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SPECTROPHOTOMETRY OF NORMAL AND COLOR-  
BLIND EYES.

BY F. L. TUFTS.

I. DEFINITIONS OF THE TERM "EQUAL LUMINOSITY" AS APPLIED  
TO COLORED LIGHTS.

THE experimental determination of the relative luminosity of the different parts of a spectrum offers very serious difficulties, and, while a number of different types of instruments have been constructed for the purpose of making such measurements, most have shown defects either in the accuracy of the results obtained or in the matter of manipulation. Instruments of the type of the Vierordt double-slit spectrophotometer, or of the Brace spectrophotometer, are of course not of this kind, and while very convenient and accurate for the comparison of the relative luminosity of different sources of light in any given part of the spectrum, give no means of determining the relative luminosity of a given source in the different parts of its spectrum. All instruments for this latter purpose may be conveniently classified under three general types depending upon the definition of the term "equal luminosity," employed for the interpretation of the results obtained when comparing different colored lights. The three definitions most frequently employed are the following :

I. Two similar surfaces, illuminated respectively by two lights of different color, may be said to be of equal luminosity if, in the judgment of the observer, they appear equally luminous.

This definition presupposes in the observer the ability to form a

judgment concerning equality of luminosity, which is not influenced by differences in color. Concerning such judgments, Helmholtz has remarked :<sup>1</sup>

"I must explain that personally, I put no confidence in my judgment concerning the equality in luminosity of differently colored surfaces. I admit, however, that of two differently colored fields, one can be so much darkened that there remains no doubt that the other is brighter."

Abney and Festing have constructed and used a spectro-photometer depending, in its action, upon this definition of the term "equal luminosity." By varying the luminosity of one of the surfaces until it appears first more luminous and then less luminous than the other, and taking a mean, they have been able to employ it in some very interesting photometric work.<sup>2</sup>

II. Two similar surfaces, white, with black markings on them, illuminated respectively by two lights of different color, may be said to be of equal luminosity if, when placed at the same distance from the eye, the details can be distinguished with the same minuteness.

According to this definition, the measure of luminosity is the amount of light, independent of color, which is necessary to enable one clearly to distinguish objects. A method of color photometry depending upon this definition of luminosity was very carefully developed by Maci de Lepinay and Nicati,<sup>3</sup> and they showed that the second definition is not always equivalent to the first. This method has been applied to the determination of the relation between energy and luminosity in different parts of the spectrum by Langley,<sup>4</sup> A. König,<sup>5</sup> and Pflüger.<sup>6</sup> A spectrophotometer has been constructed upon this principle by E. S. Ferry,<sup>7</sup> and used to determine the distribution of luminosity, according to this definition of it, in the light of a 16 candle-power Edison incandescent lamp. He also investigated the relation between luminosity as thus determined and persistence of retinal impressions in different parts of the spectrum.

<sup>1</sup> *Handbuch der Physiologischen Optik*, second edition, p. 440.

<sup>2</sup> *Color Photometry*, *Trans. Roy. Soc. Lond.*, 1886, p. 423, and 1888, p. 547.

<sup>3</sup> *Annales de Chimie et de Physique*, 5th series, vol. 24, p. 30.

<sup>4</sup> *Am. Jour. Sci.*, 36, pp. 359-380, 1888.

<sup>5</sup> *Z. Psy. Phys. d. Sinnesorgane*, 4, pp. 241-348, 1893.

<sup>6</sup> *Ann. d. Physik*, 9, pp. 185-208, 1902.

<sup>7</sup> *Am. Jour. Sci.*, 44, pp. 192-207, 1892.

III. Two similar surfaces, illuminated respectively by two lights of different color, are said to be of the same luminosity if, on rapidly replacing one by the other before the eye, there is no sensation of flickering. Methods of color photometry depending upon this definition of equal luminosity have been developed by Rood,<sup>1</sup> Whitman<sup>2</sup> and Tufts.<sup>3</sup>

It has been shown experimentally that the luminosity, as thus defined, of a white or gray light formed by combining two or more colored lights, is equal to the sum of the luminosities of the colored lights so combined. The writer is not aware that the second definition has been subjected to such an experimental test.

A new form of spectrophotometer for the measurement of color luminosities according to definition III., is described in the present paper, and the results are given of measurements of the luminosities of the different parts of the spectrum as they appear to normal and to color-blind eyes.

## II. DESCRIPTION OF THE FLICKER SPECTROPHOTOMETER.

The instrument consists of a spectroscope, Fig. 1, in which the telescope *T* and the axis of the rotating sectored disc *D* are rigidly

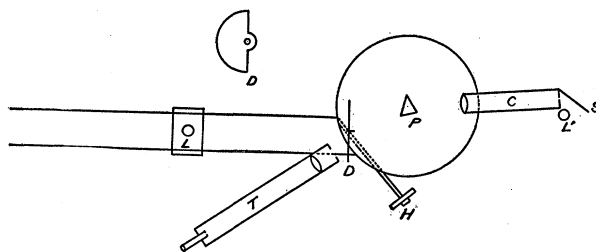


Fig. 1.

fastened to a table, while the collimator *C*, the prism *P*, the lamp *L* and the white screen *S* are rigidly connected with the graduated circle of the spectroscope. This circle, together with the connected parts, can be rotated about a vertical axis through its center by means of a screw with a graduated head *H*. The light *L* is

<sup>1</sup> *Am. Jour. Sci.*, September, 1893, September, 1899, October, 1899.

<sup>2</sup> *PHYSICAL REVIEW*, vol. 3, no. 4, 1896.

<sup>3</sup> *Trans. N. Y. Acad. Sci.*, XVI., April, 1897.

mounted on a photometer bar so that its distance from the white rotating disc  $D$  can be varied, and thus vary the luminosity of the disc. The disc  $D$  and the screen  $S$  are covered with white paper cut from the same piece. The eye-piece of the telescope is provided with a slot of adjustable width. Finally, the instrument is provided with black screens and diaphragms so placed that the photometric measurements can be made in a lighted room.

The adjustment and operation of the instrument are as follows: The lamp  $L'$  and the screen  $S$ , having been replaced by a Bunsen burner, the flame of which is colored with suitable salts, the spectroscope can be adjusted for minimum deviation of the sodium lines, and the screw  $H$  calibrated in terms of the wave-lengths of the light used. The lamp and screen may then be replaced, and the motor which rotates the disc  $D$  started. Through half of the revolution of this disc, the slit in the eye-piece is illuminated by the light from the lamp  $L$  which is reflected from the disc, while through the remaining half of the revolution it receives light of a given wave-length from the spectrum of the lamp  $L'$  reflected from the screen  $S$  through the colimator and prism. The speed of the motor rotating the disc  $D$  should be adjusted so as to give the best conditions for flickering in case there is any difference in the luminosities of the two lights. The distance of the lamp  $L$  from the disc can be varied until all flickering disappears, and the distance measured. By means of the screw  $H$ , any part of the spectrum can be made to illuminate the eye-piece slit, and its luminosity measured in terms of the luminosity of the white disc. The relation between the wave-length of any particular color and its luminosity (definition III.), in terms of the observer's white, can be plotted, using wave-lengths as abscissa, and luminosities as ordinates. The curve thus obtained will be referred to as the *wave-length luminosity curve* for the particular observer with the lights used.

Other means of adapting the flicker principle to a spectrophotometer were tried, but none proved so satisfactory as this, particularly for the testing of untrained observers. The writer has found that any person at all accustomed to looking through optical instruments, such as microscopes or telescopes, can obtain very uniform readings with this form of spectrophotometer, without any preliminary

training. By using a method of recording the distances of the lamp  $L$  from the disc, on a fillet of paper, described by Professor Rood,<sup>1</sup> the average observer can take ten readings for each of eight or ten positions in the spectrum, in from 20 to 25 minutes, and without any fatigue more than would be experienced in using a microscope or telescope for the same length of time.

### III. PHOTOMETRIC MEASUREMENTS WITH THE WRITER'S EYES.

The spectrophotometer just described was employed to investigate the relation between the luminosity of a white and the sum of

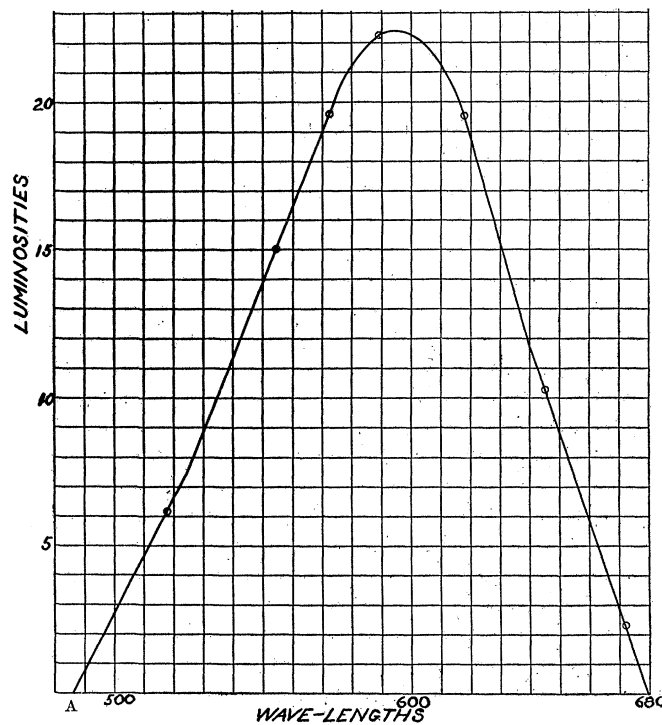


Fig. 2.

the luminosities of its constituent spectrum colors, according to definition III. of the luminosity of a colored light. The writer's wave-length luminosity curve for the reflected light from the lamp  $L'$  was determined. Each of the points recorded in Fig. 2 is the mean

<sup>1</sup>Amer. Jour. Sci., September, 1899.

of from ten to twenty readings. The prism  $P$ , Fig. 1, was then removed, and the colimator, together with the attached screen  $S$  and lamp  $L'$ , turned into such a position that the image of the colimator-slit coincided with the slit in the eye-piece. The luminosity of the white slit was then measured in terms of the same white as was used in the measurement of the luminosities of the spectrum colors. The width of the image of the colimator-slit was measured in terms of the revolution of the micrometer-screw  $H$ , the extent of the spectrum between the positions  $A$  and  $B$ , Fig. 2, having been previously determined in terms of the same unit.

Following are the results of the measurements made :

Luminosity of the image of the white colimator-slit, in terms of the unit used in the wave-length luminosity curve, Fig. 2.....	395
Width of image of colimator-slit in revolutions of the screw $H$ .....	0.15
Length of spectrum between $A$ and $B$ , Fig. 2, in revolutions of the screw $H$ .....	4.80
Length of spectrum in terms of width of image of colimator-slit.....	32
Total spectrum luminosity = $\int_A^B \text{lum. } d\lambda$ (where $\lambda$ is expressed in slit-widths) = area between the wave-length luminosity curve and the axis of abscissæ.....	408

One sees that the sum of the luminosities of the spectrum colors determined in this way is equal to the measured luminosity of the original white to within about 3 per cent., which is well within the error of spectrophotometric measurements. Other independent measurements gave similar results, the measured luminosity of the white being sometimes greater and sometimes less than the computed sum of the luminosities of its spectrum colors.

The above results are readily explained if we assume that there is, in the retina of the eye, a sense organ (we will call it the luminosity sense), which is affected in the same way by all visible radiation. The difference between the action of different wave-lengths upon this organ we will assume to be a difference in the magnitude, only, of the effect, and not in its quality.

Since in these experiments the luminosity of any color is measured in terms of the luminosity of the white of the particular observer, any change in the relative luminosity of the different spectrum colors as seen by this observer would not affect the relation of equality between the luminosity of the white of the observer and the sum of

the luminosities of its spectrum colors as seen by him. In other words, no matter how much one may change the quality of one's white, as, for example, by looking through colored glass, the luminosity of that white should always be equal to the sum of the luminosities of its spectrum colors if they also are seen through the same colored glass. Consequently, the area of the wave-length luminosity curve should be the same whether determined by using the naked eye or by making all of the observations through colored glasses, provided (and this must be carefully noted) that the distribution of luminous energy in the spectra of the two lights  $L$  and  $L'$  is the same.

With the lamps  $L$  and  $L'$  of different candle power, it is very difficult to obtain the same relative distribution of luminous energy in the two spectra. The lamps used by the writer were the ordinary 50 C.P. incandescent stereopticon lamps. These lamps were tested in the following manner: Two lamps, one at  $L$  and one at  $L'$  were adjusted for no flickering when the photometer was set in the red, the distance of the lamp  $L$  from the disc  $D$  being noted. The lamps were then interchanged and the adjustment repeated. The ratio of the luminosity of the red of one of the lamps to the luminosity of the same red of the other lamp was thus obtained. This ratio was also determined for the yellow-green and the blue of the spectrum. Unless the ratios were approximately the same, the lamps were rejected and others compared. After a number of such comparisons, two lamps were found for which the ratio did not differ in different parts of the spectrum by more than 8 per cent. of its mean value. These two lamps were used for the purpose of determining the wave-length luminosity curve for: I. The naked eye; II. The eye looking through a yellow glass; III. The eye looking through a red glass; IV. The same eye looking through a very pale blue glass.

The four curves are plotted in Fig. 3. The crosses indicate the readings for the naked eye, the letters  $Y$ ,  $R$ , and  $B$ , the readings for the same eye when looking through the colored glasses respectively. Measurements on the four curves showed them all to have approximately the same area.

When a deep cobalt blue glass was used which transmitted only

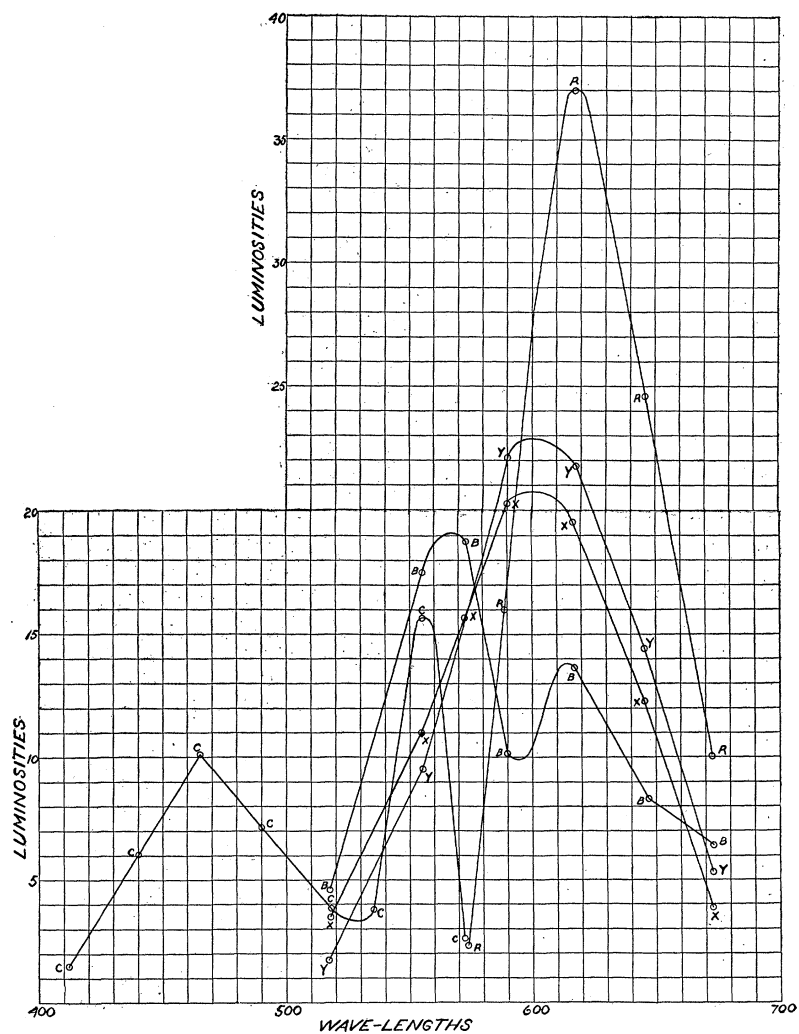


Fig. 3.

the extreme violet end of the spectrum, with a negligibly small amount of light in the red, the results were quite different. The wave-length luminosity curve for an eye looking through the cobalt glass is indicated in Fig. 3 by the letter *C*. If the area of this curve is compared with the area of the naked eye curve, it will be found to be almost 50 per cent. less. When the prism was removed



and the luminosity of the image of the colimator-slit determined by observations taken through the cobalt glass, the luminosity was found to be the same, within 2 per cent., as the luminosity determined by observations with the naked eye. It might seem, therefore, that for an eye looking through cobalt glass, the luminosity of the cobalt-eye's white was greater than the sum of the luminosities of its spectrum colors (def. 3). The phenomenon is possibly connected with the Purkinji effect and is still under investigation. The importance of this in the interpretation of the results obtained from observations with certain abnormal eyes is pointed out in the latter part of this paper.

The practical independence of our color and luminosity sensations is shown by the following experiments. It is well known that if one eye is exposed to a strong light through a green glass, for example, until the retina becomes fatigued, all objects appear to that eye as they would appear to the normal eye if it were looking through a red glass, transmitting a complementary color to the green. The color sense becomes fatigued by exposure to a given color, and it then reacts to stimuli in a way qualitatively different from the unfatigued sense. If our luminosity sense is independent of our color sense, and if its reaction is qualitatively the same for all wave-lengths within the visible spectrum, then it ought to be impossible to change the apparent luminosity of any color (measured in terms of the luminosity of the white of that eye) by fatiguing the luminosity sense of the eye with light of that particular color or its complementary. In other words, the wave-length luminosity curve for the fatigued eye should be identical with the wave-length luminosity curve of the unfatigued eye.

This assumption was tested experimentally in the following way: The wave-length luminosity curves were determined for the writer's two eyes, and were found to be practically identical. The right eye was then exposed to the light of a 100 C.P. incandescent lamp viewed through colored glass, the exposure being of sufficient duration to cause all white objects seen with the fatigued eye to appear of the complementary color to the light transmitted by the glass. The luminosity of a given spectrum color was then measured with the fatigued eye, and, immediately after, remeasured with the un-

fatigued eye. This was done for seven different positions in the spectrum. The right eye was refatigued just before each set of readings, and, in every case, the effect of the fatigue was of sufficient duration to give the complementary color effect after the set of readings had been taken.

The readings with the right eye fatigued by blue light were compared with the readings of the left, unfatigued eye, and the results

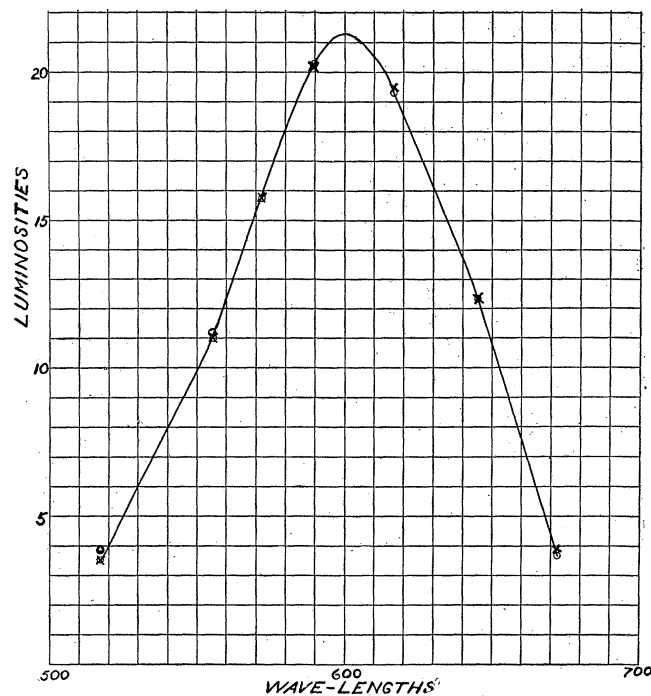


Fig. 4.

are given in Fig. 4. The crosses indicate the readings with the unfatigued eye, the circles, the readings with the fatigued eye. In every case the difference was found to be within the experimental error. Similar results were obtained by fatiguing the right eye with yellow and green lights. In every case the right eye was fatigued by looking at the incandescent filament through the colored glass, the eye being placed so near the filament that the area of the retina

covered by the image was many times the area covered by the image of the slit in the eye-piece of the spectrophotometer.

When a red glass was used (the same piece as was used for the red curve in Fig. 3) and the exposure only sufficient to produce the complementary color effect, the results obtained were similar to those obtained with the other colors. A continuous exposure, however, of several minutes, gave photometric readings with the fatigued eye which were very different from those with the normal eye. The

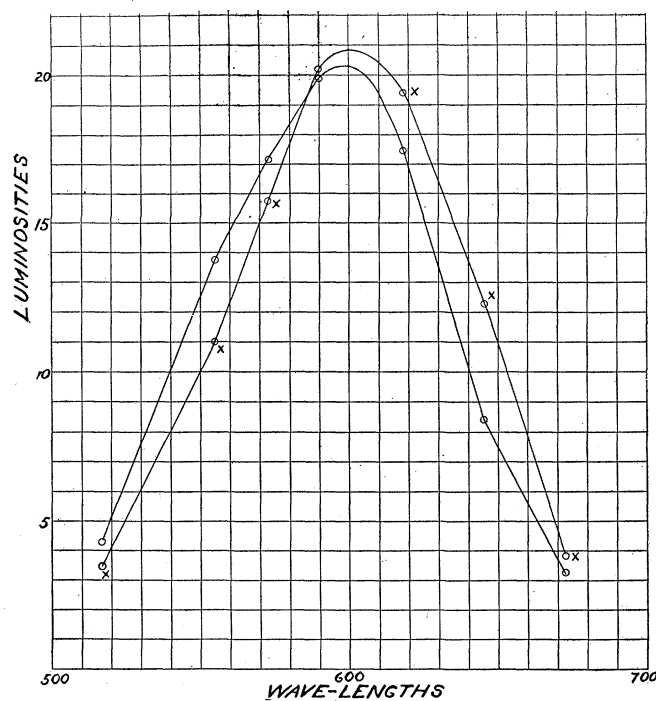


Fig. 5.

general character of the differences is shown in Fig. 5, the crosses indicating the curve for the normal eye, and the circles without crosses the readings for the fatigued eye. An inspection of the figure shows that the effect of a prolonged exposure of the retina to the long, or red rays, is to displace the maximum of the wave-length luminosity curve towards the blue end of the spectrum. This displacement is apparently due to some action of the long waves upon the lumi-

nosity sense, and is either not connected at all, or at least only indirectly, with their action upon the color sense, for the photometric readings became the same for the fatigued as for the unfatigued eye long before the vivid green after-image had disappeared.

The right eye was then fatigued by looking at the 100 C.P. lamp directly, so that vivid, colored after-images were seen as the eye recovered. The photometric readings were, however, the same for the fatigued as for the unfatigued eye. The fatigued eye was always focussed, in taking the readings, so that the image of the slit in the eye-piece was in the center of the after-image of the spiral lamp-filament. The photometric readings, however, did not change, although the background formed by the after-image changed its color as the eye recovered from its fatigue.

The above experiments show that the relative reaction of the luminosity-sense to white light and to light of different colors is not affected by ordinary fatigue produced by exposing the eye to colored or white light, but may be altered by prolonged exposure to red light. Two other persons possessing normal color vision have been kind enough to subject their eyes to the rather harsh treatment required by these experiments, and the results were, throughout, similar to those obtained from the writer's eyes. A change in the relative reaction of the luminosity sense to white and to colored lights was produced only by prolonged exposure to red light, exposure to yellow, green, blue, or white light, and moderate exposure to red, producing no similar effect.

#### IV. COMPARISON OF THE WAVE-LENGTH LUMINOSITY CURVES OF DIFFERENT EYES.

A number of different persons were kind enough to give the time required for the determination of their wave-length luminosity curves by the flicker spectrophotometer. Some twenty persons in all were examined, an effort being made to secure as many color-blind persons as possible, so that out of the twenty, six showed, by the ordinary Holmgren test, marked red-green blindness (the reds, greens, and grays, being confused in the sorting of colors). Of the fourteen persons possessing normal color-vision, according to the Holmgren test, ten showed a wave-length luminosity curve which

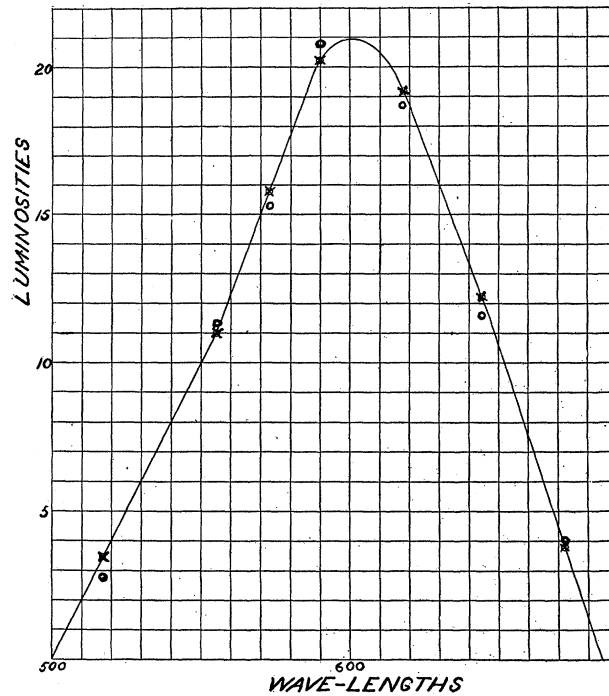


Fig. 6.

differed only slightly from the writer's curve. Representative readings for one of these observers are given in Fig. 6. The crosses indicate the writer's readings, and the circles the readings of one of the ten observers. The results, in both cases, are the mean of ten observations in each position in the spectrum.

Four of the persons studied showed a wave-length luminosity curve differing only slightly from the writer's, but the deviations were all in the same general direction, and seemed to indicate a rather distinct type of curve. One of these curves, which is representative of the four, is given in Fig. 7, and for comparison the writer's curve, indicated by crosses, is also given. The luminosity-sense of these persons seems to be less responsive to yellow, and correspondingly more sensitive to red and violet light, than the normal, thus giving a slightly flattened wave-length luminosity curve. All four persons seem to possess perfectly normal color vision.

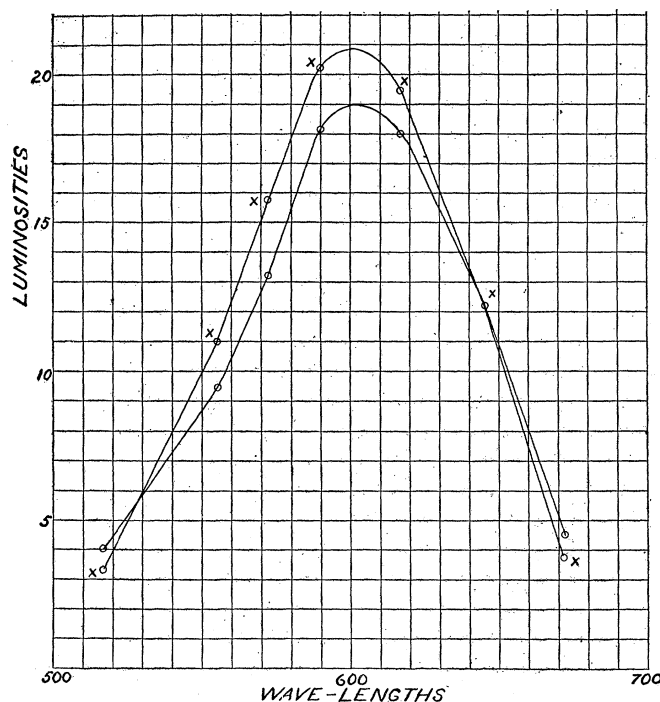


Fig. 7.

Two persons examined showed curves differing very much from the writer's. One of these, and it is almost identical with the other, is given in Fig. 8, the writer's curve being again indicated by the crosses. It is seen that the observer is more sensitive to red and less sensitive to green and blue than the writer. In other words, his wave-length luminosity curve is displaced toward the red end of the spectrum, with respect to the writer's curve. Neither of these persons made any mistake in sorting ordinary colors, but when asked to sort some extremely pale shades, both showed a slight tendency to confuse the oranges and yellow-greens.

Two other observers, both possessing perfectly normal color-vision as shown by the Holmgren test, with pronounced and also extremely pale shades of colors, gave wave-length luminosity curves that were displaced toward the green, with respect to the writer's curve. The curves also showed the peculiarity of having an area

distinctly less than that of the writer's curve. These two persons were kind enough to give the time necessary to repeat the complete set of readings on several different days; and the readings of each set were found to agree, within a few per cent., with the corresponding readings of any other set. The readings for the observer showing the greater deviation from the writer, are indicated in

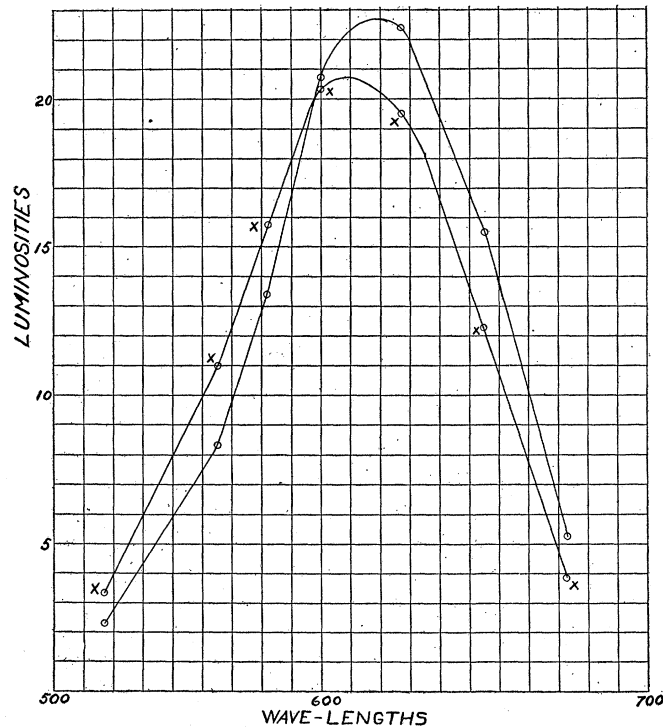


Fig. 8.

Fig. 9 by the circles, the writer's curve being indicated by the crosses. The position of maximum luminosity is seen to be displaced by a very considerable amount toward the green, and the area of the curve is less than the area of the writer's curve by as much as twenty per cent. The curve for the other observer is indicated by the dotted line in Fig. 9. The blue end of the spectrum must supply a much larger per cent. of the luminosity of the white of these observers than is the case with the normal eye, and

the smaller area of the curves might be expected after the observations with the cobalt glass described in part III. of this paper.

The observer whose curve differed most from the writer's curve, in Fig. 9, was also tested by the ordinary flicker photometer with

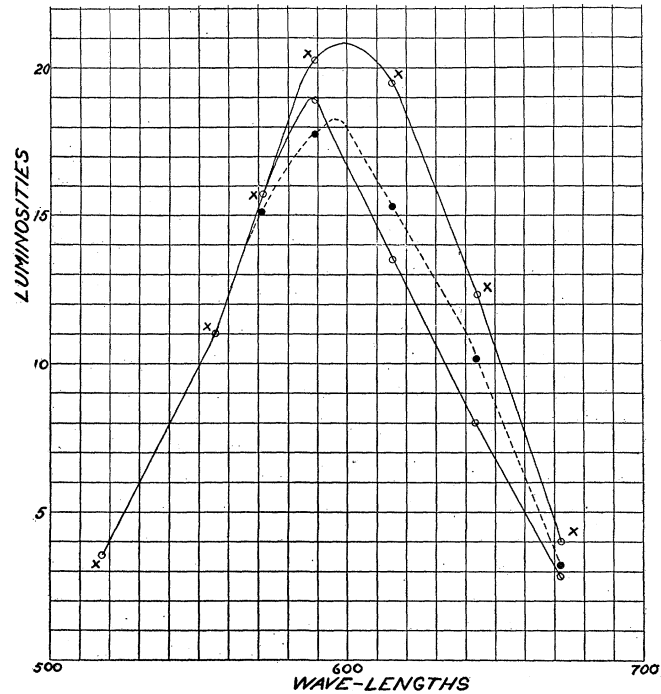


Fig. 9.

colored glasses, the method being the same as that employed by Professor Rood.<sup>1</sup> The results, expressed in terms of the same standard as that employed by Rood, are as follows, for the writer and the observer mentioned above :

Observer.	Apparent Luminosity of the Color.		
	Red.	Green.	Blue.
Rood's normal eye	100	100	100
Writer's eye	90	100	88
Observer's eye, Fig. 9	36	100	87

<sup>1</sup>On Color Vision and the Flicker Photometer, by Ogden N. Rood, Am. Jour. of Science, Vol. VIII., October, 1899.



It is therefore evident that an observer may be abnormally weak in the luminosity impression produced by a given color of light, and still be perfectly normal with respect to color sensations.

Six persons, all showing very marked red-green color-blindness by the Holmgren test, very kindly offered to give the time necessary for the determination of their wave-length luminosity curves. All

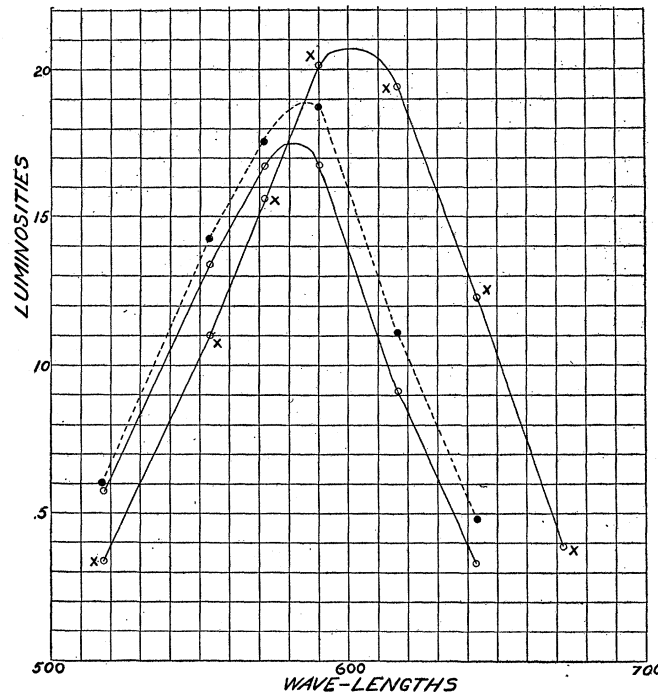


Fig. 10.

six persons confused the reds, greens, and grays, in the sorting of colors. Of the six persons, three were found to have wave-length luminosity curves in which the point of maximum luminosity was displaced towards the green, while the other three showed a displacement towards the red.

Of the first three curves, the one differing most and the one differing least from the writer's curve are given in Fig. 10, the writer's curve being indicated by crosses. All three of the curves had a much smaller area than that of the writer's curve, as might be expected after the experiments with the cobalt glass.

Of the second group of curves, showing a displacement of the maximum towards the red, the one differing most and the one differing least from the writer's, are given in Fig. 11. An inspection of these curves shows the areas to be nearly the same as the area of the writer's curve, and neither curve differs from the writer's

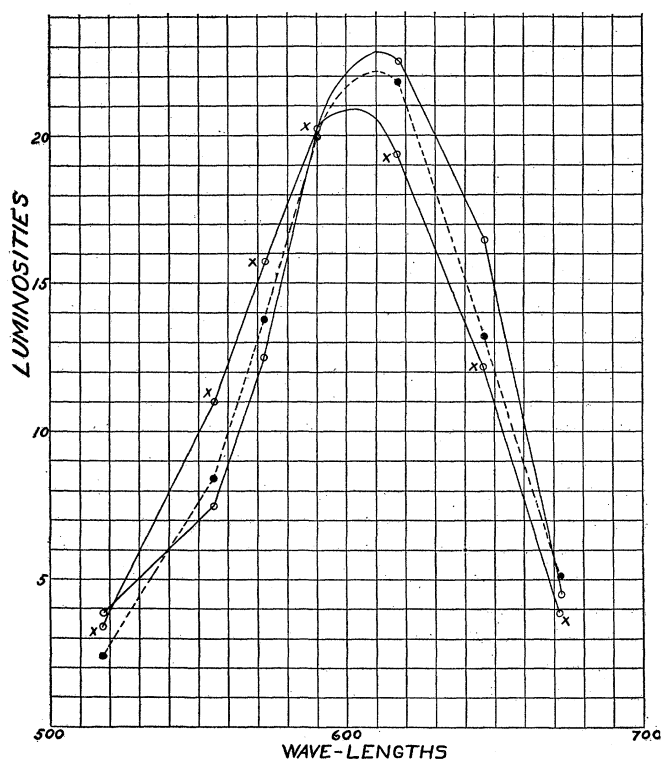


Fig. 11.

any more than the observer's curve in Fig. 8. Yet the observer of Fig. 8 showed no trace of color-blindness by the ordinary Holmgren test, while both of these observers were pronouncedly red-green color-blind.

While, therefore, the effect of light upon the color sense seems to be quite independent of its effect upon the luminosity sense, it would seem that an abnormal color sense is usually, if not always, associated with an abnormal wave-length luminosity curve. The

converse of this, however, is not true, and persons may be quite abnormal with respect to their color luminosity sense, and still be able to make perfectly normal judgments in sorting and matching colors.

It is well known that the peripheral portion of the retina is more sensitive to the luminous energy in the blue end of the spectrum than is the central portion (macula lutea), and the peripheral portion is known to contain a larger per cent. of rods than the central portion. If we assume that the wave-length luminosity curve for the rods is, with reference to the curve for the cones, displaced towards the blue end of the spectrum (and this seems the simplest explanation of these phenomena), then the differences in the positions of the maxima in the wave-length luminosity curves of different observers might be explained as due to differences in the ratio of rods to cones in the fovea centralis, if such a difference should be found to exist. Since it seems to be just as common for color-blind people to have wave-length luminosity curves displaced towards the red as towards the blue end of the spectrum, with reference to the normal curve, if the above explanation is accepted for the abnormal curves, it will not be possible to explain color-blindness as due to an abnormally large per cent. of rods in the fovea, as has sometimes been suggested (it being assumed that the cones alone contained the color sense organ).

While at present we have hardly sufficient data upon which to found a satisfactory theory of color vision, the above explanation of the differences in the luminosity of different colors (def. III.) as they appear to different observers seems to account very well for the phenomena described in this paper. Fatigue phenomena with color-blind eyes promise to give more definite information along these lines, and they are at present being investigated by the writer.

The form of flicker spectrophotometer here described lends itself readily to the determination of the per cent. of any spectrum color which must be mixed with a white of the same luminosity in order to be just discernible by the eye. Measurements which have been made upon normal eyes seem to give quite uniform results. Owing, however, to the difficulty of securing color-blind subjects who can give the requisite amount of time for the photometric tests, the collection of data is necessarily slow.

## SUMMARY.

The results of the present investigation may be summed up as follows :

I. The retina of the human eye contains two distinct sense organs — one, the luminosity sense, the other, the color sense.

II. The luminosity sense is affected qualitatively in the same way by light stimuli of all wave-lengths within the visible spectrum so that it reacts, after fatigue, always in the same way, no matter what kind of light is used to fatigue the retina. (The only exception to this is when the fatigue is caused by prolonged exposure to the long, or red, rays of the spectrum.)

III. The relation between wave-length and luminosity (def. III.) in the case of a 50 C.P. incandescent lamp may be represented by a wave-length luminosity curve which, for most eyes, is identical with the curve in Fig. 6.

IV. Deviations from this normal curve fall, for the most part, into one or the other of two classes : (1) The point of maximum luminosity may be displaced towards the red, as in Fig. 8. (2) It may be displaced towards the green, as in Fig. 10.

V. Persons possessing perfectly normal color vision may have an abnormal wave-length luminosity curve, and color-blind persons as often have a wave-length luminosity curve belonging to class 1 as to class 2.

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