Paper

Color Appearance of Object Colors in Peripheral Vision at Various Illuminance Levels

Akira YUJIRI* and Hiroshi HAMADA**

*Faculty of Engineering, Hiroshima Institute of Technology

**Graduate School of Engineering, Hiroshima Institute of Technology

2-1-1, Miyake, Saeki-Ku, Hiroshima 731-5193, Japan

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ABSTRACT

The color appearance in peripheral vision was studied for chromatic object colors over a wide illuminance range from photopic to scotopic vision. Swedish NCS color samples with the existing maximum chromaticness at each of eight different hues were used for color stimuli in the experiment. The size of the stimulus was set at 2° of the visual field and the background was N2.5. The stimuli were presented horizontal and vertical meridians, and meridians inclined at angles of 45°. The illuminance level was set at six levels in the range from 0.01lx to 1000lx. The evaluation method was to measure the chromatic, the white, and the black components, and the hue component of the stimuli. As a result, the chromatic component was found decreased with the increasing eccentricity, and the hues shifted toward yellow in the case of stimuli containing a yellow component and toward blue in the case of stimuli containing a blue component, when the illuminance level was decreased in the peripheral vision.

KEYWORDS: peripheral vision, chromatic component, hue component, object color, illuminance level

1. Introduction

In our daily life we experience the color perception response at the periphery of the retina as being inferior to the response at the fovea centralis. The study of color appearance in the peripheral vision is important, not only for clarifying the visual data processing mechanism, but also from the view point of its various applications, such as the evaluation of the color appearance of traffic signs and signals. In past studies of the color appearance in the peripheral vision, there are reports that it is different from the color appearance in the central vision. The experimental conditions of the previous studies^{1)-3),6),7),11)-14)} are shown in Table 1. In the studies using monochromatic light for the stimulus, it was reported that the saturation of the color appearance decreased significantly in parallel with an increase in the eccentricity of the peripheral vision¹⁾⁻³⁾. In the studies that examined the size of the color visual field, it was reported that the size of the opponent colors r-g was narrower than that of y-b⁴⁾⁻⁷⁾. On the other hand, Takase et al.⁸⁾ examined the saturation response properties using as experimental conditions spectral lights near to the unique hues as stimuli and with a white surround of 120 cd/m² to the daily environment, and, based upon the results, reported that the reduction in saturation due to an increase in the eccentricity of the peripheral vision was gradual and that there were negligible differences in the sizes of the color visual field for red, yellow, green, and blue lights. In all the above studies, the color appearance of the peripheral vision in the photopic vision level was examined, and it was shown

that the properties in cases with a dark background were different from those in cases with a common, bright background. The number of reports in which the object color was used for the stimuli is few. In the study by Uchikawa et al.⁵⁾, in which the color appearance of the peripheral vision at the photopic vision with color chips used as stimuli was examined, it was reported that, red and especially green responses are smaller in the periphery than in the fovea, and blue and yellow responses dominate in the periphery. This result means that the color visual field of the opponent colors r-g is narrower than that of y-b.

However, we live in illuminance levels that vary in a wide range and, furthermore, we see the object color as targets in many cases. Therefore, in view of the actual visual environment and the applications, it is important to examine the changes in the color appearance of the peripheral vision under illuminance levels of a wide range from photopic vision to scotopic vision with the object colors used as the stimuli. Hence, experiments were implemented in this paper to obtain basic data on how the color appearance of the object color in the peripheral vision varies under illuminance levels from photopic vision to scotopic vision.

Table 1 Experimental conditions of the research in a past on color appearance in peripheral vision.

No.	Authors	Test stimulus			Surround condition (Background)	Eccentricity	No. of observer
		Type	Size	Luminance (Illuminance)			
1	Moreland et al. (1958)	monochromatic 2colors 494.0nm, 582.5nm	rectangle 80'x40'	30 phot. Td	dark	horizontal nasal retina 15°, 25°, 30°, 40°, 50° Vertical lower retina 10°, 15°, 25°, 30°	2
2	Boynton et al. (1964)	monochromatic 23colors	circle 3°	1000 Td	dark	horizontal temporal retina 0°, 20°, 40°	2
3	Gordon et al. (1977)	monochromatic 22colors	circle 1.5°, 6.5°	1200 Td	dark	horizontal nasal retina 0°, 45°	6
4	Stavell et al. (1982)	monochromatic 16colors	rectangle 1°x2°	2.5log unit	dark	horizontal nasal retina 17°, 25°, 40°, 60° temporal retina 40°, 70°	2
5	Sekiguti et al. (1983)	monochromatic 2colors 450nm, 510nm, 570nm, 650nm	ellipse 2°x2.4°	equal brightness with 3cd/m ² white light at the fovea	dark	6direction 9° interval up to 90°	1
6	Takase et al. (1991)	monochromatic 4colors 465nm, 505nm, 76nm, 630nm	circle 2°	equal brightness with 250cd/m ² white light at the fovea	paint of Munsell N5.5 120 cd/m ²	horizontal temporal retina 0°, 10°, 20°, 30°, 40° (or 50°), 70°	10
7	Abramov et al. (1991)	monochromatic 23colors	circle 0.25°, 0.5°, 1°, 2° at 5°eccentricity 1°, 2°, 3°, 5° at 10°eccentricity 1°, 2°, 4°, 6° at 20°eccentricity Total : 33 stimulus fields	20 Td	dark	horizontal nasal and temporal retina 0°, 5°, 10°, 20°, 40°	6
8	Abramov et al. (1992)	monochromatic 23colors	circle 0.25°, 0.5°, 1°, 2° at 5°eccentricity 1°, 2°, 4°, 6° at 20 and 40°eccentricity Total : 25 stimulus fields	20 Td	5800K White 8TD	horizontal nasal and temporal retina 0°, 5°, 10°, 20°, 40°	4
9	Sakurai et al. (2000)	CRT Red, Yellow, Green, Blue	square 2°x2°	equal brightness with 250cd/m ² white light at the fovea	dark	horizontal temporal field 0°, 20°, 40°, 60° nasal field 0°, 20°, 40°	4

2. Experiment

2.1 Experimental Apparatus

The color appearance of the object color varies by the spectral components of the light source that illuminate the object as well as by the background color. Thus, in order to eliminate this influence, a hemisphere with a 45cm radius, painted with paint of N2.5 was used, so that the influence of the light reflected from the inside surface was avoided, as shown in Fig. 1. And it was illuminated by high-color-rendering N-EDL fluorescent lamps with the correlated color temperature of 5000K, CIE general color rendering index of R_a 95, and each of the CIE special color rendering index from R_9 to R_{15} exceeded 85.

2.2 Experimental Conditions

As the experimental condition to examine the color appearance in the peripheral vision by illuminance level, eight colors were used in this experiment: red (R), yellow (Y), green (G), and blue (B), which are judged the unique hue in the NCS color notation system, and their intermediate colors of Y50R, G50Y, B50G, and R50B. Table 2 shows the NCS notation for the color chips used, their Munsell notation and that for the background N2.5 when they were illuminated by the test light source, their CIE x, y chromaticity coordinates, and their luminous reflectance. The size of the stimuli were set at 2° of the visual field, where the cone cells are

Fig.1 Schematic drawings of experimental equipment.

Table 2. Colorimetric specifications for the 8 test color chips and a N2.5/background chip.

Test color chips		CIE specification		
NCS notation	Munsell notation	x	y	Y
1090-R	6.5R3.6/14.2	0.631	0.317	11.40
0080-Y	5.9Y8.4/12.7	0.479	0.475	67.32
2070-G	4.3G4.8/11.4	0.237	0.491	17.48
1070-B	8.6B5.1/9.8	0.203	0.262	19.75
0090-Y50R	2.3YR6.3/15.3	0.578	0.391	37.17
1080-G50Y	5.2GY6.5/10.1	0.409	0.516	35.67
2060-B50G	6.7BG5.2/9.0	0.212	0.353	20.29
3060-R50B	7.9P3.1/9.0	0.359	0.230	7.10
Background N2.5		0.348	0.346	4.58

Fig.2 The angle of eccentricity and the meridian of the presentation position of the stimulation.

concentrated, in order to enable comparison with the data from other experiments that used colored lights as well as color chips. The stimulus was set as a 1.57cm square of by means of a mask with the background N2.5 and it was observed from a distance of 45cm. As shown in Fig. 2, the positions for presenting the stimuli in the visual field were along eight directions, with the horizontal one on the nasal side of the left eye visual field as 0° and, in counter-clockwise order, at 45°, 90°, 135°, 180°, 225°, 270°, and 315°. Regarding the eccentricity, it was set so that a stimulus could be presented along all the directions with 0° at the fovea centralis and moving out to 80° at 10° intervals. The illuminance level was set at six levels — 0.01, 0.1, 1, 10, 100, and 1000lx — in order to examine the properties of the color appearance from photopic vision to scotopic vision. Adjustment of the illuminance level was made by means of adjusting the number of the lamps lit and the illuminating

area by attaching a black paper cover over the lamps. At the time of adjustment, a attention was paid so that there was no dispersion in the illuminance distribution in the hemisphere.

2.3 Procedure

Before commencing the experiment, the subjects adapted to the surface of uncolored N2.5 at 0.01lx illuminated by the test light source for more than one minute after adapting to the dark for 30 minutes. Then subjects observed the color chips presented by the experimenters to evaluate the color appearance while gazing at a fixed gazing point (diameter 5mm, value N6) with their head fixed on the chin rest. The evaluation method for measuring how the color appearance of the stimulus changed by illuminance level was as follows. The observer estimated the ratio of the chromatic, white and black components of the test stimulus, the example is shown in equation(1), and when the chromatic component value is other than zero, the observer estimated the ratio within four colors of red, yellow, green and blue in one color or two colors, the example is shown in equation (2).

$$\begin{aligned} &7(\text{chromatic component})+2(\text{white component}) \\ &+1(\text{black component})=10(100\%) \end{aligned} \quad (1)$$

$$\begin{aligned} &6(\text{red component})+4(\text{yellow component}) \\ &=10(100\%) \end{aligned} \quad (2)$$

The stimuli were presented at the positions along each direction with the eccentricity at angles of 0° to 80° in 10° intervals. As a result of a preparatory experiment, it was found that a lot of time was needed between presenting a stimulus and its recognition in some cases, since the experiment was carried out in the extremely low illuminance level of 0.01lx. Therefore, in this experiment, no limit was set on the observation time, and the subjects were instructed to evaluate the color appearance of the stimulus immediately when they recognized the stimulus. Also, a sufficient time interval was set when a stimulus was presented with a changed eccentricity. Therefore, it is considered that there was no reduction in the chromatic component due to influence of the Troxler effect. The color appearance of the eight kinds of color chips was measured at one illuminance level. Then, similar experiments were implemented with illuminance levels successively increased to 0.1, 1, 10, 100, and 1000lx. The above procedure was considered as one session and five sessions were carried out. The averages of the experimental results were processed. The measuring time for one session was around two hours per one subject, including the adaptation time, adjustment of the illuminance level, and the time required for changing the stimuli. The number of subjects was thirteen, aged from 22 to 24, all with normal color vision.

3. Results and Discussion

Although there were individual variation in the experimental results noted in the size of the chromatic component and in changes in the hue owing to the illuminance level and the eccentricity, their trends were almost the same. Hence, results that are the averages for the thirteen subjects are shown in this paper.

Fig.3 Chromatic components for R,Y,G,B test color chips as a function of eccentricity with the illuminance level at the 0° and 180° meridians.

Fig.4 Same as Fig.3, but for the 90° and 270° meridians.

3.1 Changes in Chromatic Component by Illuminance Level

Fig. 3 and Fig. 4 show the results of the chromatic component of the R, Y, G, and B stimuli by illuminance level. The symbols represent the averages for the 13 observers, and bars represent the standard deviations. In the figure,

since the bar is difficult to see it in overlapping with showing the standard deviation of all illuminance, the effect of the illuminance was shown at 1000lx and 1lx. Fig. 3 is the results in the horizontal meridian and Fig. 4 is the results in the vertical meridian, each of which shows the eccentricity along the horizontal axis and the chromatic

component along the vertical axis. As a whole, the color appearance changed largely by the illuminance level and the eccentricity, and the chromatic component was reduced due to a reduction in the illuminance level on all stimuli even in the central vision, so that the component became nearly zero at 0.01lx. This is consistent with the earlier experimental results on the central vision by Yujiri et al⁹.

Regarding the R stimulus in the results of horizontal meridian shown in Fig. 3, the chromatic component in the case of 1000lx was about 10 at the eccentricity of 0°. It seems to be because the color chip is very vividly seen, because the background is the black. It is reported observer very vividly. And it was 9 at the eccentricity of 40° in the left side, 8.2 at 60°, and 7 at 80°, while, on the right side, it was 8.6 at 40° and 7.8 at 60°, showing a larger reduction level compared to the left side. When the illuminance level was reduced, this trend became stronger, and the color perception responses were obtained only up to 50° on the left side and up to 30° in the right side in the case of 1lx, and it is noted that the corresponding chromatic component was reduced to 0.6 at 50° on the left side and to 1.1 at 30° on the right side. Moreover, when they are compared at the same angles on the left and right sides with the eccentricity of 0° at the center, it is known that the changes in the color perception response is non-linear against the changes in the angle of eccentricity and, at the same time, that they are not symmetrical on the left and right sides. This result is consistent with the results reported by Takase et al⁹, Yujiri et al¹⁰, and Sakurai et al¹¹.

Regarding the Y stimulus, it showed a similar trend as R, but its degree of reduction in the chromatic component due to a reduction in the illuminance level was smaller than that with R. Especially, the degree of reduction in the chromatic component in the peripheral vision with 10lx and 1lx was smaller than with R, and it was 4.4 (or higher than R by 1.3) at 60° on the left side with 10lx and 5.4 (or higher than R by 1.6) at 40° on the right side. Also at 1lx, R showed a chromatic component of 0 at 60° on the left side and at 40° on the right side, while Y showed 0.5 and 0.9 at these positions respectively. Thus, the color perception response in the peripheral vision with Y was proved to be stronger than that with R.

Regarding the G stimulus, the size of its chromatic component was almost the same as that for R at 1000lx and 100lx, while the degree of its reduction in the chromatic component in the peripheral vision was smaller than that of R at the illuminance level of 10lx. Its chromatic component reduced significantly at 1lx and below, and its color visual field narrowed to 30° on both the left and right sides at 1lx.

Regarding the B stimulus, a very small chromatic component was seen at illuminance levels of 0.1lx: 1.7 in the central vision and 1.0 and below with the eccentricity exceeding 10° on both the left and the right sides. In the illuminance level of 1lx and above, both of its chromatic component and size of color visual field showed almost the same properties as those of the Y stimulus.

From the above results, it was suggested that the color response of the opponent colors y-b is stronger than that for r-g in the horizontal meridian. Also, the result that the size of the color visual field and the chromatic component in the horizontal meridian were larger on the temporal side than on the nasal side is consistent with the results of Stabell et al¹² and Abramov et al^{13,14}, which showed the characteristic of the temporal side being dominant. It can be said that this indicates a higher density distribution of cones on the nasal retina than the temporal retina. It has been anatomically shown that the density distribution of cones is different between these areas¹⁵.

Regarding the results on the vertical meridian per Fig. 4, a larger decrease in the chromatic component versus the eccentricity was shown compared to the horizontal meridian.

Regarding the R stimulus, even with the high illuminance of 1000lx, the perception limit of the upper side was 50°, at which point the chromatic component reduced significantly to 6.8 compared to that of the central vision. In the lower side, there was color perception up to 60°, and the degree of reduction in the chromatic component was smaller than the upper side: 8.3 at 50° and 7.6 even at 60°. There was color recognition only up to 40° in the upper side under 100lx and 10lx, and the corresponding chromatic component was 6.1 at 100lx and 2.4 at 10lx, from which it was learned that the influence of the illuminance is large.

Regarding the Y stimulus, the chromatic component was larger than it was for the R stimulus in the peripheral vision, and the degree of reduction in the chromatic component with an increase in the eccentricity also was smaller. Furthermore, when the results of vertical meridian for Y are compared to the results of the same Y stimulus in the horizontal meridian, the reduction in the chromatic component on the upper side is outstanding. When the chromatic components are compared at 50°, which is the upper limit of color perception on the upper side, the chromatic component was 8.6 on the left side and 7.4 on the right side in the horizontal meridian, and 5.2 on the upper side and 8.1 on the lower side in the vertical meridian. Thus, it was learned that the chromatic component on the upper side got smaller.

Regarding the G stimulus, when the eccentricity was increased, the chromatic component got smaller compared to the Y stimulus and, furthermore, the color visual field got narrower by 10° on the upper side with 100lx and 10lx. Also, the degree of reduction in the chromatic component versus the eccentricity was larger in the vertical meridian compared to the horizontal meridian. When the G stimulus chromatic components are compared at 40°, which is the upper limit of color perception on the upper side, even in the case of 1000lx the chromatic component was 8.7 at 40° on the left side, 7.4 at 40° on the right side, and 8.2 at 40° on the lower side versus 7.1 at 40° on the upper side. Thus, it was learned that the chromatic component on the upper side in the vertical meridian is smaller than in the other meridians.

Regarding the B stimulus, in the case of 100lx, the color visual field got narrower by 10° on the upper side compared

to the Y stimulus, but the other properties showed almost the same results compared to the Y stimulus. When the color visual field with B stimulus is compared along the horizontal meridian, the degree of reduction in the chromatic component against the angle of eccentricity was larger. When the chromatic components are compared at 50°, which is the upper limit of color perception on the upper side, even in the case of 1000lx the chromatic component was 8.4 at 50° on the left side, 7.2 at 50° on the right side, and 7.7 at 50° on the lower side versus 5.6 at 50° on the upper side. Thus, it was learned that the chromatic component on the upper side in the vertical meridian is smaller than those in the other meridians.

Accordingly, it was suggested that the color response for the opponent colors y-b is stronger than for r-g also in the vertical meridian, which is similar to the horizontal meridian case.

From the results along the horizontal meridian and along the vertical meridian mentioned above, the properties of the chromatic component in the photopic vision level showed a tendency similar to the results reported by Takase et al.⁹⁾, Sekiguchi et al.⁹⁾, Moreland et al.⁷⁾, Stabell et al.¹²⁾, Abramov et al.¹³⁾, and Sakurai et al.¹¹⁾, in which the stimulus modes were different. The inclined directions also showed a similar tendency. It is believed that the color response was weakened in the peripheral vision, compared to the central vision, because the density of the cones reduces in parallel with an increase in the eccentricity. Similar results were shown when the intermediate colors Y50R, G50Y, B50G, and R50B were used for the stimuli. Also, when the illuminance level was lowered, the chromatic component was reduced even in the central vision, and, furthermore, when the eccentricity increased, the component was reduced significantly. From these results, it can be said that the degree of the reduction in the sensitivity of the cones increased in parallel with a reduction in the illuminance, which results in an extremely small response of the cones in the peripheral vision.

3.2 Changes in Size of Color Visual Field by Illuminance Level

Fig. 5 shows the sizes of the color visual field for the eight kinds of stimuli. Here, the results for the illuminance levels of 1000lx and 1lx are shown in order to compare the size of the color visual field in the photopic vision and the size in the mesopic vision. The size of color vision in the figure is expressed by the boundary level of the perceived chromatic component by illuminance level.

In regard to the size of the color visual field for the R, Y, G, and B stimuli, the size in the case of 1000lx was the same in each direction for all stimuli, except for the upper side with the G stimulus, which was narrower than the other stimuli by 10°. In the case of 1 lx, the size for the R and G stimuli became narrower than that for the Y and B stimuli in all directions except the upper direction.

In regard to the size of the color visual field for the intermediate colors Y50R, G50Y, B50G, and R50B, only

Y50R got wider on the upper side by 10° in the case of 1000 lx. In the case of 1 lx, the color visual field of R50B and G50Y, which included an red component and a green component, got narrower, as was the case with the R and G stimuli, while the color visual field for Y50R and G50Y did not narrow as much as those for R50B and G50Y. Especially, it is considered that the color visual field of Y50R was wide because its saturation in the Munsell notation was higher than the other stimuli and also because some subjects reported their impression that it appeared more fresh compared to the other stimuli when the angle of eccentricity was large. Also, it is considered with the B50G stimulus that the color appearance shifted toward the B side with the low illuminance and that the color visual field was larger owing to the influence of the blue component.

From the results mentioned above, it was shown that the differences in the sizes of the color visual field of the unique R,Y,G and B stimuli were small in the case of the 1000lx high illuminance, which was similar to the results reported by Takase et al.⁹⁾ that used spectral lights as stimuli. However, it was clarified that, when the illuminance level was reduced, the differences in the color visual field depending upon the kind of stimulus were enlarged and that the color visual field for the color appearances of R and G stimuli became much narrower than those for the Y and B stimuli.

3.3 Changes in Hues by Illuminance Level

Fig. 6 and Fig. 7 show the evaluation results of the changes in hue. The symbols represent the average the 13 observers, and bars represent the standard deviations. Fig. 6 shows the properties in the case of 1000lx, and there were no changes in the hue by the eccentricity in all directions for the R, Y, G, and B stimuli. This seems to be because the other response was zero within r-g or y-b opponent color response. In a study by Sakurai et al.¹¹⁾ in which a CRT was used for the stimuli, although the hue of the color appearance in the central vision was evaluated to be a color close to unique red in the case of the R stimulus and nearly unique green in the case of the G stimulus, it was reported that at the eccentricity of 60° on the temporal side of the horizontal meridian the R stimulus shifted toward yellow at the ratio of 8:2 in the red versus yellow and the G stimulus shifted toward yellow at the ratio of 5:5 in yellow versus green. It also determined that the G stimulus was very close to unique yellow at 40° on the nasal side. These results were different from the results in this experiment in which the hues were constant. It is not clear if such a difference is attributable to the difference in the mode of presenting the stimuli, to the mechanism of visual perception, or other factors. A future study on it is needed.

The intermediate color stimuli Y50R and G50Y shifted toward the yellow in all directions as the eccentricity increased. Also, the B50G and R50B stimuli shifted toward blue in all directions when the eccentricity increased. It can be said from these facts that, similar to the study of Stabell et al.¹²⁾, the response of the opponent colors y-b became

Fig.5 Chromatic limits at 1000lx and 1lx in field of left eyes.

Fig.6 Change of hue for the eight color chips as a function of eccentricity in different meridian at 1000lx.

Fig.7 Same as Fig.6, but obtained at 1lx.

stronger than that of r-g when the eccentricity increased in the peripheral vision, resulting in a shifting of the stimuli including a yellow component toward yellow and in a shifting of the stimuli including a blue component toward blue.

Fig. 7 shows the properties in the case of 1lx. Although there was no change in the hue due to the degree of the eccentricity in all directions for the R, Y, and B stimuli, the G stimulus shifted toward blue in parallel with an increase in the eccentricity and its ratio of green component to blue component became almost even at the eccentricity of 30° in all directions. The intermediate color G50Y shifted toward yellow in all directions when the eccentricity increased. Also, B50G shifted toward blue in all directions when the eccentricity increased and the proportion of the blue component became larger than that of green component. As a result, it is considered that in the mesopic vision with an illuminance level of 1lx in the response of the M cone was smaller than that of the S cone, resulting in a shift toward blue.

4. Conclusions

Considering the data from this study, we make the following major conclusions.

- (1) Similar to the results obtained in previous studies, the chromatic components in the photopic vision were greatest in the central vision and it reduced in parallel with an increase in the eccentricity. The degree of the reduction was non-linear and the size of the chromatic component was not symmetrical in all directions from the fovea centralis. It was suggested by this fact that the distribution density and sensitivity of the L, M and S cones were different by direction even if the degree of the eccentricity was the same.
- (2) It was suggested that the color response of the opponent colors y-b is stronger than that for r-g in peripheral vision, measuring the Y and B stimuli resulted in larger visual fields and the hues shifted toward yellow in cases of stimuli containing a yellow component and toward blue in cases of stimuli containing a blue component.
- (3) When the illuminance level was reduced, the chromatic components decreased in parallel with an increase in the eccentricity, but the degree of the changes varied remarkably by the kind of stimulus; the reduction in the response of the opponent colors r-g in the peripheral vision was outstanding and its size of the visual field became extremely small. Also, the hues of stimuli that contain a blue component especially shifted toward blue.

As shown above, the response of the opponent colors y-b was shown to be stronger than that of the opponent colors r-g at the photopic level, even when the object color was used for the stimuli, which is similar to the results in the previous studies, which used monochromatic light for the stimuli.

In addition, the results of this experiment clarified that, even in the case of a reduced illuminance level, the reduction in the sensitivity of y-b is smaller than that of r-g and the size of the visual field of y-b is larger than that of r-g.

We are confident that in the visual environment involving illuminance, these results are extremely helpful both to basic study and practical use.

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