explain in particular the psychological laws of color vision. I expect that in the future anatomists and physiologists will add greatly to our knowledge in these very interesting problems, but as a conclusion I think best to remind you of an old picture in Descartes's book on man (Fig. 3). Our modern representations would not differ much from Descartes's, except that the "pineal gland," which he supposed to be the "seat of imagination and common sense," is now out of date and replaced by the cortex. As to the transmission of visual messages to the brain and storage of visual engrams in the cerebral substance, we have not added a great deal to this picture of the seventeenth century. It is sometimes good, for the modern scientist who is so proud of the progress of science, to learn modesty in an old French book which was written three hundred years before the beginning of this so-called "atomic age."

STUDIES OF COLOR BLINDNESS: A UNILATERALLY DICHROMATIC SUBJECT

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Since the time of Thomas Young[1] considerations of color blindness have played an important and possibly primary role in determining the forms of various theories of color. The literature of color blindness reserves an important place for studies of unilaterally color-blind subjects, that is, persons who are color-blind in one eye but normal in the other. Judd[2] states that thirty-seven cases of unilateral color blindness have been reported in the literature, but, because of inadequate procedures, equipment, or background information, only about eight have proved useful for theory, and then not in all desirable details. 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 and thus provide us with a basis for relating the color perceptions of the color-blind eye to those of the normal.

We have recently had an opportunity to examine some visual discriminations of a unilaterally dichromatic subject. The results of that investigation form the content of this discussion.

Color Mixture.—The fact that our subject is unilaterally color-blind was established well enough in preliminary tests, but its precise specification was unequivocally established by her data on color mixture.

The color-mixture experiments show that our subject's normal eye can match any wave length of the spectrum by a mixture of three primaries—460, 530, and 650 mμ. In addition, they give data that are in accord with Wright's standard results in 10 normal subjects. The luminance units involved in the settings fall within the distribution given by Wright's subjects. In a word, our subject's right eye has normal color vision.[3]

The data on the color-blind eye are different from the data on the normal eye.

In her color-blind eye our subject can match any wave length of the spectrum with a combination of two primaries, 460 and 650 mμ. Judging by this performance, we can say that her left eye is unequivocally dichromatic. Her results are in accord with Pitt's standard data[4] on dichromats.

The color-mixture curves for our subject's left eye show that that eye is dichromatic, but they do not tell what type of dichromasy is represented. Two rare types of dichromasy are excluded, but the data do not differentiate between two forms—deuteranopia, the most frequently encountered form (sometimes inaccurately referred to as "green blindness"), and protanopia, the next most frequently encountered form (sometimes inaccurately referred to as "red blindness").

Spectral Sensitivity.—Differentiation between the two forms may be accomplished in a number of ways, all depending upon a testing of the sensitivities of the eye to red light. If a dichromatic eye is relatively insensitive to red light, it may be classified as protanopic. If the eye is sensitive to red and at the same time gives the same kind of color-mixture curve as our subject's dichromatic eye, then it is deuteranopic. Some data by Hsia and Graham[5] and by Hecht and Hsia[6] on groups of protanopic, deuteranopic, and normal subjects indicate that deuteranopes usually lose sensitivity in the blue and green regions of the spectrum.

The spectral sensitivity curves of our unilaterally color-blind subject,[7] shown in Figure 1, demonstrate that her dichromatic eye loses sensitivity in the blue-to-green region of the spectrum and has normal sensitivity in the red. She is therefore classifiable as deuteranopic. In addition, her data on spectral sensitivity strengthen the interpretation that deuteranopes usually show a loss of sensitivity in the blue-to-green region of the spectrum. Her loss in this region is well marked.

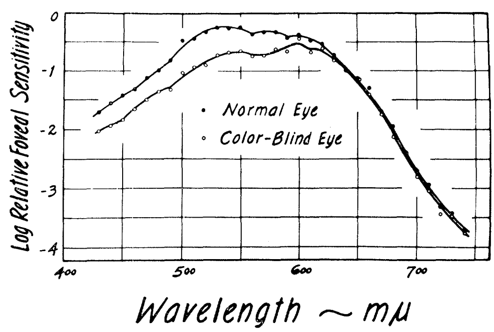

Fig. 1.—The spectral sensitivity curves for a unilaterally color-blind subject. The upper curve for the normal eye; the lower one, the curve for the color-blind eye. Data of Graham and Hsia (these Proceedings, **44,** 46–49, 1958).

Binocular Color Matches.—As part of our analysis of our subject's vision we performed an experiment on binocular color matching. This experiment had to do with the question: What colors does our subject see in her color-blind eye? The subject regarded the color of a vertical slit presented to her left eye in the visual field and simultaneously observed the color given by a horizontal slit in her normal eye. The wave length of light stimulating the normal eye could be changed until a narrow wave-length band was obtained that, in the opinion of the subject, matched the color seen in the dichromatic eye.

The results of the experiment are summarized in Figure 2. In general, it seems that in her dichromatic eye the subject matches all wave lengths greater than the neutral point (i.e., the narrow wave-length band that a dichromat sees as gray) with a wave length seen in the normal eye lying near 570 mμ. Wave lengths shorter than the neutral point in the dichromatic eye are matched in the normal

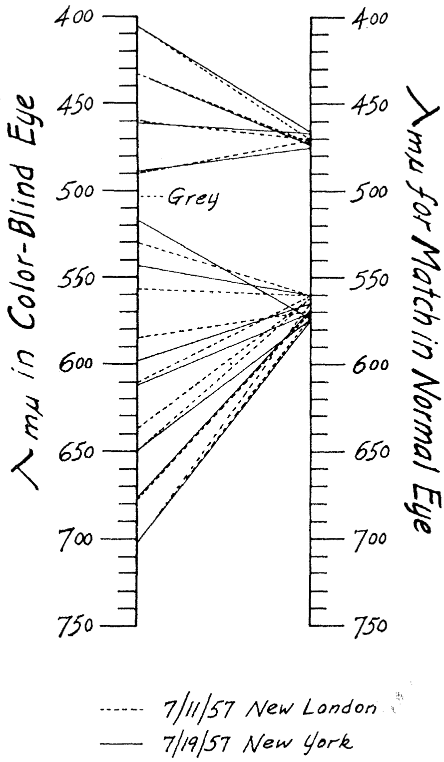

FIG. 2.—Results of the experiment on binocular matching.

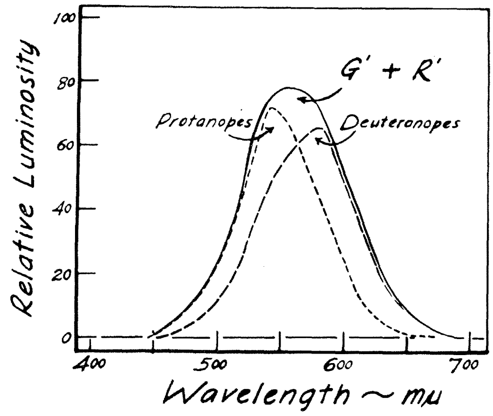

FIG. 3.—Theoretical curves. The curve drawn with a continuous line represents the sum of R' and G' at any ordinate value. R' comes about when the R curve is "transformed," i.e., shifted to shorter wave lengths (with change of shape); G' comes about when the G curve is shifted to the longer wave lengths. The ratio of G' to R' is unity and $R' + G'$ is equal to normal spectral sensitivity (except for the small contribution of a curve for blue). The right dashed-line curve represents the spectral sensitivity curve for deuteranopes, and the left dashed-line curve, the curve for protanopes.

eye by a blue of about 470 mμ. This result is in line with Judd's analysis[2] of earlier data.

Discussion.—Our subject shows a loss of spectral sensitivity in her color-blind eye and at the same time sees all wave lengths above 502 mμ as yellow. How can she (or, in fact, any deuteranope) see yellow (which we take to be a mixture of red and green) in the total or even partial absence of a green brightness mechanism?

To begin with, it seems that, in order to account for the seeing of yellow (we shall not deal with blue!) by deuteranopes, we may appeal to the Fick[8] and Leber[9] theory. This theory says that yellow is seen by deuteranopes because, in such persons, the red and green receptors become indistinguishable so far as sensory input is concerned. However, they still maintain their usual central connections, and thus, on stimulation by wave lengths longer than about 500 mμ, they provide a mixture of yellow due to excitation of the usual red and green centers. This latter consideration sets a requirement. (In discussing it, we shall refer to the normal red and green processes as R and G and their possible transformations, sensory or central, as R' and G'.) (1) It is required that spectral luminances for a mixture of yellow determined by R' and G' must be in nearly the same ratio—approximately unity—at all stimulating wave lengths. (2) In addition, a second requirement must be met. For the case of the deuteranope (or, for that matter, the protanope) the sum of the R' and G' ordinates at any wave length must add to give deuteranopic (or protanopic) luminosity, as specified, for example, by the data of our groups of dichromats.

These relations are shown in Figure 3. The full curve shows color mixture (minus the contribution of a blue fundamental) in the case of a deuteranope, comparable to one of our subjects, who shows no luminosity loss. (The curve is also nearly the luminosity curve for normal subjects.) The right dashed curve represents average deuteranopic luminosity with appropriate loss. In the latter curve, the R' and G' ordinates are taken to be in a ratio of unity, as dictated by color-mixture data. The area under the curve is assumed to be proportional to the number of R' and G' cones (both being identical in all details except their central connections). Each type contributes half the total number. Similar considerations could apply to the logical extension of Fick-Leber ideas to protanopia, as represented in the left dashed-line curve.

The results of the present experiments concerning luminosity losses in dichromats may be at least qualitatively in line with results described by Rushton in another paper of this symposium. For the moment we may regard the main merit of the present accounts as stating how trichromatic theory may account for luminosity losses and the colors seen by dichromats.[10]

* 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. Reproduction in whole or in part is permitted for any purpose of the United States government. For a fuller discussion of this research see C. H. Graham and Yun Hsia, *Science*, **127**, 675–682, 1958.

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[9] T. Leber, *Arch. Ophth.*, **15**, 26–107, 1869.

[10] We wish to express our indebtedness to our colleagues Dr. Harry G. Sperling, Mrs. Anne H. Coulson, Dr. Eda Berger, and Mrs. Shakuntala Balaraman for many contributions of time, data, and content to experiments of the program here discussed.