manipulation as focal contrast.

2. Concentration toward Border Colors between Categories

We chose border colors (B) between each pair of color categories, except for achromatic color categories (black, white, gray), as shown in Fig. 2(d). For the achromatic categories, we chose the focal colors (F) as B. The number of B was the same as that of F at each luminance level. B has saturation similar to that of F. Colors were concentrated into the nearest B in color space. This concentration was not dependent on the basic color categories, and colors did not go beyond their original categories. $B_{\max}$ is the distance from a chromaticity (C) to a border color (B); ΔB is obtained by manipulation of $B_{\max}$. The index K_{B} for concentrations toward border colors was defined as $K_{\mathrm{B}} = \Delta B/B_{\max}$. The contrast is represented as $K_{\mathrm{B}} \times 100$ [%]. Changes in the concentrated contrast were achieved by changing ΔB. We refer to this manipulation as border contrast.

3. Concentration toward Focal Colors of Different Color Categories

The colors included in a color category were concentrated toward a focal color of a nonadjacent category, as shown in Fig. 2(e). The combinations of concentrations were: red to brown, orange to green, brown to green, yellow to blue, green to purple, blue to pink, purple to red, and pink to orange. The colors in the achromatic color categories (black, white, and gray) were concentrated at the focal colors of each category as well as in focal contrast and border contrast.

However, it is possible for one of the color pairs of the combinations described above to disappear at some luminance levels (Fig. 8 below, in Appendix A). Then the colors were concentrated at the nearest focal color. $N_{\max}$ is the distance from a chromaticity (C) of each pixel in a picture to a focal color (N) of the category that is different from the category to which C happened to belong. ΔN is obtained by manipulation of $N_{\max}$. The index K_{N} for concentrations toward focal colors of different color categories is defined as $K_{\mathrm{N}} = \Delta N/N_{\max}$. The contrast is represented as $K_{\mathrm{N}} \times 100$ [%]. Changes in the contrast were achieved by changing ΔN. We represent this manipulation as nonborder contrast below.

A picture with 100% of any of the three concentrated contrasts is one in which there is no change of chromaticity. A picture consisted of the nine luminance levels. When the colors in a picture were concentrated, that is, when the picture had a lower concentrated-contrast value, the number of colors used to present the picture decreased. A 0% concentrated contrast means that the picture was represented only by colors F, B, and N of each contrast at each luminance level.

We used the contrast values 0%, 25%, 50%, 75%, and 100% for focal contrast and border contrast and the values of 0%, 50%, and 100% for nonborder contrast in the memory-identification experiment. All combinations of these values were tested at each contrast: 25 (5×5) for focal and border contrasts and 9 (3×3) for nonborder contrast combinations.

D. Experimental Conditions and Procedure

1. Experiments 1 and 2: Memory Identification

The experiment had two phases: a memory phase and a test phase. In the memory phase, after adapting to the D65 white display on the CRT at 30 cd/m^2 for 3 min, the subject viewed 20 successively presented pictures. All 20 pictures were different in pattern and contrast; the duration of each picture was 2 s, and the interstimulus interval was 1 s. Each picture differed in chromatic contrast, luminance contrast, CL contrast, or concentrated contrast. The pictures were presented in random order. A 30-s blank interval followed. During the interval, the subject remained in the booth[21,26–28]; uniform D65 white (30 cd/m^2) was displayed on the CRT screen. Next, in the test phase, the subject viewed 40 successively presented pictures and judged for each picture whether the picture had been seen in the memory phase by giving a confidence rating: *3* (certainly yes), *2* (probably yes), *1* (probably no), *0* (certainly no). The pictures in the test phase consisted of 20 of the memorized pictures and 20 new pictures. Half of the memorized pictures (10 pictures out of 20) had decreasing or increasing changes in chromatic contrast, luminance contrast, CL contrast, or one of concentrated contrasts altered within a session. The remaining half of the memorized pictures (10) were exactly the same (in spatial structure and colors) as those presented in the memory phase. The 20 new pictures also had contrast manipulation and were presented in random order. The different contrasts were almost equally included in each session (40 pictures). The number of trials for each combination of contrasts was at least 10.

The confidence rating was used in order to extract ambiguity in the judgment.[29] Subjects would respond "yes" when they could not find any color manipulations in the picture from in the memory phase. The subjects would respond "no" when they could find any changes in color of the pictures from in the memory phase, or when they observed the new pictures. Subjects were therefore instructed to pay attention to the color of a picture as well as to its pattern.

Changes in chromatic, luminance, and CL contrasts were varied within a series of sessions. Changes in the three concentrated contrasts (focal, border, and nonborder) were varied in a different series. Accordingly, these effects are discussed separately, in Section 3 (experiment 1) and Section 4 (experiment 2).

2. Experiment 3: Simultaneous Comparison

Two pictures were presented at the same time side by side on a CRT display. One of the pictures was the test picture and the other was the standard picture. These pictures were selected from the images used in the memory-identification experiments. An image was divided into three pieces. Then one of the three, which included the main feature of the original content, was chosen as a stimulus for this experiment. The constraint for the selection of the pictures (see Subsection 2.B) was also placed here. Each picture subtended 5×10 deg with a gap of 2 deg between pictures. Using the confidence rating, the subject had to judge whether the two pictures were the same. The pictures were presented until the subject responded.

For the chromatic, luminance, and CL contrasts, combinations of the contrast values of the test and the standard pictures were chosen from among the contrast values used in the memory-identification experiment: 0% (10% for luminance and CL contrast), 25%, 50%, 75%, and 100%. In addition, 12.5%, 37.5%, 62.5%, and 87.5% were used to estimate subjects' detection ability more precisely. For the concentrated contrasts, the combinations were paired with the contrast values of 0%, 25%, 50%, 75%, and 100%. Each combination was presented in random order and repeated at least ten times.

3. EXPERIMENT 1: CHROMATIC, LUMINANCE, AND CHROMATIC-AND-LUMINANCE CONTRASTS

A. Subjects

Subjects were YY (male, 31 yr), YI (female, 25 yr), TS (male, 24 yr), KM (male, 25 yr), and KS (female, 24 yr). All had normal color vision. They were aware of the purpose of the experiment.

B. Results

1. Weighted Response

Results are shown in terms of weighted response defined as follows:

$$\text{weighted response} = \frac{(2 \times n1) + (1 \times n2) - (1 \times n3) - (2 \times n4)}{N}, \tag{1}$$

where $n3$, $n2$, $n1$, $n0$ are the frequencies of the rating categories (*3*, certainly yes; *2*, probably yes; *1*, probably no; *0*, certainly no). N is the total population of responses. The weights were 2, 1, −1, −2 for each rating category of *3*, *2*, *1*, and *0*, respectively.

2. Results of Memory Identification

The results are shown in Fig. 3. Weighted responses were represented as a function of chromatic contrast, luminance contrast, and CL contrast of the pictures in the test phase. We use averaged values over subjects in the following estimates, as individual values were similar. The abscissa shows the contrasts in the test phase, and the ordinate shows the weighted response. Each symbol shows a different contrast in the memory phase. Error bars represent ±1 standard error. For the 50% contrast picture in the memory phase (open squares), the top and bot-

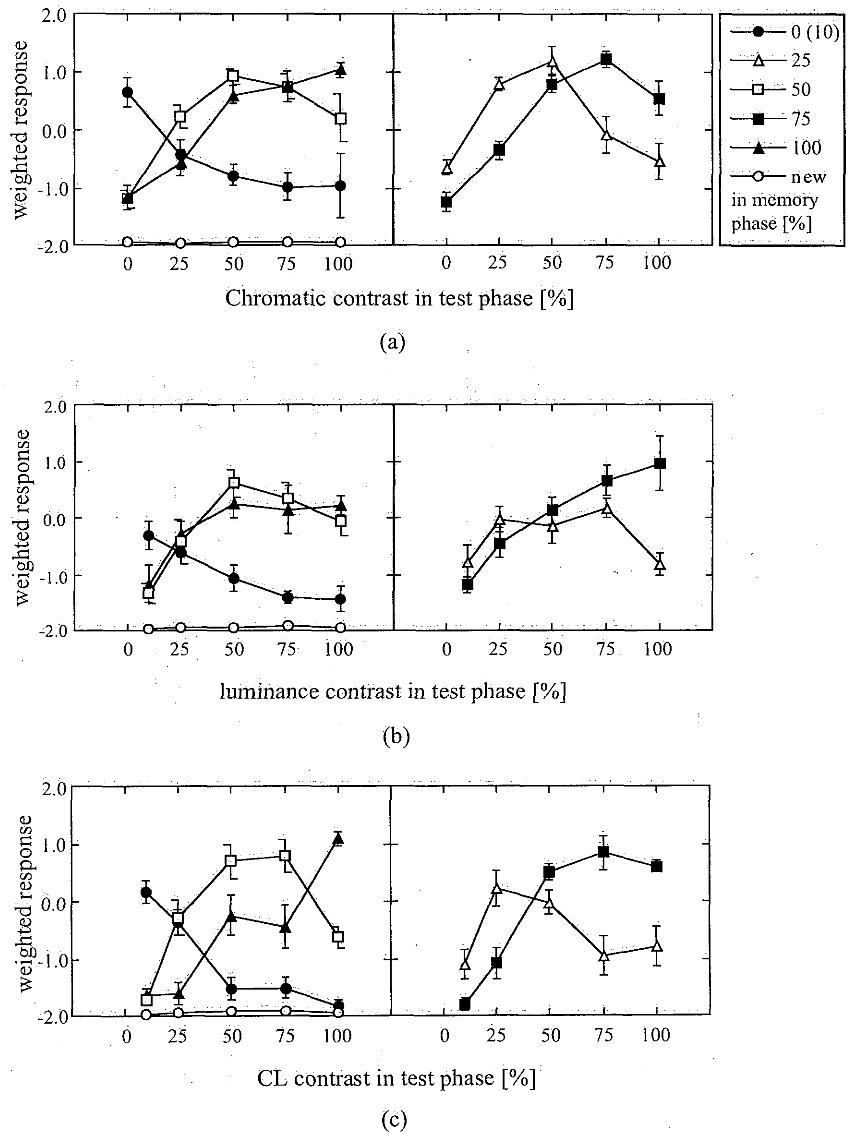


Fig. 3. Results for the memory-identification experiment (experiment 1) for (a) chromatic, (b) luminance, and (c) CL contrast. The abscissa shows the contrast values in the test phase; the ordinate shows the weighted response. The data were averaged over subjects. The left-hand panel of each figure shows the results of 0% (10% for luminance and CL contrast), 50%, and 100% contrast and the newly added picture; the right-hand panel shows results for 25% and 75% contrast. Error bars represent ±1 standard error.

tom of the error bar was shifted slightly to distinguish it from the others. If the standard error was smaller than the symbols, it was not shown. For clarity, the results for 0% (10% for luminance and CL contrast), 50%, 100% contrast pictures, and the newly added picture are shown in the left-hand panel of Fig. 3; the results for the 25% and 75% contrast pictures are shown in the right-hand panel.

We first analyze the results for the changes in chromatic contrast [Fig. 3(a)]. For 0% chromatic contrast in the memory phase (solid circles) the weighted response decreased along with the change of the contrasts from the "hit condition," in which the picture presented in the test phase was exactly the same as in the memory phase in both pattern and chromaticities. Only this curve has characteristics different from the others. Here, the weighted responses did not reach -2 (the minimum of the weighted responses) even though the difference in contrast value between phases was maximum (100%). This means that subjects tended to misjudge the 0% contrast picture to be colored despite it being black and white in the memory phase.

When subjects observed the 50% chromatic contrast picture in the memory phase (open squares), the weighted response for the 75% test picture was higher than the value for the 25% test picture despite the fact that the difference in the contrast value was 25% in both cases. Similar characteristics appeared for the 25% chromatic contrast in the memory phase (open triangles). For the 25% contrast in the memory phase, weighted responses reached a maximum at 50% contrast in the test phase, not at 25% at which the pictures in the test phase were exactly the same as in the memory phase; that is, the pictures did not have any manipulation between the two phases (the hit condition). From these results, it is clear that subjects tended to judge a picture with an increased chromatic contrast as being the same as that observed in the memory phase, which suggests that the chromatic contrast of a picture might be enhanced in visual memory. However, this effect was not obvious for the 75% contrast in the memory phase (solid squares), suggesting that the enhancement effect might have a limited range.

For the pictures with 100% chromatic contrast in the memory phase (solid triangles), the weighted response changed gradually with the changes in the chromatic contrast.

The effect of chromatic contrast in the memory phase, the effect of the contrast in the test phase, and the interaction were significant ($F_{4,64} \geqslant 10.3$, $F_{16,64} = 12.0$, $p < 0.001$). For 25% chromatic contrast in the memory phase, the difference in the weighted responses between incremental and decremental contrast from the hit condition was significant (Tukey's multiple comparison, $p = 0.05$).

Figure 3(b) shows the results of the memory-identification task for the change of luminance contrast. The profile of the curves is similar to those in Fig. 3(a). However, the overall levels of the weighted responses were closer to 0 than those for chromatic contrast. This suggests that the judgments for change in luminance contrast with black-and-white images are more ambiguous than for colored images. The hit responses for the 0% contrast picture are quite low. The enhancement effect on the contrast also appeared for the 50% contrast picture in the memory phase (open squares).

The effect of luminance contrast in the memory phase, the effect of contrast in the test phase, and their interaction were significant ($F_{4,64} \geqslant 16.7$, $F_{16,64} = 7.75$, $p < 0.001$). For 50% and 75% luminance contrasts in the memory phase, the differences from the hit condition between the weighted responses for incremental and decremental contrasts were significant (Tukey's multiple comparison, $p = 0.05$).

Figure 3(c) shows results for changes in CL contrasts. The profile of the curves is similar to those of chromatic contrast [Fig. 3(a)]. Subjects' performances were more sensitive than with luminance contrast [Fig. 3(b)]. This suggests that the chromatic components in the pictures function more significantly than the luminance components in the identification task. Results for the 25% and 50% CL contrast pictures are similar to the enhancement effect on chromatic contrast.

The effect of CL contrast in the memory phase, the effect of contrast in the test phase, and their interaction were significant ($F_{4,16} \geqslant 20.0$, $F_{16,64} = 26.2$, $p < 0.001$). For 75% CL contrast in the memory phase, the difference from the hit condition between the weighted responses for incremental and decremental contrast was significant (Tukey's multiple comparison, $p = 0.05$).

In each of these contrast changes, the weighted responses for the newly added pictures in the test phase (open circles) was almost -2, implying that subjects' judgments for these pictures were clearer than for the memorized pictures despite the variety of contrasts in the pictures.

4. EXPERIMENT 2: CONCENTRATED CONTRAST

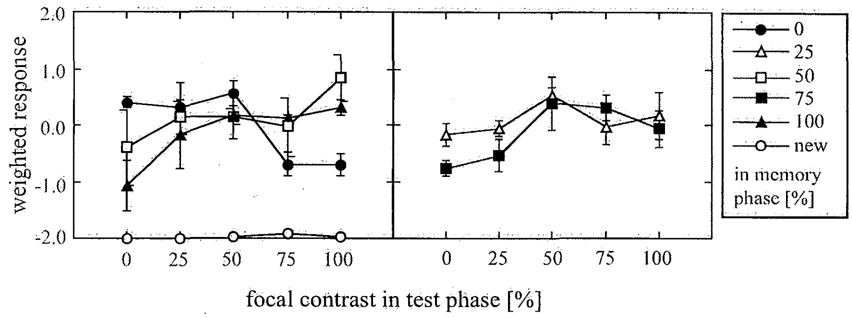
A. Subjects

Subjects were MS (male, 23 yr), YS (male, 23 yr), and KK (male, 24 yr). All had normal color vision and were aware of the purpose of this study.

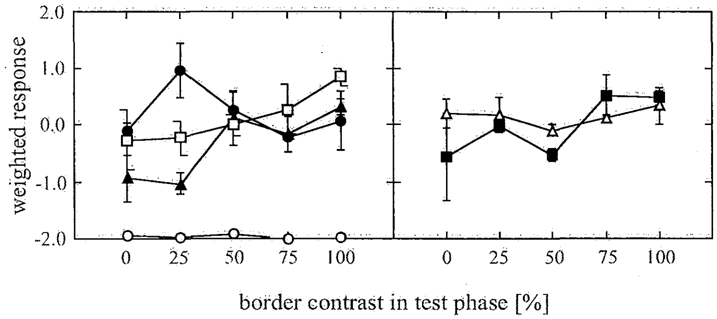
B. Results

To make color changes on the basis of the notion of categorical color, we first examined the distributions of each of the basic 11 colors in the 1976 CIE (u', v') color space. We performed a preliminary categorical-color-naming experiment. Colors to be presented in a picture were allocated nine luminance levels ($0 < L \leqslant 2$, $2 < L \leqslant 5$, $5 < L \leqslant 10$, $10 < L \leqslant 20$, $20 < L \leqslant 30$, $30 < L \leqslant 40$, $40 < L \leqslant 50$, $50 < L \leqslant 60$, $60 < L\,[\mathrm{cd/m^2}]$), and test stimuli were chosen from these levels (see Appendix A). The results shown in Fig. 8 below were used to define the three concentrated contrasts.

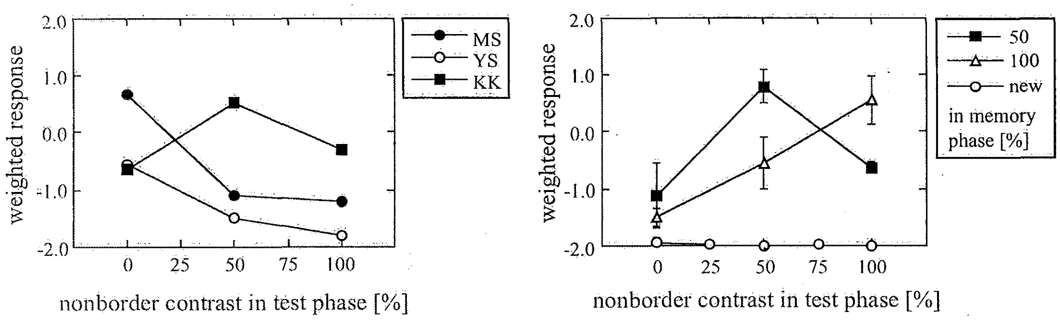
The results of the memory-identification experiment with concentrated contrasts are shown in Figs. 4(a), 4(b), and 4(c) for focal, border, and nonborder contrasts, respectively. The abscissa shows the focal [4(a)] and concentrated [4(b),4(c)] contrast in the test phase, and the ordinate shows the weighted response. Each symbol shows a concentrated contrast in the memory phase. Error bars represent ± 1 standard error.



(a)



(b)



(c)

Fig. 4. Results for memory identification for (a) focal, (b) border, and (c) nonborder contrasts. The abscissa shows concentrated contrast in the test phase; the ordinate shows the weighted response. In (a) and (b), the averaged results over subjects are shown; on the left, results for 0%, 50%, and 100% contrast in the memory phase and for the newly added picture; on the right, results for 25% and 75% contrast in the memory phase. In (c), on the left, each subject's results for 0% contrast in the memory phase; on the right, the averaged results for 50% and 100% contrast in the memory phase. Error bars represent ±1 standard error.

The results were plotted separately; those for the 0%, 50%, and 100% concentrated contrasts in the memory phase were plotted in the left-hand panels of Figs. 4(a) and 4(b), and those for the 25% and 75% contrasts were plotted in the right-hand panels of Figs. 4(a) and 4(b). For focal contrast and border contrast [Figs. 4(a) and 4(b), respectively], the average data across subjects were used because the characteristics of the subjects' responses were similar. Since, however, there was a serious difference between subjects for 0% nonborder contrast in the memory phase, the results for each subject are shown in Fig. 4(c).

First we analyzed the characteristics of the results for the changes in focal and border concentrated contrasts [Fig. 4(a) and 4(b)]. Although the whole of the response curves were nearly asymmetric at the 50% contrast in the test phase, the weighted responses of both conditions were flatter and closer to 0, even at hit conditions, than for chromatic and luminance contrasts (in experiment 1). This means that subjects' judgments were more ambiguous, suggesting that it might be difficult for subjects to detect changes in focal contrast and border contrast.

For 50% and 75% contrasts in the memory phase (open and solid squares, respectively), the weighted responses became higher with the increment of the contrast in the test phase. This effect might be similar to the enhancement effect shown in chromatic contrast (experiment 1); the possibility will be addressed in Section 6. For 100% focal and border contrasts in the memory phase (solid triangles), the weighted responses changed along the contrast values in the test phase (abscissa) with a shallow gradient.

The effect of the focal contrast in the test phase and the interaction between phases was significant ($F_{4,8} = 7.05$, $p < 0.01$, $F_{8,16} = 2.4$, $p = 0.02$). In border concentrated contrast, the effect of the contrast in both the memory phase and the test phase was significant ($F_{4,8} = 3.88$, $p = 0.05$, $F_{4,8} = 8.95$, $p < 0.01$). For 50% focal contrast in the memory phase, the difference between the weighted responses for incremental and decremental change in the contrast was significant (Tukey's multiple comparison, $p = 0.05$).

Next we analyze the results for nonborder contrast. For the 0% nonborder contrast in the memory phase, the weighted responses were significantly different between subjects [left-hand panel of Fig. 4(c)]. Subject KK's weighted responses for the hit condition was lower than those for the other contrasts. On the other hand, the responses of the other two subjects reached the maximum at the hit condition, although subject YS's sensitivity was lower. Judging from these results and subjects' introspection, the picture with the 0% value of nonborder concentrated contrast might include an attribute that made it difficult to recognize the picture. We have to remember that the manipulation of nonborder contrast might cause an unusual color appearance of objects in an image.

For the 50% and the 100% contrast pictures in the memory phase (solid squares and solid triangles, respectively), in the right-hand panel of Fig. 4(c), the characteristics of the curves were different from those of the focal contrast and border contrasts. Thus subjects could detect the change in concentrated contrast between phases. The weighted response reached maximums at the hit condition and changed along with the contrast in the test phase. Sharper curves suggest subjects' higher sensitivity.

For nonborder concentrated contrast, the interaction effect of contrast values between phases was significant ($F_{8,16} = 7.68$, $p = 0.01$). For 50% nonborder contrast in the memory phase, the difference in the performance between incremental and decremental changes was significant (Tukey's multiple comparison, $p = 0.05$).

As made clear in Section 2, for the focal and border contrasts, colors in a picture never translated beyond the color category to which the colors originally belonged. For the change in the nonborder contrast, however, the colors could be translated to different color categories when the contrast value was small. Sensitivity with changes in nonborder contrast was higher than with other contrasts. It is possible therefore that a categorical-color mechanism makes some contribution to detecting changes of concentrated contrasts. However, for the manipulation of the concentrated contrast used here, it was impossible to identify what contrast value was just on the category border. Alternatively, it is also possible that the detection of the change of concentrated contrasts might depend on color differences, not on color category. We consider this possibility in Section 6.

In these concentrated contrasts, subjects could clearly distinguish the newly added pictures (open circles), regardless of the kind of concentrated contrast and its value. This result is similar to that in experiment 1.

5. EXPERIMENT 3: SIMULTANEOUS COMPARISON

A. Subjects

Subjects YY, YI, TS, KM, and KS participated in this experiment to measure chromatic and luminance contrast. Subjects MS, YS, and KK, who participated in experiment 2, also took part in this experiment. All subjects had participated in experiment 1.

B. Results

Figures 5(a), 5(b), and 5(c) show the results for chromatic, luminance, and CL contrasts, respectively. Figures 6(a), 6(b) and 6(c) show the results for the three kinds of concentrated contrasts: focal, border, and nonborder, respectively. In all of the plots, the abscissa shows the contrasts of the test picture and the ordinate shows the weighted response. The weighted responses were aver-

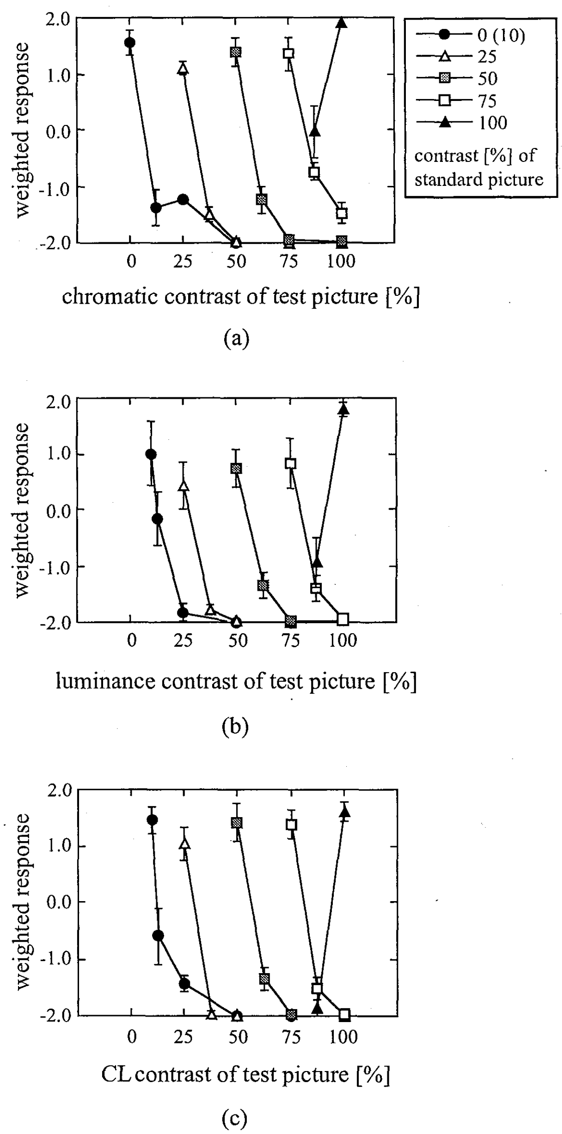


Fig. 5. Results for simultaneous comparison: (a) chromatic, (b) luminance, and (c) CL contrast. The abscissa shows the contrast of the standard picture; the ordinate shows the weighted response. The different symbols correspond to the contrasts of the test pictures. The data were averaged over subjects. Error bars represent ±1 standard error.

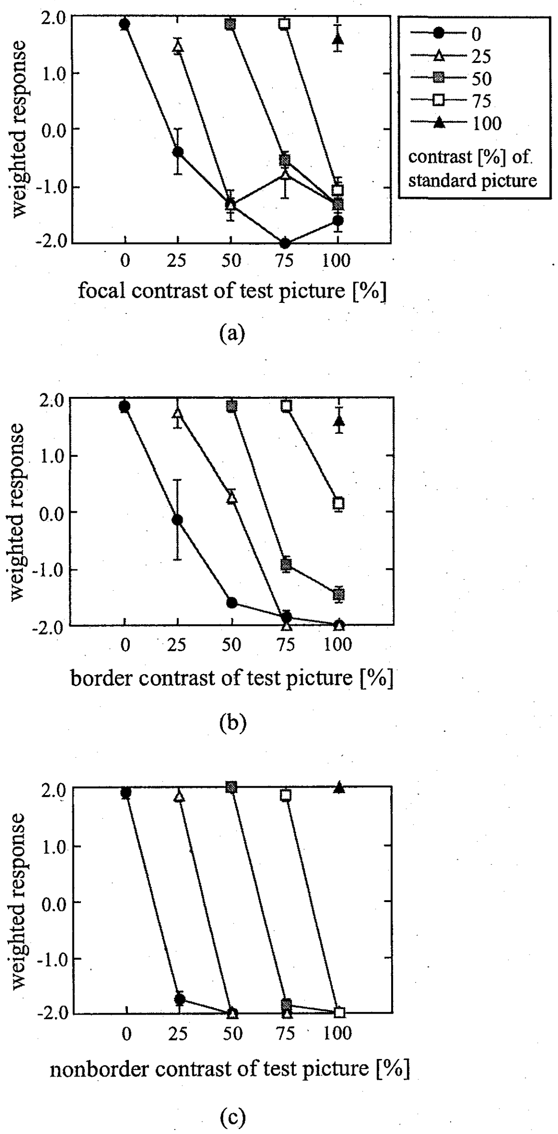


Fig. 6. Results for simultaneous comparison: (a) focal, (b) border, and (c) nonborder contrast. Details as in Fig. 5.

aged across subjects since their results were quite similar. Each symbol shows a different contrast of the standard picture. Error bars represent ±1 standard error. Subjects made judgments using the confidence-rating category *3* or *0* for most of the conditions.

In Fig. 5, for each kind of contrast—chromatic, luminance, and CL—subjects were able to make a clear judgment. For luminance contrast [Fig. 5(b)], however, the performance for the condition in which the standard picture was exactly the same as the test picture was lower than that for other contrasts. Ambiguity of judgments for the luminance contrast occurred even without memory. Performance in detecting the contrast difference was much higher than in memory identification (Fig. 3). When there was a 25% difference in contrast between the standard and the test pictures, subjects clearly detected it. That is, the interval of 25% contrast used in the memory-identification task was sufficiently large in chromatic, luminance, and CL contrasts.

For each contrast value of the standard pictures, the effect of the contrast values of the test pictures were significant for all three contrasts (it was worst for the 100% contrast picture, $F_{1,4} \geqslant 19.1$, $p < 0.001$).

For the concentrated contrasts in Fig. 6, subjects could also clearly detect the difference between the standard and the test pictures. However, we see that the gradients of the response curves for focal and border contrast are shallower than those in Fig. 5 (for instance, chromatic contrast), suggesting that the sensitivity for focal contrast and border contrast were lower. There might be confusion in subjects' judgments for changes in the same color categories even in the simultaneous comparison. We speculate that this might reflect a characteristic of categorical-color perception. Even in comparing the standard picture of 0% contrast with the test picture of 100% contrast, the weighted response was not -2. However, it could be an artifact depending on the particular picture, because all subjects misjudged the stimulus. For nonborder concentrated contrast, it was clear that the subjects could detect the difference in the contrasts.

For each of the three concentrated contrasts, subjects could distinguish the difference between the contrast values of the standard picture and the test pictures significantly (it was worst for the standard picture with 0% contrast, $F_{4,8} \geqslant 24.8$, $p < 0.001$).

It was obvious that performance was much higher than that in the memory-identification task. This shows that the characteristics that emerged in experiment 1 and 2 could be obtained with visual memory.

6. DISCUSSION

In experiment 1, with chromatic, luminance, and CL contrasts as variables, we found the enhancement effect on the contrast of memorized pictures, particularly in chromatic contrast. This suggests that chromaticness of pictures is expanded in visual memory. In experiment 3 we showed that sensitivity in detecting color manipulations without memory was much higher. This suggests that visual memory made subjects' judgments ambiguous and caused the enhancement effect.

We considered how the effect would be interpreted in some supplementary experiments. Although we tried to explain the results in terms of the difference in contrasts between the memory phase and the test phase,[30] and the ratio,[31] we had limited success. We also considered the possibility that the results might be based on the subjective similarity of the appearance of pictures with different contrasts, because it was possible that if the enhancement effect was not an effect of visual memory, the effect might be dependent on subjective appearance. In a preliminary experiment, however, we found that the enhancement effects persisted, suggesting that visual memory produced the effect. We also considered that the enhancement effect might correspond to the tendency to shift toward naturalness in the appearance of colored pictures, since a picture with higher chromatic contrast is closer to the original picture with no manipulation. Two of us investigated performance in memory identification with hue changes as a variable[32] because the hue change made the appearance of a colored picture unnatural. From the result of this experiment, the performance of the memory-identification task was never affected by this manipulation. This suggests that the naturalness of a picture may not affect performance in memory identification, consistent with previous research.[5]

In experiment 2, we used three different kinds of concentrated contrasts to investigate the role of categorical-color perception in visual memory. For focal and border contrast, the curves of weighted response had flatter characteristics. These might represent the confusion of subjects' judgment for the color changes within color categories to which the color originally belonged. We attempt to interpret this result as follows. Suppose that the categorical color process is an internal representation of the memorized colored picture. When the subject observed an original picture (100% focal contrast, for instance), colors in the picture would be clustered in each color category, and then the inner representation would be close to the pictures with decreased focal contrast, 50% for instance. It would therefore be possible that, when observing the picture with 50% focal contrast, the subject could not distinguish between the observed picture and the inner representation. The response to a change in nonborder contrast was clearer than with focal and border contrast. Uchikawa and Shinoda[19] reported that colors identified with memory tended to remain within their own color category or their neighboring color category. This might be consistent with the present results. That is, the category effect in color memory might be included in the color memory of natural images. However, it may also be possible to explain this performance by color differences, as in the following analysis (Subsection 6.A).

A common feature in experiments 1 and 2 was that newly added pictures were judged correctly regardless of the kind of contrast and its value. This means that some of the information included in the memorized pictures, possibly pattern information, may be kept in the memory robustly enough to distinguish those pictures from the newly added pictures. Such a property may represent a particular capacity of picture memory, which has been considered elsewhere.[33–35]

A. Comparison of Color Differences

We have defined the color difference as the averaged color difference over all color manipulations of all pixels in a picture. We calculated this quantity for 200 pictures chosen arbitrarily from the pictures used in the experiments. The reestimation in each of the concentrated contrasts (focal, border, and nonborder contrasts) are plotted as a function of color difference in Figs. 7(a) and 7(b), which show the difference in the value of contrast in the memory phase, for 50% and 100%, respectively. The abscissa shows the color difference, and the ordinate shows the weighted response. The different symbols indicate the three kinds of concentrated contrasts. Error bars represent ± 1 standard error.

For the 50% contrast picture in the memory phase [Fig. 7(a)], the weighted response for focal contrast and border contrast almost overlapped over a range of color differences (solid circles and open triangles, respectively). This suggests that detection for these two contrasts are subserved by a common mechanism. In addition, at color difference 0 on the abscissa, that is, at the hit condition,

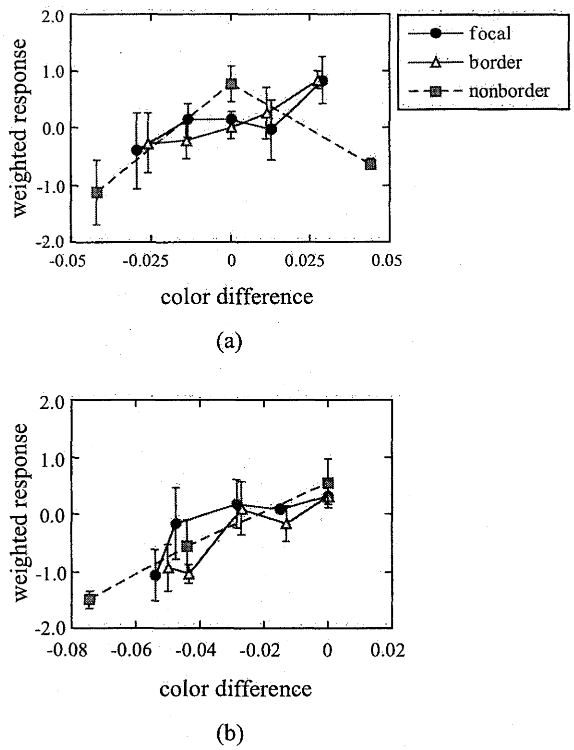


Fig. 7. Estimation by color difference between focal, border, and nonborder contrasts. The abscissa shows the color difference; the ordinate shows the weighted response. Each symbol shows a different concentrated contrast. Each column shows the difference between the contrast values in the memory phase: (a) 50%, (b) 100% contrast.

the weighted responses for focal and border contrasts were lower than for the nonborder concentrated contrast, which had a different outline. It therefore may be necessary to consider additional mechanisms.

On the other hand, for the 100% contrast picture in the memory phase [Fig. 7(b)], the weighted responses for the three kinds of concentrated contrasts declined along with the color difference, and the curves of all three contrasts were close. This suggests that color difference might play a role in the detection of changing concentrated contrasts from a 100% concentrated-contrast picture.

It may therefore be impossible to describe the whole performance exactly by a single mechanism or function of color difference. It is possible that other mechanisms, possibly cognitive ones, could be active, especially with natural images. We discuss this issue in following subsection.

B. Colored Pictures of Natural Scenes

Here we compare our present results with previously published research on memory for color. We also consider the effect of color in pictures of natural scenes.

In classic research on color memory a single color stimulus is used. It is well known that the color appearance of a colored target is affected by the context in a display. Newhall *et al.*[2] used a single color patch as a visual stimulus and performed color matching for simultaneous presentation and successive presentation (memory matching). They reported that systematic increases in purity were required for memory matching compared with simultaneous matching of the same test colors. By manipulating chromatic contrast[36] (defined in the present study) of colors in their experiment (Fig. 5 in Ref. 2) we found that the manipulation of chromatic contrast could simulate their results; the increment of saturation in memory matching was nearly 25% or less. Additionally, in the experiment of Newhall *et al.*, the increment in saturation was significant for colors of medium chroma, in the Munsell notation. The enhancement effect in the present experiment also appeared in the middle of the contrast values, for instance, at 50% chromatic contrast. Additionally, Newhall *et al.* reported that the darker colors tended to be remembered as even darker, and brighter colors as even brighter. Such characteristics seem also to correspond to our results in the manipulation of luminance contrast. We therefore speculate that there may be a common mechanism in memory of color for a single color and for various colors in a natural scene. However, in the present research, the enhancement effect of chromatic contrast appeared for pictures with 0% chromatic contrast in the memory phase. That is, the subject misjudged the black-and-white picture as a colored picture. This suggests that the direction of the expansion of chromaticness might be similar between a single color image and a natural scene image but the magnitude of the effect may be different.

Other attributes should be considered in interpreting such characteristics. We can recognize objects in a scene automatically and effortlessly, exploiting our knowledge and past experience. It may be reasonable to suppose that the cognitive processes could work for colors in the memory of natural images or equivalents even in the experimental situation.[10–12] In memory color studies[2,10–16] such attributes have been reported. Bartleson[9] wrote that the increments of saturation and lightness "tended to be more characteristic of the dominant chromatic attribute of the object in question; grass was more green, bricks more red" (p. 73). Spile and Springer[13] suggested that such an increment of chroma might be specialized for recognition of particular objects: for example, color information is an important attribute for food. Ranter and McCarthy[14] reported that typical colors of particular objects were remembered accurately. Note that the "typical color" in their words referred to "appropriateness"; for instance, the red of a stop sign. They discussed that memory color would be accounted for by the cultural variable, that is, typical knowledge of or the label for the object. Despite there being a considerable number of reports, it is still not clear what causes the perceptual differences between the actual color of an object and its memory color. It is also worth noting that Wurm *et al.*[37] reported that color improves object recognition and concluded that the mechanism may be sensory rather than cognitive.

Some researchers[6,7] have studied the nature of color memory in terms of a physical property of visual processing, that is, responses of photoreceptors. However, such approaches still do not specify an exact mechanism. Jin and Shevell[7] compared the accuracy of color memory on the L/M and the S dimensions (L, M, and S refer to excitations of the long-wavelength-sensitive, the middle-wavelength-sensitive, and the short-wavelength-sensitive cones). They reported that color memory on the L/M dimension was more accurate than on the S dimension, suggesting that the shift in memory could be in both saturation and hue. Sachtler and Zaidi[6] manipulated a test color along cardinal axes, which were defined in terms of changes in cone excitations. They showed the stability of chromatic threshold and suggested that chromatic signals were more efficient than a luminance signal. This is consistent with the results of Gegenfurtner[22] and Wichmann *et al.*[23] and also, possibly, with the present experiment, in which observers' performance for manipulation of luminance contrast was more ambiguous than for colored images.

Jin and Shevell[7] compared different stimulus configurations: an isolated single patch and a test patch surrounded by multiple colors. They argued that the different results between the stimulus configurations could be caused at the neural coding levels.

With respect to the property of categorical color in colored pictures, our findings suggest that it is difficult for subjects to detect color changes in focal and border contrasts. This possibly corresponds to the classic result for a simple color stimulus[19]; that is, the confusion in color memory may be based on color category. This explanation is consistent with Ranter and McCarthy's finding[14] that focality of object colors had an insignificant effect compared with typicality and appropriateness in simple colored pictures. The characteristics of the results for nonborder contrast (Fig. 4) were of a different nature. Observers' responses were clearer than with the other two contrasts (focal and border). In this manipulation, colors of objects in a scene could be exchanged with other colors, sometimes inappropriately. However, it was difficult to identify the effect in the present results, in which effects of both knowledge of objects and the categorical property were intermingled.

A property similar to the enhancement effect appeared for the 50% focal and border concentrated contrasts in the memory phase [Figs. 4(a) and 4(b)]. For changes in chromatic contrast, colors were changed along a uniform direction toward D65 white in color space. In contrast, in concentrated contrasts, colors in a picture were translated toward various directions in color space. By this manipulation, some colors in a picture were saturated and others were desaturated at the same time. The nature of the color manipulation could not be identical between the variables. It is therefore difficult to identify whether the effect that emerged in concentrated contrasts was the same enhancement effect as in chromatic contrast. However, focal colors in each color category had higher saturation. It may be possible that the destination of the enhancement shift of chromaticness is close to the focal colors.

Significantly, some researchers have argued for the relation of color memory to color constancy,[6,7,15] which is the invariant perception of surface color despite different spectral illuminations. Stability of color representation in memory may be important for recognizing objects under different illumination, say, indoor and outdoor. Furthermore, illumination changes cause almost uniform shifts in chromaticities of surfaces in a scene. If color mechanisms adapted to the uniform shifts, it would be

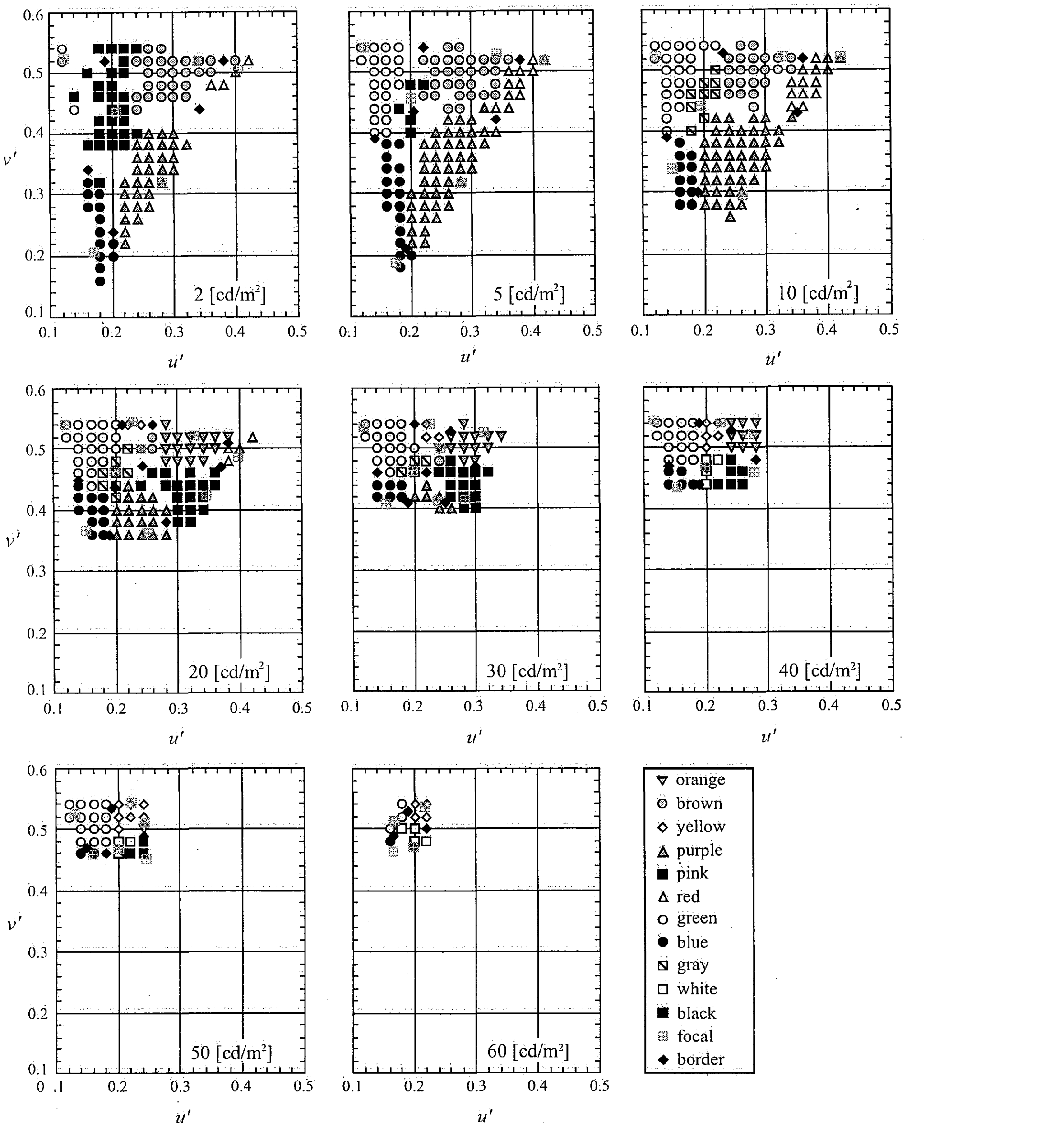


Fig. 8. Results for categorical color naming. Each symbol shows a different color category. Each panel shows the difference in the luminance level. A color name represents data that have at least four instances of naming over two sessions for three subjects. The focal colors were averaged over subjects' matches.

very hard for them to deal with a variety of directions of the translation of chromaticities at the same time, which occurred in the present study.

As discussed above, it was difficult to identify exactly what kind of visual mechanisms subserve color processing in visual memory. We have speculated that there may be multiple mechanisms for color processing in visual memory for color difference and categorical color perception and also a contribution from cognitive processing.

7. SUMMARY

Subjects tended to detect decremental changes in chromatic contrast more readily than incremental changes. For luminance contrast and chromatic-and-luminance contrast, similar responses were also evident, suggesting that the chromaticness of a natural image is expanded in memory. Responses for black-and-white images were more ambiguous than for colored images, suggesting the importance of chromatic information in visual memory. Changes in chromaticities beyond color categories could be detected more clearly than the changes within each color category, suggesting a role for categorical-color processing in memory. Subjects' performance in detecting the differences of the color contrasts was not impaired when memory load was not introduced. This suggests that the results reported were due to visual memory. In order to interpret all of this performance, it may be necessary to consider multiple mechanisms for color processing in visual memory.

APPENDIX A: PRELIMINARY EXPERIMENT: CATEGORICAL-COLOR NAMING

To make color changes based on the notion of categorical color, we investigated the distributions of each of the basic 11 colors in the 1976 CIE (u', v') uniform color space used to present the pictures. Therefore we performed a preliminary categorical-color-naming experiment.

1. Stimulus

Colors were separated into nine luminance levels ($0 < L \leqslant 2$, $2 < L \leqslant 5$, $5 < L \leqslant 10$, $10 < L \leqslant 20$, $20 < L \leqslant 30$, $30 < L \leqslant 40$, $40 < L \leqslant 50$, $50 < L \leqslant 60$, $60 < L$ cd/m^2]). The test color patch was chosen from a grid on the 1976 CIE (u', v') chromaticity coordinates based on 0.02 unit for (u', v') coordinates at each luminance level. A Mondrian-like colored pattern was used as the background of the test patch in order to approximate a natural scene with a large number of colors. The Mondrian background consisted of 255 small color patches in a 16×16 array. Each of the patches subtended 0.7×0.7 deg and had a unique color. The mean luminance of the patches in the background was 20 cd/m^2, and the mean chromaticity was (0.215, 0.463) in the 1976 CIE (u', v') chromaticity coordinates, which corresponds to (0.329, 0.315) in the 1931 CIE (x, y) coordinates. The test patch surrounded by a gray background of 0.35-deg width was superimposed at the center of the Mondrian.

2. Procedure

After adapting to D65 white at 30 cd/m^2 on the CRT display for 3 min, the subject started the session. The test patch and the Mondrian background were presented simultaneously for 2 s. Then the subject named the appearance of the test patch using one of the 11 basic color terms (red, green, blue, yellow, orange, pink, purple, brown, gray, black, and white). After a 3-s interval, in which the D65 white (30 cd/m^2) was presented, the subject observed the next color. This interval was long enough to prevent afterimages. Categorical-color naming was repeated twice at each test chromaticity. Since colors with luminance higher than 60 cd/m^2 had a chromaticity similar to D65 white, those colors were categorized as white.

After categorical-color naming all colors, subjects observed the colors again and chose a focal color or the color closest to a focal color in each color category at each luminance level. In this task, the test and the background were also presented for 2 s with a 3-s interval. Finally subjects adjusted the chromaticity using a keyboard until they were satisfied with the appearance of the color as a focal color. The selection of focal colors was also repeated twice.

3. Results

Subjects were MS (male, 23 yr), YS (male, 23 yr), and KK (male, 24 yr), who participated in experiment 2 after this experiment.

Figure 8 shows the results of categorical-color naming and chosen focal colors in the 1976 CIE (u', v') chromaticity diagram. Each symbol shows a different color category. When a name appeared not less than four times during the subjects' naming over six sessions (two sessions for each of three subjects), that name was adopted. Focal colors were averaged over subjects' settings. The focal colors averaged over subjects and the border color set by the experimenter in the definition of concentrated contrast are also shown in the diagrams.

All of the 11 basic color terms appeared over the 9 luminance levels. Black became gray when the luminance level exceeded 5 cd/m^2 and became white at 40 cd/m^2. Brown at lower luminance levels changed to orange at 20 cd/m^2. Although blue occupied a large region at lower luminance level, it diminished at higher luminance levels. It was obvious that the focal colors of chromatic categories were distributed with higher saturation.[17]

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24. Some of experimental sessions were run with another personal computer (Macintosh IIci), with which the chromaticity coordinates of the display were (0.622, 0.341), (0.273, 0.605), and (0.151, 0.058), respectively, for the R, G, and B phosphors. The calibration procedure used here ensures that the difference in computers did not cause any problems. Considering the efficiency of image processing, the computer for the display system was exchanged for the machine described in text.
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