Chromaticity Diagrams and Retinal Color Processes

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INTRODUCTION

Newton devised a circular color table to give a graphical representation to his conception on the color mixture. Subsequently Maxwell noticed that in the color mixture, the spectral colors could not be arranged on a circle, but that they had to be placed on the straight sides of a triangle.

Thus Maxwell, Helmholtz and others determined a spectral color triangle on the basis of the color mixing system by using the red, green and blue spectral lights as the three primaries.

König and Dieterici,¹⁾ Abney²⁾ and others determined the so-called primary sensation curves, which were studied in further details by many investigators such as Exner, Ives, Haschek³⁾ and others. These curves gave rise to a misunderstanding among some physiologists and physicists that they were a certain expression of physiological color processes involved, but in reality they are nothing but a product of a mathematical treatment of the data obtained from color mixing experiments.

It is certain that such a treatment is based, to a certain extent, on the trichromatic theory of Young-Helmholtz and that the trichromatic system is useful as a framework for color specification, but it does not follow from those facts that there exist three spectral physiological processes which would correspond to the scheme of the trichromatic theory.

Recently Motokawa⁴⁾⁵⁾ derived three curves very similar to the primary sensation curves from the data obtained by means of his newly devised physiological method and constructed a color diagram which closely resembles the usual chromaticity diagram. It deserves attention that a color diagram has been constructed from physiological data without resort to any color mixing procedure.

His diagram is, however, based on the data of only one subject. Therefore, we intended in the present investigation to confirm his result

on other subjects and to clarify the significance of such physiological color diagrams by comparing them with the usual chromaticity diagram based on the color mixture.

EXPERIMENTAL

Method and Results

The method used was essentially the same as that employed by Motokawa.

A pair of silver electrodes of 2×1.5 cm. in size, one on the forehead slightly above the eyebrow, and the other on the homolateral temple of the subject served for electrical stimulation of the eye. The stimulating current used was a single constant current pulse of 100 msec. in duration. An opaque glass disc of 1 cm. in diameter, which was illuminated from behind by monochromatic light from a spectroscope, was viewed from a distance of 30 cm., the visual angle subtended by the disc at the eye being 2° .

The disc was centrally fixated in all our experiments. The energy of monochromatic light was always kept constant by adjusting the width of the collimator slit to prescribed values computed from the spectral energy distribution of the light source.

The object of measurements was the effect of monochromatic illumination which was measurable as increases in electrical excitability of the retina following the illumination. Increases in electrical excitability were measured in the following manner. After preliminary dark adaptation of about 20 minutes an electrical pulse was passed through the eye so as to cause a distinct electrical phosphene. The voltage was then reduced step by step until the subject could no more distinguish the stimulus in question from one far below the threshold. One value of threshold could usually be determined after about 20—40 repeated trials. Thus the threshold at the resting level of the eye was determined. Then, similar measurements were carried out at 1, 1.5, 2 and 3 seconds after termination of a 2 sec. illumination by monochromatic light. The difference of excitabilities, reciprocals of threshold values determined with and without pre-illumination was expressed in percentage of the resting excitability and denoted by ζ .

As was shown by Motokawa,⁴⁾ ζ -time curves for red, yellow, green and blue lights had a maximum at about 1, 1.5, 2 and 3 seconds after cessation of the pre-illuminating light. The crest times which characterize the pre-illuminating light depended only on the wave-length, but not on the intensity and duration of the light. The height of the maximum, however, increased in proportion to the logarithm of the intensity within

a wide range of moderate intensities.

According to Motokawa's analysis⁵¹ ζ -values at 1, 1.5, 2 and 3 seconds after illumination indicate the excitation of the red, yellow, green and blue receptors respectively. If this interpretation is correct, the spectral distribution of ζ as determined, say—at 3 seconds after illumination—should give a spectral distribution of the excitability of the blue receptor.

Based on this principle, we determined ζ -values after 2 sec. exposure of the eye to various spectral lights, the interval between the end of illumination and the electrical stimulus being fixed at 3 seconds, and thus the spectral distribution curve B in Fig. 1 was mapped out. Similarly the curves G, Y and R were obtained by fixing the interval at 2, 1.5 and 1 seconds respectively.

For comparison, Motokawa's result is represented as the set of curves (M.) in Fig. 1. The other sets, (A.) and (O.) were obtained in the present experiments from subjects A. and O. respectively.

Fig. 1. Physiological sensation curves or response curves from 3 different individuals. Explanation in text.

As can be seen in this figure, the corresponding curves obtained from the three different subjects closely resemble one another not only in shape but also with respect to the location of the maxima.

However, the curves Y in (M.) and (A.) show two humps at the wavelengths corresponding to the maxima of the curves G and R, whereas the Y curve in (O.) has only one maximum at the yellow part of the spectrum. Motokawa⁵⁾ interpreted the Y curve in (M.) to be composed of the two processes R and G, but afterwards it was revealed by further work with an illuminating patch of much reduced visual angle that there exists an independent weak yellow process at the fovea of the human eye.^{6,7)} Therefore the curve Y in (O.) may represent the distribution curve for an independent yellow process.

Physiological color diagram

For specification of colors any color is expressed geometrically by a point on a two-dimensional color diagram such as a color triangle. The coordinate of a color in the usual color triangle is determined by the ratios $r:g:v$, where r , g and v represent the quantities of the three primaries required to prepare a color mixture well-matched with the color in question. Apart from the weak yellow process Y which may come into action at the fovea of normal trichromats, the physiological effects set up by a colored light stimulus in the fovea can be represented by three magnitudes R, G and B, which formally correspond to the quantities of the primaries r , g and v . But one must bear in mind that the quantities r , g and v are generally expressed in terms of the intensity of light, whereas our magnitudes R, G and B are expressed in terms of a physiological quantity. However, there is a linear relation between ζ and the logarithm of light intensity, as has been mentioned above. From this relationship it follows that the ratio of two intensities corresponds to the difference of two ζ -values. We can, therefore, construct a color diagram with differences of our magnitudes R, G and B in a way similar to that in which the usual color triangle is constructed from the ratios $r:g:v$. The color diagrams represented in Fig. 2 were obtained from the data of the sets of curves in Fig. 1, by plotting the difference $G-R$ as ordinate against the difference $B-G$ as abscissa. The points representing white were determined from ζ -values at 1, 2 and 3 seconds after exposure of the eye to the standard white light source C of ICI.

As can be seen in this figure, the three color diagrams for three different subjects are in shape very similar to one another; each of them is a triangle, opening at both ends of the spectrum. Both sides of these triangles are concave towards the point representing white, and the spectral order from blue to red is never retrogressive. These properties are found

Fig. 2. Physiological color diagrams obtained from 3 different individuals. Wave-lengths of spectral lights are given on the contour of the largest diagram. W's represent white points. Ordinates: difference G—R. Abscissas: difference B—G.

also in the usual chromaticity diagram constructed from color mixture data. The red-green side of these triangles slopes more steeply and is more concave than the green-blue side.

The three color diagrams represented in Fig. 2 show, however, some differences in size. It is reported that there are wide individual differences in normal color vision (Pierce,⁸⁾ Tcherning, Larson, Gibson and Tyndall³⁾). According to their views, the differences largely depend upon the individual character of each eye such as the difference of physiological elements of visual function, but partly upon the psychological elements such as the final judgment of the threshold for color perception. Wright,⁹⁾ however, reports that one and the same result for the observers under the most favorable conditions could be secured in color measuring experiments.

The individual difference of the size of color diagrams mentioned above is possibly based upon physiological differences in retinal excitation, for we usually find fairly remarkable individual differences in ζ -values obtained under one and the same experimental conditions. Such individual differences can be seen, for example, in the heights of curves represented in Fig. 1. However, it is not clear whether or not such a size difference of our color diagrams has any connection with the individual difference of optical sensitivity.

It is further to be noted that the three color diagrams are in con-

centric configuration around the white points, their homologous sides running parallel to one another.

The white points of the three subjects do not coincide with one another. Similar differences have been reported by many investigators with regard to the location of the white point in the usual chromaticity diagram.

Wright⁽⁸⁾⁻¹⁰⁾ and Parsons¹¹⁾ ascribed such differences partly to macular pigmentation, but it is difficult to explain the difference observed in our color diagrams from this point of view, because the white point of the oldest subject M., in whom the heaviest macular pigmentation is expected, is not always more displaced toward the green-red side of the color triangle, than those of the other subjects.

The relation that colors complementary to each other are situated on a straight line passing through the white point on both sides of it can be seen also in our color diagrams just as in the usual one, though some pairs of complementary colors are found slightly different from those determined in color mixing experiments. But it is no important matter in view of the circumstance that complementary colors determined by various investigators such as Helmholtz,¹²⁾ v. Frey and v. Kries,¹³⁾ König and Dieterici,¹⁾ Angier and Trendelenburg¹⁴⁾ and others show no exact agreement with one another.

DISCUSSION

As has been shown above, our physiological color diagram bears a striking resemblance to the usual color diagram obtained colorimetrically. This fact suggests that the three-color system has really a certain physiological basis as the Young-Helmholtz's theory advocated. But this does not always imply that the trichromatic theory is valid in a strict sense. As has been stated above, Motokawa *et al*⁽⁶⁾⁽⁷⁾ proved the existence of an independent yellow process at the fovea of normal trichromats, though the development of this process is generally weaker at the fovea than that of the other processes. In construction of our physiological color diagrams, the yellow process was not taken into account, because no two-dimensional diagram can be constructed with 4 components R, Y, G and B. Nevertheless, our color diagrams constructed in this way have proved to represent almost all characteristics of the usual chromaticity diagram and to be as useful as the latter for specification of colors. This situation indicates that the foveal color vision of normal trichromats is essentially trichromatic, and at the same time it may be concluded from our finding that the yellow process plays only an accessory role at the fovea of normal trichromats. Thus, the trichromatic theory has an approximate validity so far as the normal foveal vision at moderate light intensities and within a certain range of visual angle is concerned.

However, in dichromats and anomalous trichromats the yellow process is predominant over the other processes not only in the periphery but also at the fovea of the retina, as was shown by Ebe *et al.*¹⁵⁾ Even in normal trichromats the trichromatic principle no more applies to parafoveal and peripheral vision, because a very prominent yellow process besides the red, green and blue processes appears in these regions of the retina.

SUMMARY

The magnitudes of three color processes R, G and B at the fovea were measured by means of Motokawa's method, which consisted of measuring the electrical excitability of the eye after a brief illumination with monochromatic light of various wave-lengths.

Color diagrams were constructed from the measured magnitudes of R, G and B. They were found very similar to the usual chromaticity diagram constructed from color mixing data. So they can be used for specification of colors. The fact that such a color diagram can be constructed from three physiological quantities suggests that the normal foveal vision is essentially trichromatic. The limitation of the validity of the trichromatic principle was further discussed on the basis of physiological data.

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