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## PERSISTENCE OF VISION IN COLOR-BLIND SUBJECTS.

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DURING the century which has elapsed since its discovery. color-blindness has been studied from various standpoints, At first it merely aroused curiosity which gradually led to a more careful examination of its peculiarities. In the latter half of the century the importance of the subject was enormously increased by the consideration that in travelling by land and sea human life is often dependent upon the correct perception of color signals by those in charge of trains and vessels. From this economic standpoint the subject has been developed to perhaps as high a degree of excellence as is necessary. But the most interesting aspect of abnormal color vision is that of its relation to the exceedingly involved and complex question of the nature of our perception of light and color.

As is well known color-blindness was first studied by the great chemist, Dalton, who was himself troubled with it. Its investigation subsequently passed to physicists from whom it has been appropriated by the modern school of experimental psychologists and also by physiologists, who have very greatly contributed to our knowledge of the structure of the retina and the functions of its parts, to whom also are due very many of the hypotheses by which the varied phenomena of color vision are correlated.

The study of numerous cases of color-blindness has brought to our knowledge many eccentricities of vision which none of the theories can at present adequately explain. Some of the hypotheses have been devised expressly for the purpose of grouping color-blind subjects into a very few sharply defined classes. While this is a most desirable result to be attained, yet it can only be deprecated that an occasional writer has tried to establish a comprehensive hypothesis upon quite insufficient data. One theory [1] in particular has been founded on but two unique cases of color-blindness described by Holmgren.

The investigation discussed in these pages was undertaken with the object of finding out the nature and magnitude of the variations of abnormal from normal color vision as far as they can be shown by comparing the corresponding measurements of the persistence of vision of the rays of the spectrum.

In a former paper [1] I gave an account of some experiments in which the normal retina was studied under various artificially produced conditions by the Nichols method of the measurement of the duration of visual impressions. Those experiments, it was hoped, would contribute materially towards the solution of the problem of the fundamental color sensations. The present investigation is a continuation of the former both in its object and in the method used, the sole difference being that, instead of the normal retina, the eyes of color-blind persons are studied. As the paper to which reference is made contains a detailed description of the apparatus and of the manner of taking observations employed in both researches, repetition will be unnecessary. In brief, however, the method consists in rotating a sectored disc in front of the slit of a spectrometer at such a speed that there is complete fusion of the intermittent flashes of color of the part of the spectrum under observation. The speed of the disc is electrically recorded on a chronograph which enables the duration of the *greatest* intensity of the light stimulus to be very accurately determined. The time of fusion varies from point to point through the spectrum, but is

[1] Color Sensations, H. R. Droop, Phil. Mag., S. 5, 15, 1883.

[2] Effect on the Persistence of Vision of Exposing the Eye to Light of Various Wave-Lengths, Frank Allen, PHYS. REV., Vol. XI., p. 257, 1900.

dependent, however, only upon the intensity of the light and the sensitiveness of the retina.

The cases of color-blindness examined were all students in Cornell University. Many of them were found by examining several hundred members of one of the classes through the agency of the Military Department of the University. Others were obtained in the physical and chemical laboratories where they betrayed their visual defects in various ways in their work. All subjects were first examined by the Holmgren test and gave unmistakable indications of color-blindness in some degree. In finding the neutral point the Helmholtz color-mixing spectrophotometer[1] was employed. One of the collimator tubes was removed from its ordinary position and remounted so as to permit the light from the slit to be reflected by the prism into the telescope in which it appeared above the spectrum from the other collimator. On looking into the telescope there could be seen only the reflected white light and a narrow band of the spectrum occupying the upper and lower halves of the field respectively. The observer, passing the spectum in review from the red to the violet, set the instrument where the color of the field appeared uniform. The intensity of the white light could be easily varied by rotating the Nicol prism in front of the slit of the collimator. In this way most of the subjects indicated their neutral point with ease and rapidity, though a few were unable to find any at all. In the figures the neutral point is indicated by a short vertical line at the proper wave-length.

The most desired observations were those which determined the persistency curve, the general character of which will be clear on referring to the figures. Including the intervals of rest it generally required about two and a half hours for a person to make the necessary settings of the rotating disc to give sufficiently numerous and reliable data for comparison with the curve obtained by the normal eye. Complete sets of observations were made with both eyes, though in only a very few cases was any difference manifested. Taking the double sets of observations into account, twice as many curves were obtained as are shown in the plates.

[1] Helmholtz, "Physiol. Optik," p. 355.

It will be noticed that the brightest region of the spectrum to the normal eye as indicated by the lowest point of the persistency curve is a little to the green side of the sodium line. As the shifting of this point in the color-blind has been made one of the principal determining factors in their classification by the Hering theory, it will be interesting to observe where it occurs in all the cases. Many of the subjects also determined the position of the brightest point by direct observation which seemed to show that it was shifted rather more than the amount indicated by the position of the lowest part of the persistency curve. The direction of shift was, however, always the same by the two methods, though the magnitude often differed.

In order that the persistency curves may lead to any conclusions concerning the portions of the spectrum to which the retinas of the color-blind are not normally responsive, they are always shown in comparison with a normal curve.

### The Normal Persistency Curve.

The normal curves which are used as standards of comparison are those of the writer whose color vision did not seem to be defective in any way. Several normals, it will be noticed, are made use of in this paper, for the reason that at intervals the luminosity of the spectrum was changed owing doubtless to some variations of the intensity or quality of the light from the acetylene flame. The adjustments of the instruments were changed but once, the pressure of the gas was quite constant, and in addition the measurements changed also for different observers at the same time. These reasons are sufficient to assign the cause of the irregularity to some variation in the character of the light itself, and not to any inconstancy of the retinal processes. That four normal curves are used in this work is due simply to the length of time the investigation has covered; had it extended longer the number would doubtless have been increased.

The order in which the cases of color-blindness are discussed is not that in which they were examined, so that the apparently capricious manner of referring their curves to the various normals is due to grouping the cases in their natural classes. The first and second normals are much alike, differing only in the part corresponding to the middle of the spectrum. The last two differ more widely, the readings for the fourth in particular having been made after readjustment of the apparatus.

The data for the four normals are given in the following table.

TABLE I.

NORMAL CURVES.

| I | | II | | III | | IV | |
|---|---|---|---|---|---|---|---|
| λ | Persistence. | λ | Persistence. | λ | Persistence. | λ | Persistence. |
| .400 μ | .0388 sec. | .400 μ | .0388 sec. | .400 μ | .0395 sec. | .405 μ | .0410 sec. |
| .406 | .0360 | .406 | .0360 | .412 | .0365 | .412 | .0385 |
| .418 | .0323 | .418 | .0323 | .439 | .0268 | .425 | .0351 |
| .425 | .0307 | .430 | .0280 | .472 | .0196 | .440 | .0287 |
| .439 | .0264 | .450 | .0225 | .495 | .0157 | .455 | .0239 |
| .472 | .0200 | .463 | .0196 | .520 | .0135 | .472 | .0196 |
| .495 | .0160 | .485 | .0156 | .550 | .0126 | .485 | .0181 |
| .506 | .0148 | .500 | .0140 | .588 | .0126 | .502 | .0156 |
| .520 | .0131 | .567 | .0115 | .640 | .0143 | .520 | .0141 |
| .533 | .0124 | .588 | .0118 | .720 | .0243 | .538 | .0135 |
| .567 | .0115 | .613 | .0126 | .730 | .0260 | .562 | .0130 |
| .588 | .0118 | .640 | .0136 | | | .588 | .0126 |
| .613 | .0126 | .670 | .0160 | | | .613 | .0129 |
| .640 | .0136 | .720 | .0224 | | | .640 | .0138 |
| .670 | .0160 | .730 | .0240 | | | .670 | .0158 |
| .720 | .0224 | | | | | .705 | .0203 |
| .730 | .0240 | | | | | .717 | .0221 |
| | | | | | | .732 | .0236 |
| | | | | | | .745 | .0255 |

In order to see whether there was any disagreement in the measurements of the persistence of vision of persons with normal color vision, the observations necessary for the determination of their persistency curves were made by a number of my friends in the departments of psychology and physics. The results obtained by two of them are by their kind permission given here, and the measurements of the others showed substantially the same agreement. The curve shown in Fig. 1 is that obtained by Dr. Margaret Floy Washburn, and that in Fig. 2 by Mr. E. C. Roberts. These are compared with the second normal which is represented by the dotted line in the figures. Throughout this paper the dotted curves are the normals. The data are given in Table II.

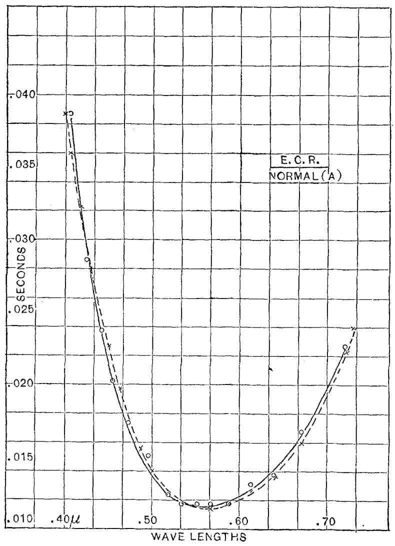



Fig. 1.

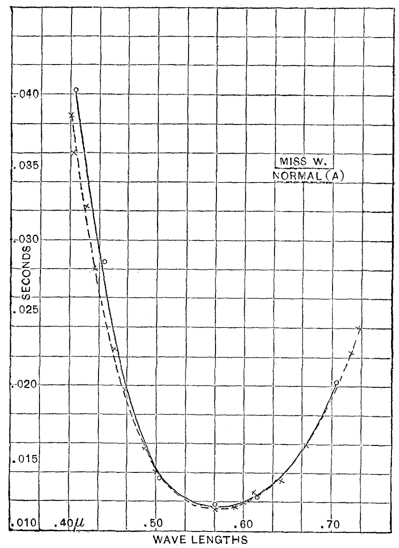



Fig. 2.

TABLE II.

| Miss Washburn. | | Mr. E. C. Roberts. | | | |
|---|---|---|---|---|---|
| λ | Persistence. | λ | Persistence. | λ | Persistence. |
| .406 μ | .0403 sec. | .406 μ | .0388 sec. | .533 μ | .0118 sec. |
| .439 | .0285 | .425 | .0283 | .550 | .0117 |
| .505 | .0136 | .439 | .0237 | .567 | .0117 |
| .567 | .0118 | .455 | .0203 | .588 | .0118 |
| .613 | .0124 | .472 | .0173 | .613 | .0131 |
| .705 | .0204 | .495 | .0150 | .640 | .0137 |
| | | .520 | .0123 | .670 | .0167 |
| | | | | .720 | .0227 |

From the results obtained by these observers we may conclude that the persistence of color impressions upon the retinas of persons with normal color vision and of not widely different ages is practically the same. That a considerable disparity in age destroys this close agreement has been shown by Ferry.[1]

[1] E. S. Ferry, The Persistence of Vision, Am. Jour. Sci., Vol. 44, p. 192, 1892.

## THE CASES OF COLOR-BLINDNESS.

The twenty-six cases of color-blindness described in this paper, of which twenty-one are new, are divided into seven classes according to the form of their persistency curves. Grouping them with reference to the position of the brightest point of the spectrum would make about three subdivisions in each class. The reasons for the classification adopted will appear as the cases are examined.

### *Class I.*

*Subject No. 1.*—Mr. W. O. B., when examined with the Holmgren worsteds, showed the usual indications of color-blindness. He determined his neutral point to be at $\lambda = .510\ \mu$. The persistency readings are given in Table III. In Plate I.,[1] Fig. 1, these results are shown in comparison with the second normal. Two parts of the curve are evidently abnormal, one from the beginning of the red to $\lambda = .670\ \mu$, and the other between the wave-lengths .440 $\mu$ and .670 $\mu$. These regions, however, differ in their meaning. The elevation above the normal *always* accompanies indications of color-blindness, while the depression signifies that to the abnormal eye the corresponding part of the spectrum is brighter than to the normal. This depression, though not found in many of the curves, is in accordance with the frequently observed phenomenon that when the retina is deficient in the power of responding to one of the fundamental sensations, the loss is somewhat compensated for by an increase in the intensity of excitation of the others.

TABLE III.

W. O. B.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 $\mu$ | .0420 sec. | .520 $\mu$ | .0107 sec. | .640 $\mu$ | .0128 sec. |
| .425 | .0319 | .533 | .0101 | .680 | .0180 |
| .455 | .0204 | .550 | .0095 | .705 | .0240 |
| .472 | .0162 | .567 | .0096 | .720 | .0282 |
| .495 | .0128 | .588 | .0101 | .730 | .0324 |
| .505 | .0118 | .613 | .0112 | | |

[1] The figures in *each* of the three plates are numbered from one to nine. The figures in the text are numbered independently.

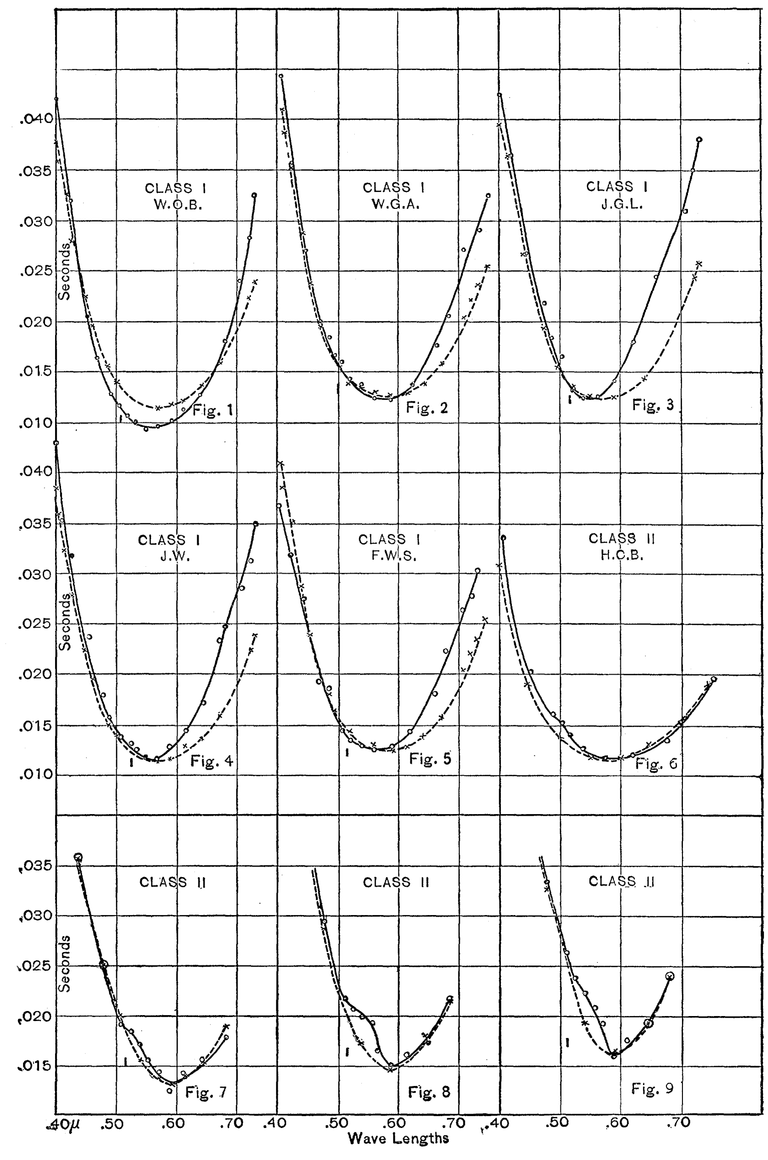

CLASS I
W.O.B.
Fig. 1
CLASS I
W.G.A.
Fig. 2
CLASS I
J.G.L.
Fig. 3
CLASS I
J.W.
Fig. 4
CLASS I
F.W.S.
Fig. 5
CLASS II
H.C.B.
Fig. 6
CLASS II
Fig. 7
CLASS II
Fig. 8
CLASS II
Fig. 9
Seconds
.040
.035
.030
.025
.020
.015
.010
.40μ
.50
.60
.70
Wave Lengths

Plate I.

The point of maximum brightness is at $\lambda = .550\ \mu$, which is a little to the green side of the normal position. The curve indicates that the part of the spectrum to which this subject is at least partially color-blind is from $\lambda = .670\ \mu$ to the end of the red.

*Subject No. 2.*—Mr. W. G. A., after the usual Holmgren test, located his neutral point at $\lambda = .500\ \mu$. The measurements of the persistence of the spectrum rays are given in Table IV. and are shown graphically in Plate I., Fig. 2, in comparison with the fourth normal. The curves agree throughout the violet end of the spectrum to $\lambda = .620\ \mu$ which is in the orange. From this wave-length the elevation extends to the end of the red. There is no displacement of the brightest point.

TABLE IV.

W. G. A.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .405 μ | .0442 sec. | .505 μ | .0160 sec. | .660 μ | .0177 sec. |
| .425 | .0356 | .520 | .0144 | .680 | .0207 |
| .446 | .0270 | .538 | .0138 | .705 | .0271 |
| .472 | .0200 | .562 | .0125 | .730 | .0292 |
| .485 | .0185 | .588 | .0124 | .745 | .0323 |
| .495 | .0168 | .620 | .0134 | | |

*Subject No. 3.*—Mr. J. G. L., a graduate student in chemistry, experienced great difficulty in his spectroscopic work in the red end of the spectrum. The usual indications of color-blindness were given with the Holmgren test, and the neutral point was located at $\lambda = .515\ \mu$.

The values given in Table V. are shown in Plate I., Fig. 3, in comparison with the third normal. The agreement of the two is close up to $\lambda = .562\ \mu$, at which the elevation begins, extending thence to the end of the red. The position of the brightest point is normal.

TABLE V.

J. G. L.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0423 sec. | .502 μ | .0165 sec. | .620 μ | .0180 sec. |
| .417 | .0364 | .520 | .0131 | .660 | .0245 |
| .446 | .0269 | .538 | .0126 | .705 | .0310 |
| .472 | .0218 | .562 | .0124 | .720 | .0350 |
| .485 | .0184 | .588 | .0141 | .730 | .0382 |

*Subject No. 4.* — Mr. J. W., a student in civil engineering, made the usual observations which are given in Table VI., and shown graphically in Plate I., Fig. 4, in comparison with the second normal. In the Holmgren test the green and red samples were correctly matched, but the magenta betrayed his defect. He indicated no neutral point at all clearly, but finally made a fairly good match with the white at $\lambda = .527\ \mu$. The elevation occurs in the part of the curve corresponding to the red end of the spectrum, and begins -at $\lambda = .567\ \mu$. The position of the brightest point is normal.

The last point in the violet in this and in several other curves is somewhat elevated. As exact observations in this region of the spectrum are rather difficult, little confidence can be attached to the last reading unless those immediately preceding show a similar displacement. The same remark will also apply to observations in the extreme red. Fortunately, however, in most cases, there is no uncertainty as to the character of the curve in all parts.

TABLE VI.

J. W.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0432 sec. | .520 μ | .0132 sec. | .640 μ | .0172 sec. |
| .412 | .0354 | .533 | .0125 | .670 | .0234 |
| .425 | .0319 | .550 | .0118 | .680 | .0249 |
| .455 | .0237 | .567 | .0116 | .705 | .0287 |
| .475 | .0181 | .588 | .0130 | .720 | .0314 |
| .485 | .0159 | .613 | .0146 | .730 | .0350 |
| .505 | .0138 | | | | |

*Subject No. 5.* — Mr. F. W. S., a student is one of the physical laboratories, matched the red correctly in the Holmgren test, but failed with the other two. His neutral point is at $\lambda = .515\ \mu$. The measurements tabulated in Table VII., are shown in Plate I., Fig. 5, in comparison with the fourth normal. The curve runs below the normal in the violet and also in the green. The point of maximum brightness is at $\lambda = .562\ \mu$, where the elevation begins which continues throughout the red. In this case the point of greatest brightness is shifted towards the green.

TABLE VII.

F. W. S.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .405 μ | .0367 sec. | .505 μ | .0147 sec. | .660 μ | .0182 sec. |
| .425 | .0320 | .520 | .0136 | .680 | .0223 |
| .446 | .0275 | .538 | .0130 | .705 | .0265 |
| .472 | .0195 | .562 | .0127 | .717 | .0278 |
| .485 | .0186 | .588 | .0130 | .730 | .0302 |
| .495 | .0164 | .620 | .0144 | | |

The five subjects in this class have persistency curves of the same type. Two of them correctly matched one or two of the Holmgren confusion samples, while the others made mistakes with them all. With one exception their neutral points agree quite closely. With three the brightest point in the spectrum occupies its normal position, while two have it displaced toward the green.

## *Class II.*

The subjects in this class seem to have imperfect color vision only in the green. It is rather remarkable that amomg the score of *new* cases described in this paper not one has given a curve of this type. But since at least six cases are on record, the type is well defined.

*Subject No. 6.* — The persistency curve shown in Plate I., Fig. 6, is that obtained by Mr. H. C. B., whose color vision is discussed in my former paper.[1] When this subject was examined no means were at hand to determine his neutral point. The elevation is but slight and is confined to the green. The position of the brightest point is normal.

*Subject No. 7.* — The three figures, 7, 8 and 9, shown in Plate I. are those of three similar cases investigated by Ferry, from whose paper[2] they are reproduced. In these the elevation in the green is very pronounced. The position of the brightest point is normal in each case, and the neutral points are indicated by the usual vertical lines.

[1] Allen, op. cit., Fig. 18, p. 287.
[2] Ferry, op. cit., Fig. 4, p. 204.

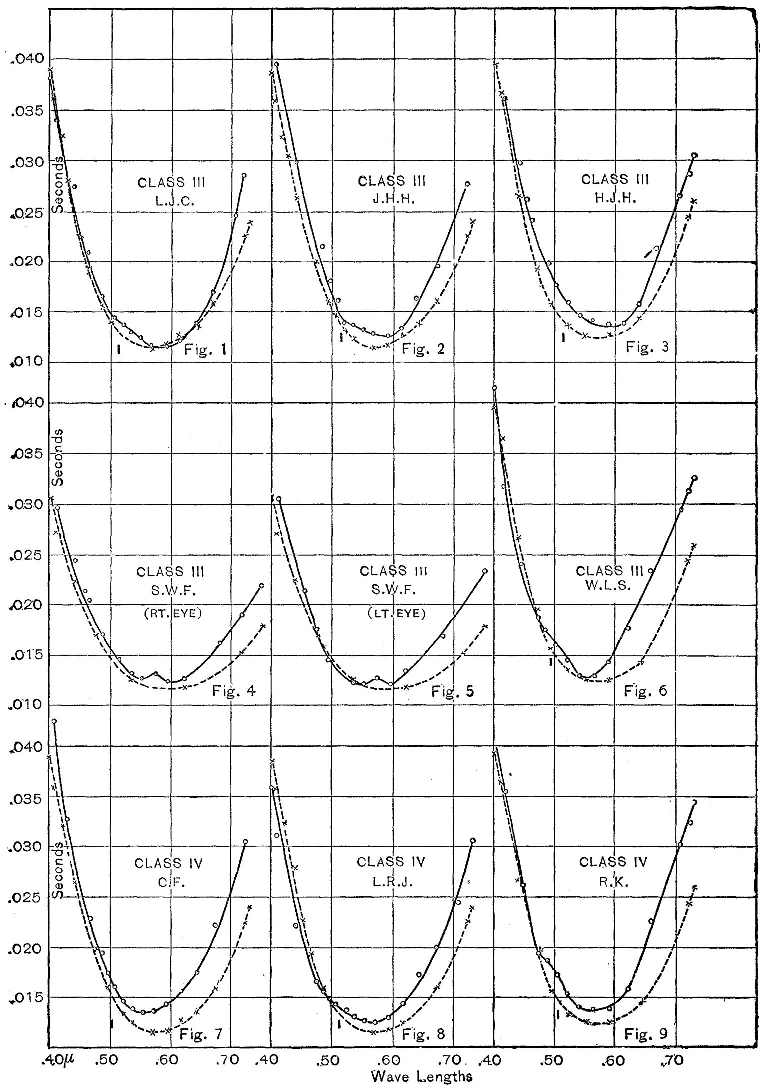

Seconds
.040
.035
.030
.025
.020
.015
.010
CLASS III
L.J.C.
Fig. 1
CLASS III
J.H.H.
Fig. 2
CLASS III
H.J.H.
Fig. 3
CLASS III
S.W.F.
(RT. EYE)
Fig. 4
CLASS III
S.W.F.
(LT. EYE)
Fig. 5
CLASS III
W.L.S.
Fig. 6
CLASS IV
C.F.
Fig. 7
CLASS IV
L.R.J.
Fig. 8
CLASS IV
R.K.
Fig. 9
.40μ .50 .60 .70 .40 .50 .60 .70 .40 .50 .60 .70
Wave Lengths

Plate II.

## *Class III.*

*Subject No. 8.* — Mr. L. J. C., a student in the Engineering Department, gave decided evidences of color-blindness with the Holmgren test. His neutral point is at $\lambda = .514\ \mu$. The data in Table VIII. are shown in Plate II., Fig. 1, in comparison with the second normal. The point of maximum brightness is at $\lambda = .585\ \mu$, and, as the figure shows, is shifted a little towards the red.

The curves are practically identical through the violet and blue to $\lambda = .500\ \mu$ where an elevation begins, extending through the green to $\lambda = .570\ \mu$. Thence the curves coincide to $\lambda = .650\ \mu$, where the second elevation commences which extends to the end of the red.

TABLE VIII.

L. J. C.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0380 sec. | .520 μ | .0139 sec. | .613 μ | .0121 sec. |
| .412 | .0338 | .533 | .0130 | .640 | .0138 |
| .439 | .0274 | .550 | .0124 | .670 | .0169 |
| .463 | .0209 | .567 | .0116 | .705 | .0248 |
| .485 | .0167 | .588 | .0115 | .720 | .0285 |
| .505 | .0144 | | | | |

*Subject No. 9.* — Mr. J. H. H. was the only one of the subjects examined who was quite ignorant of his defective color vision. His first matches of the Holmgren worsted showed a very pronounced degree of color-blindness. On being told the result of the examination he was surprised and rather mortified, and requested another trial of the worsted test. This time by closely studying the samples he made a very good selection. No part of the spectrum appeared neutral to him, but he said that "green" began at $\lambda = .515\ \mu$. It is probable that this marked his neutral point, but that excessive caution prevented an unbiased judgment.

The curve, plotted from the data in Table IX., is shown in Plate II., Fig. 2, in comparison with the first normal. The brightest point is shifted toward the red. The general elevation of the whole curve indicates a diminished luminosity of the spectrum to the subject. In addition to this continuous difference between the curves, there are two distinct elevations, one of which lies between the wave-lengths .520 $\mu$ and .590 $\mu$, and the other from $\lambda = .615\ \mu$ to the end of the red.

Table IX.

J. H. H.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .406 $\mu$ | .0396 sec. | .520 $\mu$ | .0138 sec. | .613 $\mu$ | .0131 sec. |
| .440 | .0299 | .533 | .0136 | .640 | .0162 |
| .483 | .0215 | .550 | .0131 | .670 | .0196 |
| .495 | .0180 | .567 | .0128 | .720 | .0276 |
| .505 | .0161 | .588 | .0126 | | |

*Subject No. 10.*— Mr. H. J. H. located his neutral point at $\lambda = .515\ \mu$. The persistency measurements of Table X. are shown in Plate II., Fig. 3, in comparison with the third normal. This curve is not as pronounced in its characteristics as the previous ones. The last reading in the extreme violet has been neglected for reasons stated in a similar case. The relative positions of the curves indicate diminished luminosity of the whole spectrum to the subject. The first elevation lies between the wave-lengths .500 $\mu$ and .600 $\mu$, the second extends from .630 $\mu$ to the end of the red. The region of greatest brightness is shifted toward the red and located at $\lambda = .600\ \mu$ which is the point of separation of the two elevations.

Table X.

H. J. H.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 $\mu$ | .0500 sec. | .502 $\mu$ | .0178 sec. | .640 $\mu$ | .0157 sec. |
| .417 | .0360 | .520 | .0158 | .670 | .0211 |
| .440 | .0298 | .538 | .0146 | .705 | .0262 |
| .450 | .0261 | .562 | .0141 | .720 | .0283 |
| .460 | .0240 | .588 | .0137 | .730 | .0305 |
| .485 | .0199 | .613 | .0137 | | |

*Subject No. 11.*—In my former paper[1] on color vision there was described a case of color-blindness, Mr. S. W. F., which belongs to this class, and whose persistency curves are reproduced in Plate II.,

[1] Allen, op. cit., Fig. 15, p. 284.

Figs. 4 and 5. He was unable to find any neutral point, though he divided the spectrum into "yellow" and "blue" at $\lambda = .510\ \mu$. The figures show that there are two elevations separated by the point of maximum brightness at $\lambda = .600\ \mu$.

*Subject No. 12.* — Mr. W. L. S. made correct matches with the red sample in the Holmgren test, but failed with the others. The neutral point seemed difficult to decide upon, but he finally selected a part of the spectrum about $\lambda = .495\ \mu$. The brightest point, located at $\lambda = .550\ \mu$, is shifted toward the green, and, as is usual in curves of this type, separates the elevations.

The persistency measurements of Table XI. are compared with the third normal in Plate II., Fig. 6. In the violet and blue the curves are almost identical. One of the two elevations occurs in the green from $\lambda = .485\ \mu$ to $\lambda = .538\ \mu$, and the other from $\lambda = .560\ \mu$ to the end. The point of maximum brightness is shifted toward the green.

TABLE XI.

W. L. S.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0413 sec. | .502 μ | .0160 sec. | .620 μ | .0176 sec. |
| .417 | .0318 | .520 | .0146 | .660 | .0233 |
| .446 | .0241 | .538 | .0130 | .705 | .0292 |
| .472 | .0188 | .562 | .0129 | .720 | .0311 |
| .485 | .0173 | .588 | .0142 | .730 | .0325 |

The persistency curves of this class have two elevations, one in the red and the other in the green region, the exact boundaries differing in the various cases. The first three have the same neutral point, and the brightest point is shifted toward the red. The fourth case has a slightly different neutral region and the position of the brightest point is normal. The last case has a decidedly different neutral point, occurring farther in the blue than usual, and the brightest point is displaced towards the green.

## *Class IV.*

*Subject No. 13.* — Mr. C. F., a gentleman experienced in making very exact measurements in engineering work and also in astronomy, kindly consented to make observations for the determination of his persistency curve. His neutral point is at $\lambda = .502\ \mu$. With the Holmgren worsteds he showed many indications of color-blindness, but was able to select some colors correctly, especially saturated reds, among those that were in the range of his defective color perception. The persistency curve is shown in Plate II., Fig. 7, in comparison with the first normal. To this subject the whole spectrum appears less luminous than normal. The brightest point is shifted toward the green. There is but one elevation which extends from the neutral point over the entire red end.

TABLE XII.

C. F.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .406 μ | .0424 sec. | .505 μ | .0160 sec. | .588 μ | .0142 sec. |
| .425 | .0328 | .520 | .0146 | .613 | .0156 |
| .463 | .0228 | .533 | .0138 | .640 | .0176 |
| .483 | .0194 | .550 | .0135 | .670 | .0222 |
| .495 | .0173 | .567 | .0136 | .720 | .0306 |

*Subject No. 14.*—Mr. L. R. J. could hardly be persuaded to try the Holmgren test, remarking that the pile of worsteds was hopelessly confusing. Some selections that he did make, however, were correct, but most of them indicated a decidedly defective perception of color. His neutral point is at $\lambda = .510\ \mu$. The persistency measurements in Table XIII., are shown graphically in Plate II., Fig. 8, compared with the second normal. Their relative positions in the violet and blue show that the part of the spectrum up to $\lambda = .490\ \mu$ is more than normally luminous, while from this wave-length to the end of the red there is the usual elevation indicative of corresponding visual disturbances. The position of the brightest point is normal.

TABLE XIII.

L. R. J.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0362 sec. | .505 μ | .0142 sec. | .613 μ | .0144 sec. |
| .412 | .0312 | .520 | .0137 | .640 | .0172 |
| .439 | .0222 | .533 | .0131 | .670 | .0200 |
| .472 | .0166 | .550 | .0127 | .705 | .0246 |
| .485 | .0154 | .567 | .0125 | .720 | .0265 |
| .495 | .0149 | .588 | .0129 | .730 | .0306 |

*Subject No. 15.*—Mr. R. K., the last subject in this class, displayed with the worsteds an unusually great degree of color-blindness. His neutral point is at $\lambda = .503\ \mu$. The persistency readings given in Table XIV. are shown in Plate II., Fig. 9, in comparison with the third normal. An examination of the figure shows that his color vision is normal through the violet to about the middle of the blue, $\lambda = .470\ \mu$, from which point the curves diverge, indicating defective color perception throughout the remainder of the spectrum. The position of the brightest region is normal. The last reading in the extreme violet has been neglected for the same reasons that were stated in a previous case.

The characteristic feature of this class is that the persistency curve on the violet side of the neutral point is normal and on the red side abnormal, the neutral region forming the dividing line.

Table XIV.

R. K.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0489 sec. | .502 μ | .0172 sec. | .620 μ | .0157 sec. |
| .417 | .0355 | .520 | .0152 | .660 | .0223 |
| .446 | .0261 | .538 | .0140 | .705 | .0301 |
| .472 | .0195 | .562 | .0138 | .720 | .0323 |
| .485 | .0185 | .588 | .0139 | .730 | .0343 |

## *Class V.*

The relatively large number of cases in this class indicates that it is probably the most common type of color-blindness. The characteristics of the persistency curves are two elevations occurring in the red and violet, the intervening portions being normal. Three of the seven cases have the position of the brightest point unaltered; two have it shifted toward the green and two toward the red.

*Subject No. 16.*—Mr. J. P. K. gave pronounced evidences of color-blindness with the Holmgren test. His neutral point is at $\lambda = .511\ \mu$. The persistency measurements in Table XV. are shown in Plate III., Fig. 1, in comparison with the fourth normal. In no part do the curves coincide. There is an elevation in the violet extending to $\lambda = .470\ \mu$ and a similar one from $\lambda = .720\ \mu$ to the end of the red. The depression of the curve between these elevations indicates an increased brightness of the spectrum to the subject. The position of the brightest point is normal.

TABLE XV.

J. P. K.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .405 μ | .0485 sec. | .501 μ | .0154 sec. | .660 μ | .0145 sec. |
| .412 | .0450 | .520 | .0132 | .680 | .0175 |
| .425 | .0400 | .538 | .0125 | .705 | .0212 |
| .440 | .0338 | .562 | .0117 | .717 | .0227 |
| .455 | .0284 | .588 | .0113 | .730 | .0262 |
| .472 | .0215 | .620 | .0119 | .745 | .0290 |
| .487 | .0200 | | | | |

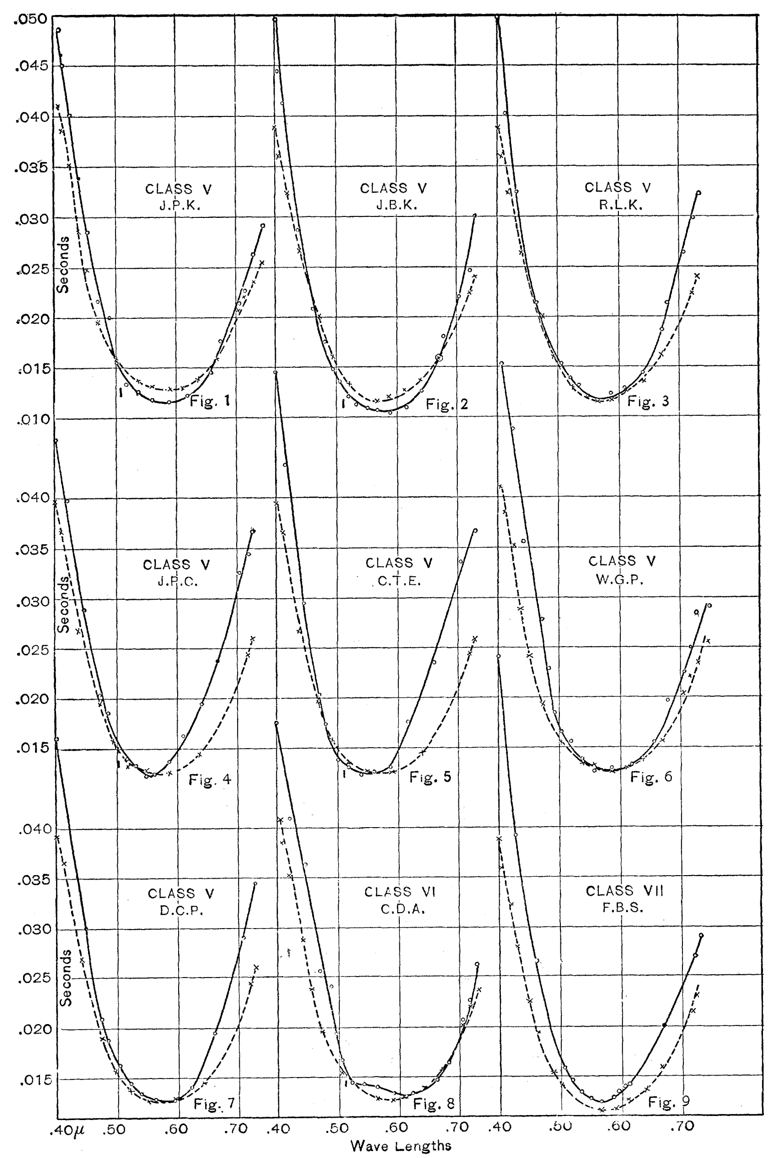
*Subject No. 17.*—Mr. J. B. K. made nearly all the mistakes possible in the Holmgren test. His neutral point is at $\lambda = .514\,\mu$. The persistency measurements given in Table XVI. are shown in Plate III., Fig. 2, in comparison with the first normal. The position of the brightest point is shifted toward the red. In other respects this curve is similar to the preceding one.

TABLE XVI.

J. B. K.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0497 μ | .505 μ | .0133 sec. | .640 μ | .0125 sec. |
| .406 | .0444 | .520 | .0120 | .670 | .0160 |
| .412 | .0412 | .533 | .0113 | .680 | .0180 |
| .439 | .0287 | .550 | .0109 | .705 | .0220 |
| .463 | .0208 | .567 | .0106 | .720 | .0247 |
| .483 | .0175 | .588 | .0104 | .730 | .0300 |
| .495 | .0148 | .613 | .0109 | | |

*Subject No. 18.*—Mr. R. L. K. in the Holmgren test matched the red and green samples correctly but failed with the third. The only part of the spectrum that seemed to him neutral was at $\lambda = .583\,\mu$, which is the wave-length at which König's red and green sensation curves intersect, and where, under some circumstances, a neutral point might be expected to occur. The data of Table XVII. are shown in Plate III., Fig. 3, in comparison with the first normal. The brightest point is in its normal position. The curves coincide between the two elevations.



.050
.045
.040
.035
.030
.025
.020
.015
.010
Seconds
CLASS V
J.P.K.
Fig. 1
CLASS V
J.B.K.
Fig. 2
CLASS V
R.L.K.
Fig. 3
CLASS V
J.P.C.
Fig. 4
CLASS V
C.T.E.
Fig. 5
CLASS V
W.G.P.
Fig. 6
CLASS V
D.C.P.
Fig. 7
CLASS VI
C.D.A.
Fig. 8
CLASS VII
F.B.S.
Fig. 9
.40μ .50 .60 .70 .40 .50 .60 .70 .40 .50 .60 .70
Wave Lengths


Plate III.

TABLE XVII.

R. L. K.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0499 sec. | .533 μ | .0130 sec. | .670 μ | .0184 sec. |
| .412 | .0402 | .550 | .0120 | .680 | .0214 |
| .430 | .0324 | .567 | .0116 | .705 | .0266 |
| .463 | .0212 | .588 | .0123 | .720 | .0299 |
| .505 | .0152 | .613 | .0127 | .730 | .0321 |
| .520 | .0138 | .640 | .0142 | | |

*Subject No. 19.* — Mr. J. P. C. made incorrect selections with all the Holmgren test samples. His neutral point is at $\lambda = .506\,\mu$. The persistency measurements are given in Table XVIII. and are shown in Plate III., Fig. 4. The curve shows that the brightest point is shifted slightly towards the green. There are the two characteristic elevations, one in the violet and the other in the part corresponding to red, orange and yellow. The curves coincide in the green.

TABLE XVIII.

J. P. C.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0457 sec. | .520 μ | .0139 sec. | .640 μ | .0194 sec. |
| .418 | .0397 | .533 | .0132 | .670 | .0235 |
| .447 | .0287 | .550 | .0123 | .705 | .0324 |
| .472 | .0202 | .567 | .0123 | .720 | .0344 |
| .485 | .0184 | .588 | .0135 | .730 | .0366 |
| .502 | .0149 | .613 | .0162 | | |

*Subject No. 20.* — Mr. C. J. E. determined his neutral point to be at $\lambda = .516\,\mu$. His persistency curve is shown in Plate III., Fig. 5, in comparison with the third normal. The brightest point is shifted toward the green. The curves coincide between the elevations. The following table contains the persistency measurements of this subject.

TABLE XIX.

C. T. E.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0526 sec. | .502 μ | .0140 sec. | .620 μ | .0177 sec. |
| .417 | .0433 | .520 | .0131 | .660 | .0235 |
| .446 | .0292 | .538 | .0125 | .705 | .0335 |
| .472 | .0202 | .562 | .0125 | .730 | .0368 |
| .485 | .0174 | .588 | .0129 | | |

*Subject No. 21.* — Mr. W. G. P., a student in one of the physical laboratories, gave very few indications of color-blindness with the Holmgren test, the only color which betrayed his defective vision being the green. No neutral point was found except a rather doubtful region in the neighborhood of $\lambda = .560\,\mu$. Three independent settings of the instrument were made at this point. The readings in Table XX. are shown in Plate III., Fig. 6, in comparison with the fourth normal.

TABLE XX.

W. G. P.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .405 μ | .0532 sec. | .505 μ | .0167 sec. | .660 μ | .0155 sec. |
| .425 | .0469 | .520 | .0155 | .680 | .0197 |
| .446 | .0357 | .538 | .0138 | .705 | .0226 |
| .472 | .0279 | .562 | .0127 | .717 | .0250 |
| .485 | .0228 | .588 | .0128 | .730 | .0284 |
| .495 | .0185 | .620 | .0131 | .745 | .0292 |

*Subject No. 22.* — Mr. D. C. P. matched correctly the red and green samples, but failed with the magenta. He could find no neutral point at all. The persistency values in Table XXI. are shown in Plate III., Fig. 7, compared with the third normal. The point of maximum brightness is shifted toward the red.

TABLE XXI.

D. C. P.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0488 sec. | .520 μ | .0142 sec. | .620 μ | .0136 sec. |
| .447 | .0300 | .538 | .0134 | .660 | .0193 |
| .472 | .0208 | .562 | .0126 | .705 | .0287 |
| .485 | .0185 | .588 | .0125 | .730 | .0344 |
| .502 | .0162 | | | | |

## *Class VI.*

*Subject No. 23.* — Only one subject belonging to this class was among the number of color-blind persons examined. Mr. C. D. A., the subject in question, failed in the Holmgren test with the green confusion sample only, and remarked that he always had trouble in distinguishing between green and brown. His neutral point is at $\lambda = .512\,\mu$, and is peculiar as being the point of coincidence of the curves, and lies between the two elevations. The persistency data are in Table XXII., and are shown in Plate III., Fig. 8, in comparison with the fourth normal. The point of maximum brightness is considerably displaced towards the red, occurring at $\lambda = .620\,\mu$. One elevation of the curve runs from the extreme violet through the blue and is terminated in the green by the neutral region; the second extends from this region to the wave-length denoting the brightest point. The curves thence coincide to nearly the end of the red, where the last reading is a little elevated. As the extreme red is difficult to observe accurately, this slight elevation is to be regarded as very doubtful.

Table XXII.

C. D. A.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .405 μ | .0508 sec. | .505 μ | .0164 sec. | .660 μ | .0148 sec. |
| .425 | .0410 | .520 | .0145 | .680 | .0165 |
| .446 | .0363 | .538 | .0142 | .705 | .0206 |
| .472 | .0256 | .562 | .0139 | .717 | .0226 |
| .485 | .0240 | .588 | .0135 | .730 | .0262 |
| .495 | .0192 | .620 | .0132 | | |

## *Class VII.*

### *A Case of Total Color-blindness.*

*Subject No. 24.* — Mr. F. B. S., a student in the Veterinary Department of the University, was noticed by one of the instructors in chemistry to make many mistakes in naming the characteristic colors of chemical reactions. Through the kindness of Dr. Turner of the Chemistry Department, the case was brought to my attention and the consent of the student gained to make several color vision tests. The subject himself stated that all "colors" were equally difficult to distinguish and that all the Holmgren worsteds were about the same to him.

Inquiry at various times elicited the following personal information: Near objects are distinguished much better than those at a greater distance. Vision can be fixated on a point for some time, but a feeling of fatigue is soon experienced which often is painful. On leaving a room and going out into the bright sunshine the light hurts his eyes occasioning an excessive flow of tears. At intervals of about half a year he has severe headaches which are accompanied by hemiopsy or "half vision," a peculiarity which also troubles one of his sisters. On two occasions complete blindness lasting several hours came gradually upon him, once when in high school and the other time during a lecture at the university. During these periods of blindness only sufficient visual power was retained to distinguish light from darkness. The pupil, he said, always dilates during these "blind intervals." As all glasses he had ever used seemed to hurt his eyes he had discontinued their use. No other member of his family or of his relatives was affected with visual trouble of any kind as far as he knew, except his sister in the way mentioned.

Very complete series of selections of the Holmgren worsteds were made, which, upon examination through suitable colored glasses, proved to be matched according to their brightness. With a light gray sample he matched light shades of very many colors. He had learned, he said, to distinguish yellow, though this was sometimes confused with neutral shades. These indications all confirmed the conclusion that his vision was achromatic, and the proof will appear complete when the various curves he obtained are examined.

As all the spectrum was supposed to appear colorless to him and to vary only in brightness, the Helmholtz color-mixing spectrophotometer, adapted for the determination of neutral points as previously described, was used to obtain a luminosity curve. This was easily done by varying the intensity of the reflected light with the Nicol prism until it matched the part of the spectrum under observation. In this way white light of some intensity was matched with every part of the spectrum. Three or four independent observations were made at each selected point and readings taken of the angle between the principal planes of the polarizer and analyzer, to the square of the cosine of which the intensity of the light is proportional. The mean values of these angles are given in the following table.

TABLE XXIII.

F. B. S. LUMINOSITY CURVE.

| λ | Angle Between Planes = α | cos² α | λ | Angle Between Planes = α | cos² α |
|---|---|---|---|---|---|
| .450 μ | 88° 12′ | .0009 | .563 μ | 71° 42′ | .098 |
| .457 | 87 0 | .0027 | .571 | 69 0 | .128 |
| .466 | 85 54 | .0051 | .582 | 66 12 | .163 |
| .475 | 85 0 | .0076 | .593 | 63 36 | .197 |
| .485 | 83 12 | .0140 | .605 | 62 30 | .213 |
| .498 | 81 42 | .0208 | .616 | 72 6 | .094 |
| .510 | 80 0 | .0301 | .628 | 76 36 | .054 |
| .524 | 78 30 | .0398 | .640 | 82 18 | .018 |
| .537 | 77 18 | .0482 | .655 | 84 18 | .009 |
| .545 | 75 36 | .062 | .670 | 85 48 | .005 |
| .554 | 73 36 | .080 | .685 | 87 54 | .0009 |

These values, plotted in Fig. 3, give the usual form of luminosity curve. One very remarkable feature is that the maximum occurs

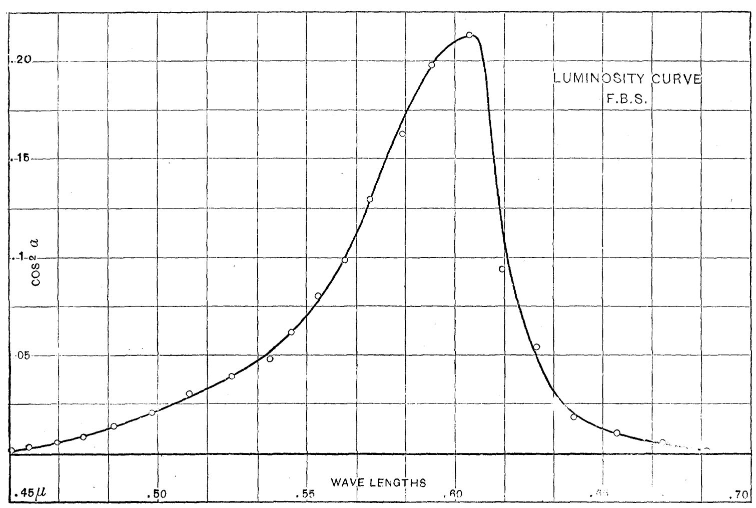



Fig. 3.

at $\lambda = .605\,\mu$, or is practically normal; usually it is found at the line $E\,(\lambda = .527\,\mu)$, and Abney[1] in particular has studied several cases

[1] Sir W. de W. Abney, "A Case of Monochromatic Vision," Proc. Roy. Soc., Vol. 66, 1900, p. 179. Also Color Vision (Tyndall Lectures), Chap. 12, p. 148.

in which the maximum luminosity is so displaced. The line *E* is also the normal maximum brightness when the intensity of the spectrum is so much reduced that all color disappears, leaving only a substratum of gray. The coincidence of the luminosity maximum of the faint light spectrum to the normal eye with that of the normal spectrum to the totally color-blind retina is of much theoretical interest. In this case, however, the agreement does not occur.

Persistency curves were also obtained for both eyes, but since they agree completely only one is here given, the data for which are recorded in Table XXIV. The curve is shown in Plate III., Fig. 9, in comparison with the second normal. Readings were taken, it will be observed, at points very close together through the yellow and green in order to see if there were any indications of three separate elevations as might be expected from any trichromatic theory. The curve, however, is simply elevated throughout its entire extent, the increase in the duration of color impressions varying from a maximum in the violet to a minimum in the yellow, the increase in the red being intermediate in value.

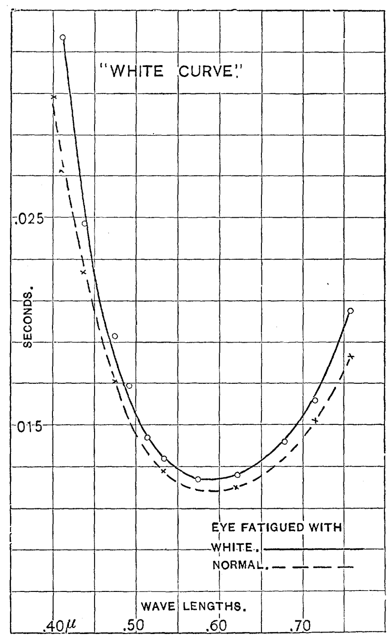



Fig. 4.

Both curves have their lowest point at $\lambda = .570\,\mu$ which indicates that the region of greatest brightness is not shifted. The luminosity curve showed the brightest point to be at $\lambda = .605\,\mu$. Direct observation located it at $\lambda = .570\,\mu$. The three determinations should agree, though the cause of the variation may be in the difference between the spectra upon which the two sets of measurements were made. The spectrum used for persistency observations was much more highly dispersed than the one by which the luminosity curve was obtained. If the brightest point is shifted, the displacement in any case is but little.

In my former paper on color vision to which reference has already been made, there was described an experiment in which the normal eye was fatigued with white light and a persistency curve obtained with it in this condition. The effect of this fatigue was to diminish the sensitiveness of the retina for all colors. The curve showing this effect is reproduced in Fig. 4. The similarily of this figure with that (Plate III., Fig. 9) showing the measurements of the totally color-blind person is very apparent.

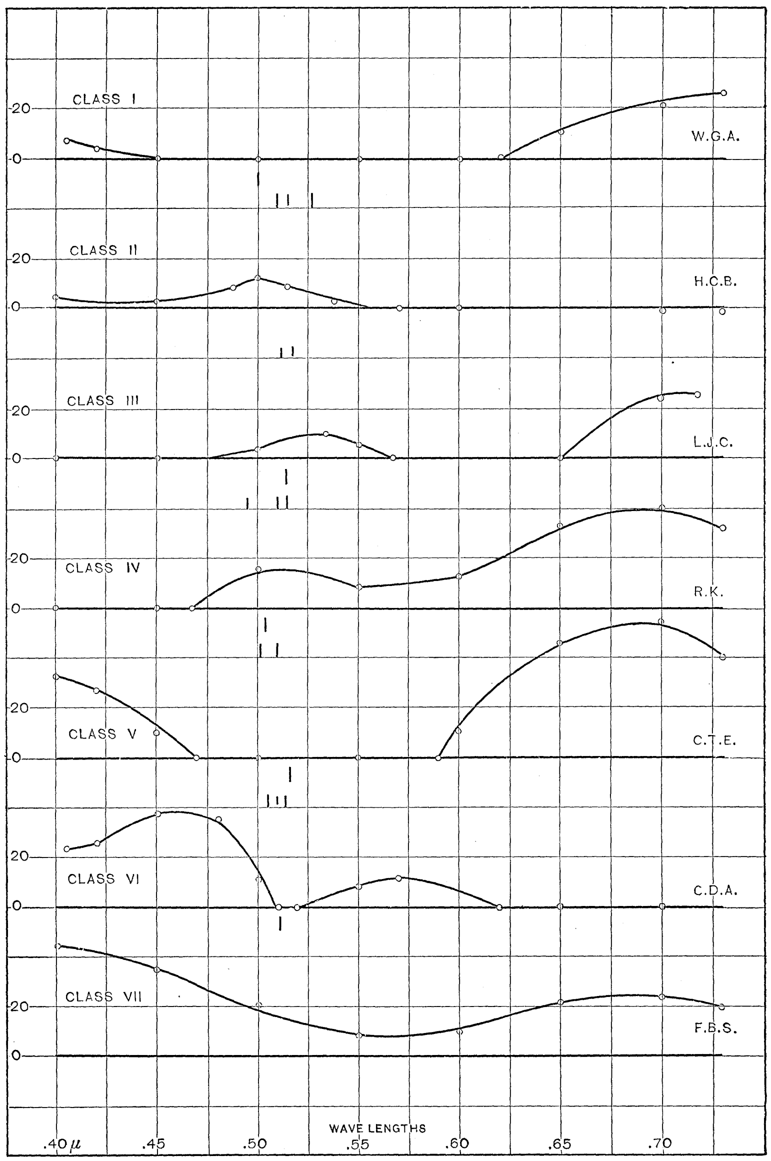
TABLE XXIV.

F. B. S.

| λ | Persistence. | λ | Persistence. | λ | Persistence. |
|---|---|---|---|---|---|
| .400 μ | .0570 sec. | .533 μ | .0134 sec. | .605 μ | .0138 sec. |
| .430 | .0391 | .550 | .0127 | .613 | .0142 |
| .463 | .0264 | .567 | .0124 | .670 | .0200 |
| .505 | .0159 | .588 | .0128 | .720 | .0270 |
| .520 | .0145 | .597 | .0133 | .730 | .0288 |

## DISCUSSION OF THE SYSTEM OF CLASSIFICATION.

The regularity of the curves and the general uniformity of the measurements which have been examined in the preceding pages naturally excite in one a feeling of confidence in their reliability, a feeling which is deepened by the almost ideal manner in which the results permit themselves to be classified. And yet, strange as it may seem upon reflection, considerable criticism has been levelled at the persistency of vision method of studying the phenomena of color perception on account of this very uniformity of the observations. It has been gravely asserted that the eye is such a delicate organ, troubled by so many imperfections, and the measurements themselves subject to so many sources of error, that constancy of duration of visual impressions is impossible to realize. Undoubtedly there are sources of error which affect the results, but they must enter to an equal extent in observations in all parts of the spectrum ; and as the conclusions are drawn from a *comparison* only of the results obtained by normal and by abnormal eyes under exactly similar conditions, the effect of these errors must be vanishingly small.



CLASS I
W.G.A.
CLASS II
H.C.B.
CLASS III
L.J.C.
CLASS IV
R.K.
CLASS V
C.T.E.
CLASS VI
C.D.A.
CLASS VII
F.B.S.
20
0
WAVE LENGTHS
.40μ
.45
.50
.55
.60
.65
.70


Fig. 5.

The criticism affects far more than the results discussed in this paper. The experiments of Abney and of König, as well as those of numerous other investigations in the domain of color vision, are equally discredited. And indeed the acceptance of the standpoint of this criticism would put a stop to further exact experiments in this branch of science. If experimental evidence is allowed its rightful precedence over theory this criticism becomes of no effect.

Attention has been directed to the general results of the Holmgren test with the subjects considered in this paper. Some failed with all the test samples, others with two, and others still with but one. The Holmgren test, valuable as it is for the rapid detection of color-blindness, is manifestly a very inaccurate method of classifying the cases. Those who are aware of their visual imperfections are able from experience to avoid many indications of their condition. Other tests than this are generally used to provide a basis of classification, such, for example, as the location of the neutral region or of the point of maximum brightness.

For the general discussion of the results which have been considered in detail, one curve of each of the seven classes is shown in Fig. 5 so that they may be readily compared. In this figure the normal curve is everywhere reduced to the same ordinate making that curve a straight horizontal line. The abnormal curves[1] are reduced in the same ratio thus permitting their characteristics to be more strikingly shown.

This method of representation has the additional merit of enabling the mutual relationship of the classes of curves, and therefore of the divisions of color-blindness, to be comprehended in one figure. Though we cannot yet determine the full meaning of the abnormal persistency curve, yet it has been seen that certain parts agree with the normal and other parts disagree in a thoroughly systematic manner. The elevations, being a sure accompaniment of color-blindness, must be characteristic of it. But that some parts of the curve are normal cannot necessarily imply that the corresponding portions of the spectrum are always perceived normally, for the

[1] In Fig. 5 the neutral point of the subject whose curve is shown is represented by the vertical line standing alone. The neutral points of the other subjects of the class are marked by similar lines below the other.

neutral region, which as its name indicates is devoid of color, very often occurs in the normal part of the curve. Indeed in one case (*C*, *D*, *A*, Plate III., Fig. 8) the neutral point is the only normal part between the two elevations. The persistency curve shows the variation of the perception of brightness of the spectrum, and involves color only in so far as it is connected with the sensation of brightness.

A brief summary of the characteristics of the classes of curves is given as follows:

*Class I.* — Curves have one elevation which occurs in the part corresponding to red and orange, the rest of the curve being normal.

*Class II.* — Curves have one elevation in the part corresponding to the green region, extending into the yellow and blue.

*Class III.* is a combination of the first two classes. Curves have two elevations, one in the red and the other in the green, separated by a normal portion.

*Class IV.* is a modification of the third class. The curves have one elevation extending over all the region from the beginning of the green on the violet side to the end of the red.

*Class V.* — Curves have two elevations, one in the red and the other in the violet, the intervening portion being normal.

*Class VI.* — Curve has two elevations, one in the green and the other in the violet.

*Class VII.* — The whole curve is elevated above the normal.

In the different classes corresponding elevations do not always extend over the same portion of the spectrum. The elevation in the red sometimes covers the orange and even yellow. The elevation in the green is sometimes shifted very much towards the yellow, and the limits of the violet elevation also vary to some extent. These peculiarities do not, however, invalidate the general conclusions; for color-blindness may be characterized by a modification of the color apparatus as well as by the absence of one or more of the primary sensations, and this may easily result in the variation of the position of the elevations.

## Bearing of the Curves on Color Theories.

The Hering theory of color vision postulates two pairs of antagonistic color processes, one resulting in the red and green sensations, the other in the yellow and blue. Any modification of the red or yellow sensations must be accompanied by a modification of the green and blue respectively. It therefore follows that red or green color-blindness cannot exist alone. Both sensations are normal together or both abnormal. From the theory yellow-blue blindness is possible, though some consider it very improbable.

From the standpoint of this hypothesis there are three possible types of persistency curves: one in which elevations would occur in the red and green portions, a second in which they would occur in the yellow and blue, and the third in which the whole curve would be elevated. Curves with single elevations in any part are directly opposed to the provisions of the theory in question. The curves comprising the third, sixth and seventh classes may be considered to be in harmony with the theory, the remainder are impossible to be accounted for by it.

The same objections obtain with the other hypotheses of color vision which are mere modifications of Hering's or constructed by analogy with it, such as, for example, the theory of Müller and that of Ebbinghaus. To many of the minor theories which have been devised in such abundance, application of these results is perhaps needless.

Turning our attention from four-color to three-color theories, the case is at once seen to be very different. In this connection the classification may be advantageously discussed from the standpoint of the Young-Helmholtz theory. From the number of fundamental color sensations and their independent character, the possible types of abnormal persistency curves may be determined. Any of the three primaries, red, green or violet may be absent or modified separately because of their independence. The resulting persistency curves would show the defect by a single elevation in the part of the curve corresponding to those light waves to which the retina is not normally responsive. For it has been repeatedly shown that the luminosity curves of the color-blind indicate decreased brightness of certain parts of the spectrum, which in the persistency curve shows itself by one or two elevations.

The Young-Helmholtz theory also admits the possibility of types of color-blindness in which two sensations are simultaneously modified or lacking, the absent ones being red and green, red and violet, or green and violet. The persistency curves corresponding to each of these cases would have two elevations appropriately situated.

The original form of the theory not admitting the possibility of total color-blindness, its experimental demonstration has necessitated some modification. Adopting the modern form of the theory, one is led to the conclusion that there may be anticipated types of persistency curves corresponding to the seven possible cases of color-blindness described. Curves corresponding to six of these types have been obtained and described in this paper, the missing one being that in which one elevation would occur in the violet. No case of violet-blindness was found among the subjects examined, though Abney[1] has described one.

The curves in this paper it will be remembered have been grouped into seven classes, but III. and IV. are perhaps essentially the same.

With the general provisions of the Franklin theory, which now has its champions in the lists, these experiments are also in harmony, except in the selection of blue instead of violet for one of its triad of fundamentals.

The twenty-six cases of color-blindness which have been discussed comprise comparatively few who have defective color perception confined to one sensation. Most of them have red-blindness in some degree combined with either green- or violet-blindness, the majority falling into the latter division. Since abnormal perception of green or red separately is comparatively infrequent, there is a good basis for Hering's conclusion that red- and green-blindness are always associated together. Though this is partially correct, a statement nearer the truth is that red-blindness is nearly always associated with a similar defect in either violet or green, more commonly the former.

The study of the phenomena of color vision by the method of the persistence of visual impression sheds no light apparently on the nature of the retinal processes themselves. Whether they are concerned with nerve fibrils, photo-chemical substances, the mechanical tearing down of complex color molecules, or with any other of the numerous devices for transforming certain radiant energy into sub-

[1] "Colour Vision," p. 73.

jective color sensation, the method is not competent to decide. Nor does it afford any explanation of after-images, contrast colors, fields of color, and the numerous other phenomena of chromatic vision which all contribute to make the subject of color perception so peculiarly elusive. While all these demand explanation and incorporation into acceptable theories, no less do the very striking characteristics of the persistency curves, intimately associated as they undoubtedly are with abnormal color vision.

The curves, more especially those obtained by the totally color-blind subject, seem to show quite definitely the existence of an underlying white sensation. Color, whatever else it may be, manifests itself in part as an added luminosity to the fundamental white. When some one color process is not present in the retina, or is present in a modified form, the part of the spectrum which would be its normal stimulus, is perceived less intensely, and the persistency curve through this region is that of the underlying white alone, or of white mingled with traces of the fading color sensation, which gives it the familiar elevated appearance. So that while the physiological processes involved are very obscure, yet the uniformity of location of the elevations seems to have almost a determining influence upon the choice of red, green and violet as the color fundamentals.

Some of the more important conclusions which seem to be justified by the general character of the results which have been examined may be conveniently collected here.

1. Persons with normal color vision, and of not widely different ages, have the same persistency curve under similar circumstances; or, all color impressions have the same duration in their retinas.

2. The persistency curves of the color-blind always have characteristic elevations, either one or two in number, which occur in general in those portions of the curves corresponding to the red, green and violet in the spectrum.

3. On the basis of the modified form of the Young-Helmholtz theory there are seven possible types of color-blindness: those in which only one of the primaries is absent or modified, those in which any two may be simultaneously absent or modified, and total color-blindness. Persistency curves corresponding to six of

these types have been described in this paper, none having been obtained to illustrate violet-blindness.

4. The results are entirely opposed to the assumption of four fundamental color sensations, but are in harmony with the selection of red, green and violet as primaries. The existence of a white sensation is also to be inferred, and that color consists, in part at least, of an additional brightness superposed upon this underlying white.

In an investigation of this kind I am necessarily under great obligations to many persons. Without the courteous coöperation of those who have shown such interest and patience in making the careful observations discussed in these pages, the successful prosecution of the work would have been impossible. In particular Dr. Margaret Floy Washburn and Mr. E. C. Roberts have obtained for me important results which have been referred to in their place. To Professor E. L. Nichols, whose method of studying the effects of light upon the retina has been followed, and under whose direction the research was carried on, I am indebted for numerous suggestions which have been incorporated in the work.

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