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CURRENT PROBLEMS IN RESEARCH

Color Defect and Color Theory

Studies of normal and color-blind persons, including a subject color-blind in one eye but not in the other.

C. H. Graham and Yun Hsia

Different color theories differ greatly in matters of detail, but in one thing they are in agreement: the data of color vision cannot be accounted for in terms of the actions of a single set of receptors or processes with homogeneous characteristics. Rather the facts probably require the postulation of three or more sets of elementary mechanisms, the interactions of which provide the data of various discriminations of color. Thus, the Young-Helmholtz theory (*1, 2*) presumes the existence of three groups of receptors with different absorption characteristics, while the Hering theory (*3, 4*) postulates the existence of three pairs of antagonistic processes in the neural pathways of the visual system. Other theories make use of other devices to account for the phenomena of color.

Theoretical discussions of color vision have, since the time of Young, been influenced to a great extent by considerations of color blindness. It is interesting that Young, at the time he put forward his account of color in the Bakerian lecture for 1801, discussed the important theoretical role of color blindness despite the fact that reliable knowledge of that subject had been in existence for less than a quarter of a century (*5*). The reason for the theoretical importance of color blindness is not far to seek. In its simplest form, as exemplified in Young's ideas, one can think of a specific form of color deficiency as representing the loss of one of the fundamental processes from the total set that exists in normal vision. Since on this basis the eye of the color-blind can be thought of as essentially a reduced system, involving fewer than the normal number of fundamental processes, it might be expected that one could evaluate the missing process by comparing the color discriminations of a normal and color-blind eye. We shall see that such an expectation has, at best, some but certainly not complete support in what is known of the facts of color blindness.

Types of color blindness. There are several kinds of color-blind individuals classifiable in relation to normal subjects and to each other on the basis of their performances in different test situations.

Normal individuals are called *trichromats.* They can achieve a match between two mixtures of lights if one of the mixtures is a combination of a spectral color and a single color from a given unchanging set of three, called primaries, while the other mixture consists of the two remaining primaries. Conventionally, it is said that any spectral color can be matched by a mixture of three primaries, one of the primaries (the one mixed with the spectral color) having a negative value assigned to it. It is by reason of the match involving three primaries that persons with normal color vision are called trichromats.

Dichromats constitute a major class of color-blind individuals. Individuals of this group can establish a match between two mixtures that involve a spectral color and two primaries. Most dichromats are red-green blind; they "confuse" red, yellow, and green. The general class of dichromats may be subdivided into at least three types. The first class is the *protanope* whose sensitivity to wavelengths in the red end of the spectrum is greatly reduced. Another class is the *deuteranope* whose sensitivity is not deficient in the *red.* Protanopes and deuteranopes match a yellow to any amounts of red or green which will give an appropriate matching brightness (or luminance). A third type of dichromat, the *tritanope,* confuses blue and green (*6*).

Nothing will be said in what follows about *monochromats,* individuals who can match all wavelengths of the spectrum against any other wavelength or a white light by the proper adjustment of luminance, nor shall we elaborate on the functions of *anomalous trichromats,* people who, despite the fact that they confuse parts of the spectrum, still need three primaries to match a single wavelength.

The present experiments. This paper (*7*) is concerned with the visual functions of protanopes and deuteranopes, especially deuteranopes. It deals in particular with two theoretically important problems: (i) How is brightness sensitivity distributed in the spectrum for protanopes and deuteranopes? (ii) What colors do such persons *see*? On the basis of the experimental data, some proposals are made bearing on the nature of color function generally and dichromatism specifically (*8*).

Luminosity Curves of Dichromatic and Normal Subjects

The luminosity curve shows how the sensitivity of the eye varies for various wavelengths. Sensitivity (or luminosity) is measured in terms of the reciprocal of the energy required, for example, to pro-

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duce threshold. Figure 1 shows the luminosity curve for the normal subject as well as the curve for the protanope and deuteranope (*9*). Sensitivity for the foveal cones of the normal subject is low in the blue, at a maximum in the yellow-green, and low again in the red.

The curves, as drawn by Hecht and Hsia (*10*), show the data of Pitt (*11*) for dichromats and Gibson and Tyndall (*12*) for normal subjects. The figure shows that, compared with normal luminosity, the curve for the protanope seems to be displaced toward the blue, whereas the deuteranope's curve is displaced a little toward the red.

It has classically been considered that protanopes show a loss of sensitivity in the red part of the spectrum. It is not so certain, however, that deuteranopes show a decrease in sensitivity in any part of the spectrum.

The curves in Fig. 1 are drawn in the traditional way of considering each luminosity function by itself and by placing the point of maximum luminosity for each at 100 percent. It will be shown that this method of representing data provides a difficulty, for it does not tell us whether the sensitivities at the 100-percent values differ in absolute value. For example, one can ask: Does the 100-percent value for the protanope refer to the same energy value as the 100-percent value for the normal subject? Arguments based upon comparisons of curves that demonstrate arbitrarily set maxima are certainly not conclusive. Specifically, the question arises whether the curves of Fig. 1 really have the same height in energy ordinates, and if not, what their relative heights are. This is the question with which we are now concerned.

If color blindness is assumed to represent the loss or inactivation of one of three receptor systems, then the loss of a receptor system should show itself in some loss of brightness in the spectrum as seen by the color-blind. One might expect, for example, each curve for a color-blind subject (Fig. 1) to have a lower maximum than the curve for normal subjects. Abney (*13*) drew such lowered luminosity curves for color-blind subjects. However, his reduced curves were not found from measurements but were formulated in terms of theory. Such reduced curves have only been presented once as the result of experimental research: by Hecht and Hsia (*10*) eleven years ago.

Because of the need for more information on this general question, we decided to investigate the relative heights of the three curves shown in Fig. 1 by measuring the actual energy thresholds of color-blind and normal subjects in different parts of the spectrum. The idea is to determine for a given portion of the spectrum the light energy required at the foveal threshold of normal persons and of color-blind persons, and to do this for different parts of the spectrum.

Selection of subjects. The testing of our subjects involved the usual "screening" tests for color-blindness, the Ishihara and Stilling plates in particular, as well as the determination of the luminances of red and green required to match a yellow on the Hecht-Shlaer (*14, 15*) anomaloscope. In addition, determinations were made, in the case of the protanopes and deuteranopes, of the neutral point in the spectrum—that is, the narrow wavelength band that dichromats see as white. (Normal subjects never see spectral white.) The determinations of the neutral point were made with a modified Helmholtz color mixer (Hecht and Shlaer, *14*). Our final experimental groups included seven normal subjects, five protanopes, and six deuteranopes. The subjects numbered 16 men and 2 women between the ages of 20 and 35 years. (Both of the women had normal vision.)

Apparatus and procedure. Stimulating energies of light were obtained by means of a double monochromator calibrated for radiant flux. The wavelength, energy, duration, and retinal position of the stimulus could be controlled. Observations involved finding the energy threshold for the foveal cones for many narrow wavelength bands throughout the spectrum. Exposure time of each stimulus flash was 4 milliseconds.

At the beginning of each session, the subject became dark adapted for 10 minutes, a sufficient time for the cones to gain full sensitivity. Then the spectral lights were presented to him and he indicated whether or not he saw the light.

Results on normal subjects. Figure 2 gives the average log sensitivity curves for the seven normal subjects, the five protanopes, and the six deuteranopes.

The basic data of these curves are relative energies required for the cones to respond to the spectral lights at the absolute threshold; the logarithms of the reciprocals of these values (that is, log sensitivity values) are here plotted.

The peak of the average curve is arbitrarily set at zero (that is, maximum sensitivity is set at unity). It is to be noted that absolute energies may be calculated by observing that, at $\lambda = 578$ millimicrons (mμ), the average normal threshold is 3.5×10^{-8} erg. This figure amounts to about 10,000 quanta. It may be compared with a figure of about 100 quanta at the cornea obtained by Hecht, Shlaer, and Pirenne (*16*) for the much more sensitive peripheral retina with a small stimulus of $\lambda = 510$ mμ exposed for 1 millisecond.

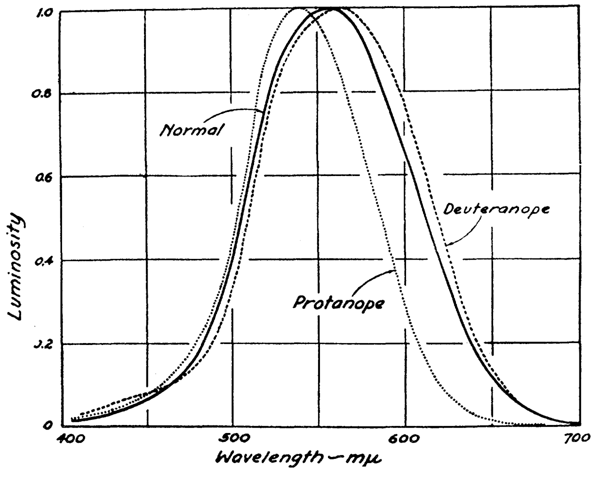
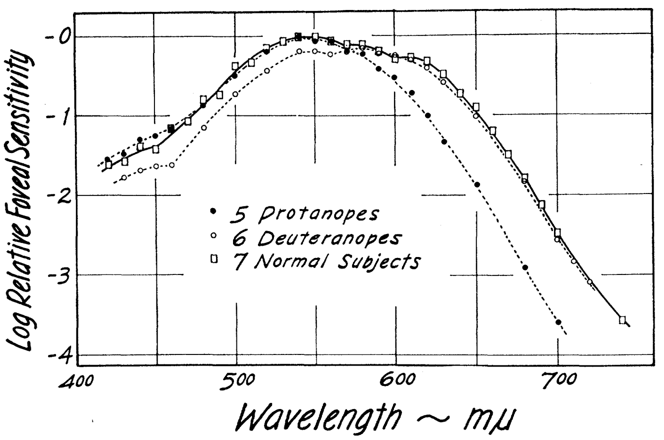


Fig. 1. Pitt's curves (*11*) for protanopes and deuteranopes and the data of Gibson and Tyndall (*12*) for normal subjects. The curves as drawn are from Hecht and Hsia (*10*.)

It is not necessary here to labor the general fact of the "humps" in the blue and in the orange of the normal curve, near 450 and 610 mμ. Presumably they are associated with the positions of curves representing the fundamental processes.

Results on protanopes. The average luminosity curve for five protanopes is given in the same figure. It is to be observed that the average curve for protanopes indicates a greatly increased energy requirement in the red end of the spectrum. In the blue, the energy requirement for protanopes is similar to that for normals.

Results on deuteranopes. Most writers



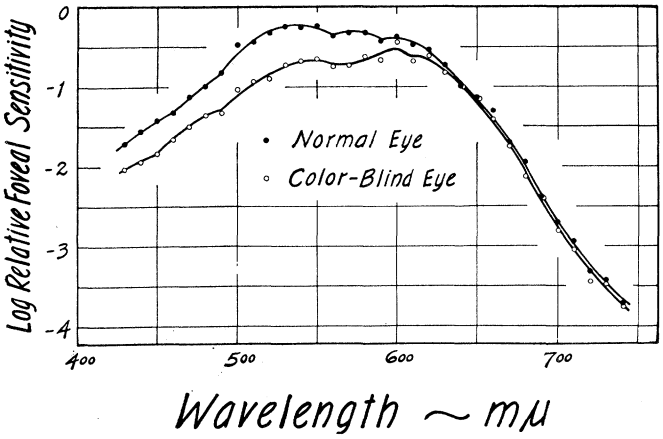


Fig. 2 (Left). The luminosity curves for normal subjects, protanopes, and deuteranopes in experiments by Hsia and Graham (*9*). Fig. 3 (Right). Luminosity curves of a unilaterally color-blind subject. The upper curve is the curve for the normal eye; the lower one, the curve for the color-blind eye. Data of Graham and Hsia (*24*).

on color blindness have not accepted the possibility that deuteranopes exhibit a loss of luminosity as contrasted with normals. Hecht and Hsia, on the basis of some determinations, maintained that a loss does occur, but their findings have met with considerable resistance, particularly by Walls and Mathews (*17*). Our experiment seems to demonstrate that deuteranopes usually do, in fact, lose luminosity. Five of our six cases demonstrate a loss.

The average log luminosity given by our deuteranopes is shown in Fig. 2. The luminosity for the deuteranope in the green and blue is less than the corresponding luminosity values for the normal. In the red, the values are comparable. According to our data, then, deuteranopes show a loss of luminosity in the green and blue.

General result. In general, one can say that the normal curve in this figure is a broad function that encompasses the extremes of the color-blind curves. The protanope has normal luminosity in the blue but shows loss in the red; the deuteranope shows normality in the red but a loss in the green.

Discussion. Interpretations of the data for color-blind individuals have been predominantly made in a context of trichromatic theory, developed from Young's notion that there are three receptor systems in the retina. These systems may be designated B, G, and R to indicate their properties of yielding blue, green, and red processes when they are brought into action by light. The discriminations produced by various parts of the spectrum result from the combined action of the three systems in different degrees. Thus the combined actions of the G and R system result in the seeing of yellow, while seeing white represents the combined actions of B, G and R. The action of the receptors contributes brightness as well as color, and luminance matches show the property of additivity.

Young supposed that the usual dichromatic forms of color blindness are due to the loss of one of the three receptor systems. Since Young's time this interpretation has usually been accepted in the case of protanopes: protanopes are presumed to have lost the R receptors.

Because the evidence did not seem to support an interpretation of loss for the deuteranope, another sort of account was required for this type of color defective. This account has entailed the idea of a "transformation" system, as described independently by Leber (*18*) and Fick (*19*). One might think of the transformation system as representing a failure of the R and G receptors to become differentiated from one another during development. In any case, the R and G receptors are presumed to be similar insofar as absorption goes, but they have different central connections. The result is that red stimulates both the central R and G systems. On this basis it would be expected that all long wavelengths would be called yellow by the deuteranopic subject. Leber and Fick's idea has seemed to be in line with data on subjects who were reported to be normal in one eye and deuteranopic in the other. Classically, such cases have reported that they see yellow in the long wavelengths.

Hecht and Hsia concluded on the basis of their experiment that Young's idea of a loss system was supported by their results. However, they were not clear about how the loss notion could account for the color-naming responses attributed to unilateral deuteranopes and protanopes. The reasons for the problem are clear. How could yellow, if it is a mixture of red and green, be reported in the absence of either red or green receptors?

Color Discriminations of a Unilaterally Color-Blind Subject

It is in connection with this question that we feel fortunate in having obtained the services of a young woman who gave color-blind discriminations with her left eye and normal discriminations with her right eye.

It would be difficult to exaggerate the importance of data obtained on unilaterally color-blind subjects. No ordinary color-blind subject can tell us how the colors he sees compare with those seen by a normal subject, but this is precisely what a unilaterally color-blind subject can do. He can make a direct comparison of colors seen by his color-blind and normal eyes.

Judd (*20*) reports that 37 cases of unilateral color blindness are described in the literature, only eight of which have provided data of value to a scientific analysis. The last of these studies was one by Sloan and Wollach (*21*) in 1948. [See also a recent historical note by Berger (*22*).]

Our subject's first test results seemed to indicate that she was deuteranopic, and so we began our experiments with the expectation that we should gain crucial information on the relation between deuteranopic luminosity loss and color naming. As our observations multiplied, we found that our subject did not give completely typical deuteranopic responses (*23*), particularly in hue discrimination. However, it seems clear that she is more nearly classifiable as a deuteranope than as any other type of color-blind individual, and we believe that her results have a particular bearing on deuteranopia.

Luminosity curves. The luminosity curves (*24*) of our subject are shown in Fig. 3. The luminosity curves for her two eyes differ in luminosity values in the blue and green regions of the spectrum. Contrasted with her normal eye, the luminosity of her color-blind eye shows considerable loss. In the red end of the spectrum both eyes have about the same sensitivity. It is possible that, as contrasted with the ordinary deuteranope, our subject's luminosity loss is greater and begins at wavelengths farther into the red than is usual. In any case, she shows a considerable loss in the green and blue for her color-blind eye as compared with her normal eye.

Flicker curves. We have believed it important to find out whether or not the types of luminosity loss that occur at threshold for our subject are maintained at high intensity levels. In order to investigate this problem we, together with Eda Berger (*25*), have measured flicker frequency thresholds at various luminances of different colors.

A considerable number of curves in the normal and color-blind eye were obtained with a number of color filters, but the general nature of the result can be demonstrated by a comparison of curves for spectral regions that a trichromatic person sees as blue, green, and red. The data are shown in Fig. 4.

The curves for blue light are shown at the top of the graph. In both the normal and color-blind eye, critical flicker frequency increases with intensity, the respective curves flattening out and then probably dropping at high luminance values. The positions of the two curves differ, however. The curve for the color-blind eye is displaced downward on the flicker axis compared with the position of the curve for the normal eye. The downward displacement is reminiscent of the effect of decreasing the area, hence the total number of excited receptors, of a flickering stimulus (Granit and Harper, *26*).

The curves in the lower left-hand graph represent the data for green light. The displacement of the curve for the color-blind eye below the position of the curve for the normal eye is striking. In magnitude it is considerably more than was shown for blue light. In general, the displacement means that, at any given intensity, fusion frequency is higher in the normal eye than in the color-blind eye in a manner comparable to an area effect. The latter statement may be especially significant, for it means that, if critical frequency represents activated receptor units, then the type of color blindness represented by our subject is attributable to the loss of green receptors and possibly of some blue receptors also.

The story for red light is different: the same curve represents the data for the color-blind eye and the normal eye. No increased intensity requirement or fusion frequency loss for the color-blind eye is discernible in these data. No luminosity loss exists for red, even at the high intensities giving rise to critical frequencies near the maximum.

The results of the present investigation point to the conclusion that the type of color blindness represented by our subject may be characterized as a loss or inactivation of some of the receptor mechanisms that mediate sensitivity in the green and blue portions of the spectrum. Furthermore, the data show that the selective luminosity loss for our subject is not a phenomenon that exists only at cone threshold levels.

Binocular color matching. Our experiments as discussed up to the present seem to indicate that the color-blind eye of our subject, like the eyes of deuteranopes generally, shows a maximum of luminosity loss in the green region of the spectrum. What data does our subject give us on binocular color matches involving her normal and dichromatic eye? What colors does she see in her color-blind eye?

The apparatus used in the experiment on binocular color matching was essentially a mirror stereoscope arranged so as to provide slits of color in the left and right eyes, a vertical slit in the left eye and a horizontal slit in the right eye. The subject regarded the essentially monochromatic color given by the vertical slit in her dichromatic eye and simultaneously observed, in the binocular field, the monochromatic color provided by the horizontal slit in her normal eye. The subject reported that, under her conditions of viewing, the horizontal and vertical slits seemed almost to touch at the middle of the latter but did not ordinarily overlap. Wavelengths stimulating the normal eye could be changed until a monochromatic band was obtained that, in the opinion of the subject, matched the color seen by the dichromatic eye.

The results of the experiment are summarized in Fig. 5. In general, it seems that, in her dichromatic eye, the subject matches all wavelengths greater than her neutral point (which occurs at about 502 mμ) against a wavelength in the normal eye lying at about 570 mμ. In a word, all wavelengths greater than 502 mμ in the dichromatic eye are seen as a yellow

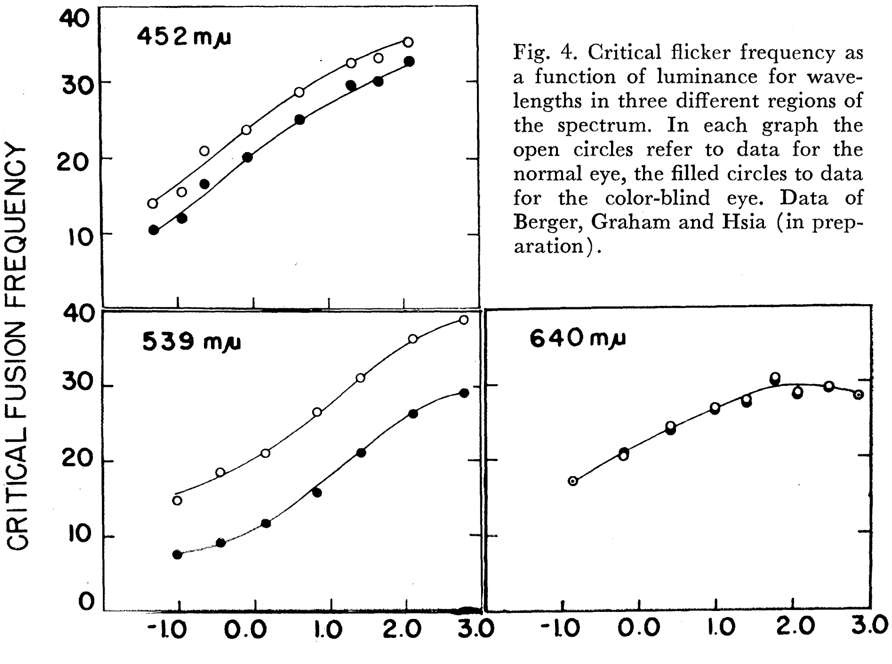


Fig. 4. Critical flicker frequency as a function of luminance for wavelengths in three different regions of the spectrum. In each graph the open circles refer to data for the normal eye, the filled circles to data for the color-blind eye. Data of Berger, Graham and Hsia (in preparation).

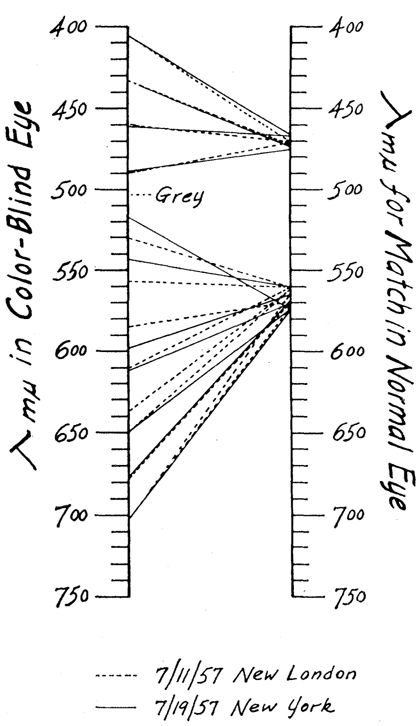


Fig. 5. Results of the experiment on binocular color matching. The wavelengths seen by the color-blind eye (left scale) are matched by the indicated wavelengths in the normal eye (right scale).

of about 570 mμ in the normal eye. Wavelengths shorter than the neutral point in the dichromatic eye are matched in the normal eye by a blue at about 470 mμ. Thus the two sides of the spectrum below and above the neutral point are seen, respectively, as a blue equivalent to about 470 mμ and a yellow equivalent to about 570 mμ in the trichromatic eye (*27*). These results are in accord with the data of several earlier experiments on unilaterally color-blind subjects as summarized by Judd (*20*).

Hue discrimination. Hue discrimination curves show how the just noticeable difference in wavelength, Δλ, varies with wavelength. Such data were obtained on our unilaterally color-blind subject by means of a modified Helmholtz color mixer (*14*). Careful attention was paid to making appropriate intensity adjustments so that all wavelength discriminations were obtained at the same constant level of luminance throughout the spectrum. A curve was obtained on each eye of our subject. The curves are presented in Fig. 6.

In general, the curve for the normal eye does not seem to be greatly different from the usual hue discrimination curve obtained on normal individuals (*28*). The poorest discrimination, as shown by the largest Δλ, takes place in the red. Minima occur in the middle range of wavelengths; and our subject shows especially low thresholds in this range. It is quite clear that the normal eye of our subject does not show defective hue discrimination.

The curve for the left eye, the color-blind eye, is an entirely different function. In the violet the curve shows some insensitivity to wavelength change, but near 450 mμ it shows a great rise in Δλ, indicating very poor hue discrimination. Discrimination improves to a minimum threshold value near 500 mμ, in the region of the neutral point; thereafter Δλ rises to very high values near 600 mμ. The behavior of hue discrimination in the spectral region from 500 to 750 mμ is similar to that found in the usual deuteranope (*11, 28*).

Color mixture. The final set of results given by our subject are her data on color mixture (*29*). One way of specifying the data of color mixture is in terms of the trichromatic coefficients. Any color, including a spectral color, can be specified in terms of three numbers. Since the numbers add to unity, the position of a color on a two-dimensional grid, the chromaticity diagram, is uniquely specified when two of the coefficients are known. Each trichromatic coefficient represents the percentage contribution of one of three primaries in providing a match for a given color. A plot of the trichromatic coefficients against wavelength results in a graph of the sort shown in the upper graph of Fig. 7. In this graph the three ordinate values at each wavelength value represent the amounts of the three primaries as percentages of the unit color (more exactly, chromaticity) of the wavelength.

The curves of the upper figure are the data for our subject's normal eye (*30*). In these curves, a negative trichromatic coefficient means simply that a particular primary is combined with the test wavelength to match the two remaining primaries. The curves are to be contrasted with Wright's well-known results (*28, 31*), on ten normal eyes as represented by the dashed lines.

Our primaries are the same as Wright's: 460, 530, and 650 mμ. The units for the red and green primaries have been so specified that they are taken to be equal at 582.5 mμ, while the green and blue primaries are equal for the match at 494 mμ. Our color-blind subject's normal eye gives, except for minor differences, the same sort of color mixture data as are represented in Wright's data. In addition, it can be stated that the relative luminance values of the primaries for matches at 582.5 and 494 mμ are comparable to those reported by Wright.

The data for our subject's color-blind eye, shown at the bottom of Fig. 7, are entirely different from the data for the normal eye. The graph shows that our subject can match any wavelength of the spectrum with a combination of two primaries, 460 and 650 mμ (the units being taken as equal at 494 mμ). The dashed line represents Pitt's data (*11*) on the color mixture of deuteranopes.

The open and solid circles indicate two different types of result that were obtained in the short wavelength region depending on the method used. (i) If the subject matched a given short wavelength by a mixture of the two primaries, 460 and 650 mμ, then the results are as given by the solid-circle curves. They show that, as wavelength decreases below 460 mμ, more and more of the red primary must be added to the blue pri-
exhibited by Pitt's subjects. It should be
show the small degree of negative red
results, even though our subject did not
much closer to Pitt's data than are our
shown by the open circles. This result is
primaries, the result is different, as is
to match the mixture of red and blue
test light is mixed with the red primary
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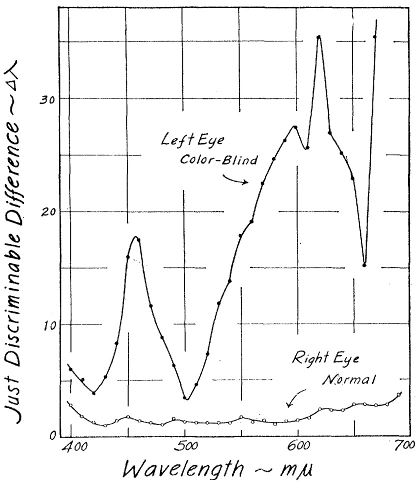

Fig. 6. The hue discrimination of a unilaterally color-blind subject. The open circles refer to data for the normal eye; the filled circles, to data for the color-blind eye.

pointed out that our first method gives results that seem to be in line with our data on hue discrimination. (It will be remembered that our subject's dichromatic eye gave good hue discrimination thresholds in the short wavelength region of the spectrum.)

Discussion

Consider now the significance of some of our data.

First, the data on color mixture demonstrate that our unilaterally color-blind subject has normal vision in her trichromatic eye and dichromatic vision in her color-blind eye. This finding means that we possess a degree of specification that was often lacking in early experiments on unilateral color blindness. We are surer of the status of our subject than were most of our predecessors. The results given by our subject on hue discrimination show the usual low thresholds characteristic of the normal eye and the high thresholds of the dichromatic eye, except, for the latter, in the blue region below 450 mμ, where discrimination is better than the usual deuteranope's.

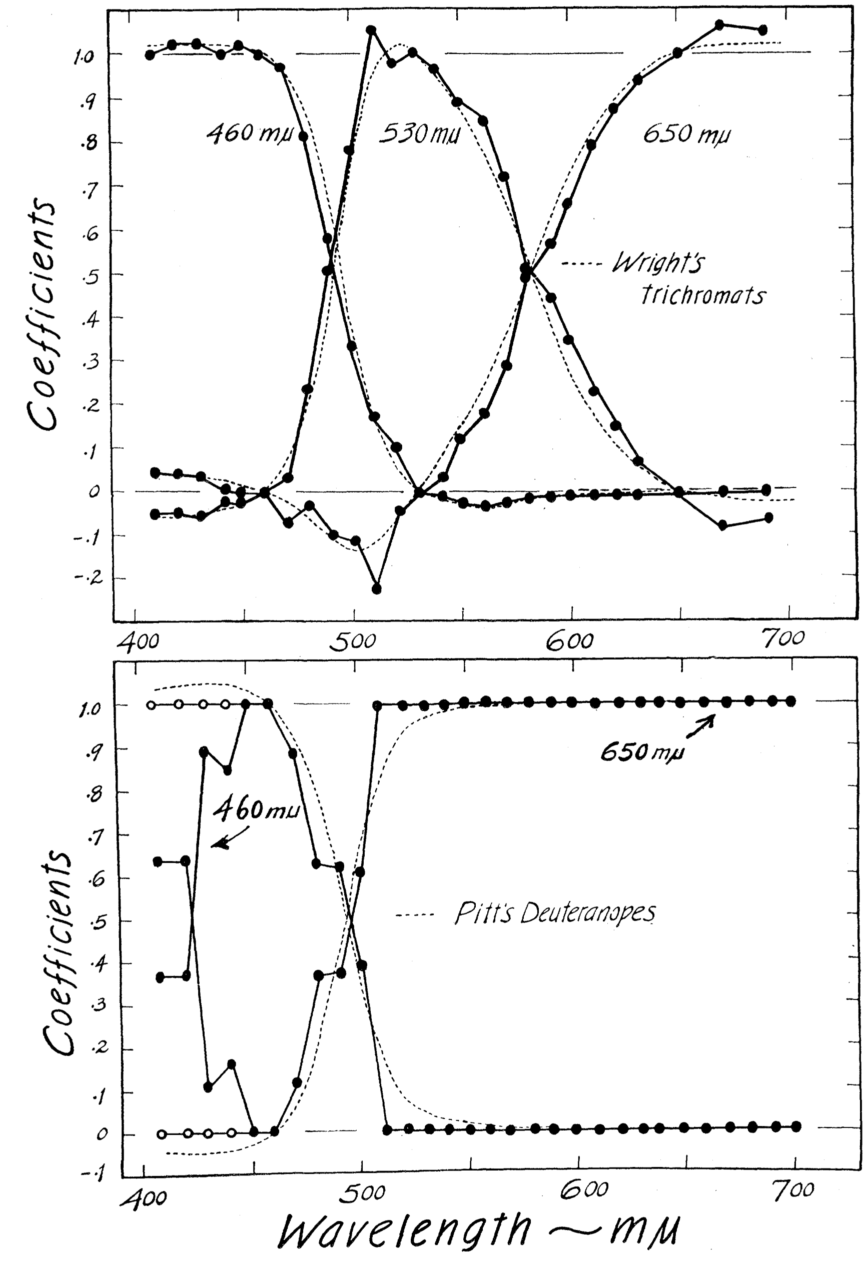

Fig. 7. The upper curve gives the trichromatic coefficients for the normal eye of our unilaterally color-blind subject. The dashed line represents Wright's data (*28, 31*). The lower curve gives the dichromatic coefficients for the color-blind eye of the same subject. The dashed lines represent Pitt's data (*11*) for deuteranopes.

Some important results on both our unilaterally dichromatic subject and our groups of color-blind individuals demonstrate the existence of luminosity losses in dichromatic vision. Our finding with respect to our group of protanopes is the usual one: protanopes lose luminosity in the red region of the spectrum. Our observations on a small population of deuteranopes as contrasted with normal subjects give results that are in line with some reported by Hecht and Hsia (*10*): five of our six deuteranopes show a loss of luminosity in the green-to-blue region of the spectrum.

A well-marked luminosity loss (over the spectral range from about 400 to 625 mμ) is shown by the dichromatic eye of our unilaterally color-blind subject. In the red region of the spectrum both of her eyes show comparable luminosity values, but in the green and blue, her color-blind eye shows a marked luminosity loss. The subject shows clear evidence of a luminosity loss over the spectral range from about 625 to about 450 mμ.

These results mean that luminosity loss is not only the usual finding for protanopes; it also exists in deuteranopes.

The second main result of our experiment concerns the findings on binocular color matches as given by our unilaterally color-blind subject. It has been demonstrated that her color-blind eye sees two hues: blue below the neutral point at about 502 mμ and yellow above it. As shown by binocular color matches, the blue she sees is equivalent, in her normal eye, to a wavelength of about 470 mμ; the yellow, to about 570 mμ.

How can these two sets of results, the one on luminosity loss and the one on binocular color matching, be reconciled within a coherent account?

What will now be presented is a statement that may have some of the advantages of the Fick-Leber hypothesis in accounting for the seeing of blue and yellow in the spectrum by protanopes and deuteranopes. It is hoped that the description can give a possible explanation of how luminosity losses can also occur in line with a transformation or "collapse" system, thereby removing what has been a shortcoming of such an account.

Let it be supposed that in deuteranopia, for example, the R fundamental curve in the upper graph of Fig. 8 (the presumed sensitivity curve for the R receptors) moves toward the short-wave part of the spectrum, with of course a change in sensitivity brought about by virtue of the transformed absorption ma-

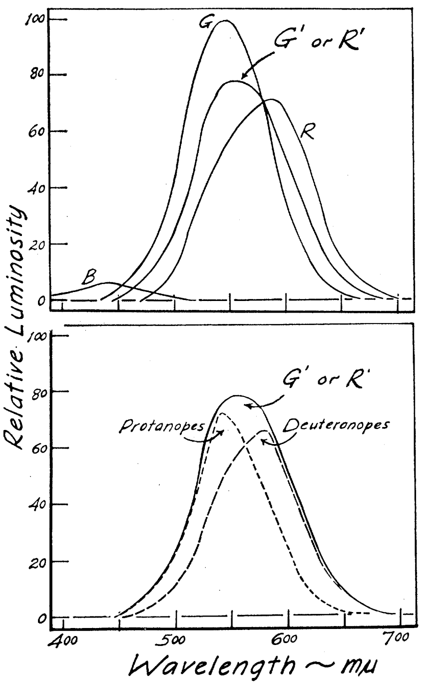

Fig. 8. Theoretical curves. The upper graph represents the transformation of the R and G curves (to superimposed R′ and G′ curves) to provide for the seeing of yellow by a dichromat who shows no luminosity loss. The lower graph represents the effect, for protanopes and deuteranopes, of luminosity losses.

terials. The new curve can be called R′. At the same time, the green fundamental curve G moves toward the red and becomes G′. (The blue fundamental curve will be disregarded in what follows.)

The curves, in their new positions, meet certain requirements. (i) Spectral brightnesses due to R′ and G′ must be in the same ratio at all wavelengths in order to give yellow. (The ratio shown in Fig. 8 is taken to be unity—that is, the R′ and G′ curves are superimposed.) A wavelength that stimulates the now identical R′ and G′ substances gives yellow, for although both fundamental processes have the same absorption spectrum, they are connected centrally with the usual R and G mechanisms. (ii) The spectral brightnesses of R′ and G′ add to give normal sensitivities. The dichromat represented by the latter requirements shows no luminosity loss. (We have already stated that one of our deuteranopes could be so described.)

Any sensitivity loss can now be introduced, as in the lower graph of Fig. 8, by assuming a curve for deuteranopes (or protanopes for that matter) that lies beneath the normal sensitivity curve as shown in the lower graph of the figure. The sensitivity losses in this figure were computed on the basis of the group data for protanopes and deuteranopes given in Fig. 2.

The lower curves of Fig. 8 do two of the things we want them to do: (i) They account for the seeing of yellow by dichromats in the long-wave region of the spectrum, in a manner not unlike simple Fick-Leber theory (*18, 19*). (ii) They provide for the existence of luminosity losses in the eyes of both deuteranopes and protanopes. The implications of the account should probably be tested in further observations. Its main merit now lies in the extent to which it approximates a useful statement of how trichromatic theory can account for luminosity losses and the manner of seeing spectral colors by deuteranopes and protanopes.

Summary

It is important to find answers to two questions concerning the visual discriminations of dichromatic persons, especially deuteranopes: (i) Do such persons show a loss of sensitivity to various wavelengths of the spectrum as compared with normal subjects? (ii) What colors do they see?

A number of experiments were performed on the first question.

First, luminosity curves were determined on three groups of subjects, consisting respectively of five protanopes, six deuteranopes, and seven normal individuals. As compared with normal subjects, protanopes show a loss of luminosity in the red, whereas deuteranopes show a loss in the blue-to-green region of the spectrum (See *10*).

Second, we examined the luminosity curves of a subject whose right eye is classifiable (on the basis of color-mixture determinations) as normal and whose left eye is classifiable as dichromatic. (The hue discrimination curve for her dichromatic eye seemed comparable to the curve of the usual deuteranope except in the violet, where it manifested relatively good discrimination.) The luminosity function for this subject's dichromatic eye, determined by data on threshold and flicker, exhibits the same type of luminosity loss in the blue and green regions of the spectrum as was shown by our group of six deuteranopes.

Only unilaterally dichromatic subjects can tell us how colors seen by a dichromatic eye appear to a normal eye. In the color-blind eye, our unilaterally dichromatic subject sees wavelengths below and above her neutral ("grey") point (which occurs at 502 mμ) as, respectively, a blue equivalent to about 470 mμ and a yellow equivalent to about 570 mμ in her normal eye.

The results on (i) luminosity loss and (ii) the seeing of wavelengths above 502 mμ as yellow are considered theoretically. The seeing of yellow by deuteranopes and protanopes may be accounted for by an idea based on Leber-Fick transmation theory. It is proposed that the characteristic sensitivities of the red and green receptors become similar while no change takes place in their central brain connections. Losses may be introduced into the transformed sensitivity curves to indicate appropriate degrees of luminosity deficit for deuteranopes and protanopes.

References and Notes

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5. See D. B. Judd [*J. Opt. Soc. Am.* 33, 294 (1943)] for references on the early history of color blindness, including Dalton's famous account (1798) and Tuberville's early statement (1684).
6. It has been proposed that a very rare type, the tetartanope, should also be listed. The tetartanope, it is claimed, also confuses blue and green, but whereas other dichromats can match a single region of the spectrum by white, the tetartanope can so match two such regions.
7. This work was supported by a contract between the Office of Naval Research and Columbia University and by a grant-in-aid from the Higgins fund of Columbia University. This article contains the essential content of a vice-presidential address given by one of us (C.H.G.) to the Psychology Section of the AAAS in December 1956. Further accounts of some of these experiments have been prepared for *Proceedings of the Symposium on Visual Problems of Color* (London: Her Majesty's Stationery Office, London, in press); *Proc. Am. Phil. Soc.* (in press); and *Symposium on Visual Mechanisms* (National Institutes of Health, Bethesda, Md., in press). Reproduction of this article, in whole or in part, is permitted for any purpose of the U.S. Government.
8. We wish to express our indebtedness to our colleagues Dr. Harry S. Sperling, Mrs. Anne H. Coulson, Dr. Eda Berger, and Mrs. Shakuntala Balaraman for many contributions of time, data, and content to the experiments here discussed.
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15. Protanopes and deuteranopes call green or red, properly adjusted for luminance, a match for yellow; hence the color-matching performance of a protanopic or deuteranopic subject on an anomaloscope (which provides standard conditions for such matches) is diagnostic of dichromatism. Protanopia seems to be indicated when a greater than usual luminance of red is required to match a yellow. When a normal luminance of red is used for the match, the subject is said to be deuteranopic.

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23. It should also be mentioned that Dr. Gertrude Rand and Miss Catherine Rittler of the Laboratory of Ophthalmology, Columbia University College of Physicians and Surgeons, kindly examined our subject and concluded that, although her right eye was normal, her dichromatic eye did not fit a simple category of classical color defect. We are indebted to Dr. R. L. Pfeiffer, of the Ophthalmological Institute, Columbia University College of Physicians and Surgeons, for the ophthalmological examination of our subject. No organic disease was found.
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27. A separate experiment on color naming gives data in line with the results on binocular color matching. The subject reports only two colors in her color-blind eye: blue below her neutral point at about 502 mμ, and yellow above the neutral point.
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29. Some experiments on color mixture were performed at Columbia University, but the final data were obtained in collaboration with Dr. Harry G. Sperling and Mrs. Anne H. Coulson, on the Fry colorimeter at the Medical Research Laboratory of the Submarine Base, New London, Conn. A detailed account of these and other findings will be prepared as a joint report from Columbia and the Medical Research Laboratory, under Bur. Med. Project Number NM22 01 20, by C. H. Graham, H. G. Sperling, Y. Hsia, and Anne H. Coulson. We are indebted to our collaborators and to Commander Dean Farnsworth and Captain J. Vogel, officer-in-charge of the Medical Research Laboratory, for their cooperation in these experiments.
30. The relative values of the luminous units of the primaries are $l_{460} = 0.051$; $l_{530} = 1.000$, and $l_{650} = 0.814$. Matches were made by flicker photometry between the first two at 494 mμ, and for the second and third, at 582.5 mμ. The luminous units are within the range reported by Wright (*28*) for his normal subjects. The experiments were done with retinal illuminances of test wavelengths equal in all cases to 500 trolands as established by flicker photometry.

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Production of U.S. Scientists

Trends in the number of doctorates granted in the major fields of science and in the humanities.

Office of Scientific Personnel,
National Academy of Sciences–National Research Council

Recent events have focused attention on the subject of the production of scientists in the United States. Discussion relating to science production inevitably involves educational problems outside the field of science specifically and factors affecting education generally in the United States. The present article is intended to furnish up-to-date information with respect to the output of scientists by the United States universities during the past 20 years and to put this in the context of long-term trends in advanced education.

The main body of data for this article is the doctorate records file built up over the past decade by the Office of Scientific Personnel of the National Academy of Sciences–National Research Council. Through the cooperation of all the graduate schools in the United States which grant third-level degrees, and by means of funds furnished by the Office of Naval Research, the National Science Foundation, the Carnegie Corporation, and the Ford Foundation, a comprehensive and accurate roster has been produced of all persons who have earned the Ph.D. degree or its equivalent in all the science and nonscience disciplines in the United States universities since 1936. Data for the periods 1936–1945 and 1936–1950 have been published previously (*1*). The data are now available for the first 20 years of this survey: 1936 to 1955, inclusive. The data for 1956 and 1957 are being checked for completeness and accuracy and are not yet available for publication. In addition, the Office of Scientific Personnel has drawn upon data previously assembled by Douglas Scates from many sources, including chiefly the United States Office of Education. These data, covering the years 1885 to 1935, were published by the American Council on Education in 1951 (*2*).

In compiling data for the long time span indicated above, a number of difficulties necessarily arise concerning such problems as definition of a field or discipline, the development of new interdisciplinary fields into specialties which acquire significance in their own right, and the convergence of fields originally dissimilar. These problems, however, are of importance chiefly with respect to the finer subdivisions of any discipline and do not preclude a clear picture where only a gross breakdown of general fields is concerned. In the present article, emphasis is placed on gross trends in major fields, while certain problems with respect to the minor fields are noted in passing.

Trends

Figure 1 represents the over-all production of doctoral degrees in all fields, compiled for the 70-year span 1885–1955. Because the production of doctorates has roughly doubled in each decade since the earliest records were maintained, it is convenient to show this gross trend on a semilogarithmic scale. The result is an approximation to a straight-line graph because of the logarithmic increment on the vertical axis. In Fig. 1, a straight line has been projected through

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This article was prepared by the staff of the Office of Scientific Personnel, National Academy of Sciences–National Research Council. M. H. Trytten is director.