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색채 잔상 지각에서 배경 색에 의해 유도된 색의 가산 혼합 현상 탐구*

The additive mixture of induced colors by background colors in the afterimage

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요 약 등광도인 두 색으로 이루어진 배경(적색/녹색, 청색/녹색, 혹은 청색/황색 배경) 위의 중앙에 회색 원이 놓일 때 이 회색 원에 대한 잔상은 본래의 두 배경 색에 대한 가산 혼합 색인 것으로 나타났다. 잔상에 나타난 이러한 혼합 색은 두 배경 색의 광도가 다를 때에도 나타났고, 회색 원의 크기가 증가하였을 때에도 나타났다. 나타난 잔상의 채도는 순응 배경 자극의 평균 광도 값이 증가할수록, 그리고 회색 원의 크기가 감소할수록 증가하는 것으로 나타났다. 하지만 검사 자극의 중앙에 유채색 혹은 무채색의 경계선이 놓일 때 순응 자극의 두 배경 색에 대한 가산 혼합 색은 더 이상 나타나지 않았다. 검사 자극에 놓인 경계선은 검사 영역의 양 쪽에서 유도된 색들이 반대편의 영역으로 퍼져나가는 것을 방해하고, 결과적으로 유도된 색이 두 색으로 분리된 상태로 유지하도록 하여 서로가 혼합되지 않도록 돕는 작용을 하는 것으로 추정된다. 검사 자극에 경계선이 놓이지 않는 경우, 잔상에서 유도된 색은 유도된 두 색 사이에 주관적 경계선을 형성하기에는 너무 약한 색 정보를 가지기 때문에 결과적으로 두 색이 반대편의 영역으로 퍼져 색채 혼합이 일어나는 것으로 추정된다.

주제어 색채 잔상, 색채 대비, 색채 가산 혼합

Abstract Additive color mixture of two different background colors appeared in the afterimage of a gray circle centered on an isoluminant bichromatic background (red/green, blue/green, or blue/yellow background). The chromatic mixture still appeared in the afterimage of a gray circle on a bichromatic background at different luminance levels, and also appeared on a large test field. The saturation of the induced color was observed to increase as the overall luminance of adaptation background stimulus increases or the size of test field decreases. It was found that the chromatic mixture does not appear with a chromatic or achromatic boundary inserted on the center of the test field. The boundary seems to prevent the induced color on each side of test field from spreading to the other side so that the induced color does not appear mixed but divided into two different colors. Without a boundary on the test stimulus, the color information induced in the afterimage seems to be too weak to create a subjective boundary between the two colors and consequently propagate inward appearing mixed.

Keywords color afterimage, color contrast, additive color mixture

INTRODUCTION

Prolonged viewing of a highly saturated color produces its complementary color in the neutral test field. For example, you can see a faint yellow negative afterimage in a white background after staring at a blue square for a while. This phenomenon of chromatic adaptation is sometimes called successive color contrast, and it occurs when prolonged

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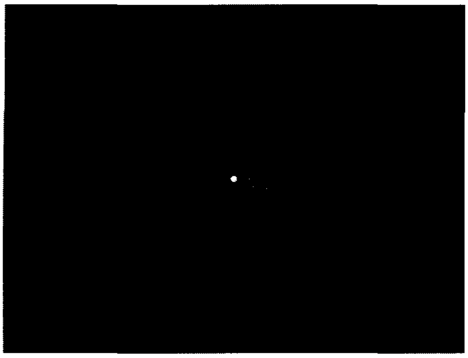
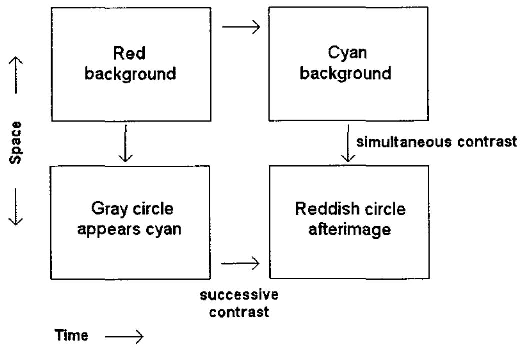


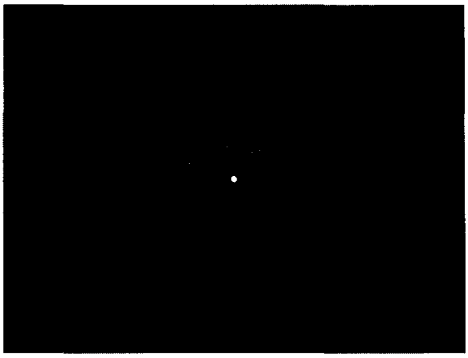
(Fig. 1) Color contrast effects. A uniform gray circle (with a fixation point in the center) appears greenish or cyanic against the red background (simultaneous color contrast). In the afterimage on a white background following a certain period of adaptation to this stimulus, the area corresponding to the red background appears cyan (successive color contrast), and the central area corresponding to the gray circle appears reddish. See text for details.

exposure to light of a specific color reduces the visual sensitivity to that color immediately afterward [14].

In addition to successive color contrast, the induced complementary colors are also perceived in the phenomenon of simultaneous color contrast. When a neutral test field is surrounded by a colored background, the complementary color of the background is induced on the test field. An example is a greenish or cyanic neutral gray circle against the red background (Fig. 1). This phenomenon depends on neural



(Fig. 2) Schematic diagram of color contrast phenomenon showed in Fig. 1. The afterimage of the gray circle appears reddish after adapting with a red background. This could be caused by successive contrast, simultaneous contrast, or both processes. Adapted from Anstis et al. [2].



(Fig. 3) A uniform gray circle on a bichromatic left-half red and right-half green background. Two kinds of hue (red and green) in the background induce colors on the gray circle. See text for details.

interactions of a visual space with another [11] and is known to be generated by concentrically organized double opponent cells in visual cortex [10].

In Fig. 1, furthermore, when you look at a white background after staring at the center of the gray circle for about 20 seconds, the afterimage of the red background appears cyan, and the central area corresponding to the gray circle of the original image appears reddish. The reddish circle in the afterimage may be the results of successive contrast caused by the cyanic gray circle on the original red background, simultaneous contrast caused by the cyan afterimage corresponding to the red background, or both. These two possible explanations for the reddish afterimage of the gray circle are represented in the diagram of Fig. 2 [2].

Then, how do you expect a uniform gray circle to appear on a bichromatic left-half red and right-half green background (Fig. 3)? Not a single-colored homogeneous background but a two-colored background affects the appearance of the gray circle in Fig. 3. Most people report the gray circle to appear cyan, the complementary color of red, on its left side and magenta, the complementary color of green, on its right side. When you look at a white background after a certain period of adaptation to this stimulus, the left and the right fields corresponding to the red and the green backgrounds appear respectively cyan and magenta. You would expect the central area corresponding to the gray circle to appear half red and half green on the white background. The assumption could be explained by the fact that the cyan and the magenta colors induced on the left and the right sides of the gray circle could cause the appearance of red and green, respectively (successive color contrast), and also the cyan and the magenta colors induced in the white background could cause the appearance of red and green to the central area (simultaneous color contrast). Contrary to this expectation, however, the central area corresponding to the gray circle appears uniformly yellowish on the white background.

A question then arises as to where the yellowish color is derived, and how it occurs in our color system. The present study was designed to investigate the characteristics of this unexpected phenomenon since no empirical data have been reported on the perceived color of the phenomenon.

The yellowish color induced on the central area in the white background seems phenomenally to derive from the additive mixture of two colors in the adaptation background. To confirm such possibilities, the effects of several combinations of equiluminant background colors were tested on the central area in the afterimage corresponding to the gray circle (from Fig. 3) in Experiment 1.

One could suggest that the equiluminant attribute of the two-colored background may generate the mixture of the colors because the afterimage color by the two-colored background might be mixed easily rather than divided due to their same amount of luminance levels. Ejima, Redies, Takahashi and Akita [6] showed the neon color effect in the Ehrenstein pattern is dependent on illuminance. In their experiments, the luminance ratios of the stimuli were one of the main factors in the magnitude of the neon color spreading. In Experiment 2 of the present study, the background colors at different luminance levels were applied in the adaptation stimuli to determine whether the additive mixture phenomenon is dependent on luminance contrast.

The watercolor effect, which was first described by Pinna [15], demonstrated long-distance spatial induction by color spreading from simple inducing lines [16]. They found that the coloration in the watercolor effect appears over distances of up to 45 degrees, and they emphasized that the large spatial extent of color spreading suggests large receptive fields in perceiving filling-in color in the watercolor effect. The afterimage color observed in stimuli such as Fig. 3 might also extend to a long distance and then be explained by neuronal mechanisms at higher levels. In the present study, the spatial range of the effects was examined with various sizes of the gray circle in Experiment 3 to determine whether the mixture in the afterimage constantly appears as the size of the gray circle increases.

According to Grossberg's [7] model of neural network, the perception of objects is based on two types of visual system: a boundary contour system (BCS), which generates invisible boundaries, and a feature contour system (FCS), which generates featural filling-in of brightness and color signals. FCS fills the space until the spreading brightness and colors hit either their first boundary or are diminished due to spatial spread [8, 9]. Hence, in the present stimuli, I postulated that the color signals induced on each side of the central area in the afterimage diffuse inward, and that the induced colors have too weak chromatic information to generate a boundary between the two colors. Consequently, the weakened boundary lets the colors spread around and create an additive mixture of the two colors. To examine the possibility of spreading colors flowed beyond the weakened boundary, the additive mixture phenomenon was tested on the central area split by a visible boundary in the test stimulus in Experiment 4.

EXPERIMENT 1: ADDITIVE MIXTURE IN THE AFTERIMAGE

Experiment 1 was conducted to test the hypothesis that the color perceived on the afterimage of the gray circle in adaptation stimulus shown in Fig. 3 derives from the additive mixture of two colors in the bichromatic background. Euclidean distances for saturation and angles for hue difference in the CIE 1931 (International Commission on Illuminance) 2° standard observer's chromaticity diagram were used to define the colors induced in the afterimages.

Method

Observers

Three observers took part in the experiment; two of the observers (one female, the other male) were naïve as to the purpose of the experiment, and the third observer was the author (female). All the three observers had corrected-to-normal acuity, and normal color vision as evaluated by the Ishihara Pseudoisochromatic Plates.

Apparatus and Stimuli

Stimuli were presented on a 17-inch calibrated monitor (LG FLATRON 775FT) with 60 Hz refresh rate controlled by a Pentium-III computer. The monitor and the surroundings were covered with black cardboard to minimize light reflection and scattering, and display luminances were measured by using a Minolta LS-110 Luminance-Meter.

The stimulus display consisted of three parts: adaptation duration, test duration, and blanking duration to remove afterimages by the previous trial.

Adaptation stimulus had a central gray circle (with a fixation point in the center) placed on a two-colored background. The diameter of the gray circle was 3° in visual angle. The left and the right sides of the background were respectively red and green at equiluminance in one of the three conditions. Four primary colors, red, green, blue and yellow, were used for stimuli, and accordingly the adaptation background colors could be one of the combinations of highly saturated and equiluminant "red/green", "blue/green", and "blue/yellow" depending on conditions. The luminances and the CIE 1931 xy coordinates of the background colors were slightly different through observers based on their equiliminance points for each combination of background colors. The equiluminance points of each observer were measured by means of minimum motion technique [1, 3]. In the combination of blue/yellow background, the appearance of yellow was nearly greenish because the luminance of yellow was degraded for the equilumance point with blue.

Test stimulus had a white uniform background with a fixation point in the center. During blanking duration, white field of 159 cd/m2 was replaced by black field of 0.1 cd/m^2, and they were alternated at 2 Hz in a two-stroke cycle. The size of backgrounds through the whole experiment was constant at 15.6° x 11.83°, and the central fixation point "+" (0.16° x 0.16° visual angle) was presented throughout all the trials.

Procedure

Participants sat in a darkened room with his/her eyes 57 cm from the monitor, were stabilized by a chin rest to reduce head movement, and were informed to respond without eye movements if at all possible. Each adaptation stimulus was presented for 20 seconds, and the 5 second test stimulus followed. The test duration was fixed at 5 seconds because the induced afterimage could fade out for longer test duration. Participants matched the color induced on the central circle area in the afterimages by means of mouse clicking on the color selection box after the test duration, and the 30 second blanking duration was inserted between trials. Participants had no difficulties in memorizing the induced color for the color matching in preliminary experiments.

Three combinations of background colors, "red/green", "blue/green", or "blue/yellow", were presented randomly, and each combination was repeated twice in a block. Two blocks were conducted, and the total number of trials was 12.

Results

The CIE 1931 xy chromaticity coordinates transformed from RGB values which observers matched on the color selection box were used as dependent variable for analysis, and average response values for each condition were calculated. The afterimage color of the gray circle on "red/green", "blue/green" or "blue/yellow" adaptation background appeared desaturated yellow (CIE 1931 chromaticity, x = 0.3282, y = 0.3553), desaturated cyan (CIE 1931 chromaticity, x = 0.3024, y = 0.3343) or gray (CIE 1931 chromaticity, x = 0.3092, y = 0.3355), respectively, and the chromaticity space was centered on the white point (x = 0.3172, y = 0.3290; ITU-R Recommendation BT.709, 1990). If the perceived afterimage of the gray circle on the bichromatic "red/green" background lies between the two afterimage colors of a gray circle on each uniform "red" and uniform "green" background, this lets us assume that a mixture of red and green produces yellow and the perceived afterimage of the gray circle on the bichromatic "red/green" background comes from an additive mixture of red and green. To verify the assumption, the CIE chromaticity coordinates of each afterimage of a gray circle on a uniform "red" background and on a uniform "green" background were obtained from each observer, and the same design was applied to the other combinations of bichromatic background, which was "blue/green" and "blue/yellow". The angle in the CIE chromaticity coordinates referring to hue difference was hypothesized to be significantly different from each condition, and the distance in the CIE chromaticity coordinates referring to saturation was hypothesized not to be significantly different from each condition. (Fig. 4) shows the results. The diagrams in (Fig. 4) are magnified to the white point because the chromaticity values of afterimages are desaturated and gathered near the white point. Repeated-measures ANOVA was used to determine whether each chromaticity value obtained from the two uniform backgrounds was significantly different from the chromaticity value obtained from a bichromatic background. Euclidean distances (from the white point) in terms of saturation difference were obtained from equation (1):

$$\sqrt{(x_w - x)^2 + (y_w - y)^2} \quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

and in equation (1), x_w and y_w are the chromaticity coordinates of the white point. Angles (from the axis liking the white point to a point of [x = 0.8, y = 0.3290]) in terms of hue difference were obtained from equations (2), (3), and (4):

$$\mathrm{acos}((x - x_w) / \sqrt{(x_w - x)^2 + (y_w - y)^2}) \times 180^\circ / \pi \quad (x>x_w,\ y< y_w) \quad \cdots (2)$$

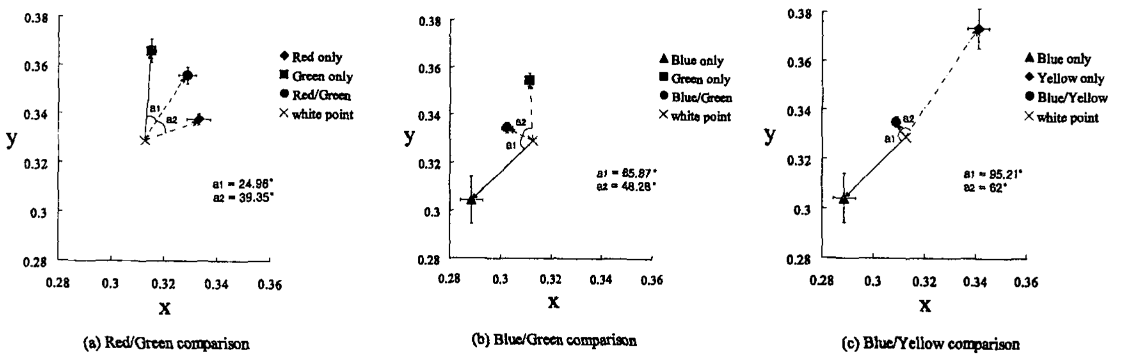
$$180^\circ - \mathrm{acos}((x_w - x) / \sqrt{(x_w - x)^2 + (y_w - y)^2}) \times 180^\circ / \pi \quad (x<x_w,\ y< y_w) \quad \cdots (3)$$

$$180^\circ + \mathrm{acos}((x_w - x) / \sqrt{(x_w - x)^2 + (y_w - y)^2}) \times 180^\circ / \pi \quad (x<x_w,\ y< y_w) \quad \cdots (4)$$

There were no significant differences between the saturation levels (in Euclidean distances) in all comparisons: red/green comparison ($F(2, 4) = 4.225$, *n.s.*), blue/green comparison ($F(2, 4) = 1.651$, *n.s.*), and blue/yellow comparison ($F(2, 4) = 2.098$, *n.s.*). In terms of hue (in angles), however, there were significant differences in all comparisons: red/green comparison ($F(2, 4) = 12.858$, $p < .05$), blue/green comparison ($F(2, 4) = 30.558$, $p < .05$), and blue/yellow comparison ($F(2, 4) = 110.231$, $p < .05$), except for the difference between the afterimage of a gray circle on a uniform red background and that on a bichromatic "red/green" background ($F(1, 2) = 6.279$, *n.s.*). As shown in (Fig. 4), first, the chromaticity value for the afterimage of a gray circle on a bichromatic "red/green" background is located between the chromaticity value for the afterimage of a gray circle on a red background and that on a green background in diagram (a). Second, the chromaticity value for the afterimage of a gray circle on a bichromatic "blue/green" background is located between the chromaticity value for the afterimage of a gray circle on a blue background and that on a green background in diagram (b). Third, the chromaticity value for the afterimage of a gray circle on a bichromatic "blue/yellow" background is located between the chromaticity value for the afterimage of a gray circle on a blue background and that on a yellow background in diagram (c). In conclusion, the color perceived in the afterimage of the gray circle on a bichromatic background derived from the additive mixture of the two colors of background in the adaptation stimulus.

EXPERIMENT 2: LUMINANCE CONTRAST

Experiment 2 was conducted to determine whether the additive mixture is dependent on luminance contrast. A background with two colors at various luminance contrasts was used as adaptation stimulus in the experiment. Observers and apparatus were the same as in Experiment 1. Euclidean distances for saturation and angles for hue difference in the CIE 1931 xy coordinates were used to define the colors



(Fig. 4) Zoomed-in view of CIE 1931 xy chromaticity diagram. Each comparison of "red only" and "green only" background to a bichromatic "red/green" background is shown in (a). Each comparison of "blue only" and "green only" background to a bichromatic "blue/green" background is shown in (b). Each comparison of "blue only" and "yellow only" background to a bichromatic "blue/yellow" background is shown in (c). Each point represents the mean and standard error of the mean of the color induced in each condition, and x indicates the white point (x = 0.3172, y = 0.3290). The angles represented as a1 and a2 indicate the hue differences between the colors induced in each condition.

induced in the afterimages. The distance referring to saturation was hypothesized to increase without hue changes as the total luminance of background increases.

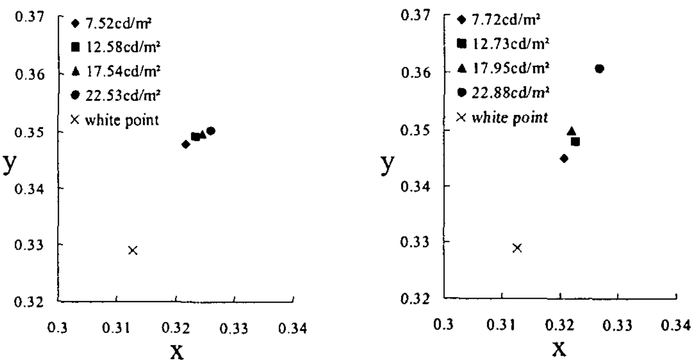
Method

Stimuli and procedure

The background color used in adaptation stimulus was a pair of red and green at different luminance levels. The luminance differences between the two colors in the background varied between approximately 5 cd/m^2 to 20 cd/m^2 (step size nearly 5 cd/m^2). With a constant 27.73 cd/m^2 red on the one side of the background, the green on the other side ranged from 7.72 cd/m^2 to 22.88 cd/m^2, and with a constant 27.54 cd/m^2 green on the one side of the background, the red on the other side ranged from 7.52 cd/m^2 to 22.53 cd/m^2 . The number of trials in a block was 8, and each condition was presented in a random order. Two blocks were conducted, and the total number of trials was 16. Observers were informed to report at the end of the experiment if any case of the appearance of the central area in the afterimage looked different, for instance, if the color appeared in the afterimage was not homogeneous, and if there was no chromatic appearance at all. The rest of the procedure was identical to that of Experiment 1.

Results

When the two colors on the background in adaptation stimulus had different luminant values, the chromatic mixture of afterimages still appeared, and the afterimage corresponding to the gray circle of adaptation stimulus did not appear to be divided into two different colors. The average color perceived on the afterimage was desaturated yellow (CIE 1931 chromaticity, x = 0.3235, y = 0.35), and (Fig. 5) shows the average chromaticity value for each condition. In (Fig. 5 (a)), the saturation of afterimage was significantly correlated with the overall luminance of background (r = .917, p < .05), that is, the afterimage appeared more saturated as the overall luminance of adaptation stimulus increased by the luminance increment of green background with a constant luminance of red background. The saturation of afterimage was strongly correlated with the overall luminance of background (r = .988, p < .05) as shown in Fig. 5 (b), that is, the afterimage appeared more saturated as the overall luminance of adaptation stimulus increased by increasing the luminance values of red background with a constant luminance of green background. To sum up, the mixed color still appeared in the afterimage of the gray circle on a bichromatic background with various luminance ratios, and the saturation of the induced color increased as the total luminance values of background increased. The appearance of chromatic mixture induced in the afterimage was verified to be independent of the luminance ratio of the adaptation background colors, but the saturation of chromatic mixture induced in the afterimage



(b) Green background: 27.54cd/m² (a) Red background: 27.73cd/m²

(Fig. 5) Zoomed-in view of CIE 1931 xy chromaticity diagram. x indicates the white point (x = 0.3172, y = 0.3290). The luminance of green on a red/green bichromatic background increases with a constant luminance of red background in (a). The luminance of red on a red/green bichromatic background increases with a constant luminance of green background in (b). The average chromaticity of the induced color in the afterimage of the gray circle was desaturated yellow (x = 0.3235, y = 0.35).

was proved to be dependent on the overall luminance of the adaptation background colors.

EXPERIMENT 3: SPATIAL RANGE OF ADDITIVE MIXTURE

Experiment 3 was conducted to investigate the spatial range of the colors induced on the afterimage. Various sizes of the gray circle were used in the experiment. Observers and apparatus were the same as in Experiment 1. Euclidean distances for saturation and angles for hue difference in the CIE 1931 xy coordinates were used to define the colors induced in the afterimages. The distance referring to saturation was hypothesized to decrease without hue changes as the size of gray circle on a bichromatic background increases.

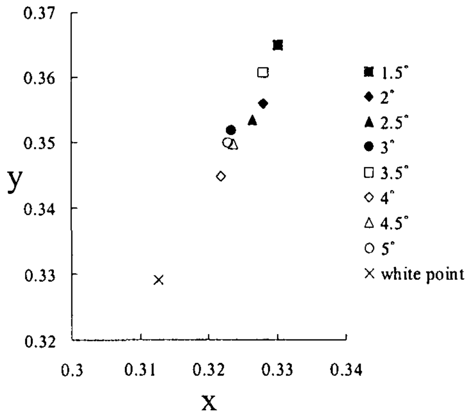
Method

Stimuli and procedure

The stimuli used in Experiment 3 were identical to those used in Experiment 1 except for the size of the uniform gray circle. The sizes of the gray circle varied between 1.5° to 5° (step size 0.5°). The background color used in adaptation stimulus was a pair of red and green at equiluminance. The gray circle of each size was presented twice in a random order through the experiment, and thus the total number of trials was 16. Observers were informed to report if any case of the appearance of the central area in the afterimage looked different, for instance, if the color appeared in the afterimage was not homogeneous, and if there was no chromatic appearance at all. The rest of the procedure was identical to that of Experiment 1.

Results

Although the sizes of the neutral gray circle on a bichromatic background in adaptation stimulus varied through the experiment, the chromatic mixture of afterimages still appeared, and the afterimage corresponding to the gray circle in adaptation stimulus did not appear divided into two different colors in any condition. The average color perceived on the afterimage was desaturated yellow (CIE 1931 chromaticity, x = 0.3254, y = 0.3538), and Fig. 6 shows the average chromaticity value for each condition. The saturation of afterimage was negatively correlated with the size of gray



(Fig. 6) Zoomed-in view of CIE 1931 xy chromaticity diagram. x indicates the white point (x = 0.3172, y = 0.3290). The smaller the size of gray circle was, the more saturated the yellow tended to appear. The average response chromaticity was desaturated yellow (x = 0.3254, y = 0.3538).

circle on the background (r = -.718, p < .05), that is, the perceived color on the afterimage tended to appear more saturated as the size of the gray circle decreased.

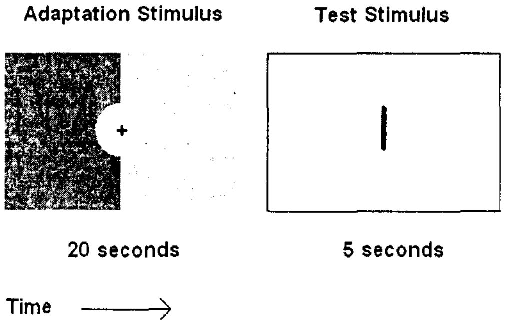
EXPERIMENT 4: VISIBLE BOUNDARY

Experiment 4 was designed to test the effects of visible boundary crossing the central area of the afterimage corresponding to the gray circle of adaptation stimulus. A boundary which split the central area was inserted in the test stimulus. Observers and apparatus were the same as in Experiment 1.

Method

Stimuli and procedure

The stimuli used in Experiment 4 were identical to those used in Experiment 1 except for the presence of a line in test stimulus. The background color used in adaptation stimulus was a pair of red and green at equiluminance. The central area in the test stimulus was split by a physically existing boundary. The boundary could be achromatic or chromatic, and the width of the boundary was 0.2° in visual angle. The reason for using both achromatic and chromatic boundaries was to define whether both boundaries would have the same effects on the perceived color in the afterimage. The



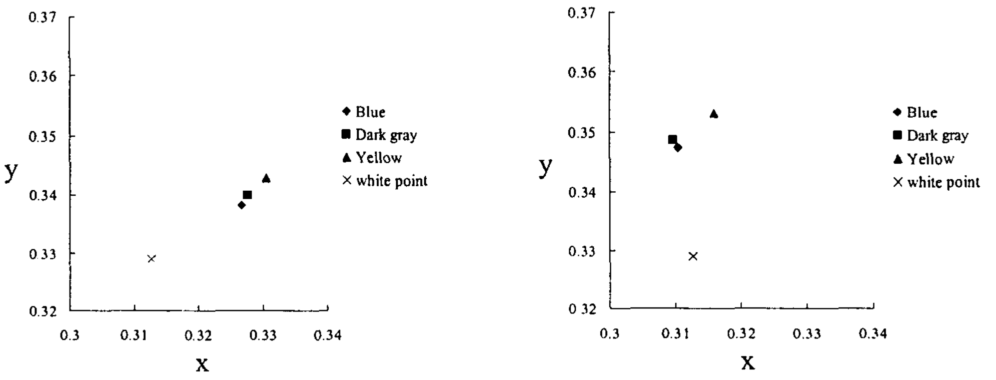
(Fig. 7) Adaptation and test stimuli of Experiment 4 in a gray scale. The line (0.2° width) on the test stimulus could be dark gray (7.69 cd/m^2), blue (19.15 cd/m^2) or yellow (96.61 cd/m^2).

achromatic boundary might not have any influence on the perceived color, or the boundaries having chromatic properties might have different effects on the perceived color in the afterimage. The achromatic boundary was dark gray of 7.69 cd/m^2, and the chromatic boundary was blue of 19.15 cd/m^2 or yellow of 96.61 cd/m^2. The color of chromatic boundary was chosen among four primary colors except for red and green colors used in adaptation stimulus. (Fig. 7) shows the stimuli and the procedure for adaptation and test in Experiment 4. Observers indicated if the central area split by the boundary in the afterimage appeared divided into two colors by a yes-no key pressing before they matched the perceived color on the color selection box. In the case that they responded there were two colors divided on the central area in the afterimage, the color selection box showed up twice, one for the left field and the other for the right field of the central area in the afterimage. The rest of the procedure was identical to that of Experiment 1.

Results

All the observers reported that the central area in the afterimage was divided into two colors when the area was split by a visual boundary no matter which color of line was inserted in the test stimulus. The left field of the central area in the afterimage appeared reddish orange (CIE 1931 chromaticity, x = 0.3281, y = 0.3403) on average, the right field of the central area in the afterimage appeared green (CIE 1931 chromaticity, x = 0.312, y = 0.3498) on average. The results with three kinds of boundary color are shown in Fig. 8. The blue, yellow, and dark gray lines inserted in the test stimuli made the afterimages of the gray circle on a bichromatic background appear divided into two separated colors. The Euclidean distance referring to saturation and the angle referring to hue difference of each point were not significantly correlated with the boundary colors used in the test stimulus (saturation on the left field from the central line: r = .975, angle on the left field from the central line: r = .981, saturation on the right field from the central line: r = .957, angle on the right field from the central line: r = -.809).

In brief, boundaries put centered on the test stimulus could let the induced color in the afterimage be divided into two



(a) Left field from the central line (b) Right field from the central line

(Fig. 8) Zoomed-in view of CIE 1931 xy chromaticity diagram. x indicates the white point (x = 0.3172, y = 0.3290). (a) The left field of the central area in the afterimage appeared reddish orange (x = 0.3281, y = 0.3403) on average. (b) The right field of the central area in the afterimage appeared green (x = 0.312, y = 0.3498) on average.

adaptation background colors (not mixed), and any of three boundaries including achromatic boundary had the same effect on the perception of the afterimage. The boundary in the test stimulus seems to prevent the induced color on each side of the test field from spreading to the other side of the test field so that the induced color on one side cannot be mixed with the induced color on the other side. The explanations for the results are elucidated more minutely in discussion section. Supplementarily, the fact that especially the achromatic dark gray could make a border for the spreading colors agrees with the hypothesis of Kelly and Martinez-Uriegas [12] that color and luminance signals share the parvocellular pathways. In other words, it was possible for the achromatic boundary to hinder the induced color from propagating inward because the achromatic signals take the same pathways as the chromatic signals take in some ways.

DISCUSSION

The present study has tried to demonstrate that the perceived color on the afterimage of a gray circle on a bichromatic background derives from the additive mixture of two colors in the background. The results of Experiment 1 showed that the afterimage of a gray circle on an equiluminant red/green background appeared yellow, the afterimage of a gray circle on an equiluminant blue/green background appeared cyan, and the afterimage of a gray circle on an equiluminant blue/yellow background appeared achromatic gray. In the case of the blue/yellow background, the afterimage of the gray circle appeared somewhat greenish gray because the yellow in the background became more like green for an equiluminant point with blue in Experiment 1. In sum, the afterimage of a gray circle on a bichromatic background appeared a color between two colors of the background in the CIE chromaticity diagram, and this result leads to the conclusion that an additive mixture of two background colors is perceived in the afterimage of a neutral patch on a bichromatic background.

To disprove the hypothesis that the equiluminant state of the two colors in the background might be the reason for the phenomenon of additive color mixture in the afterimage, Experiment 2 was conducted with various luminance differences between the two colors in the background. The chromatic mixture of the afterimages still appeared with a bichromatic background at different luminance levels. The results of Experiment 2 disagree somewhat with the works of Watanabe and Sato [17] on neon color spreading in the Ehrenstein-plus-cross configuration. In their works, illusory contour did not occur when the cross and the outer segments were equiluminant. In the present study, the chromatic mixture of afterimages occurred both in equiluminance conditions and in different luminance conditions. On the other hand, the results of the present study agree with some of the findings of Ejima et al. [6]: the luminance ratios of the stimuli were one of the main factors in the magnitude of the neon color spreading. As the overall luminance levels increased, the perceived color on the afterimage of the gray circle appeared more saturated. This shows that the saturation of the afterimage depends upon the luminance of the adaptation stimuli.

The spatial range of the induced color on the afterimage of the gray circle was investigated in this study. Pinna, Brelstaff and Spillmann [16] found that the watercolor effect [15] had large spatial extent by color spreading from a flanking line, and their results coincided with those of the present study. The sizes of the gray circle ranging from 1.5° to 5° were used to examine the spatial extent of the induced color on the afterimage, and the perception of the color was constant even though the saturation of the induced color slightly decreased as the size of the gray circle increased. It is, however, hard to suggest that the large spatial extent of the chromatic mixture in the afterimage proves large receptive fields in perceiving the induced color on the afterimage of the gray circle just as Pinna [15] suggested because the phenomenon shown in the present study could be caused by assimilation of the afterimage to the color induced on the very center of the gray circle. The very center area of the gray circle has a strong possibility to be adapted to both background colors because the control of eye movement by participants might be imperfect and this could interrupt the successful adaptation to the stimuli, and then the yellow color induced by adaptation to both red and green might assimilate greatly into the rest of the test field like the well-known Craik-O□Brien-Cornsweet effect [4, 5, 13].

The most interesting aspect of the chromatic mixture of the afterimage is that the mixture phenomenon did not occur with a line crossing the center in the test stimulus. Grossberg and Mingolla□s [8] model of boundary contour system and feature contour system supports the results of the present study. Without a boundary on the test stimulus, the induced colors on the afterimage spread inside of the central area corresponding to the gray circle of the adaptation stimulus, and the color information is too weak to create a subjective boundary between the two colors and consequently the colors propagate inward, fill the surface, and finally appear mixed. Contrarily, with a boundary on the test stimulus, the two induced colors do not leak out of the boundary on both sides of it. The visual line on the test stimulus locks the induced colors in their originated fields, and therefore the color does not appear mixed with the other one. This could explain why red and green were separately appeared on each side of the central circle afterimage in Experiment 4. In the present study, however, the luminance levels used for adaptation could have not been sufficient to generate vivid afterimages and make the generated color information create a subjective boundary between the two colors. If the generated color information was strong enough to produce the subjective boundary, the afterimages might not appear mixed but separated into two different colors. Further study is needed to testify the possibilities by applying higher luminance levels for adaptation. It is also necessary to elucidate the temporal properties of color spreading and mixing of the afterimages in further research.

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