Art. XXVI.—*Persistence of Vision*; by Ervin S. Ferry.

[Contributions from the Physical Laboratory of Cornell University, No. 10.]

Ever since the time of Aristotle, it has been known that when the eye is impressed by light, the sensation persists even after the exciting cause has ceased to act. In his work on dreams, Aristotle describes duration of impressions in the retina and then deduces as the cause of dreams a similar persistence of impression on the sensorium of things experienced when awake. The ancients noticed and correctly explained many optical illusions by persistence of vision; but it was not till twenty centuries after Aristotle that anyone attempted to measure the duration of visual impression. Segner* measured the duration of the light impression from a spark of a rotating stick and adopted 0·1 second as the probable value. D'Arcy,†

* De raritate luminis (Göttingen, 1740, pp. 5–8).
† Mémoire sur la durée de la sensation de la vue (1768).

Cavallo,* and Parrott† have since fully substantiated this value by accurate measurements. Plateau,‡ in 1829, found that when discs divided into sectors alternately black and of some special color were rotated, different speeds were required to produce uniformity of tint, depending upon the color of the pigment used to paint the alternate sectors. By noting the angular size of the black and the colored sectors and the speed just necessary to produce uniformity of tint, he was enabled to determine the absolute duration of the maximum impression for the different colors experimented upon. By using the different discs painted in sectors, each having black alternating with some one color, Plateau obtained the following values for the duration of impression for these particular colors:—

White	0·191	secs.
Yellow	0·199	"
Red	0·232	"
Blue	0·295	"

One great difficulty with this method is that since no pigment gives a pure color and since pigments vary so widely in tint, the results obtained hold only for the particular specimens experimented upon. To overcome this difficulty, Dr. E. L. Nichols§ employed a revolving disc having sectors cut out, in front of the slit of the spectroscope, and defined his colors by their wave-lengths. In this manner by suitably choosing the wave-lengths used for observation, a curve was drawn showing the relation between the duration of impression and the color corresponding to any wave-length.

From the results obtained by Plateau, Emsmann,‖ Nichols and others, it was reasoned that the duration of retinal impressions depends upon the intensity of the light-giving source and upon the color of the light entering the eye. To test the validity of this latter proposition, and to determine the principal factors producing persistence of vision has been the object of the series of experiments now to be described.

Apparatus and Method of Observation.

The plan of the investigation was to obtain curves showing the relation between duration of the retinal impression of the normal eye and wave-length of light observed for spectra of

* The elements of natural or experimental philosophy (London, 1803), vol. iii, p. 135.

† Entretiéns sur la physique (Dorpat, 1819), vol. iii, p. 235.

‡ Dissertation sur quelques propriétés des impressions produites par la lumière sur l'organs de la vue. (Liege, 1829).

§ On the Duration of Color Impressions upon the Retina, this Journal, vol. xxviii, p. 243.

‖ Ueber die Dauer des Lichteindrucks, Pogg. Ann., xci (1854), p. 611.

different intensities; to compare these curves with another showing the distribution of luminosity in the spectrum used; and finally to compare similar curves obtained from dichroic eyes.

The apparatus for the measurement of the retinal impression consisted of a diffraction-grating spectrometer; a sectored disc that could be revolved by an electric motor, interposed between the lamp and collimator; and a chronograph to register accurately the number of revolutions of the disc. The source of light was a hundred-volt Edison incandescent lamp supplied by a secondary battery, and it was kept at constant candle power by varying the resistance in circuit so that a volt-meter would always indicate one hundred volts. In front of the lamp was mounted a large condensing lens for the purpose of projecting upon the collimator slit an enlarged image of the filament. In this way a uniform distribution of light was obtained in all parts of the field of the spectrometer. At the focus of the eye-piece of the telescope was placed a diaphragm so as to isolate from the spectrum the single color it was desired to observe. The disc had a ninety-degree sector cut out from each end of a diameter so that when the disc revolved there would be seen in the telescope equal periods of illumination and of darkness. The speed of the disc was controlled by means of a friction-brake managed by the observer. On the shaft of the disc was mounted a contact device by means of which an electric circuit was made for an instant on each revolution of the disc. This current was conducted to the primary of an induction coil having the secondary so connected to a chronograph cylinder that a spark would puncture a blackened paper on the cylinder every time the sectored disc revolved. Pressing against the chronograph cylinder was a stylus electrically connected to the escapement of a standard clock. By this device the number of revolutions of the sectored disc in a second could be very accurately determined.

When taking an observation, the experimenter sits at the telescope of the spectrometer with one hand on the brake regulating the speed of the sectored disc. The disc is first made to revolve so slowly that the field of view in the telescope flickers, and then the speed is gradually increased till the point is reached when the field just becomes quiet; then a key is pressed and an assistant rotates the chronograph cylinder for five seconds and takes the record of the speed of the sectored disc. This gives the duration of the maximum impression on the retina. Such a short time of observation as here used has many manifest advantages. Even when the disc is steadied by a heavy fly-wheel as was done in these experiments, and rotated by a powerful motor, the speed can be kept constant for only a short time. Other experimenters have taken oneminute observations or longer, and found their separate observations differing by a large per cent from the mean. With this apparatus a difference of more than three per cent between two observations of the same region in a spectrum of ordinary brightness is rare. The observations at regions of low brightness are more difficult.

The eye was subjected to the intermittent light for as short a time as possible so as to avoid the secondary colors described by Signor Cintolesi.* After each observation on colored light the eye was rested by looking at white light and the succeeding observation was invariably made on a different color. Thus the disproportionate increase of sensitiveness of the eye for more refrangible rays due to adaptation, as noticed by M. H. Parinaud,† was guarded against. These observations were made in a room with blackened walls and every attempt was made to exclude extraneous light. It was also soon found that precautions were necessary to eliminate the slight tremor produced by the motor and the disc, because a vibration of the lamp or of the diffraction-grating produces a flicker in the field of view that cannot be distinguished from the appearance produced by a too slow rotation of the sectored disc.

Duration of Light Impressions on the Normal Retina.

To represent the normal eye, three persons were selected of about the same age, whose eyes were free from Daltonism, astigmatism, near- and far-sightedness and from such abnormal color sensations as have been recently observed by Captain Abney‡ in confirmed users of narcotics and stimulants. How very closely the duration of retinal impression for each part of the spectrum agreed for these cases is shown in the following table:

TABLE I.

Wave-length.	Duration of retinal impression in seconds.		
λ	E. S. F.	G. W. B.	E. F. N.
·435	·0357	·0357	·0333
·480	·0250	·0263	
·510	·0200	·0186	·0200
·540	·0156	·0152	
·570	·0139	·0139	·0139
·589	·0132	·0128	·0128
·615	·0141	·0142	
·645	·0156	·0152	
·684	·0192	·0179	·0192

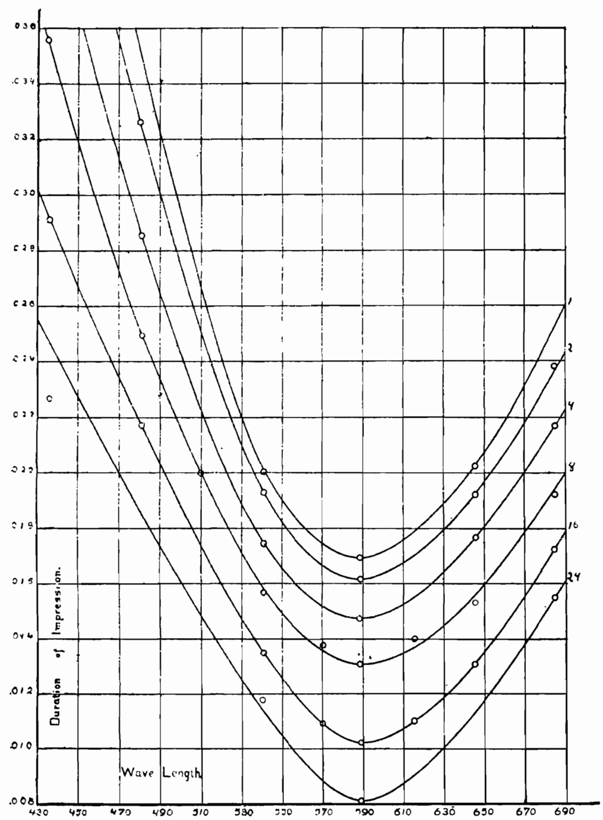
* Ann. di Optalmol. II and III, 1879.

† De l'intensité lumineuse des couleurs spectrales, Comptes Rendus, xcix, p. 937.

‡ On the Examination for Color of cases of Tobacco Scotoma, and of Abnormal Color-blindness. Roy. Soc. Proc., xlix (1891), p. 491.

The values given in this table as well as in all the succeeding tables are not averages of a number of observations, but are the values of a single set of readings. The third and fourth columns are the values obtained by two observers who had only used the apparatus for about an hour, and are hence less reliable than the values in the second column which have been many times repeated. The curve platted from the values in the second column is shown in fig. 1, curve 8.

1.



Duration of Impression of normal eye for different colors and different intensities.

The fact was noticed with some surprise that on different days the observations were nearly identical, if the eyes had not been strained or made more than normally sensitive by remaining for a long time in a dark room. And it was also found that the sensitiveness of the eye might have changed by several per cent without producing any noticeable difference in the duration of the retinal impression. This shows two things: first, that the personal equation, or more properly the personal error, in this sort of investigation is less formidable than ordinarily supposed; and secondly that a comparatively large change of sensitiveness of the eye is required to produce a marked change in the duration of the retinal impression.

An examination of this curve (8, fig. 1) shows that the retinal persistence is very different for different parts of the spectrum. As in the curves published by Dr. Nichols, in the paper already cited, the minimum duration is near the D line, and from this point the duration steadily increases toward each end of the spectrum. The observations were carried relatively farther into the blue than in the red, which largely accounts for the apparent unsymmetrical form of the curve. The curve is of the general form of a parabola with its apex approximately at the D line and the two branches becoming parallel to the ordinates of the ends of the spectrum.

Duration of Retinal Impression for light of different Intensities.

In the early part of this century Plateau* noticed that there was an intimate connection between duration of retinal impressions and the intensity of the light producing them. One of the principal objects of this investigation was to determine the law connecting these quantities. To do this, values of duration of retinal impression were obtained for monochromatic light of different intensities. The light intensity was varied by changing the width of the collimator slit according to Vierordt's method. The plan followed was to obtain a spectrum of a certain brightness, and measure the duration of retinal impression at sufficient points in it to be able to plat a curve showing the relation between the retinal persistence and wave-length. Then changing the width of the collimator slit by a definite amount, so as to obtain a spectrum of a brightness in known proportion to that of the preceding spectrum, to determine the duration of impression for the same points as before. In this way the following values were obtained for the duration of retinal impression of monochromatic light of different color and different intensity.

* Dissertation sur quelque propriétés des impressions produites par la lumière sur l'organs de la vue. (Liege 1829.)

TABLE II.

Duration of retinal impressions for monochromatic light of different wave-length, of relative brightness from 1 to 24.

Wave-length.	Duration of retinal impressions in seconds. 1.	2.	4.	8.	16.	24.
·435				·0357	·0294	·0227
·480		·0328	·0286	·0250	·0217	
·510				·0200		
·540	·0200	·0192	·0172	·0156	·0133	·0119
·570				·0139	·0109	
·589	·0170	·0161	·0147	·0132	·0102	·0081
·615				·0141	·0111	
·645	·0204	·0192	·0179	·0156	·0130	
·684		·0238	·0217	·0192	·0172	·0156

These values are platted in the curves shown in fig. 1. The numbers affixed to the curves indicate the relative brightness of the spectra.

These curves show that with increased brightness the values of retinal presistence do not shift their positions relative to wave-length; that as the brightness of the spectrum increases, the duration becomes less in such a manner that each point in the curve is shifted downward by a nearly constant amount; and that the distance separating the different curves has a definite relation to the difference of the light intensity of the spectra from which the curves were obtained.

If the values be noticed for the duration of impression of all the curves, corresponding to any single wave-length, it will be perceived that the following statement is approximately true: as the intensity of light increases in geometrical ratio, the duration of the corresponding retinal impression decreases in arithmetical ratio. This statement can be concisely expressed in the form of the approximate empirical law—the difference of the duration of two retinal impressions produced by two lights of the same color, is inversely proportional to the logarithm of the quotient of the respective luminous intensities.

The value obtained for the ends of the spectrum deviate from this law, but this is probably due to the uncertainty of the observations in these faintly illuminated regions. The relation between duration and light intensity, thus far deals simply with lights of the same color. The next object of the experiment was to test the generality of this law, by determining if it would hold for lights of different color.

Relation between Luminosity and Duration of Retinal Impression.

By luminosity is meant the physiological effect of light upon the eye by means of which vision is accomplished. The measure of luminosity is the amount of light necessary to enable one to clearly distinguish objects. The spectra of various light sources are so very different in the distribution of luminosity, that it was considered necessary to determine these values for the particular lamp used in these experiments.

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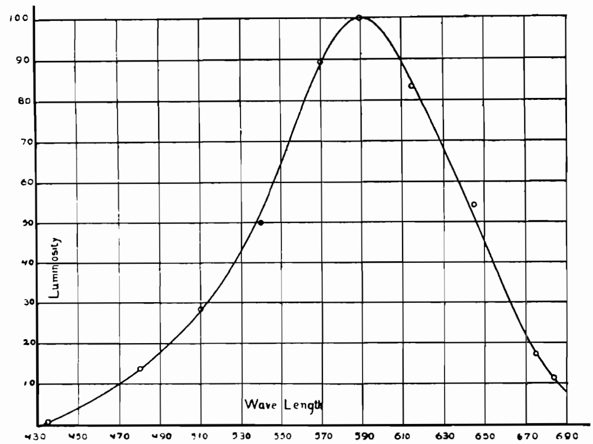

Distribution of Luminosity in 16-candle power, 100-volt Edison Incandescent Lamp

The method employed was to insert an object into the eye piece of the spectrometer and to reduce the aperture of the objective of the observing telescope by means of a fine micrometer slit till the object was just visible. The reciprocals of the micrometer slit areas gave the relative luminosities of the different parts of the spectrum. This method is less convenient and possibly less accurate than the Rumford photometer method used by Abney and Festing* but it gave a probable error of only about five per cent.

TABLE III.

Distribution of Luminosity in normal spectrum of a 16 C. P. 100 volt Edison Incandescent lamp—Platted in Fig. 2.

Wave-length.	Relative luminosity.	Wave-length.	Relative luminosity.
·435	1·86	·589	100·00
·455	3·06	·615	83·25
·480	13·89	·645	54·37
·510	28·28	·675	17·12
·540	50·00	·684	11·16
·570	89·25		

* Colour Photometry, Trans. Roy. Soc. Lond., 1888, p. 547.

The form of this curve suggested the possibility of luminosity bearing a reciprocal relation to duration of impression. This idea was tested in two ways. First, one particular region in the spectrum was chosen and its luminosity varied so as to be equal to the luminosity of different parts of the normal spectrum as given in Table III; the duration of retinal impression was then measured for these luminosities and gave the following values:

TABLE IV.

Duration of impression for a single color having its luminosity varied so as to equal the luminosities of different parts of the normal spectrum.

Relative luminosity.	Corresponding to wave-length.	Given duration of impression in seconds.
1·86	·435	·0333
13·89	·480	·0227
28·28	·510	·0200
50·00	·540	·0161
89·25	·570	·0143
100·00	·589	·0138
83·25	·615	·0143
54·37	·645	·0161
11·16	·684	·0192

The luminosities taken in this table are the same as in the normal spectrum that gave the values in the fifth column, Table II. A comparison of the third column, Table IV, and the fifth column, Table II, indicates that luminosity is the important factor in persistence of vision. To farther test this deduction, observations were made on the duration of impression for different colors of the normal spectrum, when each color was brought to the same luminosity. If the above deduction is valid, then if each color is brought to the same absolute luminosity, the retinal persistence of each color will give the same value. The values obtained are given below.

TABLE V.

Duration of impression when each spectral color is brought to the same luminosity.

Wave-length.	Duration in seconds.
·510	·0151
·540	·0147
·570	·0149
·589	·0147
·615	·0147
·645	·0147

Duration of Light Impressions on Color-Blind Eyes.

As a still farther test of the theory that retinal persistence is practically independent of color but depends principally upon luminosity, duration of impression curves were obtained from dichroic eyes. It is well known that a color-blind person not only lacks one of the fundamental color sensations but also that he perceives other colors differently from the normal. For instance, according to Holmgren,* in the spectrum as seen by red-blind persons yellow begins at about line C and extends an orange, yellow and yellowish green and ends near F. At this neutral zone the blue begins and extends to the end of the normal spectrum. If now duration of retinal impression does depend in any way upon color, one would expect that the curves obtained from color-blind persons would differ from those of the normal in a way that could not be explained by considerations of luminosity alone. An examination of about two hundred members of a large class in physics, by Holmgren's worsted method furnished eight cases of color-blindness, one being red-blind, the remainder being green-blind. The proportion of color-blind in even this limited number was about the same as found by Dr. Jeffries† from the examination of 175,000 persons.

These color-blind students were examined for the neutral point by the method of A. Koenig‡ which consists in determining the color that they will match with white or gray. A prism having one face coated with magnesium white was so mounted in the Helmholtz color-mixing spectroscope, that a ray of light from the collimator passing through the prism would be dispersed into a spectrum, while a ray from a second source falling on the white surface would be reflected directly into the telescope. If now the eye-piece of the telescope be removed, one-half the field of view will be filled with color and the other half with pure white or gray. With this arrangement a color-blind person will very accurately set the instrument to the exact point where the two halves of the field of view appear of exactly the same color to him.

After their neutral points had been found in this manner, these gentlemen very kindly offered to spend the time necessary to obtain curves for their retinal persistence.

Mr. W. C. W. is a marked case of inherited blindness to red. His father, uncles and brothers are similarly affected. The red end of his spectrum ends at about ·688 λ, and his neutral point is at ·510 λ. His eyes are otherwise normal.

Mr. H. S. has inherited green-blindness from his *maternal* relatives. Daltonism is so very rare among women that his case was studied with great interest. He is making a specialty

* How do the color-blind see the different colors? Proc. Roy. Soc. Lond., xxxi (1880), p. 302.

† 3·95 per cent among males. "Color Blindness: its dangers and detection." (Boston: 1879.)

‡ Zur Kentniss dichromatischer Farbensysteme. Wied. Ann., xxii (1884), p. 567.

of botany and finds no great inconvenience in any of his studies except chemistry. This subject he was obliged to discontinue as he could not distinguish the characteristic colors of the reactions. His neutral point was sharply located at ·516 λ. This gentleman wore glasses for near-sightedness.

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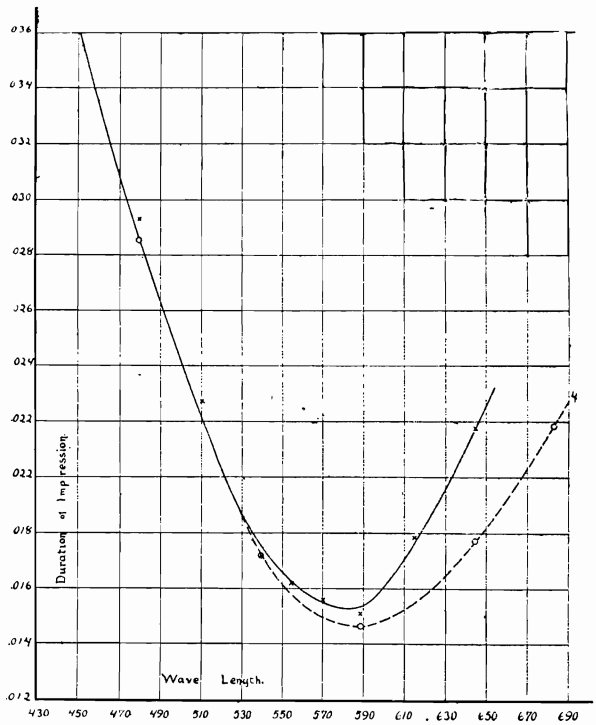

Duration of Impression for different colors of red-blind Eye.

The other observers were not aware of any similar cases in their families. The neutral point of Mr. G. A. W. was located at ·517 λ; Mr. W. M. at ·5165 λ; Mr. L. M. W. at ·518 λ; Mr. H. C. H. at ·516 λ. They are all green-blind and their eyes appear to be otherwise perfect with the exception of Mr. W. M., who is near-sighted. Their values of duration of impression are given in the annexed table.

The values of Mr. W. C. W. are platted in the full curve fig. 3; the broken curve being the curve of the normal eye for the same brightness of spectrum. The values obtained by Messrs. W. M., H. C. H., and L. M. W. are platted in the curves in fig. 4. The normal curves are drawn in as before to show the relation between the normal and color-blind eyes for persistence of vision.

TABLE VI.

Duration of Retinal Impression for Dichroic Eyes.

(The numbers at the head of each column indicate the brightness of the spectrum.)

Wave-length.	Duration of Impression in Seconds.					
	Red Blind.	Green Blind.				
	Mr. W. C. W.	Mr. H. S.	Mr. G. A. W.	Mr. W. M.	Mr. H. C. H.	Mr. L. M. W.
λ.	4.	8.	4.	2.	4.	8.
·435	----	----	----	·0357	----	·0357
·480	·0294	·0357	·0278	·0333	·0294	·0250
·510	·0227	·0227	·0227	·0263	·0217	·0192
·525	----	·0208	·0200	·0238	·0208	·0185
·540	·0172	·0200	·0185	·0222	·0200	·0172
·555	·0161	·0175	·0179	·0208	·0193	·0156
·570	·0156	·0161	·0161	·0192	·0166	·0143
·589	·0152	·0143	·0152	·0159	·0151	·0125
·615	0179	·0154	·0156	·0175	·0161	·0143
·645	·0217	·0175	·0167	·0192	·0172	·0156
·684	----	·0210	·0227	·0238	·0217	·0179

These curves show that light impressions of red last much longer on the retina of red-blind persons than on the normal, yellow somewhat longer than normal and the other colors about the same as normal. With green-blind persons, however, green impressions persist much longer than normal, red a little less than normal and the other colors the same as normal.

An explanation of the difference between the duration curves of dichroic and normal eyes was found in the difference in the sensitiveness for different colors of the dichroic from the normal eye. Messrs. Macé and Nicati* from the examination of a number of dichroic eyes obtained luminosity values which indicate, first, that red-blind people perceive red weakly, yellow nearly normal, green better than normal; second, that the green blind have better perception than normal for red, green feeble, yellow and blue normal. A later determination by Abney and Festing† confirmed their conclusions. In this experiment luminosity values were also obtained from Mr. W. C. W. which agree with the two determinations just cited. This shows that if account be taken of the difference between the sensitiveness of the normal and the dichroic eye for different

* De la distribution de la lumière dans le spectre solaire (spectre des Daltoniens). Comptes Rendus, xci, p. 1078.

† Colour Photometry. Trans. Roy. Soc. Lond., 1888, p. 547.

regions of the spectrum, that the curves of retinal persistence of the dichroic and the normal eye will be of the same form.

This appears to make the evidence conclusive that color is at most a slight factor in retinal persistence, and that luminosity is the all-important function.

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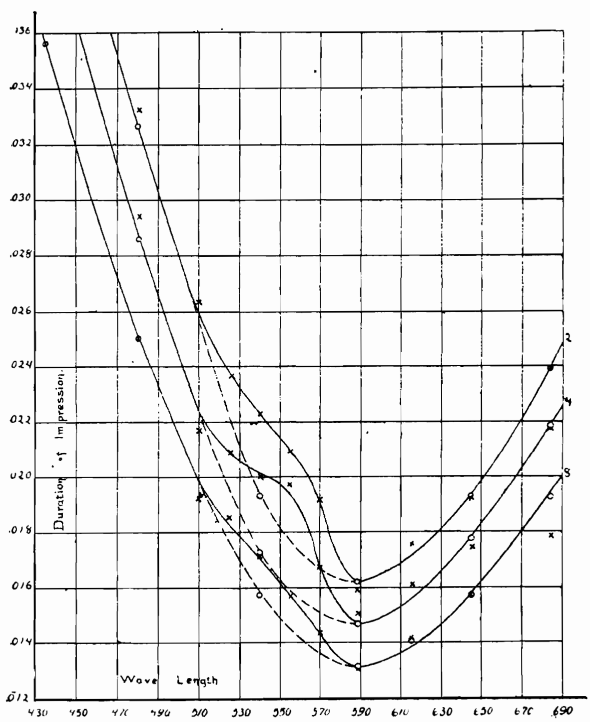

Duration of Impression of Green-blind Eye.

The law previously derived connecting duration of impression and luminosity of lights of the same color can now be made general and independent of color. This approximate empirical law can now be expressed in the concise form—*duration of retinal impression is inversely proportional to the logarithm of the luminosity*, or in the form of the equation

$$D = \frac{1}{k \cdot \log l}.$$

It is interesting to note the similarity of this with Fechner's law* connecting the intensity of stimulus and the sensation

* Revision der Hauptpunkte der Psychophysik (Leipsig), p. 184.

produced. Fechner's law was also empirically deduced and has since been confirmed, for mean values, by Dalbouf's memoir to the Belgian Academy. It can be expressed in the form

$$s = k_{,} \cdot \log x$$

where s denotes intensity of sensation and x intensity of stimulus. In this particular case the stimulus is luminosity, hence we have

$$D = \frac{1}{k_{,,} \cdot s}$$

which means simply that retinal persistence varies inversely as the intensity of the sensation producing it. This seems to agree with ordinary experience and thus to confirm the validity of the law connecting retinal persistence and luminosity.

Effect of Age upon Retinal Persistence.

It was thought that possibly as a person advanced in years, the retina might become selective in its sensitiveness for different colors and that therefore the curve of duration of retinal impression might be different from that of a younger person. Two professors in the University kindly permitted their eyes to be tested for retinal persistence and the values obtained are given in the annexed table.

TABLE VII.

Wave-length. λ	Duration of retinal impression in seconds. Prof. S. G. W.	Prof. E. L. N.
·435	·0417	·0417
·480	·0333	·0357
·510	·0217	·0227
·540	·0179	·0185
·570	·0156	·0161
·589	·0147	·0155
·615	·0156	·0166
·645	·0185	·0192
·684	·0227	·0227

These values platted in fig. 5 seem to indicate that for both Dr. Nichols and Prof. Williams the more refrangible part of the spectrum is proportionately less luminous than to the eyes assumed to be normal. But the violet end of the spectrum is so feeble that observations in it are very difficult, and certainty cannot be obtained without more extended observations. If anything can be deduced from so few observations, these curves show to a high degree of probability that age increases retinal persistence to a considerable amount and that the increase is nearly uniform for all wave-lengths. This fact would be naturally expected, for it is well known that age decreases retinal sensitiveness; and as the sensitiveness decreases the action of the retina would be less quick either to receive an impression or to dismiss one.

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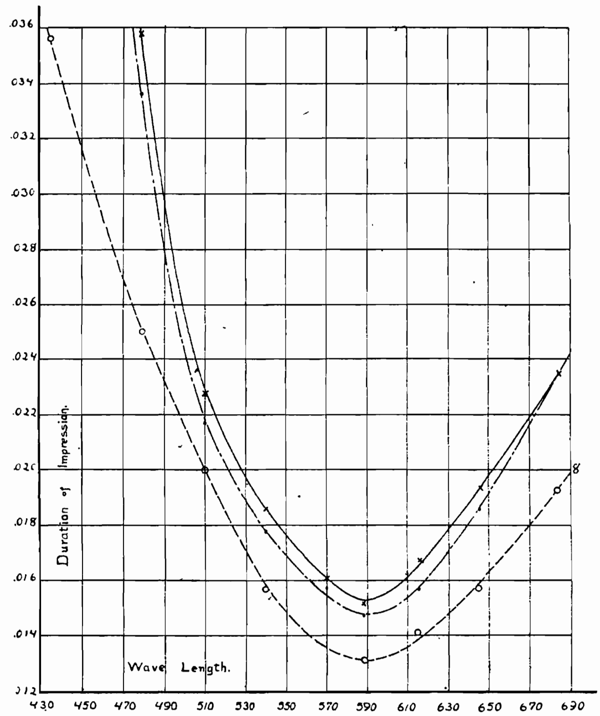

Summary of Results.

I. The duration of retinal impression is very different for different regions in the spectrum, being at a minimum value at the region of maximum luminosity and gradually increasing to maximum values at the ends of the spectrum.

II. If the luminosity of any region in the spectrum be so changed that the values vary in geometrical ratio, the corresponding values of duration of impression will approximately vary in arithmetical ratio for regions of ordinary brightness.

III. Color has, at most, very slight influence upon retinal persistence. Luminosity,—including the brightness of the light and the retinal sensitiveness—is the all-important factor.

IV. For ordinary values the following empirical law is approximately true—*Retinal persistence varies inversely as the logarithm of the luminosity.*

V. The values of retinal persistence in dichroic eyes is very different than in normal eyes. For instance, light impressions of red last much longer on the retina of red-blind persons than on the normal, yellow somewhat longer than normal and the other colors about the same as normal. With green-blind persons, green impressions persist much longer than normal, red a little less than normal and the other colors the same as normal.

VI. The very marked departure from the normal values of retinal persistence in dichroic eyes for the region of their lacking color sensation, affords a precise and convenient method of determining color-blindness.

VII. Within the range of these experiments, it seems probable to a high degree that age increases the duration of retinal impressions to a nearly equal amount in all regions of the spectrum.

In conclusion I wish to express my obligation to Mr. E. Gordon Merritt for his very valuable assistance in taking observations in these experiments.

Physical Laboratory of Cornell University, June, 1892.