RELATIVE SENSIBILITY OF THE AVERAGE EYE TO LIGHT OF DIFFERENT COLORS AND SOME PRACTICAL APPLICATIONS TO RADIATION PROBLEMS

By W. W. Coblentz and W. B. Emerson

CONTENTS

I. INTRODUCTION

Numerous investigations[a] have been made to determine the relation between luminous sensation, "light," and radiant energy; that is to say, the relative visibility of radiation in different parts of the spectrum.

The difficulties encountered in such an investigation are due to the fact that the relative brightness varies not only for different colors but also for changes in size and brightness of the illuminated field. It is therefore necessary to work under specified conditions. Having decided upon these conditions, a further difficulty encountered is the radiometric evaluation of the light stimulus.

Some of the disagreements in previous investigations seem to be due, in part, to uncertainties in the radiometric measurements. The present investigation, therefore, was undertaken in view of this Bureau's complete equipment for evaluating light stimuli radiometrically and in view of the large staff of trained investigators available for cooperation in the work. This investigation is somewhat statistical, the aim being to obtain extensive data on the relative sensibility of the eye to light of different colors, but a complete study of color perception is not attempted.

The method of comparing the light stimuli is photometric. The application of the results obtained is photometric and radiometric; as, for example, in applying corrections to spectrophotometric measurements made on narrow spectral bands, in designing lenses, and in the determination of the factor for converting visual sensation into luminous power, i. e., the mechanical equivalent of light.

II. METHODS FOR DETERMINING THE VISIBILITY OF RADIATION

Various methods are available for determining the visibility of light in different parts of the spectrum; that is, the relative sensibility of the eye to light of different wave lengths.

1. THRESHOLD OF VISION

This method has been used by Ebert,[1] by König and Dieterici,[2] and by Pflüger,[4] who determined the minimum amounts of energy required to produce a luminous sensation in different parts of the spectrum. Pflüger used a Nernst glower as a source of light and

[a] Throughout this paper the reference *numbers* occurring in text refer to the bibliography at the end of the paper. It is therefore necessary to use letters for footnote references, the notes to which appear in the text proper.

measured the energy at the slit by means of a thermopile. He examined a dozen subjects, but the data are very irregular and, owing to the low intensities required, they are of but little use in practice.

This method of determining the relative sensibility of the eye for spectral colors shows that at very low intensities the maximum sensibility lies at 0.49 to 0.53 μ.

2. VISUAL ACUITY

By this method of comparison the visibility is defined by the amount of light, independent of color, which is necessary to enable the eye to distinguish objects, such as, for example, fine print. The most noteworthy investigation by this method was made by Langley,[6] who determined with a bolometer the energy required to distinguish fine print which was illuminated by light from various parts of the spectrum. Recently Bender[7] has used the method in comparison with the flicker method, to be mentioned presently.

3. CRITICAL FREQUENCY

This method has also been termed "the persistence of vision." It has been used by Allen [12] and others in studying the response of the eye of subjects having normal vision and also of subjects who are color blind. In this method a sectored disk is rotated in the spectrum at such a speed that no flicker is perceived, the velocity of rotation giving a measure of the duration of the images of the light upon the retina. The method is based upon the principle that for the disappearance of flicker different speeds are required for different colors. The results obtained by Allen will be discussed in their proper place in this paper. It will suffice to add that the writers of the present paper tried the method and found their results in agreement with those obtained with the methods used in their work. This method and the following ones have been thoroughly investigated by Ives [16] in his search for the best methods available for the photometry of lights differing in color.

4. EQUALITY OF BRIGHTNESS

In this method two differently colored lights illuminate the two parts of a photometric field, and they are said to produce the same illumination when they give a sensation of equal brightness. The difficulty with the method lies in the inability of most observers to form a judgment concerning equality of brightness which is not influenced by differences in color. Among others the method has been used by König,[3] Ives,[16] and Houstoun.[17] The latter had 52 observers. The field illumination was low. For an illumination of one-half meter candle the wave length of maximum visibility was at $\lambda_m = 0.502\mu$ and for one-six-hundredths meter candle the maximum was at $\lambda_m = 0.466\mu$. Of the nine women examined none showed systematic differences from the men.

One difficulty encountered in this method is that some observers find it impossible to make consistent comparisons when large color differences are involved. In the case of the observers examined by the present writers the majority considered it guesswork that had no meaning. In fact, their opinions came close to Helmholz's appraisement of the method. Helmholz [15] had no confidence in his judgment concerning the equality of brightness of differently colored surfaces, although he was willing to admit that of two differently colored fields one can be so much darkened that there remains no doubt that the other is the brighter. No doubt most observers make their settings subconsciously in this manner—that is, the observer sets one part of the field too bright, then the other part of the field too bright, and finally a setting is made which is called "equality," in spite of a subconscious feeling that the two halves of the photometric field are not of equal brightness. Only a few of the subjects examined could distinguish an inequality of brightness due to slight change in intensity in the two parts of the photometric field, and even these few (including the writers, who made a prolonged test of this phenomenon) would at unexpected moments make very erratic settings in the midst of a series of closely agreeing measurements.

A few observers were found who, although they had not had previous experience in making photometric comparisons, obtained an exact coincidence in their visibility curves by this and the following method.

In view of the fact that the equality-of-brightness method is considered by some [18] to be the only one that will give true results, in the present investigation it was decided to test the equality-of-brightness method at a number of points on the spectrum to determine whether, among the erratic settings made by various observers, there is a systematic deviation from the visibility curve as obtained by the flicker photometer.

From all the work that has been done by Ives,[16] Crittenden, and Richtmyer,[29] Middlekauff and Skogland,[46] and others the equality-of-brightness method of photometry appears to be insensitive and often lacking in consistency. The erratic variations in the equality-of-brightness settings are so large that no trustworthy data seem to be at hand to prove definitely that there is a systematic difference in the results obtained by the equality-of-brightness and the flicker photometers.

5. THE FLICKER PHOTOMETER

In the flicker photometer the two illuminations are viewed alternately. "At a certain speed of alternations," says Cobb,[28] "the two colors disappear, giving place to a uniform color with a flicker superimposed upon it. Then, when the relative intensities of the two illuminations are so altered that this flicker disappears the two illuminations are by this method equal. Color flicker has a lower critical frequency than brightness flicker, and on reaching this frequency we get rid of color difference and can make a comparison of brightness."

In view of the fact that the visual sensations aroused by lights differing in color rise to their maximum brightness at different rates, the accuracy of this method of photometry has been challenged.[18] The present writers, however, do not concern themselves with this phase of the question. The flicker method is quick, precise, and gives reproducible results when operated under specified conditions, as has been shown by the extensive investigations of Whitman,[21] Tufts,[22] Thürmel,[25] Ives,[23] Bender,[26] Nutting,[27] and others. The flicker method has merits not possessed by the other methods just discussed, and the results are definite and consistent for all observers. It is, therefore, a practical method for intercomparison of various observers and hence for the establishment of the sensibility curve of the average normal eye. If it can be shown, after a prolonged investigation of a small group of observers having normal color vision, that the curve is slightly too low in the red (as the result of underestimation due to the fact that the stimulus has not had sufficient time to arouse the maximum sensation) and too high in the blue, then all the data given herewith can be easily corrected. The time of the persons who were willing to have their eyes examined was very valuable, and it would not have been fair, at this stage of the knowledge of the subject, to ask them to devote more time to this question.

The question of photometric methods should be given further study. However, from the data presented herewith on 130 subjects, whose sensibility in any part of the spectrum is rarely in agreement as close as 1 to 2 per cent (which is the error of observation of a single observer), it seems futile to devote much time to obtain a method with which any one observer can make measurements with an accuracy of a small fraction of 1 per cent.

III. APPARATUS AND METHODS

The arrangement of the apparatus is illustrated in Fig. 1.

1. THE SPECTROMETER LENSES

The spectrometer was a very substantial instrument, with an automatic attachment for maintaining the prism at minimum deviation, constructed in this Bureau's instrument shop. A photographic illustration of it is given in a previous paper.[41] The collimating lens is a triple achromat of 18 cm focal length, by Zeiss. For the present investigation the exactly similar objective lens was replaced by an achromatic doublet, *L*, of 33 cm focal length, especially made in the Bureau's shop for this work. The special preparation of this lens consisted in giving it a very fine polish in order to eliminate stray light. The surfaces were quite free from pit marks remaining from grinding with coarse-grained enemy, and although the polishing was not as perfect as is possible the field of view was remarkably free from diffuse light as compared with other spectrometer lenses which were tested for this defect. Using a hand spectroscope, an examination of the light emerging from the slit, *I*, as used in this investigation gave no marked indications of stray light (white light) from adjacent parts of the spectrum. The test was applied in various parts of the spectrum, and it was concluded that no corrections were to be made for diffuse light[a] in view of the fact that if it were present in a measurable amount it would be included in the direct radiometric measurement. It is to be understood, of course, that this apparatus, like all others, is not entirely free from diffuse light. Using intense light from a Nernst glower placed close to the slit, diffuse light was detected with a hand spectroscope.

2. THE PRISM

The prism was of light flint glass. With the 33 cm focal length lens it produced a spectrum which was 14 mm in length between the red and the blue-violet helium lines ($\lambda = 0.667\mu$ and $\lambda = 0.447\mu$).

[a] See Appendix 1 at the end of this paper.

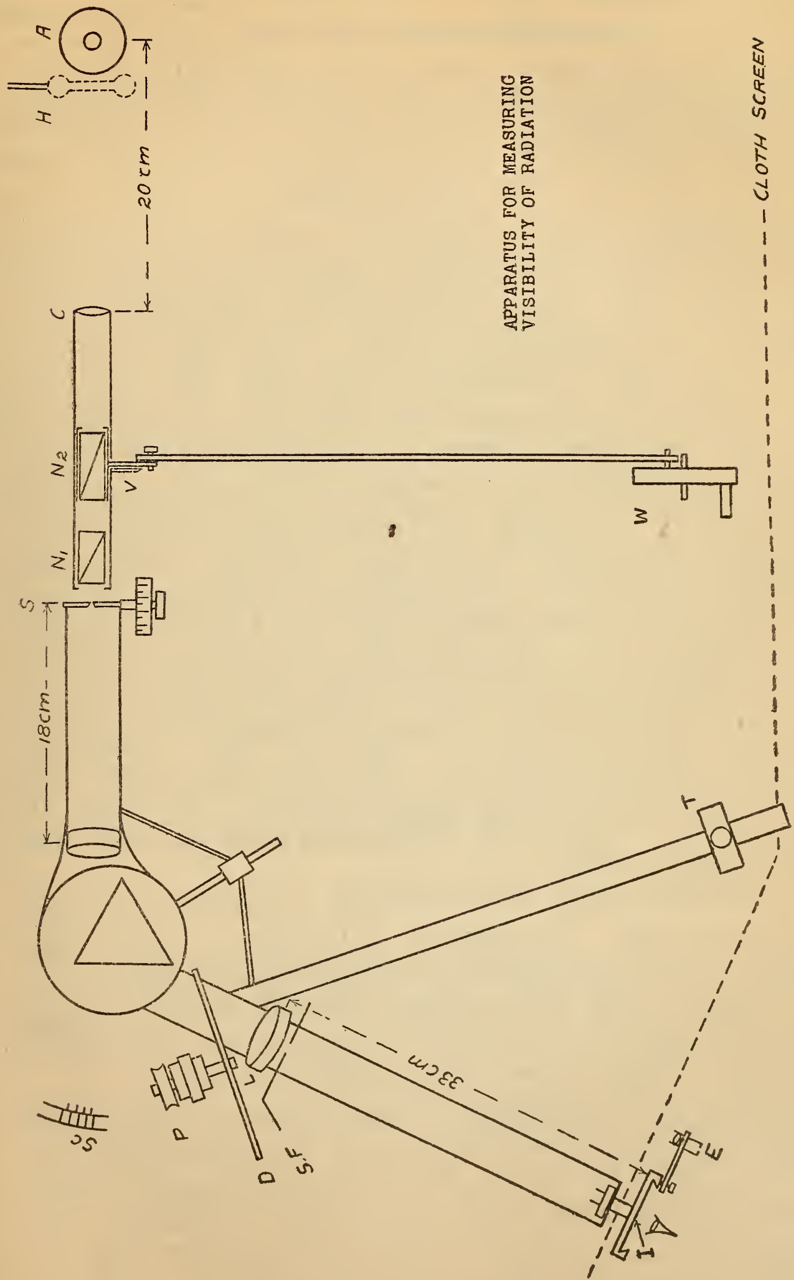

FIG. 1.—*Arrangement of apparatus used in obtaining visibility data*

The surfaces were given a special polish to reduce diffuse light. The prism and the collimating telescope were entirely inclosed to eliminate extraneous light. The spectrum (the · spectrometer circle *Sc*) was calibrated by means of the helium lines, the adjustments being maintained by means of the yellow helium line from a tube inserted temporarily at *H*. For making this adjustment the eyepiece *E* was focused upon the slit *I*.

3. THE LIGHT SOURCES

For a standard source of white light, *T*, Fig. 1, a duplicate set 8, 16, and 38 candlepower vacuum tungsten lamps was provided. These lamps were carefully seasoned and standardized by Mr. Mulligan, of the photometric division. They were operated at 1.2 watts per candle, which specifies their color. For most of the work the 8-candlepower lamps were used, and the constancy of their light was frequently tested by intercomparing them in this apparatus, using some part of the spectrum of the acetylene flame as a standard of comparison. It is understood, of course, that it is important to operate the lamp at a constant current while obtaining a visibility curve, but a change in candlepower by aging of the lamp is of minor importance. This lamp was operated from a storage battery, the current being easily maintained constant by means of a milliammeter (the scale of which was read by means of a low-power lens). A change of current of 0.001 ampere would affect the readings by 1 to 2 per cent, which is better than the individual settings of the average observer. By sliding the lamp *T* along its support, the illumination could be varied from 15 to 800 meter candles.

As a standard source of spectral light a cylindrical acetylene flame, *A*, was used. The intensity of the light emitted is quite constant. On several occasions it was found that the flame burned at a somewhat lower (but constant) intensity although the gas pressure remained the same, but the cause of this could not be determined. This, however, did not affect the results.[a]

The acetylene flame was used as a standard of spectral radiation because of its high intensity and because its spectral-energy distribution [40] is well known and easily maintained constant within the limits of errors in the visual measurements. A tungsten lamp

[a] The acetylene was used as it came from the generator, without further purification. Rands (Phys. Rev., XIV) has shown that ordinary acetylene is 99 per cent pure. Acetylene might contain a small amount of H_2S, but spectroradiometric investigations (Coblentz, Investigation Infra-red Spectra, Publication No. 35, p. 44, Carnegie Institute, Washington, 1905), do not show impurities.

might have been used, but its energy distribution would be difficult to determine and the lamp would require frequent standardization.

4. THE ENERGY MEASUREMENTS

The visual measurements are not sufficiently refined to warrant undertaking the long and difficult task of determining directly the energy value of the light stimulus in different parts of the spectrum. In fact, in the yellow-green, where but little energy is required to excite a luminous sensation, it would be quite impossible to measure this energy accurately with a radiometer. To avoid this difficulty, the usual procedure is to measure radiometrically the energy in an intense source and reduce it (by a known amount) by absorption screens, Nicol prisms, etc., to the intensity utilized in the visual observations.[65]

In the present investigation the distribution of energy in the spectrum of the acetylene flame [40] was determined in the usual way by placing the flame at *S*, Fig. 1, and exploring the complete visible spectrum with a thermopile placed in the illuminator attachment *I*, as described elsewhere.[42] This gives the prismatic-energy distribution, and hence the energy of the stimulus as applied to the eye. Proper corrections (which are small) of course must be applied for losses by reflection from the Nicol prisms and the lens when the acetylene flame is placed at *A*, as used in the visual observations. When the flame is placed at *A* and the Nicol prisms *N* and condensing lens *C* are in place, the light is reduced by one-half, so that accurate energy measurements could be made only in the longer wave lengths beyond 0.6μ. The results obtained, however, were in agreement with those obtained with the flame [a] at *S*.

The energy distribution was redetermined after a month of visual observations and found in exact agreement with the earlier measurements.[b] The candlepower of the flame changes with pressure, which is easily kept constant; but, as shown in a more complete paper [40] on this subject, this does not affect by an appreciable amount the relative energy distribution in the spectrum.

In any part of the spectrum the energy arriving at *I* is determined by the light transmitted through the Nicol prisms.

The flame was entirely inclosed, the light emanating through an opening 8 mm high and about 2 mm wide.[40] The image of

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[a] See Appendix 1, "On diffuse light and spectral energy measurements."
[b] See Appendix 1 for further verification.

this opening as projected upon the spectrometer slit S was about 1 by 5 mm.

When making the energy measurements, the shield $S\ F$ was removed and the space between L and I was inclosed with a cardboard tube to exclude extraneous light and air disturbances from the thermopile.

As already mentioned, the amount of diffuse light present in the stimulus is very small and immeasurable. (See Appendix 1.) Numerous attempts, during the past 10 years, to measure such small amounts of stray light have always been a failure. Hence radiometrically the diffuse (white) light is negligible.

5. THE NICOL PRISMS

The light from the acetylene flame A is focused upon the spectrometer slit by means of the achromatic lens C. The function of the two Nicol prisms (N_1 is stationary) is to vary the intensity of the light falling upon the slit, and hence to vary the intensity in any part of the spectrum. The light transmitted is proportional to $\sin^2 \theta$, where θ is the angle through which the Nicol N_2 is rotated from the position in which there is complete extinction. A circular scale divided into even degrees and a vernier, V, enable one to read the amount of rotation of the Nicol. When the angular opening (θ) is 90°, the transmission is taken 100 per cent. The accuracy of the transmission for different openings (90°, 60°, 45°, 30°, 0°) was determined radiometrically by placing a thermopile at the exit opening, between S and N_2, and after correcting for a slight amount of infra-red transmitted when the Nicols were crossed, $\theta = 0°$, it was found that the observed and the computed transmissions were in agreement within the errors of observation. For example, the ratio of the galvanometer deflections for 30° and 90° openings was ($4.01 \div 16.18 =$) 0.248, while the computed transmission for $\sin^2 30°$ is 0.2499.

The incomplete extinction of the infra-red energy from the flame A when the Nicols are crossed, $\theta = 0°$, was not found in another pair of Nicols, hence it is not a common property, and tests made with a solution of cupric chloride show that the infrared is easily eliminated. The device therefore is useful in making an apparatus (crossed Nicols and quartz plate) for transmitting light proportional to the visibility curve of the eye (as proposed by Mr. Priest), in place of the visibility solution mentioned in this paper.

The size of the Nicol was 8 by 10 by 25 mm. A diaphragm 7 mm in diameter, placed in front of N_2, confined the incident light to the central part of the optical system.

A further provision for varying the light entering the spectrometer is the bilateral slit *S*, which is provided with a graduated drum.

The observer at *I* rotated the Nicol by turning a wheel, *W*, which was connected with the Nicol mounting by means of a long rod.

6. THE FLICKER PHOTOMETER

The arrangement of the flicker photometer is practically the same as recommended by Ives.[23] The photometer field is 10 mm or about 2° in diameter. A "surrounding field," *S F*, was also provided, although this is not absolutely necessary for this work. To provide a convenient surrounding field, *S F*, illuminated from the standard lamp *T*, the objective lens *L* was mounted securely in a brass frame attached to a heavy iron bar, which was used in place of the usual telescope tube. The surrounding field was placed close in front of this lens. It consisted of a piece of stiff cardboard covered with white filter paper, which was covered with magnesium oxide. The opening in this cardboard was adjusted so that the lower edge of the hole (10 mm in diameter) in it came just above the optical axis of the lenses. In this manner the numerous small spectra (visible in any spectroscope), caused by reflections from the surfaces of the lenses and prism, were entirely eliminated from the field of view. This is a very important desideratum when viewing the extreme ends of the visible spectrum.

The sectored disk *D*, 15 cm in diameter, was made of brass, which was covered with a thick, even layer of magnesium oxide, obtained by burning magnesium ribbon. The edges of the sectors were beveled, and after depositing the magnesium oxide a sharp, smooth edge was produced by removing the overhanging oxide by means of a sharp knife.

The illumination incident upon the disk *D* was approximately 50 meter candles. It was adopted for use with the various observers after a preliminary investigation of various incidental phases of the subject. In this preliminary work visibility curves were obtained for intensities varying from 25 to 780 meter candles upon the sectored disk. It was found that for the lower (25-meter candles) intensity the eye seemed to be more variable from day to day in its response to stimuli in the green, and it seemed more difficult to make the settings at these low intensities. On the other hand, the 100 meter-candle intensity did not permit determining the visibility curve over a great range of the spectrum without changing the slit opening, which meant delays in completing the most important part of the sensibility curve. Hence, the 50-meter-candle intensity was adopted in view of the fact that our results are in agreement with those of other experimenters, [52, 23, 27], showing that the shape and position of the maximum of the visibility curve of the central retina is the same, within experimental errors, for all these high intensities, as shown in Fig. 2.

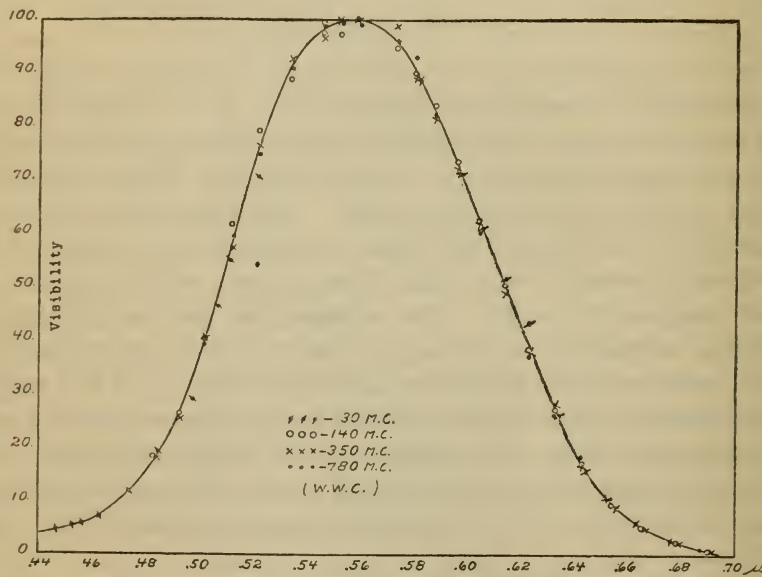

FIG. 2.—*Relative spectral sensibility of the eye when subjected to stimuli of various intensities*

In making these measurements the observer, at *I*, viewed a part of the spectrum coming through an opening 0.52 mm wide and 2.63 mm high.

The disk was connected by a flexible belt (rubber or coil of spring steel) with a small direct-current series-wound motor, the speed of which could be varied by means of a variable resistance in series with it. No attempt was made to record the speed, in view of the fact that it is different for different intensities, different colors, and different observers, and in view of the fact that previous investigations [16] show that it has no direct bearing upon the problem under investigation.

The motor was fixed to the base of the spectrometer. The disk *D* and the support for the standard lamp *T* were securely attached to the spectrometer arm *I L*, which was movable, in order to view different parts of the spectrum. By this arrangement the light from the lamp *T* was always normal upon the disk *D*, and conditions were thus the same throughout the series of measurements.

This apparatus was used in a dark room illuminated only by the stray light from the acetylene flame and the lamps which were used to read the scale *Sc* and vernier *V*. A cloth screen prevented light from reaching the observer at *I*.

7. METHODS OF OBSERVATION

In making the photometric measurements the observer, at *I*, rotated the Nicol prism by means of the wheel *W* and adjusted the speed of the motor to produce no flicker. In a few cases the observer preferred to use minimum flicker. The assistant made the spectrometer settings *Sc*, read the photometer scale *V* (the rotation of the Nicol N_2), and recorded the data.

In the preliminary work it was found that the eye becomes adapted to the conditions of this work in less than five minutes. The observer, therefore, made a series of preliminary measurements to learn the method and to adapt the eye. Measurements were then made in the yellow and extended every 10 seconds of arc on the spectrometer circle to the end of visibility in the red. The measurements in the yellow were then repeated (and always found the same as in the beginning) and extended, for every predetermined spectrometer setting (5 and 10 seconds of arc), to the limit of visibility in the violet. The settings in the yellow-green were then repeated, when, in some cases, the sensibility was a little higher.[44] This, however, disappeared after a few settings of the Nicol prism. New settings were then made at intermediate points (the 5-seconds intervals on the spectrometer circle) extending to the end of visibility in the red, also the alternate 10-seconds settings were repeated, especially if the sensitivity of the eye had changed, which was of rare occurrence. In this manner the complete visibility curve was obtained for every 0.01μ extending from 0.49 to 0.69μ. In this series the slit *S* was 0.1 mm in width, the Nicol opening being about 12° in the yellow for the majority of the observers.

For those observers who could give the time the visibility curve was then extended to 0.75μ in the red and about 0.435μ in the violet. This was accomplished by opening the slit *S* to 0.6 mm and by placing the lamp at a greater distance (73.5 cm), which reduced the illumination to about 15 meter candles on the disk. That this procedure is permissible was determined in the preliminary work, in which the visibility curve of one of the writers was determined (by using a still lower illumination) to 0.77μ in the red and 0.40μ in the violet. It is, of course, understood that on both sides of the maximum of the visibility curve, which was obtained for a 50 meter-candle illumination, measurements were made also for the 15 meter-candle illumination in order to obtain the factor for superposing the two curves. This factor was somewhat different for the two sides of the curve, due, no doubt, to diffraction caused by the narrow slit. This, however, is of minor importance.

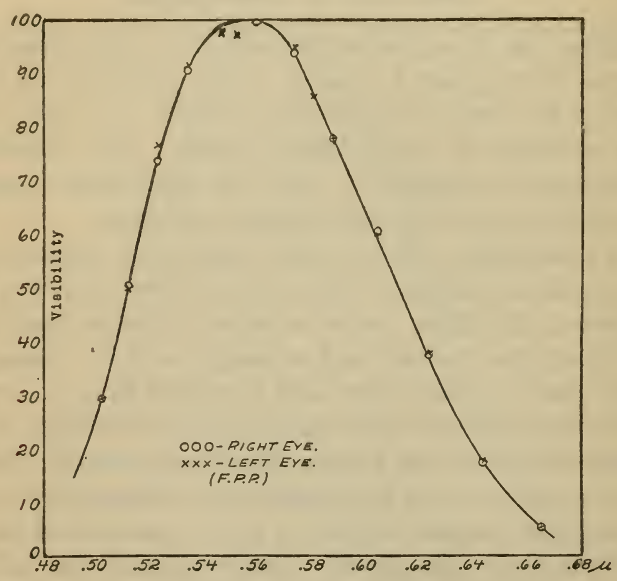

FIG. 3.—*Sensibility of right and left eye*

In the preliminary investigation it was found that the variation in the observations for the right and the left eye (W. W. C.) were from 1 to 3 per cent, which was the accuracy attained on different days using the right eye. One observer (F. P. P.) kindly volunteered to make the test of both eyes on the same day. The observations are in exact agreement throughout the curve (see Fig. 3), showing that the visibility curve, characteristic of a given observer, can be obtained by examining either the right or the left eye, as had been found by previous measurements.[7, 12, 22]. The various observers, therefore, were permitted to use the eye which they were accustomed to using and which they considered the "best" physically.

In order to make the equality-of-brightness measurements, the disk D was placed so as to bisect (horizontally) the photometric field. In this manner one-half of the field was illuminated by the standard lamp T and the other half of the field was illuminated with spectral light of a given color. In view of the great difficulty experienced by most observers in making such settings, it was deemed of greater importance to spend the time in making numerous settings in a few parts of the spectrum instead of attempting to obtain the complete visibility curve. The results of this test will be discussed on a subsequent page.

For the information of the reader not entirely familiar with the subject, it may be added that the visiblity of radiation is the reciprocal of the measurements recorded. For example, in the yellow-green the Nicol opening (rotation) may be 13° and at 0.68μ the opening may be 60°. The energy transmitted therefore would be 5 and 75 per cent, respectively, of the value observed radiometrically at these two wave lengths. In the curves given herewith the reciprocals of these energies are plotted; for by definition the sensibility of the eye, or the visibility of radiation, V_λ, at any wave length is the ratio of the luminous intensity measured in light units to the intensity of the light measured in energy units, viz, $V_\lambda = I_\lambda \div E_\lambda$. The curve obtained is the visibility for an equal-energy spectrum.

For most of the observers the visibility was determined only once, in view of the fact that but little variation of the visibility curve was found on different days (as was previously found by Bender[26]), especially when the observations were made after a night of sound sleep. Observers suffering from lack of rest, "cold," or "grippe" gave variable results, especially in the green. Part of this difficulty seemed to be due more to the inability to fix the attention upon the flickering field than to an actual change in sensitivity of the eye.

IV. DISCUSSION OF DATA

Heretofore it has been the practice to publish the visibility curves of the individual observers. For convenience in illustration, the present data have been arbitrarily grouped according to characteristics which occur in common in certain visibility curves.

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In order to classify these data, each visibility curve was set to the scale 100 at its maximum. The appropriate factors are given in column 5 of Table 1. These factors differ, of course, due to differences in retinal sensibility and, to some extent, to small changes in brightness of the acetylene flame[a] and to recoating the disk with magnesium oxide. This has no effect upon the relative visibility, in view of the fact that the scale of ordinates in the spectral-energy curve of the acetylene flame might have been chosen, for example, so that the average factor would have been 1.0 instead of 1.2. (See Table 1.) Because of the extensive data it did not seem necessary to weight the visibility curves by reducing them to the same area before taking their mean value, as has been done heretofore.

These visibility curves, plotted in terms of equal maxima, were then compared with the average by viewing them over an illuminated ground glass and classified in the groups illustrated on the following pages. It is to be understood, of course, that this characteristic grouping is not always as sharply defined as illustrated, although in some instances there is a tendency toward distinct grouping.[b]

This classification shows (1) wide curves with the maximum shifted toward the red, "red sensitive," (2) narrow curves with a sharp maximum in the green, and (3) curves with the maximum shifted toward the violet. A fourth group of observers has very wide curves embracing much of the three preceding groups. A fifth group has the average sensibility in the red and yellow, but has a low sensibility in the blue, while a sixth group has the average sensibility in the blue, but has a low sensibility in either the yellow or red or throughout this entire region of the spectrum.

The visibility of radiation data obtained by various observers (all but two having normal color vision) are given in Table 1. In this table column 2 gives the type of visibility curve. The classification *Sub. R.* includes several subjects whose visibility is below the average in the yellow and orange part of the spectrum.

It is to be noticed in this table that several subjects having the same type of visibility curve came in succession in the order of making observations. From this it might appear as though the

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[a] Caused no doubt by variation in humidity. Thus far it has not been possible to establish a change in the shape of the spectral-energy curve of acetylene (in the visible spectrum) for small changes in brightness caused by variation in humidity or gas pressure.

[b] Such groups are recognized by writers on physiological optics (c. f., Nagel, von Kries, Goldhammer), who use the terms "monochromats," "dichromats," "trichromats," "red anomalous," "green anomalous," etc.

shift from the average curve might be due to lack of adjustment of the apparatus.[a]

This occurrence of so many subjects in succession having the same characteristics is due to the fact that the observers were often selected from a classified list previously obtained from the photometric tests made by Crittenden and Richtmyer.[29]

In Table 1 the fourth column gives the color of the eyes (*Bl* = blue, *Gr* = gray, *Br* = brown, *L. Bl.* = light blue), which data were obtained for the reasons explained on another page.

The last column of Table 1 gives the position of maximum visibility as read from the individual curves. The mean value of the 125 observers is $\lambda_m = 0.5576\ \mu$.

Before discussing these various groups of visibility curves, it is of interest to give some references to subjects who have very marked abnormalities of color vision.

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[a] At the time of making the test the abnormal observations were always checked by the attendant (W. B. E.), whose visibility is very close to the average.

TABLE 1

Visibility of Normal Subjects—Blue End of Spectrum

[NOTE.—Footnotes at end of table. See p. 193.]

Subject	Visibility[a]	Age.	Eye color[b]	Factor	λ= 0.427	λ= 0.435	λ= 0.444	λ= 0.450	λ= 0.456	λ= 0.463	λ= 0.474	λ= 0.485	λ= 0.493	λ= 0.502	λ= 0.5125	λ= 0.523	λ= 0.534	λ= 0.546	λ= 0.552	λ= 0.559	λ= 0.573
W. W. C.[c]	W.	42	Br.	......	[d] 21.6	33.7	38.1	45.5	57.5	78.0	118.0	197.0	265	396	589	757	887	973	991	1000	973
E. D. T.	N.	35	Bl.	1.18	......	......	......	......	......	......	......	......	221	347	562	754	890	989	1000	[e] 969	963
W. B. E.	W.	25	Bl.	1.17	......	......	......	......	......	......	......	......	253	389	575	756	910	966	958	1000	940
F. P. P.[c]	G. S.	26	......	......	18.8	20.1	......	27.4	......	34.4	......	86.4	151	292	492	752	905	973	998	1000	938
R. F. J.[c]	N.	35	......	......	......	27.7	......	34.1	......	57.3	......	151.0	192	325	528	738	920	991	1000	999	956
C. F. S.	B. S.	25	......	1.05	......	29.6	......	42.4	......	70.0	......	165.0	249	382	601	818	949	1025	1000	992	943
P. D. F.	Sub. B.	29	Gr.	.965	......	......	13.0	17.6	......	26.4	......	93.1	124	242	435	720	868	969	1000	984	938
I. G. P.[f]	Sub. R.	30	......	1.04	......	25.7	35.0	38.7	49.7	61.7	104.0	160.0	220	389	571	779	932	992	1000	1000	930
H. J. M.[f]	N.	23	......	......	21.1	27.0	34.3	40.4	50.9	70.8	107.0	163.0	227	356	550	755	866	974	962	1000	942
C. G. P.[c]	N.	29	......	......	[g] 23.3	29.7	36.5	46.9	59.8	77.4	102.0	175.0	257	399	567	747	909	984	1000	998	941
W. W. B.	R. S.	30	Bl.	1.10	......	......	......	......	......	......	......	......	211	340	531	763	924	975	991	1000	1010
C. O. F.	R. S.	26	Bl.	1.24	......	......	......	......	......	......	......	......	......	[h] 334	513	742	889	985	986	1000	965
J. W. S.	Sub. B.	......	......	1.12	......	......	......	11.6	14.3	21.2	36.0	60.0	100	210	409	681	857	965	1010	991	935
W. F. M.[f]	R. S.	27	......	......	......	......	19.8	23.0	26.0	35.1	69.0	93.0	152	242	452	672	852	963	1000	995	1027
I. N. K.	R. S.	22	Bl.	1.28	......	......	24.9	27.0	35.4	48.0	74.3	109.0	173	283	478	687	850	936	971	1000	981
H. R.	B. S.	34	Bl.	......	......	......	......	......	......	......	......	......	291	418	552	792	906	982	1012	985	940
B. M.	R. S.	34	Bl.	1.30	......	......	......	......	20.1	30.6	51.7	73.9	124	[i] 239	437	662	803	922	964	977	1000
K. B.	Sub. R.	35	Br.	1.09	......	......	......	......	......	......	......	......	186	318	532	776	942	1017	985	978	910
P. V. W.	R. S.	26	Bl.	1.06	......	......	......	......	......	......	......	......	209	350	544	740	835	946	944	1000	987
G. K. S.	N.	27	Br.	.992	......	......	......	......	......	......	......	144.0	210	367	571	745	880	967	991	967	955
A. N. I.	G. S.	20	Bl.	1.04	......	......	......	19.0	23.6	34.0	57.0	84.2	148	280	513	744	881	990	......	991	940
E. C. C.	W.	35	......	1.28	......	......	......	......	......	......	......	198.0	295	397	608	798	906	949	1000	980	970
C. L. C.	Sub. R.	20	Br.	1.24	......	......	......	......	......	......	......	......	194	336	544	762	926	1025	1000	995	[j] 943
R. G. W.	G. S.	26	L. Bl.	1.29	......	......	......	......	......	......	......	......	......	251	448	717	882	960	981	1010	960
C. S. C.	Sub. R.	23	Bl.	1.09	......	......	......	......	......	......	......	......	202	336	554	826	890	963	995	1000	872
M. S. V.	N.	24	Br.	1.26	......	......	......	......	......	......	......	......	230	355	553	778	903	......	685	1600	954

Visibility of Normal Subjects—Red End of Spectrum

Subject	Visibility	Age	Eye color	Factor	λ= 0.580	λ= 0.5876	λ= 0.5964	λ= 0.604	λ= 0.613	λ= 0.623	λ= 0.633	λ= 0.643	λ= 0.654	λ= 0.665	λ= 0.678	λ= 0.690	λ= 0.703	λ= 0.717	λ= 0.730	λ= 0.746	λ= max
W. W. C.[c]	W.	42	Br.	......	925	855	758	667	525	406	285	183.0	98.8	50.4	25.0	10.4	4.41	1.61	0.656	0.264	0.559
E. D. T.	N.	35	Bl.	1.18	926	858	774	650	536	398	273	167.0	92.8	45.2	20.3	......	......	......	......	......	.559
W. B. E.	W.	25	Bl.	1.17	898	790	712	621	502	375	271	166.0	102.0	47.0	21.7	8.91	3.88	k1.45	......	......	.558
F. P. P.[c]	G. S.	26	......	......	853	780	691	599	488	376	246	174.0	93.6	49.3	20.6	9.15	3.44	1.26	.572	l.237	.555
R. F. J.[c]	N.	35	......	......	890	790	694	600	470	346	246	151.0	84.5	41.9	18.6	8.44	3.64	1.46	.514	.243	.558
C. F. S.	B. S.	25	......	1.05	870	780	689	623	468	357	235	143.0	89.0	38.3	18.3	8.18	3.83	1.33	.490	.237	.553
P. D. F.	Sub. B.	29	Gr.	.965	910	810	730	627	466	365	250	153.0	78.1	38.9	17.7	7.27	2.84	1.05	.395	......	.557
I. G. P.[f]	Sub. R.	30	......	1.04	857	761	693	597	462	348	229	144.0	84.6	41.5	18.3	7.90	3.29	1.36	.485	.199	.554
H. J. M.[f]	N.	23	......	......	942	829	732	642	527	393	277	167.0	95.1	45.7	21.0	8.75	4.07	1.54	.562	.242	.559
C. G. P.[c]	N.	29	......	......	886	811	720	620	498	378	270	164.0	89.2	42.0	19.0	8.10	3.40	1.33	.443	m.220	.556
W. W. B.	R. S.	30	Bl.	1.10	929	886	789	701	581	435	309	193.0	118.0	57.2	27.9	11.3	......	......	......	......	.559
C. O. F.	R. S.	26	Bl.	1.24	928	898	779	705	562	427	316	194.0	113.0	56.2	25.4	10.1	......	......	......	......	.560
J. W. S.	Sub. B.	......	......	1.12	894	817	......	642	......	387	......	184.0	......	52.4	......	9.29	......	1.54	......	.244	.558
W. F. M.[f]	R. S.	27	......	......	999	944	865	802	674	541	370	245.0	137.0	70.4	31.3	13.0	5 46	1.85	.666	.257	.570
I. N. K.	R. S.	22	Bl.	1.28	979	948	872	788	674	533	363	244.0	129.0	69.0	30.4	13.7	5.68	1.99	.761	.282	.568
H. R.	B. S.	34	Bl.	......	850	764	699	610	506	374	254	173.0	105.0	44.4	20.7	......	......	......	......	......	.555
B. M.	R. S.	34	Bl.	1.30	962	897	839	745	626	508	359	240.0	132.0	63.4	30.2	13.0	5.28	1.88	757	.319	.568
K. B.	Sub. R.	35	Br.	1.09	836	735	628	548	417	313	214	133.0	72.0	35.7	15.7	......	......	......	......	......	.551
P. V. W.	R. S.	26	Bl.	1.06	962	869	812	704	592	462	330	213.0	118.0	59.8	26.9	10.8	......	......	......	......	.562
G. K. S.	N.	27	Br.	.992	873	841	751	631	524	364	234	153.0	81.6	39.0	17.5	7.06	......	......	......	......	.561
A. N. I.	G. S.	20	Bl.	1.04	865	778	693	597	455	350	229	142.0	72.2	34.8	16.0	6.60	2.73	1.02	.392	.173	.555
E. C. C.	W.	35	......	1.28	925	820	734	646	530	412	282	188.0	103.0	51.6	23.7	......	......	......	......	......	.558
C. L. C.	Sub. R.	20	Br.	1.24	852	777	669	568	438	330	216	137.0	72.1	38.5	16.8	......	......	......	......	......	.554
R. G. W.	G. S.	26	L. Bl.	1.29	883	814	715	586	476	360	239	156.0	82.7	41.0	18.3	......	......	......	......	......	.558
C. S. C.	Sub. R.	23	Bl.	1.09	849	760	673	556	435	312	221	134.0	76.4	36.2	16.2	......	......	......	......	......	.551
M. S. V.	N.	24	Br.	1.26	886	809	711	636	486	389	......	177.0	......	48.8	......	......	......	......	......	......	.558

TABLE 1—Continued

Visibility of Normal Subjects—Blue End of Spectrum

Subject	Visibility	Age.	Eye color	Factor	λ= 0.427	λ= 0.435	λ= 0.444	λ= 0.450	λ= 0.456	λ= 0.463	λ= 0.474	λ= 0.485	λ= 0.493	λ= 0.502	λ= 0.5125	λ= 0.523	λ= 0.534	λ= 0.546	λ= 0.552	λ= 0.559	λ= 0.573
C. F. H.	N.	32	L. Bl.	1.27	......	......	......	......	......	......	......	......	205	342	544	794	913	1000	996	997	967
F. A. W.	R. S.	26	Br.	1.32	......	......	......	......	......	......	......	......	193	352	520	721	883	966	990	990	987
A. H. T.	R. S.	30	......	1.22	......	......	......	......	......	......	......	......	......	257	499	762	866	934	981	1000	977
H. G. B.	N.	35	Br.	1.23	......	......	......	......	......	......	......	......	215	365	584	826	913	1027	......	982	948
E. D. W.	G. S.	24	L. Bl.	1.23	......	......	......	27.0	38.0	52.2	73.3	122.0	200	360	545	707	882	973	1006	994	947
H. B. S.	B. S.	30	......	1.04	......	40.3	57.1	66.2	88.6	107.0	171.0	261.0	341	480	657	792	913	995	989	987	867
C. G. C.	R. S.	23	Bl.	1.20	......	......	......	......	......	......	......	......	141	260	473	690	849	957	982	967	959
J. S. P.	N.	21	Bl.	1.08	......	......	......	......	......	......	......	......	267	402	596	743	849	930	986	1010	935
A. N. G.	N.	29	Bl.	1.10	......	......	......	......	......	......	......	......	261	392	606	817	877	962	991	1000	988
A. M. P.	G. S.	27	Bl.	......	......	......	......	......	......	......	......	......	179	311	503	708	872	968	997	1000	925
W. J. K.	N.	24	Br.	1.12	......	......	......	......	......	......	......	......	232	385	567	786	880	991	1000	986	931
R. E. L.	Sub. R.	37	Bl.	1.00	......	......	......	......	......	......	......	......	170	289	511	775	912	998	1040	1000	934
H. W. B.	B. S.	34	......	1.25	......	......	......	......	......	......	......	......	304	445	605	775	928	971	......	1000	950
E. D. G.	Sub. R.	28	Bl.	1.15	......	......	......	......	......	......	......	......	211	358	586	778	948	1000	1000	990	917
R. M. W.	R. S.	27	Bl.	1.37	......	......	......	......	......	......	......	......	253	380	532	726	844	941	967	987	1000
L. R. H.	R. S.	19	Br.	1.32	......	......	......	......	......	......	......	......	175	321	506	724	887	983	987	986	971
W. S. J.	R. S.	24	Bl.	1.24	......	37.8	45.4	49.0	60.2	79.6	115.0	161.0	242	364	546	771	892	960	974	1000	975
R. W. W.*f*	G. S.	22	Gr.	......	......	24.7	25.9	27.5	32.5	52.9	77.3	130.0	176	310	538	777	920	982	998	1000	940
H. B. H.	N.	22	Br.	1.23	......	......	......	......	......	......	......	......	246	388	560	748	903	981	1010	989	954
E. F. M.	B. S.	33	Br.	1.25	38.6	53.0	62.8	71.2	97.4	124.0	164.0	259.0	335	470	631	786	877	937	1000	997	944
H. A. B.	Sub. B.	25	Bl.	1.13	......	......	......	......	21.7	33.1	57.8	87.3	138	254	465	715	878	941	989	980	980
D. H. S.	Sub. R.	26	Br.	1.08	......	......	......	......	......	......	......	......	201	335	562	800	922	1017	987	1000	920
W. C. B.	W.	33	Bl.	1.23	......	......	......	......	......	......	......	258.0	343	477	654	831	932	986	992	1000	954
R. C. S.	B. S.	29	Br.	1.10	......	......	......	......	......	......	......	190.0	296	454	666	814	960	1000	990	1040	947
M. H. S.	B. S.	30	Gr.	1.08	......	......	......	......	......	......	......	198.0	284	427	638	819	924	983	986	1000	949
G. W. M.	Sub. B.	46	Gr.	1.20	......	......	......	......	......	......	......	......	183	311	544	760	899	992	1006	966	958
A. L. T.	G. S.	26	Bl.	1.03	......	......	......	......	......	......	......	......	163	293	534	754	925	968	960	990	930
A. F. P.	Sub. B.	43	......	1.12	......	......	......	......	22.4	33.8	55.6	85.2	135	275	482	739	876	961	1000	993	951

Visibility of Normal Subjects—Red End of Spectrum

Subject	Visibility	Age	Eye color	Factor	λ= 0.580	λ= 0.5876	λ= 0.5964	λ= 0.604	λ= 0.613	λ= 0.623	λ= 0.633	λ= 0.643	λ— 0.654	λ= 0.665	λ= 0.678	λ= 0.690	λ= 0.703	λ— 0.717	λ— 0.730	λ= 0.746	λ max
C. F. H.	N.	32	L. Bl.	1.27	888	812	706	626	484	376	246	157.0	89.4	41.8	19.0	......	......	......	......	......	0.556
F. A. W.	R. S.	26	Br.	1.32	942	910	820	737	619	468	347	228.0	131.0	59.4	28.9	12.3	......	......	......	......	.562
A. H. T.	R. S.	30	......	1.22	934	852	784	655	555	433	307	196.0	110.0	56.1	24.1	......	......	......	......	......	.560
H. G. B.	N.	35	Br.	1.23	913	834	745	627	524	396	256	167.0	93.1	44.2	20.4	......	......	......	......	......	.554
E. D. W.	G. S.	24	L. Bl.	1.23	824	766	685	591	474	388	271	182.0	100.0	51.0	24.2	9.70	4.32	1.46	0.589	0.316	.556
H. B. S.	B. S.	30	......	1.04	798	701	588	491	344	253	161	98.3	53.7	25.2	11.2	4.74	1.96	.792	......	......	.551
C. G. C.	R. S.	23	Bl.	1.20	971	888	756	659	554	423	305	193.0	116.0	54.3	24.3	9.68	......	......	......	......	.563
J. S. P.	N.	21	Bl.	1.08	895	803	716	605	500	373	264	173.0	94.2	49.0	23.7	......	......	......	......	......	.558
A. N. G.	N.	29	Bl.	1.10	910	824	735	653	500	377	269	167.0	87.3	44.0	19.4	......	......	......	......	......	.560
A. M. P.	G. S.	27	Bl.	......	875	793	669	594	491	351	262	170.0	89.0	46.8	20.3	8.12	......	......	......	......	.557
W. J. K.	N.	24	Br.	1.12	890	806	692	627	522	423	299	187.0	109.0	56.5	25.2	10.06	......	......	......	......	.555
R. E. L.	Sub. R.	37	Bl.	1.00	869	772	669	571	446	315	203	125.0	63.7	31.0	14.1	......	......	......	......	......	.553
H. W. B.	B. S.	34	......	1.25	874	843	747	658	522	400	......	167.0	91.0	46.6	21.8	......	......	......	......	......	.557
E. D. G.	Sub. R.	28	Bl.	1.15	877	744	635	558	432	334	221	128.0	73.5	37.4	16.4	......	......	......	......	......	.553
R. M. W.	R. S.	27	Bl.	1.37	949	860	804	702	603	453	324	209.0	116.0	59.5	25.4	......	......	......	......	......	.564
L. R. H.	R. S.	19	Br.	1.32	921	858	786	687	588	438	300	203.0	108.0	55.5	25.4	......	......	......	......	......	.560
W. S. J.	R. S.	24	Bl.	1.24	975	901	820	742	617	485	352	224.0	126.0	66.4	29.5	12.8	5.10	1.95	.762	.343	.561
R. W. W.*f*	G. S.	22	Gr.	......	873	783	711	601	467	340	231	146.0	78.6	38.2	17.2	10.2	3.22	1.21	.528	.287	.555
H. B. H.	N.	22	Br.	1.23	902	831	710	630	509	407	277	182.0	98.9	52.0	25.3	10.4	......	......	......	......	.558
E. F. M.	B. S.	33	Br.	1.25	885	793	709	624	519	402	270	168.0	89.7	46.6	21.2	9.74	4.38	1.59	.543	.386	.556
H. A. B.	Sub. B.	25	Bl.	1.13	918	842	729	648	510	385	265	170.0	90.9	44.1	21.4	8.92	3.75	1.69	.694	.323	.560
D. H. S.	Sub. R.	26	Br.	1.08	873	769	692	560	454	312	217	130.0	76.8	35.7	16.3	......	......	......	......	......	.552
W. C. B.	W.	33	Bl.	1.23	894	816	757	657	551	411	296	186.0	110.0	51.5	23.6	10.2	......	......	......	......	.556
R. C. S.	B. S.	29	Br.	1.10	889	797	691	554	489	353	222	140.0	78.2	39.4	21.3	......	......	......	......	......	.555
M. H. S.	B. S.	30	Gr.	1.08	890	800	706	592	490	381	271	167.0	94.8	46.6	21.3	9.06	......	......	......	......	.554
G. W. M.	Sub. B.	46	Gr.	1.20	889	840	739	663	542	411	302	205.0	109.0	59.0	25.7	10.7	......	......	......	......	.558
A. L. T.	G. S.	26	Bl.	1.03	848	739	660	534	449	328	236	140.0	82.2	40.8	19.6	......	......	......	......	......	.553
A. F. P.	Sub. B.	43	......	1.12	900	815	736	598	509	366	255	159.0	86.7	41.5	20.0	8.06	3.48	1.39	.529	......	.559

TABLE 1—Continued

Visibility of Normal Subjects—Blue End of Spectrum

Subject	Visibility	Age	Eye color	Factor	λ= 0.427	λ= 0.435	λ= 0.444	λ= 0.450	λ= 0.456	λ= 0.463	λ= 0.474	λ= 0.485	λ= 0.493	λ= 0.502	λ= 0.5125	λ= 0.523	λ= 0.534	λ= 0.546	λ= 0.552	λ= 0.559	λ= 0.573
F. B. S.	Sub. B.	26	Br.	1.09	......	......	23.3	26.6	32.2	42.9	71.6	115.0	163	290	485	736	887	1005	990	996	921
J. L.	G. S.	37	Gr.	1.06	......	......	22.1	26.6	29.8	40.5	65.7	104.0	150	296	432	681	876	963	968	1000	939
M. P. S.	N.	36	Gr.	1.13	......	......	......	......	......	......	......	164.0	243	352	520	736	890	990	1011	951	942
J. A. S.	Sub. B.	45	Gr.	1.17	......	......	23.7	28.4	30.9	41.3	68.1	98.6	160	298	512	759	917	1000	1000	982	947
H. K. G.	N.	30	r.	1.17	......	......	......	......	......	......	......	......	200	348	564	771	905	990	1000	981	920
W. S. S.	R. S.	29	......	1.17	......	......	......	......	......	......	......	......	181	304	510	758	928	984	962	1000	924
P. G. A.	W.	35	......	1.23	35.4	47.5	63.2	76.4	90.5	127.0	177.0	257.0	325	464	626	786	899	945	992	1000	971
H. I. S.	N.	25	......	1.10	......	31.6	40.4	45.7	56.8	76.3	120.0	165.0	231	361	516	750	853	944	944	1000	953
E. L. P.	R. S.	33	......	1.24	......	34.2	43.0	52.6	68.6	73.1	98.2	168.0	244	389	544	696	873	952	966	1000	979
L. W. S.	Sub. B.	26	Br.	1.19	......	......	32.2	33.4	37.5	49.5	76.0	116.0	180	358	530	760	924	982	1020	968	939
J. H. D.	Sub. R.	29	Bl.	1.05	......	29.0	35.3	41.0	52.2	65.2	114.0	152.0	215	347	548	781	909	934	985	1015	920
R. L. S.	R. S.	31	......	1.25	......	......	37.8	38.6	45.3	75.5	121.0	160.0	250	362	580	705	886	971	991	1000	948
C. W. B.	B. S.	42	......	1.17	......	......	......	......	......	......	......	198.0	285	431	612	815	940	999	1000	967	924
D. R. M.	R. S.	33	......	1.25	......	......	......	......	......	......	......	......	265	369	576	772	889	970	980	1000	936
G. W. V.	B. S.	33	Br.	1.24	......	......	......	......	......	......	......	......	251	406	596	801	926	994	987	994	943
G. E. P.	G. S.	36	......	1.15	......	......	......	......	......	......	......	......	150	323	486	746	928	985	982	1016	953
O. L. S.	G. S.	32	Gr.	1.26	......	......	18.4	24.1	28.5	37.5	66.4	101.0	166	270	498	720	874	950	1000	989	955
M. J.	R. S.	24	Br.	1.41	......	......	......	......	......	......	......	......	182	307	521	706	870	911	970	989	950
J. F. M.	G. S.	40	Br.	1.15	......	......	......	......	......	......	......	......	193	319	546	774	915	973	1000	992	904
P. D. L.	B. S.	23	Br.	1.20	......	34.6	......	58.8	80.2	115.0	153.0	240.0	317	452	602	770	902	988	1024	966	918
R. Y. F.	N.	40	Bl.	1.14	......	25.2	32.3	34.7	50.6	54.4	97.3	152.0	219	359	584	784	895	981	1000	974	923
W. A. C.	R. S.	21	Br.	1.44	......	......	......	......	......	......	......	......	276	400	562	744	861	939	958	981	1000
F. J. B.	N.	39	......	1.35	......	......	......	......	......	......	......	......	......	308	514	765	914	994	1000	993	960
P. J. H.	B. S.	22	Gr.	1.30	......	......	......	......	......	......	......	227.0	......	455	n 581	......	844	953	1000	995	871
T. R. H.	R. S.	25	Br.	1.30	......	......	......	......	......	......	......	......	181	316	500	735	868	954	978	1020	988
H. A. E.	N.	24	Br.	1.16	......	......	......	......	......	......	......	......	180	329	501	734	913	984	1014	976	915
E. C. P.	Sub. B.	22	Br.	1.24	......	......	......	......	......	......	......	......	153	264	439	759	881	968	1000	991	958
C. H. M.	B. S.	23	......	1.36	......	......	......	......	......	......	......	......	270	420	615	779	939	974	1007	974	861

Visibility of Normal Subjects—Red End of Spectrum

Subject	Visibility	Age	Eye color	Factor	λ= 0.580	λ= 0.5876	λ= 0.5964	λ= 0.604	λ= 0.613	λ= 0.623	λ= 0.633	λ= 0.643	λ= 0.654	λ= 0.665	λ= 0.678	λ= 0.690	λ= 0.703	λ= 0.717	λ= 0.730	λ= 0.746	λ= max
F. B. S.	Sub. B.	26	Br.	1.09	905	807	752	667	540	432	308	195.0	103.0	51.4	23.2	9.84	4.18	1.53	0.596	0.280	0.557
J. L.	G. S.	37	Gr.	1.06	875	792	707	560	462	337	224	150.0	82.4	42.6	19.5	9.32	3.66	1.41	.617	.325	.558
M. P. S.	N.	36	Gr.	1.13	868	825	731	624	506	375	247	158.0	88.2	43.0	19.1	......	......	......	......	......	.557
J. A. S.	Sub. B.	45	Gr.	1.17	913	826	737	609	521	394	270	175.0	95.3	48.0	22.3	10.1	4.17	1.48	.690	.331	.558
H. K. G.	N.	30	Gr.	1.17	879	818	723	630	522	394	285	178.0	102.0	47.7	22.6	......	......	......	......	......	.557
W. S. S.	R. S.	29	......	1.17	882	848	764	678	559	415	304	186.0	106.0	54.3	24.4	......	......	......	......	......	.560
P. G. A.	W.	35	......	1.23	946	872	779	705	572	416	290	185.0	102.0	50.0	22.8	9.26	4.42	1.62	.675	.364	.561
H. I. S.	N.	25	......	1.10	875	818	737	629	519	400	279	178.0	96.9	51.8	22.8	9.57	4.26	1.66	.668	.365	.559
E. L. P.	R. S.	33	......	1.24	971	904	816	738	576	446	327	210.0	110.0	56.9	25.7	10.1	4.82	1.67	.675	.320	.565
L. W. S.	Sub. B.	26	Br.	1.19	879	835	740	620	503	385	264	162.0	92.1	44.5	20.6	7.98	3.69	1.46	.574	.303	.557
J. H. D.	Sub. R.	29	Bl.	1.05	872	774	664	558	396	305	193	121.0	65.4	34.0	15.0	5.73	2.68	.970	.429	.224	.556
R. L. S.	R. S.	31	......	1.25	937	891	803	682	578	452	316	202.0	109.0	54.7	27.0	10.6	5.30	1.95	.766	.383	.562
C. W. B.	B. S.	42	......	1.17	857	769	675	592	448	345	228	142.0	83.2	38.6	17.3	......	......	......	......	......	.553
D. R. M.	R. S.	33	......	1.25	921	850	751	681	563	438	310	200.0	116.0	56.5	26.5	9.85	......	......	......	......	.559
G. W. V.	B. S.	33	Br.	1.24	860	776	688	599	449	355	236	142.0	85.9	42.8	19.3	......	......	......	......	......	.554
G. E. P.	G. S.	36	......	1.15	867	803	723	596	......	366	......	153.0	......	41.9	20.7	......	......	......	......	......	.556
O. L. S.	G. S.	32	Gr.	1 26	878	788	698	598	475	364	261	154.0	89.3	44.3	19.3	9.14	3.85	1.37	.518	.249	.554
M. J.	R. S.	24	Br.	1.41	967	867	796	707	618	477	371	217.0	136.0	65.8	29.8	12.6	......	......	......	......	.568
J. F. M.	G. S.	40	Br.	1.15	867	773	660	589	492	362	257	161.0	96.5	48.6	21.5	......	......	......	......	......	.554
P. D. L.	B. S.	23	Br.	1.20	884	808	689	600	476	351	237	147.0	84.4	41.5	17.7	7.85	3.21	1.16	.470	......	.557
R. Y. F.	N.	40	Bl.	1.14	858	790	720	621	513	375	261	171.0	93.9	45.1	21.1	9.11	4.07	1.62	.526	.251	.555
W. A. C.	R. S.	21	Br.	1.44	975	920	860	754	656	499	373	214.0	121.0	64.2	29.1	11.8	......	......	......	......	.559
F. J. B.	N.	39	......	1.35	894	832	750	612	515	371	251	157.0	86.8	44.2	18.6	......	......	......	......	......	.559
P. J. H.	B. S.	22	Gr.	1.30	832	757	613	538	430	327	232	147.0	80.1	40.0	20.6	......	......	......	......	......	.555
T. R. H.	R. S.	25	Br.	1.30	959	928	854	743	625	470	337	224.0	125.0	62.0	27.7	12.6	......	......	......	......	.566
H. A. E.	N.	24	Br.	1.16	898	814	748	605	498	394	250	162.0	89.1	42.7	17.2	......	......	......	......	......	.557
E. C. P.	Sub. B.	22	Br.	1.24	884	813	726	632	515	401	274	172.0	102.0	51.2	24.6	10.4	......	......	......	......	.557
C. H. M.	B. S.	23	......	1.36	809	727	647	535	444	321	213	132.0	74.5	35.7	16.5	......	......	......	......	......	.551

TABLE 1—Continued

Visibility of Normal Subjects—Blue End of Spectrum

Subject	Visibility[a]	Age.	Eye color[b]	Factor	λ= 0.427	λ= 0.435	λ= 0.444	λ= 0.450	λ= 0.456	λ= 0.463	λ= 0.474	λ= 0.485	λ= 0.493	λ= 0.502	λ= 0.5125	λ= 0.523	λ= 0.534	λ= 0.546	λ= 0.552	λ= 0.559	λ= 0.573
C. E. B.	N.	22	Br.	1.44	......	......	......	......	......	......	......	......	262	390	564	770	904	960	1015	994	955
C. A. B.	B. S.	33	Bl.	1.50	......	......	......	......	......	......	......	......	326	472	634	849	914	991	1000	994	943
W. S. L.	R. S.	32	Bl.	1.39	......	......	......	......	......	......	......	......	210	381	531	744	893	960	992	1000	982
T. B. F.	R. S.	34	Br.	1.42	......	......	......	......	......	......	......	......	......	268	462	681	822	953	945	1000	986
D. R. H.	R. S.	31	Bl.	1.39	......	35.2	43.4	48.9	62.2	73.6	......	173.0	251	362	567	752	905	965	980	1022	951
P. D. S.	R. S.	24	Gr.	1.43	......	......	......	......	......	......	......	......	267	383	583	732	844	920	957	1000	942
A. N. F.	R. S.	34	Br.	1.30	......	......	......	......	......	......	......	......	......	318	539	708	876	966	988	972	986
G. T. M.	R. S.[p]	26	Bl.	1.43	......	......	......	......	......	......	......	......	......	273	447	672	822	914	941	989	984
H. S.	N.	22	Bl.	1.34	......	......	......	......	......	......	......	......	242	318	502	782	906	971	1020	1018	950
H. B. K.	B. S.	28	Bl.	1.17	......	......	......	......	......	......	......	......	248	390	599	771	926	992	1000	983	914
S. I.	N.	26	Bl.	1.21	......	......	38.9	42.5	53.5	78.6	108.0	169.0	256	370	574	801	942	1000	1000	984	956
J. L. F.	Sub. R.	25	Bl.	1.29	......	35.4	41.6	45.6	61.4	76.0	115.0	173.0	258	386	568	760	882	959	981	1012	968
A. B. L.	N.	26	Bl.	1.34	......	......	32.9	38.0	46.5	61.2	93.3	136.0	194	338	528	778	902	941	986	1000	898
O. S. P.	W.	32	Gr.	1.47	......	......	......	......	......	......	......	......	283	414	609	770	903	968	976	1000	986
W. H. Sm.	B. S.	29	Br.	1.35	......	......	......	......	......	......	......	......	264	404	630	863	950	986	1000	976	886
L. A. G.	Sub. R.	29	Br.	1.35	......	......	......	......	......	......	......	......	207	354	562	746	892	982	957	994	880
A. B.	Sub. R.	23	Br.	1.33	......	......	......	......	......	......	......	......	213	351	531	736	873	976	1009	948	892
G. C. H.	Sub. R.	26	Bl.	1.46	......	......	......	......	......	......	......	......	189	340	533	782	911	967	988	1000	918
T. R. E.[q]	Sub. R.	23	Bl.	1.45	......	......	......	......	......	......	......	......	226	339	553	789	900	941	994	1000	928
A. J. H.[r]	Sub. R.	23	Bl.	1.44	......	......	......	......	......	......	......	......	......	370	578	796	930	1010	985	970	905
H. M. R.[f]	B. S.	25	......	......	......	......	......	......	......	......	......	......	309	447	660	825	921	991	1000	989	895
B. C. C.	N.	23	Br.	1.28	......	......	......	......	......	......	......	......	229	358	581	784	885	962	986	1000	952
G. K. B.	Sub. B.	42	Bl.	1.28	......	......	......	......	......	......	......	......	......	249	463	718	881	964	986	1000	953
P. H.	Sub. R.	24	Br.	1.24	......	......	......	......	......	......	......	......	240	405	587	800	896	993	976	1008	934
H. S. P.	B. S.	33	Br.	1.33	......	......	......	......	......	......	......	184.0	254	416	618	840	980	1000	973	950	871
H. H. B.	Sub. R.	30	Br.	1.16	......	......	......	......	......	......	......	......	198	341	592	773	911	986	1013	973	835
H. A. B.	G. S.	26	Bl. Gr.	1.47	......	......	......	......	......	......	......	......	189	333	536	743	906	994	991	991	924
R. D.	R. S.	28	Bl.	1.67	......	......	......	......	......	......	......	......	......	279	503	724	921	961	978	1000	983

Visibility of Normal Subjects—Red End of Spectrum

Subject	Visibility	Age	Eye color	Factor	λ= 0.580	λ= 0.5876	λ= 0.5964	λ= 0.604	λ= 0.613	λ= 0.623	λ= 0.633	λ= 0.643	λ= 0.654	λ= 0.665	λ= 0.678	λ= 0.690	λ= 0.703	λ= 0.717	λ= 0.730	λ= 0.746	λ max
C. E. B.	N.	22	Br.	1.44	888	806	755	649	532	401	292	186.0	110.0	54.8	25.6	......	......	......	......	......	0.556
C. A. B.	B. S.	33	Bl.	1.50	871	779	701	581	482	368	252	153.0	85.1	44.8	18.3	......	......	......	......	......	.555
W. S. L.	R. S.	32	Bl.	1.39	936	870	785	697	......	432	......	204.0	......	60.7	26.1	......	......	......	......	......	.560
T. B. F.	R. S.	34	Br.	1.42	959	908	804	724	635	493	350	214.0	125.0	61.4	26.4	9.26	......	......	......	......	.565
D. R. H.	R. S.	31	Bl.	1.39	936	856	763	687	589	446	311	195.0	120.0	61.2	30.5	12.8	5.10	2.03	0.804	......	.559
P. D. S.	R. S.	24	Gr.	1.43	966	897	802	719	599	461	320	195.0	116.0	55.4	24.5	10.4	......	......	......	......	.565
A. N. F.	R. S.	34	Br.	1.30	957	946	869	770	642	466	332	194.0	107.0	53.0	24.4	......	......	......	......	......	.566
G. T. M.	R. S.[p]	26	Bl.	1.43	978	927	884	787	661	520	381	250.0	151.0	70.0	35.0	14.3	......	......	......	......	.570
H. S.	N.	22	Bl.	1.34	920	840	744	673	568	407	281	185.0	104.0	53.0	23.9	......	......	......	......	......	.558
H. B. K.	B. S.	28	Bl.	1.17	880	805	711	593	463	340	226	143.0	79.0	38.4	16.6	......	......	......	......	......	.556
S. I.	N.	26	Bl.	1.21	897	818	698	620	531	362	254	159.0	89.1	45.3	18.6	8.04	3.90	1.54	.584	......	.554
J. L. F.	Sub. R.	25	Bl.	1.29	884	792	689	590	488	341	249	141.0	82.7	42.1	18.3	7.19	3.23	1.19	.485	......	.559
A. B. L.	N.	26	Bl.	1.34	880	806	731	593	508	384	269	170.0	90.9	48.4	22.5	8.90	4.20	1.72	.658	0.355	.559
O. S. P.	W.	32	Gr.	1.47	954	872	799	722	596	474	333	201.0	119.0	58.8	27.6	......	......	......	......	......	.563
W. H. Sm.	B. S.	29	Br.	1.35	836	756	664	545	404	314	198	129.0	76.8	36.0	18.2	......	......	......	......	......	.549
L. A. G.	Sub. R.	29	Br.	1.35	865	760	674	582	484	346	253	164.0	96.2	46.1	19.9	......	......	......	......	......	.558
A. B.	Sub. R.	23	Br.	1.33	888	786	697	563	454	359	246	158.0	86.6	43.2	18.1	9.35	......	......	......	......	.558
G. C. H.	Sub. R.	26	Bl.	1.46	851	768	688	604	485	373	264	168.0	91.2	48.6	22.8	......	......	......	......	......	.557
T. R. E.[q]	Sub. R.	23	Bl.	1.45	945	788	719	604	496	372	240	160.0	88.6	45.6	19.5	......	......	......	......	......	.557
A. J. H.[r]	Sub. R.	23	Bl.	1.44	838	780	689	582	479	366	262	165.0	100.0	48.5	22.1	......	......	......	......	......	.550
H. M. R.[f]	B. S.	25	......	......	832	774	694	567	......	355	......	161.0	......	46.1	......	......	......	......	......	......	.551
B. C. C.	N.	23	Br.	1.28	891	815	748	652	521	388	275	173.0	97.2	46.8	22.0	......	......	......	......	......	.559
G. K. B.	Sub. B.	42	Bl.	1.28	879	804	731	631	......	385	......	178.0	......	52.7	......	......	......	......	......	......	.557
P. H.	Sub. R.	24	Br.	1.24	852	764	653	527	389	281	187	112.0	59.9	30.3	13.3	......	......	......	......	......	.556
H. S. P.	B. S.	33	Br.	1.33	820	734	638	546	411	311	204	120.0	69.2	32.8	15.6	......	......	......	......	......	.549
H. H. B.	Sub. R.	30	Br.	1.16	734	658	558	436	......	237	......	94.6	53.3	26.4	12.9	......	......	......	......	......	.550
H. A. B.	G. S.	26	Bl. Gr.	1.47	874	771	689	567	451	345	236	144.0	79.3	41.5	18.6	......	......	......	......	......	.555
R. D.	R. S.	28	Bl.	1.67	953	876	799	716	......	486	......	226.0	......	65.2	31.1	......	......	......	......	......	.562

TABLE 1—Continued

Visibility of Normal Subjects—Blue End of Spectrum

Subject	Visibility	Age	Eye color	Factor	λ= 0.427	λ= 0.435	λ= 0.444	λ= 0.450	λ= 0.456	λ= 0.463	λ= 0.474	λ= 0.485	λ= 0.493	λ= 0.502	λ= 0.5125	λ= 0.523	λ= 0.534	λ= 0.546	λ= 0.552	λ= 0.559	λ= 0.573
E. S. P.	R. S.p	24	Br.	1.65	......	......	......	......	......	......	......	......	......	306	502	662	813	920	949	975	1003
W. H. St.	N.	26	Gr.	1.52	......	......	......	......	......	......	......	......	......	330	553	726	910	1003	986	990	974
M. D. S.	N.	21	Br.	1.37	......	......	......	......	......	......	......	......	......	290	520	780	911	992	1010	963	969
E. B.	G. S.	49	Bl. Gr.	1.49	......	......	......	......	......	......	......	......	......	259	490	716	890	972	984	1010	958
J. L. B.	W.	26	Br.	1.54	......	......	......	......	......	......	......	......	373	475	614	730	878	976	990	984	966
J. B.	B. S.	20	Br.	1.38	......	......	......	......	......	......	......	......	302	446	607	769	900	1004	1000	973	910
E. E. W.	B. S.	27	Br.	1.42	37.4	49.5	66.0	76.7	89.5	119.0	182.0	244.0	339	482	648	845	970	1000	976	990	922
C. P. K.	Sub. B.	58	Br.	1.48	......	......	......	......	......	......	......	......	......	259	549	734	894	949	......	996	974
M. S.	N.	28	Br.	1.45	......	......	......	......	......	......	......	......	233	375	577	766	920	956	961	1000	940
J. C. P.	Sub. R.	37	......	1.37	......	......	......	......	......	......	......	......	212	352	581	782	900	981	1010	985	878
P. D. M.	R. S.	27	Bl.	1.71	......	......	......	......	......	......	......	......	......	305	522	729	896	969	986	1012	948
H. D. H.	N.	45	Bl.	1.72	......	......	......	......	......	......	......	......	227	349	551	762	871	972	988	1000	928
P. W. M.	B. S.	29	Bl.	1.30	......	......	......	......	......	......	......	......	242	387	604	804	956	977	1000	984	883
N. S. O.	N.	41	Gr.	1.48	......	......	......	......	......	......	......	......	......	353	517	723	883	935	974	1000	938
A. D. C.	N.	29	Gr.	1.57	......	......	......	......	......	......	......	......	......	339	526	735	918	1000	998	987	943
Mean uncorrected value					28.0	33.6	36.6	39.8	48.9	63.1	98.7	157.0	225	351	548	758	897	973	989	992	944
Mean value (λ_{max} = 1000)					28.2	33.9	36.9	40.1	49.3	63.6	99.5	158.0	227	354	552	764	904	981	997	1000	952
Corrected for slit width					28.0	33.7	36.7	39.7	48.6	62.8	98.1	155.0	221	346	548	765	904	981	997	1000	954
Final value (corrected for 0° Nicol and for scattered light)					28.4	34.1	37.2	40.1	49.1	63.4	98.8	155.0	223	350	553	771	908	983	998	1000	952

Visibility of Normal Subjects—Red End of Spectrum

Subject	Visibility	Age	Eye color	Factor	λ= 0.580	λ= 0.5876	λ= 0.5964	λ= 0.604	λ= 0.613	λ= 0.623	λ= 0.633	λ= 0.643	λ= 0.654	λ= 0.665	λ= 0.678	λ= 0.690	λ= 0.703	λ= 0.717	λ= 0.730	λ= 0.746	λ max
E. S. P.	R. S.p	24	Br.	1.65	956	939	898	797	709	546	379	265.0	153.0	82.2	36.7	......	......	......	......	......	0.570
W. H. St.	N.	26	Gr.	1.52	903	827	727	644	514	406	272	166.0	95.9	46.2	22.5	......	......	......	......	......	.557
M. D. S.	N.	21	Br.	1.37	899	831	757	684	556	393	279	171.0	89.0	47.3	23.4	......	......	......	......	......	.555
E. B.	G. S.	49	Bl. Gr.	1.49	873	810	706	616	508	362	251	149.0	86.2	41.3	26.6	......	......	......	......	......	.558
J. L. B.	W.	26	Br.	1.54	902	840	771	663	581	447	318	197.0	109.0	56.5	28.2	13.0	......	......	......	......	.560
J. B.	B. S.	20	Br.	1.38	866	776	......	596	......	381	......	159.0	99.0	47.8	24.1	......	......	......	......	......	.551
E. E. W.	B. S.	27	Br.	1.42	862	796	706	597	477	357	251	153.0	89.0	43.3	20.6	8.96	3.84	1.48	0.614	0.283	.551
C. P. K.	Sub. B.	58	Br.	1.48	910	817	747	628	512	420	281	185.0	89.0	52.5	22.6	11.0	......	......	......	......	.559
M. S.	N.	28	Br.	1.45	880	790	703	606	493	381	280	165.0	97.6	50.0	23.6	......	......	......	......	......	.557
J. C. P.	Sub. R.	37	....	1.37	796	748	658	575	473	371	269	166.0	97.2	47.3	23.2	......	......	......	......	......	.552
P. D. M.	R. S.	27	Bl.	1.71	895	878	801	725	550	430	299	192.0	108.0	57.1	24.7	......	......	......	......	......	.560
H. D. H.	N.	45	Bl.	1.72	874	835	746	637	......	416	......	195.0	......	56.0	26.0	......	......	......	......	......	.558
P. W. M.	B. S.	29	Bl.	1.30	811	728	648	527	366	296	200	128.0	63.8	32.9	14.2	......	......	......	......	......	.552
N. S. O.	N.	41	Gr.	1.48	861	808	738	637	557	425	327	197.0	117.0	55.7	25.6	......	......	......	......	......	.559
A. D. C.	N.	29	Gr.	1.57	913	833	738	652	......	381	......	180.0	......	61.9	......	......	......	......	......	......	.554
Mean uncorrected value					893_4	818	731	632	516	391	272	172.0	96.1_4	48.3	22.1	9.77	3.97	1.49	.591	.288	.5576
Mean value (λ_{max} =1000)					900	825	737	637	520	394	274	173.0	96.9	48.7	22.3	9.85	4.00	1.50	.596	.290	......
Corrected for slit width					901	825	736	637	518	390	266	164.0	95.6	47.7	21.7	9.55	3.86	1.43	.589	.286	......
Final value (corrected for 0° Nicol and for scattered light)					899	823	734	636	517	390	267	165.0	94.5	45.9	20.2	8.56	3.36	1.21	.485	.230	.5576

[a] Classification of curves: N., average; W., wide; R. S., red sensitive; B. S., blue sensitive; G. S., green sensitive; Sub. R., subnormal red; Sub. B., subnormal blue [b] Bl., blue; Gr., gray; L. Bl., light blue; Br., brown; Bl. Gr., blue-gray. [c] Mean of 3 sets. [d] λ=0.422, V=18.7; λ=0.417, V=16.7; λ=0.412, V=13.6; λ=0.406, V=9.18; λ=0.401, V=8.34. [e] λ=0.566, V=997. [f] Mean of 2 sets. [g] λ=0.422, V=20.2. [h] λ=0.498, V=242. [i] λ=0.498, V=166. [j] λ=0.566, V=978. [k] λ=0.728, V=1.08. [l] λ=0.765, V=0.120. [m] λ=0.765, V=0.110. [n] λ=0.528, V=761. [o] λ=0.477, V=141. [p] Also color blind. [q] Close to normal. [r] Subnormal in yellow.

1. TOTAL COLOR BLINDNESS

The investigation of subjects who are entirely lacking in color sensation is of interest in connection with the various theories of color vision. At low illumination only the rods are considered to respond to light and no color is perceived. The maximum sensibility of the fovea of the normal eye lies between 0.49 μ and 0.53 μ for low illuminations.

In the case of total color blindness the maximum visibility is in the region of 0.52 μ, as shown in Fig. 4 (data from Bender [26]).

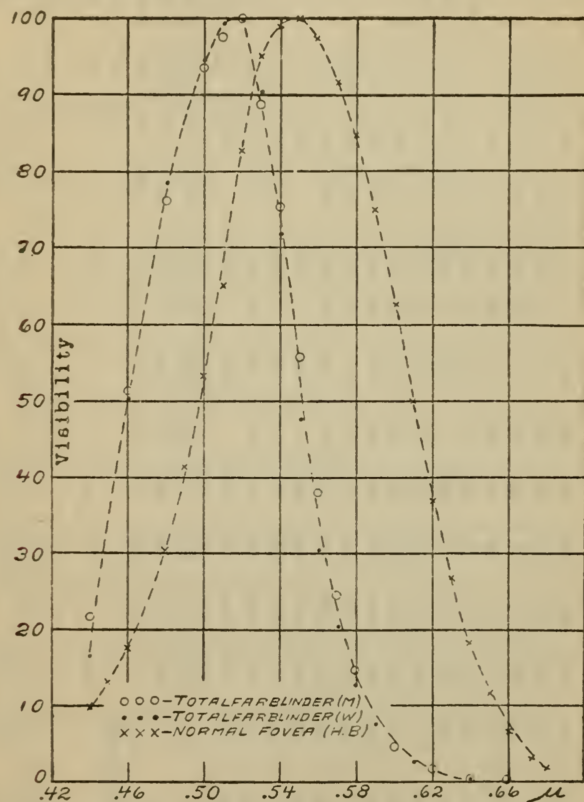

FIG. 4.—*Relative sensibility of the eye to different wave lengths in the case of total color blindness (data from Bender)*

From this it would appear that the color perception, in the case of so-called total color blindness, is similar to that of normal foveal color vision under very low illumination, and to that of rod vision (i. e., peripheral vision) under high illumination. As shown by Bender,[26] the curve for the peripheral retina (normal rod vision) coincides with that of the foveal visibility curve of totally color-blind subjects. This phenomena is of rare occurrence, and hence it is difficult to find subjects for investigation.

2. PARTIAL COLOR BLINDNESS [a]

This phenomenon is of frequent occurrence. Ferry [11] found eight cases in a group of 200 students, which is close to the average (3.95 per cent among males) found by Dr. Jeffries [43] in a group of 175,000. Among women color blindness is only about one-tenth as frequent as among men. It is well known that a partially color-blind person is not only greatly lacking in one of the fundamental color sensations, but also that he perceives other colors quite differently from the "normal."

Ferry [11] gives the results of an examination of eight color-blind persons. One was a case of inherited red blindness. The visibility of this red-blind subject was very much depressed in the red as compared with that of normal color vision. The other seven persons were green blind. In all cases their persistence of vision (visibility) curves were normal except in the green, where there was a marked depression. These cases are somewhat different from the observations of de Lepinay and Nicati,[5] whose results for dichroic vision indicate that in red blindness the visibility curve is abnormally high in the green and that in green blindness the sensibility is abnormally high in the red (but normal in the blue and, of course, below normal in the green), which agrees with the observations recorded in the present paper.

Allen [12] has described the curve of a green-blind subject in which the visibility was normal for all parts of the spectrum except in the green, also a red-blind subject in which the visibility curve was depressed below the normal only in the red. Another red-blind subject showed depressions in both the red and the green.

Of the persons showing very marked red-green color blindness by the Holmgren yarn test, examined by Tufts,[22] three had the point of maximum visibility displaced toward the green and the other three had the maximum shifted toward the red. As in the present investigation, he had another subject whose visibility curve was similarly shifted toward the red, although the observer showed no trace of color blindness by the ordinary Holmgren test.

In persons exhibiting color blindness the most common phase is a low visibility in the green, producing quite an indentation, as shown in Fig. 5. However, persons having normal vision may

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[a] The writers adhere to the older nomenclature, in which the term "color blindness" was applied to cases of color confusion by the Holmgren tests. It is beyond the scope of the present paper to attempt a discussion of the newer ideas concerning color vision, in view of the fact that it deals with monochromatic brightness sensation in different parts of the spectrum and does not attempt to analyze the results obtained when applying a heterochromatic stimulus.

have a temporary depression of the visibility in this region of the spectrum, as was found (W. W. C.) in the preliminary part of the present investigation.

Of the subjects examined who exhibit green color blindness, two (A. F. and J. F. S.) confused reds and greens in making the Nagel color test. Another subject (A. A. L.), an instrument maker, can not distinguish brass from copper. An unusual case

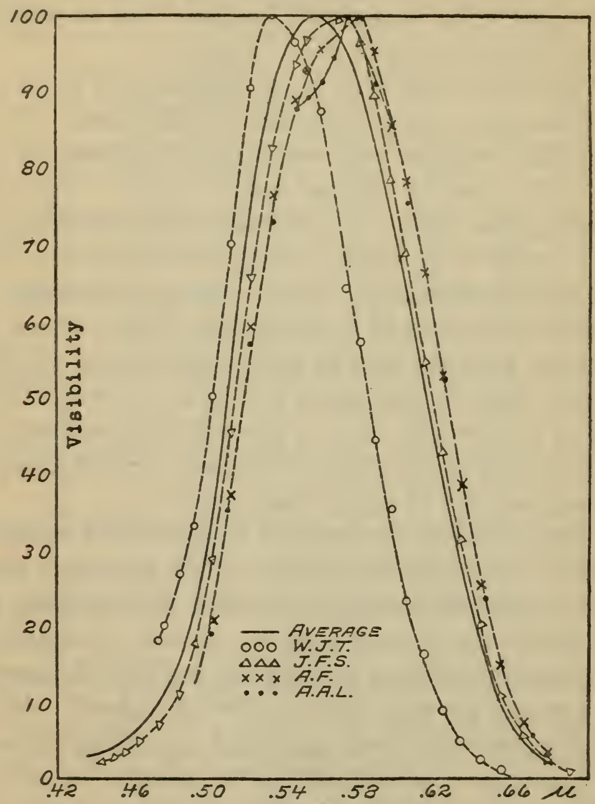

FIG. 5.—*Spectral sensibility curves of eyes affected by partial color blindness*

(W. J. T.) of red blindness was found. The subject is engaged in agricultural pursuits and can not distinguish red apples or red roses from the green leaves except by their shape. His visibility curve (Fig. 5) is unusually low in the red and high in the blue. A somewhat similar curve is shown in Fig. 7 (H. B. S.), but in this case the subject did not confuse colors when tested with the Nagel and the Stilling color cards.

The results of the present investigation are in agreement with those of Ferry [11] and Tufts [22] and others, showing that the effect of light upon the color sense is quite independent of its effect upon the brightness sense.[a] An abnormal color sense is associated with an abnormal (brightness sensibility) visibility curve; but the converse is not true, as is shown by the examples of abnormal visi-

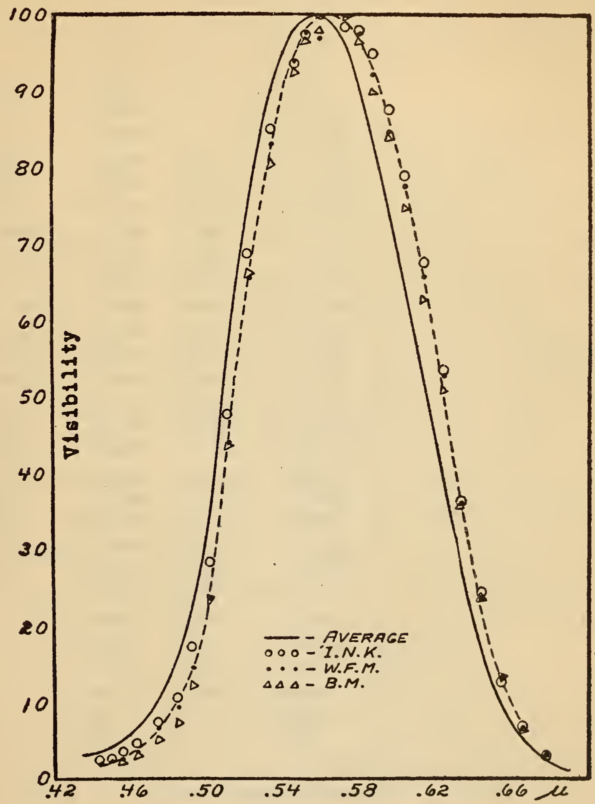

Fig. 6.—*Visibility curves of observers who are red-sensitive but not color blind*

bility curves (Fig. 6) of persons having normal judgments in sorting and matching colors. The data of all but two of the group of observers who were known to be color blind are given in Table 2. If all the observers had been tested, no doubt others would have been found who confused colors.

[a] See Appendix 4. "On color perception versus brightness perception."

59467°—18——3

TABLE 2

Visibility of Color-Blind Subjects

Wave length μ	J. F. S. Eye, blue factor, 120 $\lambda_m=0.568$	A. F. Eye, blue factor, 1.26 $\lambda_m=0.578$	C. W. K. Eye, brown factor, 1.67 $\lambda_m=0.567$	W. J. T. Eye, blue factor, 1.01 $\lambda_m=0.539$	A. A. L. Eye, brown factor, 1.75 $\lambda_m=0.573$
0.444	22.5	....	43.8	....	....
0.450	29.0	....	50.0	....	....
0.456	35.6	....	60.6	....	....
0.463	50.4	....	80.1	....	....
0.474	71.4	....	123.0	182.0	....
0.485	108.0	....	180.0	[a] 270.0	....
0.493	180.0	....	273.0	337.0	....
0.502	300.0	210.0	403.0	502.0	208.0
0.5125	468.0	375.0	560.0	701.0	375.0
0.523	669.0	591.0	750.0	907.0	571.0
0.534	817.0	766.0	862.0	1003.0	730.0
0.546	918.0	889.0	928.0	967.0	880.0
0.552	947.0	928.0	945.0	926.0	892.0
0.559	943.0	957.0	998.0	874.0	916.0
0.566	1000.0	....	1000.0	....	1000.0
0.573	989.0	990.0	1025.0	633.0	1000.0
0.580	957.0	1000.0	963.0	566.0	962.0
0.5876	891.0	952.0	886.0	443.0	910.0
0.596_4	799.0	858.0	863.0	354.0	858.0
0.604	725.0	783.0	758.0	236.0	759.0
0.613	588.0	664.0	632.0	165.0	....
0.623	483.0	530.0	483.0	90.6	526.0
0.633	325.0	390.0	338.0	50.6	....
0.643_2	196.0	254.0	219.0	23.7	256.0
0.654	118.0	150.0	121.0	11.7	....
0.665	56.4	73.6	61.6	....	73.4
0.678	23.6	35.0	27.3	....	32.2
0.690	8.88	15.1	11.0	....	15.4
0.703	3.83	....	4.71	....	....
0.717	1.60	....	1.93	....	....
0.730	.919	....	.830	....	....
0.746	.290	....	.458	....	....

[a] $\lambda=0.477\mu$; V=202.

3. RED SENSITIVENESS

It was noticed early in the investigation that out of two dozen subjects one-fourth were abnormally sensitive in the red, as illustrated in Fig. 6. If the investigation had been terminated at that time, the shape of the visibility curve of the average normal eye and the position of its maximum would have been considerably different from the curve resulting from averaging the data of all the subjects investigated.

Of the 10 subjects examined by Bender [26] the average visibility curves of three observers is separated by a wide gap from the others in the red part of the spectrum and the maximum visibility is located at 0.55 μ, while the maximum visibility of the others is located at 0.535 μ. Of these three red sensitives two were women, while the remaining two women of the group of 10 subjects were abnormally sensitive in the blue-violet. From this it would appear that while color blindness may be far less frequent among women than among men their visibility curves are probably subject to as great variation as is to be found among men. Houstoun[17] likewise found no systematic deviation of the observations of nine women as compared with the men.

Of the 26 red-sensitive subjects found in the present investigation (some of which may have been color blind), the visibility curve of W. F. M. is of special interest in view of the fact that two series of observations were made on a Saturday and the following Monday. The intervening day of rest and recreation had no effect upon the curve, the observations coinciding exactly throughout the whole spectrum. Even the observation of the sharp maximum at 0.573 μ was repeated. Another peculiarity exhibited by this observer was the very low speed required in order to cause disappearance of flicker. The speed was only about 3 cycles per second, which shows an unusually long persistence of the visual impression. Apparently the speeds for disappearance of color flicker and brightness flicker are closely the same in this subject, who does not appear to confuse colors.[a] Tufts[22] had two observers who were abnormally sensitive in the red, and they showed a slight tendency to confuse oranges and yellow greens.

As shown in the composite curve of the 125 observers, Fig. 13, the distinct grouping of red sensitives, which is conspicuous in the composite curve (of only 10 observers) published by Bender,[26] is obliterated by a general gradation in the shift of the various red-sensitive curves from the normal to the extreme red.

4. BLUE SENSITIVENESS

Persons who are markedly sensitive in the blue are not found quite so frequently as are the red sensitives just described. A very marked example is given by Nutting,[27] also one by Bender,[26] in which the maximum visibility is greatly shifted toward the violet, and in which the whole visibility curve is shifted as compared with the average normal curve.

As was to be expected, a close parallelism was found between the observations of Crittenden and Richtmyer[29] and the results

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[a] See Appendix 4 for further tests on this subject.

of the present investigation. In their test of the transmission of yellow and blue solutions (or glasses) they found one observer (H. B. S.) whose data indicated an apparently high sensibility in the blue or low sensibility in the red as compared with the group of normals. As shown in Fig. 7, the peculiarity of the vision of this subject is in its low sensibility in the red and a high sensibility in the blue, thus causing a shift of the whole curve. A

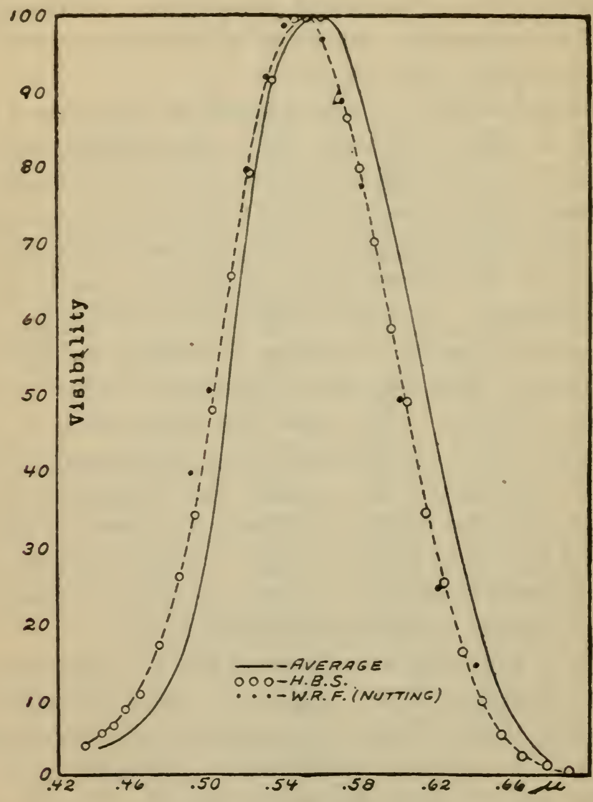

FIG. 7.—*Visibility curves of blue-sensitive subjects*

similar case has just been described (W. J. T.) in which this shift of sensibility was accompanied by color blindness to the red. Other observers (e. g., I. G. P. and K. B.) who were slightly more sensitive in the violet than the normals, as indicated by the observations of Crittenden and Richtmyer, were found to have visibility curves which are somewhat above the normal in the blue part of the spectrum.

5. GREEN SENSITIVENESS

A characteristic group of observers have narrow visibility curves in the sense that the curves fall below the normal in the yellow and the blue and terminate rather sharply at the maximum in the green. The group of subjects examined by Nutting [27] has several marked examples of this type, about one-fourth of the whole group showing this characteristic to some extent. In Fig.

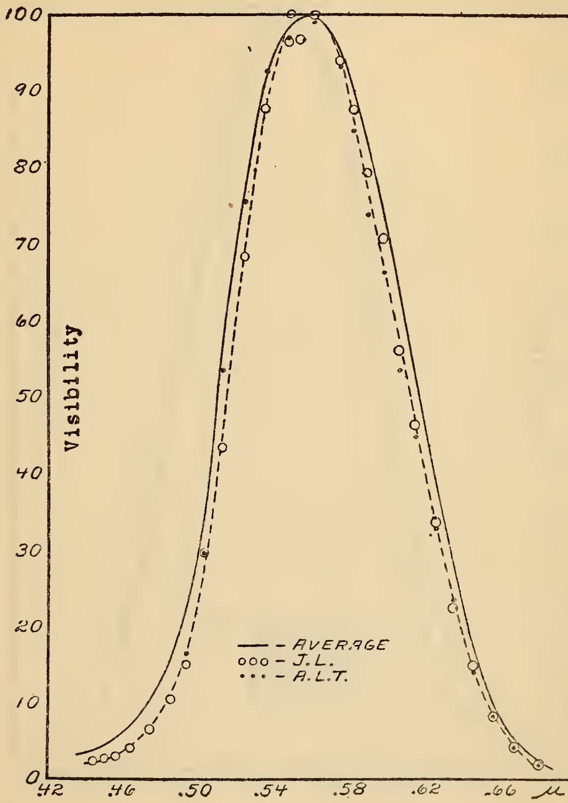

Fig. 8.—*Visibility curves of green-sensitive subjects*

8 the visibility curves of a number of subjects are given which exhibit this peculiarity. In the green-sensitive subject the response of the red and the blue is not up to the average eye.

6. RED-BLUE SENSITIVENESS

This class includes a characteristic of infrequent occurrence, in which the visibility curve is very wide as compared with the normal curve. Curves of this classification are given in Fig. 9. This type is not as common as that of red sensitiveness, only 1 marked example being present among the 21 observers recorded by Nutting [27] and 7 among the 130 examined in the present investigation.

7. SUBNORMAL BLUE SENSITIVENESS

Among those who might be classed as yellow sensitive by some tests is a group of observers whose visibility curves coincide very

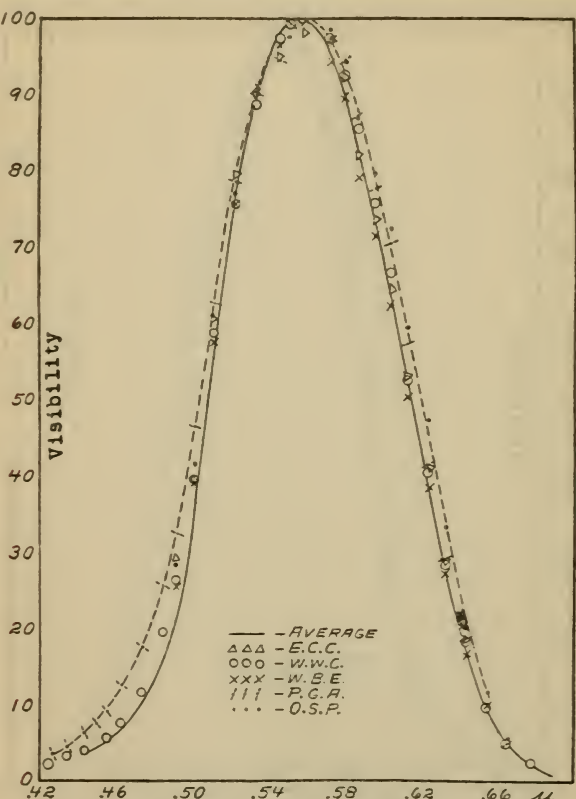

FIG. 9.—*Visibility curves of subjects having a high sensibility over a wide range of wave lengths*

closely, if not exactly, with the average visibility curve throughout the spectrum except in the blue violet, where the visibility falls below the average value. Before making the test several of the observers in this group reported that their eyes were not very sensitive to the blue. The curves of several observers having a low sensibility in the blue, but having the average visibility in the remainder of the spectrum are given in Fig. 10.

8. SUBNORMAL RED SENSITIVENESS

Among those who might be classed sensitive in the blue-green by some tests (e. g., the tests by Crittenden and Richtmyer [29]) is a group of observers whose visibility curves are low in the red and yellow but coincide very closely with the average visibility curve in the green and blue parts of the spectrum. Illustrations of this type of color sensibility are given in Fig. 11. They differ

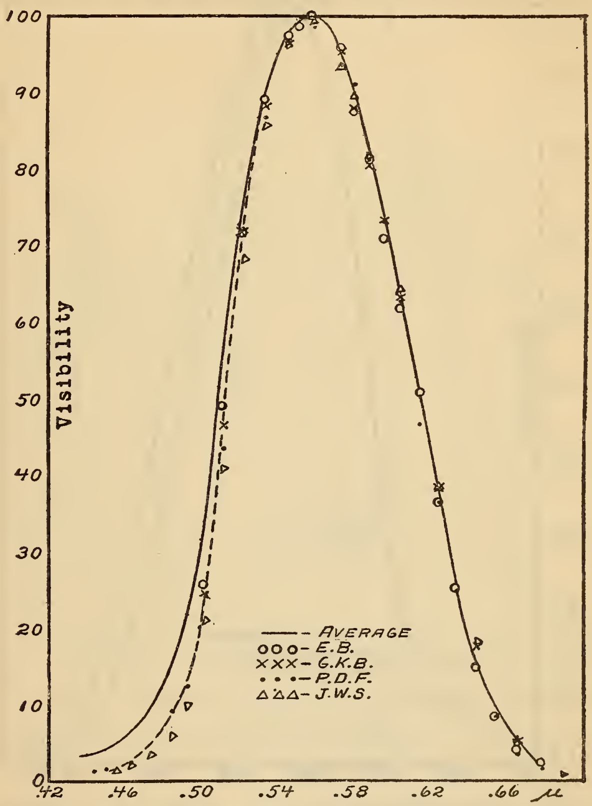

FIG. 10.—*Visibility curves of sub-normal blue-sensitive subjects*

from the curves (Fig. 7) of high sensibility in the blue in that in the latter the whole visibility curve is shifted to the blue. Furthermore, in the latter the shape of the curve in the blue is different from that of the average curve, so that it is not possible to superpose them nicely in the blue, as is possible with the curves in the present and in the preceding classification.

This classification includes a number of subjects whose visibility curves fall below the average in the yellow and orange instead of the deep red, but it did not seem necessary to classify them in a separate group.

9. AVERAGE COLOR VISION

In this group are to be found about one-fourth of the total number of persons examined. The visibility curve is smooth and free from indentations, and it is quite symmetrical with the maximum

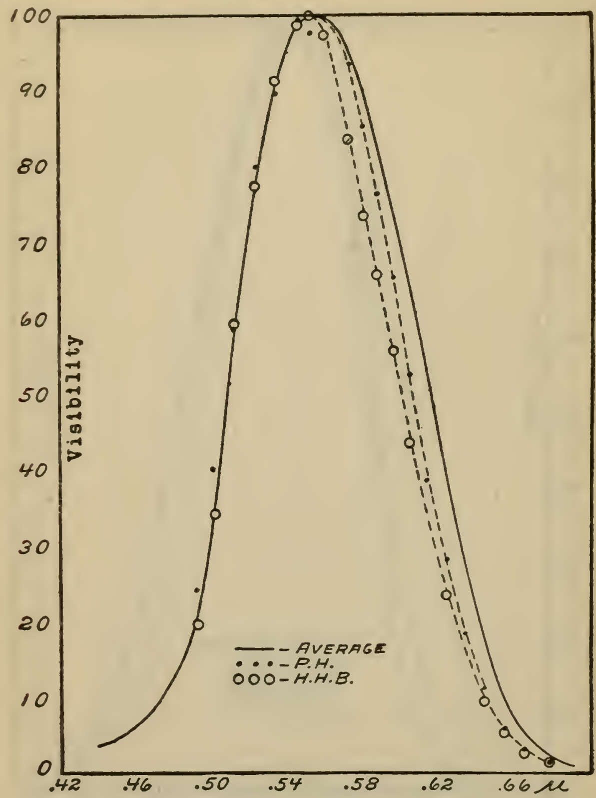

FIG. 11.—*Visibility curves of sub-normal red-sensitive subjects*

visibility at about 0.557μ. It is the type of curve one obtains after arbitrarily eliminating the red and the blue sensitive observers, and it may be slightly different from the visibility curve of the "average eye," which means the inclusion of all individuals who are considered to have "normal" color vision. In Fig. 12 are shown the observations of a group of observers whose visibility curves are closely the same as that of the average eye.

In Table 3 are given statistical data, by various observers, regarding the number of persons in each type of color sensibility mentioned in this paper. The characteristics of the eyes examined by Tufts are not fully described.

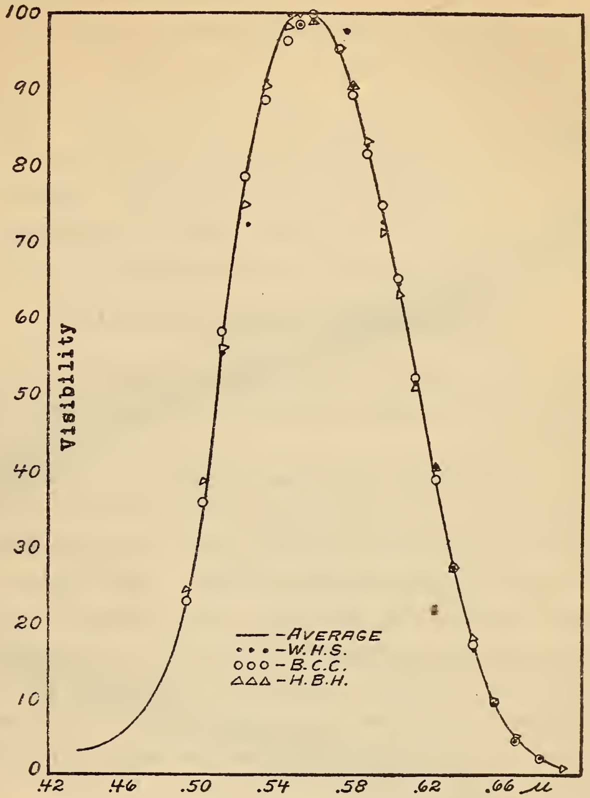

FIG. 12.—*Visibility curves of observers having a sensibility close to the average*

TABLE 3

Grouping of Subjects According to Dominant Color Sensibility

Subjects	Observer Tufts	Observer Ives	Observer Bender	Observer Nutting	Observers Coblentz and Emerson
Total number	18	18	10	21	125
Red sensitive	2	5	3	7	26+11 Sub. B
Blue sensitive	2	5	3	5	20+17 Sub. R
Green sensitive (narrow)	....	5	2	4	13
Red-blue sensitive (wide)	4	1	....	1	7
Average	[a] 10	2	2	4	29

[a] Classification by Tufts; curves not published.

The data given by the various investigators mentioned in Table 3 are sufficiently complete to show that among a group of persons having "normal" color vision (roughly estimated) 60 per cent of the cases fall into three quite evenly divided groups which are either (1) red sensitive, (2) blue sensitive, or (3) average. Similarly 30 per cent of the cases examined are quite evenly divided into three groups which fall below the average in (1) the red, (2) in the blue, or (3) in both the red and the blue, thus giving rise to an apparently high sensitivity in the green. One person in about 20 has a wide visibility curve as compared with the average.

The composite visibility curve of all these observers is illustrated in Fig. 13. It is of especial interest in showing the small range of variation in sensibility in the region of 0.51 to 0.52μ.

10. REMARKS ON OBSERVATIONAL DATA

Under this title are recorded various comments regarding the characteristics of the data obtained by various observers given in Tables 1 and 2.

W. W. C.—Equality-of-brightness settings are usually close to the flicker settings, but in the midst of these closely agreeing observations an occasional set of readings was obtained which differed by 20 per cent from the normal settings. (See Table 4.) No disproportionate increase in sensibility was observed as the result of adaptation when exposing the eye to the blue rays. The fatigued (right) eye and the unfatigued (left) eye gave the same flicker readings. For the 30-meter candle illumination there seemed to be a tendency for supernormal sensibility at 0.623μ on some days.

C. G. P.—A poor visibility curve (Mar. 9, 1916) was caused by fatigue from reading during the greater part of the preceding night. His equality-of-brightness curves (for Mar. 4 and 9) coincided better than the flicker curves. Prolonged exposure to the blue did not increase the sensibility to the yellow. For equality of brightness his Nicol readings gradually increase (sensibility decreases) to a normal—probably slow adaptation.

B. M.—His eye was more sensitive to the yellow after making readings in the blue. Parinaud's [44] data indicate a disproportionate increase in sensibility of the eye for the blue rays, due to adaptation.

W. M. S.—A rather poor curve; eyes tire very easily.

R. C. S.—Very low and irregular readings in the yellow when making equality-of-brightness settings.

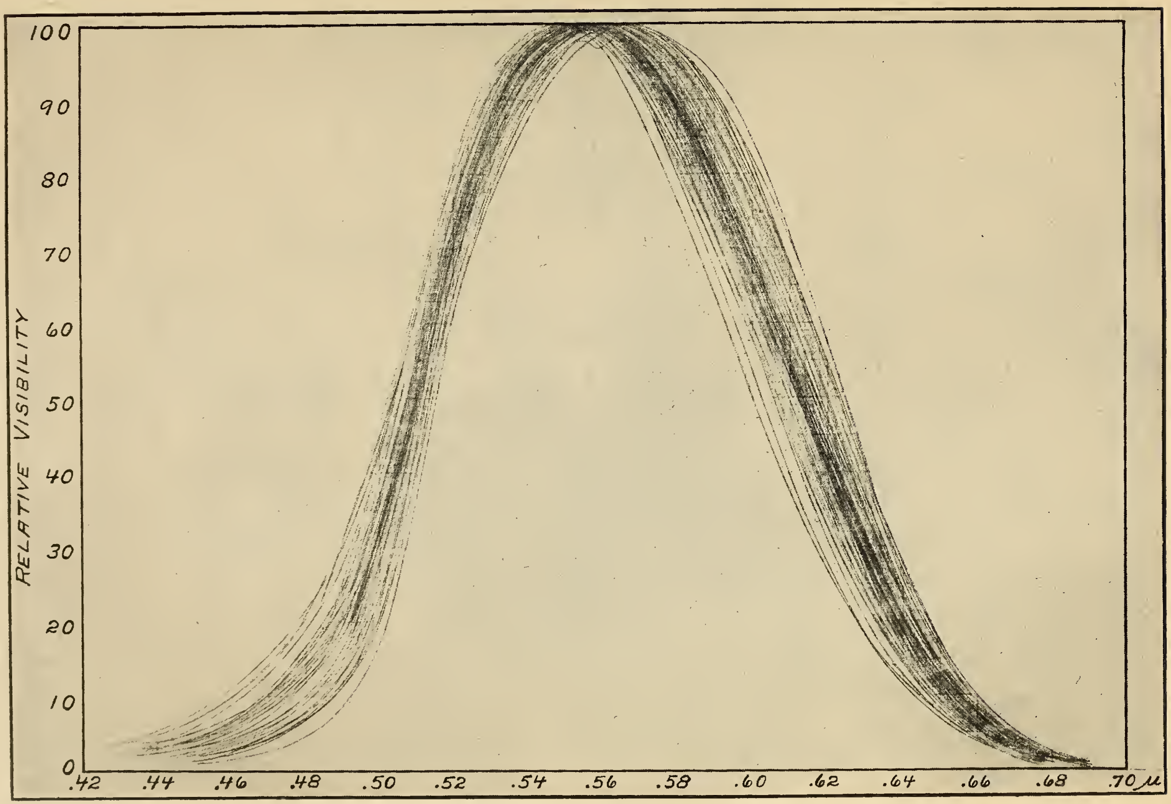

FIG. 13.—*Composite visibility curve of 125 persons*

J. W. S.—Unusual settings for equality of brightness. Practically the same settings (sensibility) throughout the spectrum. (See Table 4.)

J. S. P.—Equality-of-brightness settings are low. After being shown the appearance of the photometric field for a flicker setting his measurements gradually returned to the former equality-of-brightness settings.

F. P. P.—Made several sets of observations (Feb. 23, 25, 26, and Mar. 1, 1916). On June 27 he repeated the flicker observation of February 23, using the right and the left eye. The results for the two eyes are identical, and they agree with his previous observations.

P. J. H.—The visibility curve of this subject is very unusual in that it is higher than the average in the blue, 0.48μ; lower in the blue-green, 0.53μ; normal in the green, 0.555μ; and lower than the average in the yellow and red, 0.57μ to 0.66μ. The equality-of-brightness settings are extremely high, especially in the blue.

11. FATIGUE AND ADAPTATION

If the fatigue is the same for white and for colored light, then it should not affect the settings. From the data at hand it would appear that there is no rule as to what one should expect.

Pflüger,[4] Bender,[26] and others report a great constancy in the observations made on different days. In the present investigation it was found that closely agreeing observations were obtained on different days, provided the subject was in normal health (free from "cold," "grippe," etc.) and had sufficient sleep (rest) the preceding night.

From the data published by Allen,[12] after fatiguing the eye with white light from the electric arc the sensibility is quite proportionately reduced throughout the spectrum and, in general, fatigue caused by exposure to light of a given wave length (say in the green) depressed the sensibility in that part of the spectrum. It is to be noted, however, that the test was made before the eye could recover from the effect. Tufts,[22] using the flicker photometer, found no effect upon the visibility curve as the result of fatiguing the eye with white or colored light (red, yellow, blue), but an effect was observed after prolonged exposure to red light.

In the present investigation prolonged tests were made on the effect of fatigue upon the flicker-photometer settings. For example, making a setting with the right eye after a long series of observations and immediately thereafter repeating this setting with the left eye (which had not been used at all) gave the same results. Similarly, making a no-flicker setting with the right eye, then staring at the uncovered standard lamp or at the sky, did not change the setting. These tests were made at 0.604μ, 0.576μ, and 0.456μ. Only at the latter position in the spectrum was the no-flicker setting changed, and this was not greater than the observational errors (3 to 4 per cent) which one would make in such a test.

All the tests show that the eye adapts itself to the conditions of the experiment in a few minutes. Only in a few cases (see "Remarks on observational data") did the sensibility change due to adaptation in changing from the blue to a less refrangible part of the spectrum.

12. FLICKER VERSUS EQUALITY-OF-BRIGHTNESS MEASUREMENTS

As already mentioned, it is an unsettled question whether the flicker method gives the same results as the equality-of-brightness method. At the conclusion of the flicker-photometer measurements the observer made measurements in selected parts of the spectrum, using the equality-of-brightness method and an illumination of 50 meter candles on the disk, as previously described.

From data obtained by other tests, when using the flicker method of photometry, one would expect to find the observations underestimated in the red and overestimated in the blue as compared with similar measurements made with the equality-of-brightness method.[18] This is due to the fact that the sensations aroused by lights differing in color appear to rise to their maximum brightness at different rates when using the flicker method. A further investigation of this inportant question is desirable, using a large number of observers and apparatus that remains in exact adjustment to insure that some of the phenomena observed are not due to instrumental difficulties.

Of the five subjects examined by Ives,[23] (using an illumination of 250 meter candles) one observer underestimated the red and overestimated the blue (which is the expected result), two overestimated the red and underestimated the blue, one had a symmetrical curve and one was indeterminate. Using an illumination of 10 meter candles upon the disk, all five observers overestimated the red and underestimated the blue. From these data it seemed quite probable that, for the intensity (50 meter candles) used in the present work, there would be about as frequent overestimation as underestimation in any part of the spectrum when using the flicker method. Hence, as already explained, the flicker method was adopted to obtain the complete visibility curve, and the question of overestimation or underestimation was tested by using the equality-of-brightness method in selected parts of the spectrum which are best adapted to demonstrate this alleged effect.

In the preliminary tests by the writers it was found that on some days there was an underestimation and on other days an overestimation in the same part of the spectrum, when measurements were made with the flicker method as compared with the equality-of-brightness method.

The results of the present investigation are given in Table 4. The mean value for 110 observers, using the flicker method, differs but little from that of the 125 observers.

TABLE 4

Comparison of Flicker and Equality-of-Brightness Measurements in Selected Parts of the Spectrum

Observer	Wave length, 0.493μ			Wave length, 0.523μ			Wave length, 0.5876μ			Wave length, 0.623μ			Wave length, 0.654μ		
	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent
W. W. C.:															
30 m. c.—															
Feb. 2, 1916	....	....	....	....	....	....	608.0	760.0	−20.0	416.0	436.0	− 4.6	100.0	101.0	− 1.0
Feb. 4, 1916	....	....	....	....	....	....	748.0	794.0	− 5.8	445.0	429.0	+ 3.8	101.0	101.0	0.0
Feb. 9, 1916	268.0	249.0	+ 7.6	....	....	....	846.0	864.0	− 2.1	473.0	443.0	+ 6.8	....	....	....
140 m. c.—															
Feb. 10, 1916	....	....	....	793.0	800.0	− 0.9	....	....	....	415.0	402.0	+ 3.2	....	....	....
350 m. c.—															
Feb. 10, 1916	205.0	245.0	− 16.3	....	....	....	810.0	810.0	0.0	....	....	....	100.0	103.0	− 2.9
100 m. c.—															
Feb. 17, 1916	250.0	265.0	− 5.7	....	....	....	770.0	862.0	−10.7	345.0	397.0	− 13.1	....	....	....
Feb. 18, 1916	....	....	....	....	....	....	894.0	853.0	+ 4.8	397.0	400.0	− 0.8	....	....	....
E. D. T	....	....	....	....	....	....	893.0	858.0	+ 4.1	359.0	398.0	− 9.8	....	....	....
F. P. P.:															
Feb. 23, 1916	142.0	153.0	− 7.2	....	....	....	796.0	782.0	+ 1.8	445.0	369.0	+ 20.6	122.0	93.6	+ 30.3
Feb. 25, 1916	....	....	....	....	....	....	736.0	812.0	− 9.3	418.0	391.0	+ 6.9	....	....	....
Feb. 26, 1916	212.0	160.0	+ 32.5	....	....	....	757.0	757.0	0.0	494.0	361.0	+ 36.9	....	....	....
R. F. J.:															
Feb. 23, 1916	233.0	181.0	+ 28.8	....	....	....	913.0	764.0	+19.5	....	....	....	103.0	85.1	+ 21.0
Feb. 24, 1916	199.0	156.0	+ 27.5	....	....	....	748.0	690.0	+ 8.4	446.0	315.0	+ 41.6	....	....	....
C. F. S	186.0	249.0	− 25.3	....	....	....	882.0	780.0	+13.1	....	....	....	73.8	89.0	− 17.1
P. D. F	152.0	124.0	+ 22.6	896.0	720.0	+ 24.4	828.0	810.0	+ 2.2	392.0	365.0	+ 7.4	93.9	78.1	+ 20.2
I. G. P	192.0	220.0	− 12.7	830.0	779.0	+ 6.6	950.0	761.0	+24.8	....	....	....	153.0	84.6	+ 82.0
H. J. M	245.0	227.0	+ 7.9	846.0	755.0	+ 12.0	932.0	829.0	+12.4	....	....	....	141.0	95.1	+ 48.2

C. G. P.:															
Mar. 4, 1916	208.0	223.0	− 6.7	559.0	714.0	− 21.7	800.0	800.0	0.0	421.0	413.0	+ 1.9	94.7	110.0	− 13.9
Mar. 9, 1916	296.0	261.0	+ 13.4	784.0	820.0	− 4.4	860.0	827.0	+ 4.0	426.0	363.0	+ 17.4	89.9	83.2	+ 8.1
Mar. 14, 1916	192.0	268.0	− 28.3	726.0	794.0	− 8.6	919.0	821.0	+11.9	362.0	362.0	0.0	76.0	80.7	− 5.8
W. W. B	286.0	211.0	+ 35.5	892.0	763.0	+ 16.9	786.0	886.0	−11.3	639.0	435.0	+ 47.2	187.0	118.0	+ 58.4
C. O. F				749.0	742.0	+ 0.9	954.0	898.0	+ 6.2	567.0	427.0	+ 32.7	135.0	113.0	+ 19.5
J. W. S				483.0	681.0	− 29.1	506.0	817.0	−38.1	342.0	387.0	− 11.6			
W. F. M	151.0	156.0	− 3.2	956.0	672.0	+ 42.3	960.0	944.0	+ 1.7	459.0	540.0	− 15.0	86.6	137.0	− 36.8
I. N. K	176 0	173.0	+ 1.7	756.0	687.0	+ 10.0	948.0	948.0	0.0	409.0	533.0	− 23.3	103.0	129.0	− 20.1
B. M				1043.0	662.0	+ 57.6	1273.0	897.0	+41.9	774.0	508.0	+ 52.6	242.0	132.0	+ 83.3
K. B	293.0	186.0	+ 57.6	1030.0	776.0	+ 32.8	491.0	735.0	−33.2	83.6	313.0	− 73.4	53.8	72.0	− 25.3
C. G. C	890.0	141.0	+530.0	2100.0	690.0	+204.0	1060.0	888.0	+19.4	310.0	423.0	− 26.7	146.0	116.0	+ 25.9
J. S. P	209.0	267.0	− 21.7	492.0	743.0	− 33.8	822.0	803.0	+ 2.4	204.0	373.0	− 45.3	54.4	94.2	− 42.3
W. J. K	480.0	232.0	+107.0	2275.0	786.0	+189.0	1119.0	806.0	+38.8	761.0	423.0	+ 80.0	243.0	109.0	+123.0
P. V. W	271.0	209.0	+ 29.7	1140.0	740.0	+ 54.0	905.0	869.0	+ 4.1	671.0	462.0	+ 45.3	210.0	118.0	+ 78.0
G. K. S	200.0	210.0	− 4.8	657.0	745.0	− 11.8	708.0	841.0	−15.8	529.0	364.0	+ 45.3	83.2	81.6	+ 2.0
A. N. I	155.0	148.0	+ 4.7	677.0	744.0	− 9.0	753.0	778.0	− 3.2	247.0	350.0	− 29.4	33.7	72.2	− 53.3
E. C. C	460.0	295.0	+ 55.9	1130.0	798.0	+ 41.6	948.0	820.0	+15.6	529.0	412.0	+ 28.4	123.0	103.0	+ 19.4
C. L. C	650.0	194.0	+235.0	1983.0	762.0	+160.0	1303.0	777.0	+67.7	529.0	330.0	+ 60.2	136.0	72.1	+ 88.6
R. G. W				686.0	717.0	− 4.3	802.0	814.0	− 1.5	181.0	360.0	− 49.7	55.0	82.7	− 33.5
C. F. H	214.0	205.0	+ 4.9	590.0	794.0	− 25.7	767.0	812.0	− 5.5	284.0	376.0	− 24.5	83.6	89.4	− 6.5
F. A. W	641.0	193.0	+232.0	2878.0	721.0	+299.0	1135.0	910.0	+24.7	859.0	468.0	+ 83.5	246.0	131.0	+ 87.7
A. H. T				748.0	762.0	− 1.8	806.0	852.0	− 5.4	377.0	433.0	− 12.9	106.0	110.0	− 3.6
H. G. B	351.0	215.0	+ 63.2	1115.0	826.0	+ 35.0	859.0	834.0	+ 3.0	603.0	396.0	+ 52.3	107.0	93.1	+ 14.9
E. D. W	282.0	200.0	+ 41.0	800.0	707.0	+ 13.2	988.0	766.0	+29.0	603.0	388.0	+ 55.4	131.0	100.0	+ 31.0
H. B. S	286.0	341.0	− 14.8	1207.0	792.0	+ 52.4	773.0	701.0	+10.3	274.0	253.0	+ 8.3	56.4	53.7	+ 5.0
R. E. L	230.0	170.0	+ 35.3	467.0	775.0	− 39.8	804.0	772.0	+ 4.1	259.0	315.0	− 17.8	32.5	63.7	− 49.0
R. M. W	460.0	253.0	+ 82.0	840.0	726.0	+ 15.7	784.0	860.0	− 8.8	516.0	453.0	+ 13.9	139.0	116.0	+ 19.8
L. R. H				557.0	724.0	− 23.1	766.0	858.0	−10.7	400.0	438.0	− 8.7	93.4	108.0	− 13.5
W. S. J	181.0	242.0	− 25.2	532.0	771.0	− 31.0	782.0	901.0	−13.2	597.0	485.0	+ 23.1	225.0	126.0	+ 78.5
R. W. W	301.0	176.0	+ 71.0	1259.0	777.0	+ 62.0	626.0	783.0	−20.0	468.0	340.0	+ 37.7	145.0	78.6	+ 84.5
H. B. H	272.0	246.0	+ 10.6	857.0	748.0	+ 14.6	864.0	831.0	+ 4.0	702.0	407.0	+ 72.4	174.0	98.9	+ 75.8
E. F. M	458.0	335.0	+ 36.7	1151.0	786.0	+ 46.4	926.0	793.0	+16.8	470.0	402.0	+ 16.9	166.0	89.7	+ 85.0
H. A. B				899.0	715.0	+ 25.7	458.0	842.0	−45.6	373.0	385.0	− 3.1	77.7	90.9	− 14.5

TABLE 4—Continued.

Comparison of Flicker and Equality-of-Brightness Measurements in Selected Parts of the Spectrum—Continued.

Observer	Wave length, 0.493μ			Wave length, 0.523μ			Wave length, 0.5876μ			Wave length, 0.623μ			Wave length, 0.654μ		
	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent
D. H. S.	263.0	201.0	+ 30.7	1177.0	800.0	+ 47.1	830.0	769.0	+ 7.9	410.0	312.0	+ 31.4	91.2	76.8	+ 18.7
W. C. B.	360.0	343.0	+ 5.0	756.0	831.0	− 9.0	848.0	816.0	+ 3.9	458.0	411.0	+ 11.4	95.3	110.0	− 13.4
R. C. S.	173.0	296.0	− 41.5	250.0	814.0	− 69.3	408.0	797.0	−48.8	95.4	353.0	− 73.0	55.4	78.2	− 29.2
M. H. S.	269.0	284.0	− 5.3	673.0	819.0	− 17.8	675.0	800.0	−15.6	198.0	381.0	− 48.0	68.9	94.8	− 27.3
G. W. M.	163.0	183.0	− 11.0	631.0	760.0	− 17.0	1012.0	840.0	+20.5	489.0	411.0	+ 19.0	164.0	109.0	+ 50.5
A. L. T.	.....	.....	.....	1140.0	754.0	+ 51.1	705.0	739.0	− 4.6	402.0	328.0	+ 22.5	.....	.....	.....
A. F. P.	.....	.....	.....	528.0	739.0	− 28.5	588.0	815.0	−27.8	317.0	366.0	− 13.4	96.8	86.7	+ 11.7
F. B. S.	203.0	163.0	+ 24.5	588.0	736.0	− 20.1	948.0	807.0	+17.4	602.0	432.0	+ 39.4	138.0	103.0	+ 34.0
J. L.	292.0	150.0	+ 94.7	446.0	681.0	− 34.5	768.0	792.0	− 3.0	278.0	337.0	− 17.5	87.9	82.4	+ 6.8
J. A. S.	196.0	160.0	+ 22.5	1134.0	759.0	+ 49.4	818.0	826.0	− 1.0	563.0	394.0	+ 43.0	146.0	95.3	+ 53.2
H. K. G.	510.0	200.0	+155.0	1061.0	771.0	+ 37.6	837.0	818.0	+ 2.3	488.0	394.0	+ 23.9	134.0	102.0	+ 31.4
W. S. S.	203.0	181.0	+ 12.2	735.0	758.0	− 3.0	891.0	848.0	+ 5.1	615.0	415.0	+ 48.2	138.0	106.0	+ 30.2
P. G. A.	182.0	325.0	− 44.0	493.0	786.0	− 37.3	832.0	872.0	− 4.6	927.0	416.0	+123.0	89.0	102.0	− 12.7
H. I. S.	211.0	231.0	− 8.6	734.0	750.0	− 2.1	770.0	818.0	− 5.9	408.0	400.0	+ 2.0	101.0	96.9	+ 4.2
E. L. P.	224.0	244.0	− 8.2	778.0	696.0	+ 11.8	980.0	904.0	+ 8.4	636.0	446.0	+ 42.6	148.0	110.0	+ 34.6
L. W. S.	452.0	180.0	+151.0	934.0	760.0	+ 22.9	850.0	835.0	+ 1.8	353.0	385.0	− 8.3	162.0	92.1	+ 75.9
J. H. D.	172.0	215.0	− 20.0	508.0	781.0	− 34.9	492.0	774.0	−36.5	214.0	305.0	− 29.8	55.9	65.4	− 14.5
R. L. S.	221.0	250.0	− 11.6	727.0	705.0	+ 3.1	1481.0	891.0	+66.3	.....	.....	.....	161.0	109.0	+ 47.7
C. W. B.	462.0	285.0	+ 62.0	1236.0	815.0	+ 51.6	887.0	769.0	+15.3	374.0	345.0	+ 8.4	113.0	83.2	+ 35.8
D. R. M.	356.0	265.0	+ 34.3	850.0	772.0	+ 10.1	859.0	850.0	+ 1.0	275.0	438.0	− 37.2	80.2	116.0	− 30.8
O. L. S.	145.0	166.0	− 12.7	907.0	720.0	+ 26.0	573.0	788.0	−27.3	403.0	364.0	+ 10.7	155.0	89.3	+ 73.5
M. J.	354.0	182.0	+ 94.6	1593.0	706.0	+126.0	1007.0	867.0	+16.1	551.0	477.0	+ 15.5	267.0	136.0	+ 96.4
J. F. M.	227.0	193.0	+ 17.6	560.0	774.0	− 27.6	624.0	773.0	−19.3	118.0	362.0	− 67.4	84.0	96.5	− 12.9
P. D. L.	285.0	317.0	− 10.1	893.0	770.0	+ 16.0	944.0	808.0	+16.8	423.0	351.0	+ 20.5	95.9	84.4	+ 13.6
R. Y. F.	322.0	219.0	+ 47.0	974.0	784.0	+ 24.2	1019.0	790.0	+29.0	538.0	375.0	+ 43.5	146.0	93.9	+ 55.5

F. J. B	....	....	....	1050.0	765.0	+ 37.2	832.0	832.0	0.0	371.0	371.0	0.0	69.5	86.8	− 20.0
P. J. H	....	....	....	....	....	....	469.0	757.0	−38.1	509.0	327.0	+ 55.6	149.0	80.1	+ 86.0
T. R. H	531.0	181.0	+193.0	2011.0	735.0	+174.0	946.0	928.0	+ 1.9	846.0	470.0	+ 80.0	310.0	125.0	+148.0
H. A. E	357.0	180.0	+ 98.3	726.0	734.0	− 1.1	714.0	814.0	−12.3	324.0	394.0	− 17.8	112.0	89.1	+ 25.7
E. C. P	292.0	153.0	+ 90.8	1019.0	759.0	+ 34.2	509.0	813.0	−37.4	554.0	401.0	+ 38.1	143.0	102.0	+ 40.2
C. H. M	205.0	270.0	− 24.1	812.0	779.0	+ 4.2	805.0	727.0	+10.7	254.0	321.0	− 20.9	56.3	74.5	− 24.4
C. E. B	....	....	....	2710.0	770.0	+252.0	1007.0	806.0	+25.0	706.0	401.0	+ 76.1	....	....	....
C. A. B	265.0	326.0	− 18.7	650.0	849.0	− 23.4	694.0	779.0	−10.9	357.0	368.0	− 2.9	91.1	85.1	+ 7.1
T. B. F	....	....	....	546.0	681.0	− 19.9	1079.0	908.0	+18.8	322.0	493.0	− 34.7	144.0	125.0	+ 15.2
D. R. H	....	....	....	717.0	752.0	− 4.6	663.0	856.0	−22.5	259.0	446.0	− 41.9	94.8	120.0	− 21.0
P. D. S	412.0	267.0	+ 54.3	1333.0	732.0	+ 82.1	966.0	897.0	+ 7.7	572.0	461.0	+ 24.1	303.0	116.0	+161.0
A. N. F	....	....	....	627.0	708.0	− 11.4	844.0	946.0	−10.8	509.0	466.0	+ 9.2	117.0	107.0	+ 9.3
G. T. M	....	....	....	697.0	672.0	+ 3.7	878.0	927.0	− 5.3	570.0	520.0	+ 9.6	150.0	151.0	− 0.7
H. S	299.0	242.0	+ 23.6	903.0	782.0	+ 15.5	668.0	840.0	−20.5	362.0	407.0	− 11.1	91.2	104.0	− 12.3
H. B. K	704.0	248.0	+184.0	1549.0	771.0	+101.0	836.0	805.0	+ 3.9	585.0	340.0	+ 72.2	178.0	79.0	+125.0
S. I	341.0	256.0	+ 33.2	854.0	801.0	+ 6.6	618.0	818.0	−24.5	465.0	362.0	+ 28.5	140.0	89.1	+ 57.0
J. L. F	177.0	258.0	− 31.4	586.0	760.0	− 22.9	778.0	792.0	− 1.8	399.0	341.0	+ 17.0	118.0	82.7	+ 42.7
A. B. L	154.0	194.0	− 20.6	324.0	778.0	− 58.4	741.0	806.0	− 8.1	302.0	384.0	− 21.4	85.2	90.9	− 6.3
O. S. P	244.0	283.0	− 13.8	634.0	770.0	− 17.6	554.0	872.0	−36.5	257.0	474.0	− 45.8	99.8	119.0	− 16.1
W. H. S	210.0	264.0	− 20.5	661.0	863.0	− 23.4	966.0	756.0	+27.8	385.0	314.0	+ 22.6	99.5	76.8	+ 29.6
A. B	194.0	213.0	− 8.9	608.0	736.0	− 17.4	579.0	786.0	−26.4	448.0	359.0	+ 24.8	116.0	86.6	+ 33.9
G. C. H	198.0	189.0	+ 4.7	996.0	782.0	+ 27.4	898.0	768.0	+16.9	582.0	373.0	+ 56.0	129.0	91.2	+ 41.4
T. R. E	486.0	226.0	+115.0	1394.0	789.0	+ 76.7	876.0	788.0	+11.2	683.0	372.0	+ 83.6	182.0	88.6	+106.0
A. J. H	....	....	....	788.0	796.0	− 0.9	730.0	780.0	− 6.4	514.0	366.0	+ 40.4	101.0	100.0	+ 1.0
B. C. C	384.0	229.0	+ 67.6	1267.0	784.0	+ 61.6	895.0	815.0	+ 9.8	653.0	388.0	+ 68.4	123.0	97.2	+ 26.5
G. K. B	....	....	....	1165.0	718.0	+ 62.3	916.0	804.0	+13.9	531.0	385.0	+ 38.0	....	....	....
P. H	311.0	240.0	+ 29.5	672.0	800.0	− 16.0	633.0	764.0	−17.2	214.0	281.0	− 23.9	52.0	59.9	− 13.2
H. S. P	192.0	254.0	− 24.4	250.0	840.0	− 70.2	152.0	734.0	−79.3	93.6	311.0	− 70.0	50.6	69.2	− 26.9
H. H. B	960.0	198.0	+385.0	2356.0	773.0	+205.0	601.0	658.0	− 8.6	632.0	237.0	+167.0	160.0	53.3	+200.0
H. A. B	243.0	189.0	+ 28.6	548.0	743.0	− 26.2	358.0	771.0	−53.6	299.0	345.0	− 13.3	83.6	79.3	+ 5.4
E. S. P	....	....	....	702.0	662.0	+ 6.0	914.0	939.0	− 2.6	546.0	546.0	0.0	159.0	153.0	+ 3.9
W. H. St	....	....	....	859.0	726.0	+ 18.3	757.0	827.0	− 8.4	353.0	406.0	− 13.1	106.0	95.9	+ 10.5
M. D. S	....	....	....	508.0	780.0	− 34.8	795.0	831.0	− 4.3	178.0	393.0	− 54.8	41.1	89.0	− 53.8
E. B	....	....	....	692.0	716.0	− 3.3	1005.0	810.0	+24.1	365.0	362.0	+ 0.8	86.2	86.2	0.0

TABLE 4—Continued

Comparison of Flicker and Equality-of-Brightness Measurements in Selected Parts of the Spectrum—Continued

Observer	Wave length, 0.493μ			Wave length, 0.523μ			Wave length, 0.5876μ			Wave length, 0.623μ			Wave length, 0.654μ		
	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent	Equality of brightness	Flicker	Δ Per cent
J. L. B.	324.0	373.0	− 13.1	672.0	730.0	− 8.0	948.0	840.0	+12.9	321.0	447.0	− 28.2	103.0	109.0	− 5.5
E. E. W.	453.0	339.0	+ 33.6	1057.0	845.0	+ 25.1	785.0	796.0	− 1.4	492.0	357.0	+ 37.8	104.0	89.0	+ 16.9
M. S.	249.0	233.0	+ 6.9	797.0	766.0	+ 4.0	976.0	790.0	+23.6	494.0	381.0	+ 29.6	110.0	97.6	+ 12.7
J. C. P.	263.0	212.0	+ 24.0	985.0	782.0	+ 25.9	811.0	748.0	+ 8.4	326.0	371.0	− 12.1	72.8	97.2	− 25.1
P. D. M.	....	....	....	1410.0	729.0	+ 93.4	1065.0	878.0	+21.3	684.0	430.0	+ 59.1	220.0	108.0	+104.0
P. W. M.	313.0	242.0	+ 29.3	980.0	804.0	+ 21.9	708.0	728.0	− 2.7	351.0	296.0	+ 18.6	96.9	63.8	+ 51.9
N. S. O.	....	....	....	935.0	723.0	+ 29.3	768.0	808.0	− 4.9	348.0	425.0	− 18.1	175.0	117.0	+ 49.6
Mean of 110 eyes	300.8	226.4	....	929.8	757.2	....	815.1	810.5	....	442.1	395.5	....	121.3	96.7	....
$\Delta \frac{EqB-Fl}{Fl}=$	+32.9%		....	+22.8%		....	+0.6%		....	+11.8%		....	+25.4%		....
Mean of 125 eyes	....	225.0	....	....	758.0	....	....	818.0	....	....	391.0	....	....	96.1	....

The observations using the equality-of-brightness and the flicker photometer, obtained at a given wave length, are arranged side by side in order to facilitate comparison. From this table it is to be observed that there is no regularity in the over or under estimation (of equality of brightness as compared with the flicker photometer) at the same wave length or at different wave lengths on different days. For example, the visibility reading of one observer (W. W. C.) at 0.623μ was 41.6 per cent of the maximum visibility by the equality-of-brightness method and 43.6 by the flicker method, or an underestimation of 4.6 per cent by the equality-of-brightness method. Two days later these measurements were repeated, giving an overestimation of 3.8 per cent, which would be expected from psychological data. However, the sum of all the measurements (Table 4, underestimation in per cent is minus (−) and overestimation is plus (+), is practically zero. That is to say, the visibility curves obtained by equality-of-brightness and by flicker photometry are the same for this observer. It is to be noted, however, that in the midst of these very closely agreeing settings there are very erratic ones deviating 20 per cent or more, although they were made in a region of the spectrum (0.5876μ) where there was the least color difference in the two sources of light. Some observers (e. g., W. C. B.), without having had previous training in photometry, made very closely the same settings by these two methods of photometry. Other observers made very erratic settings (e. g., J. W. S.), which were different (c. f., F. P. P. and C. G. P.) as regards overestimation and underestimation on different days.

In the yellow ($\lambda = 0.5876\mu$) there are about as many observers who overestimated as underestimated in making the photometric settings, and the magnitude of the variations (0 to 50 per cent) are within reasonable limits. In the blue and in the red ends of the spectrum a greater number of observers overestimated than underestimated their equality-of-brightness settings. Moreover, the magnitude of this overestimation varied from 5 to 500 per cent. These variations in the photometric settings by different observers are out of all proportion as compared with similar settings made with the flicker photometer, and it is not a fair test to take the mean of the under and over estimated values.

The mean values of the equality-of-brightness measurements (Table 4, corrected for slit width) are indicated by the large crossed circles in Fig. 14. If we admit that such settings have a definite meaning, then the visibility of radiation curve, for the central retina, obtained by the equality-of-brightness method of photometry is higher in the red and in the blue (just the opposite from the

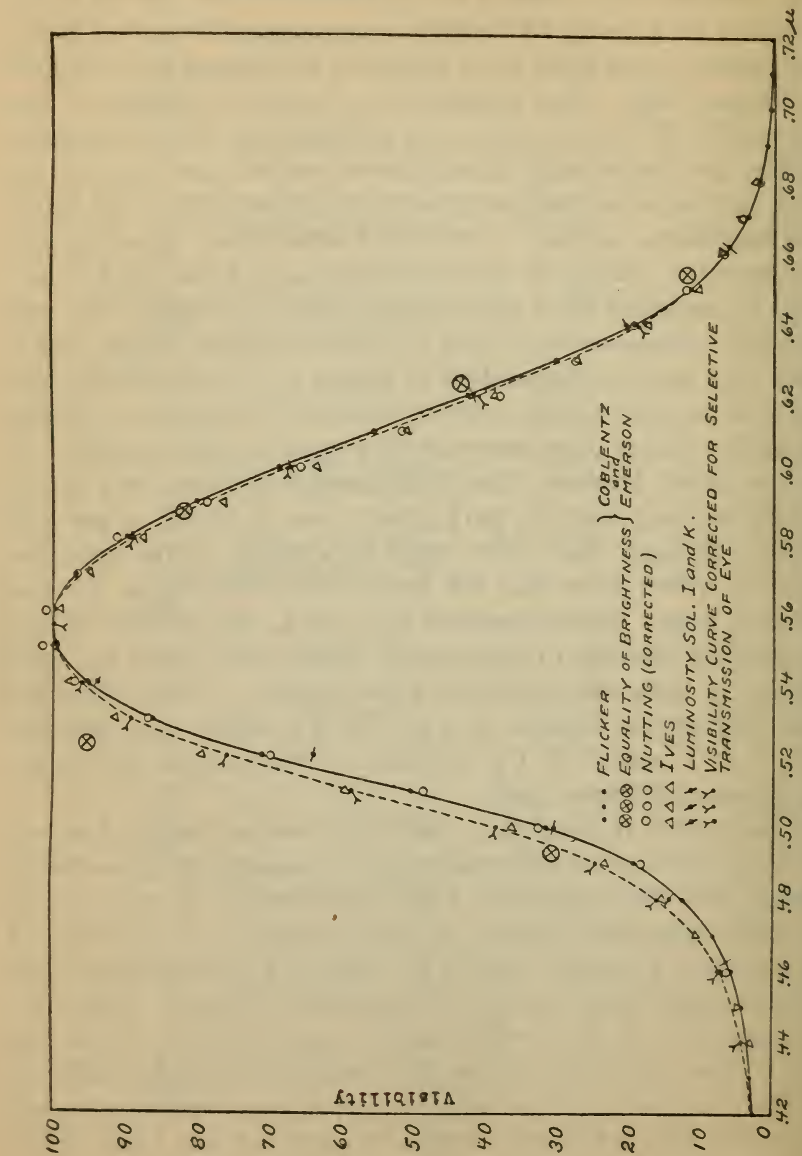

FIG. 14.—*Comparison of data of various investigators*

expected [18] result) than the one obtained with the flicker photometer, and its maximum lies at shorter wave lengths (0.55μ) than obtains for the flicker method. Although this tentative conclusion is substantiated by the direct measurements and by the total number of persons who overestimated in making the settings, it is evident that a far greater number of persons must be examined before exact conclusions can be drawn.

As already stated, most of these observers objected to making the quality-of-brightness settings, saying that no meaning could be attached to such measurements and that it was all guesswork.

13. EFFECT OF AGE UPON VISIBILITY

It is well known that the absorption of the ocular media is highly selective in the blue and violet and that this absorption increases with age.[11] The age of the majority of the subjects

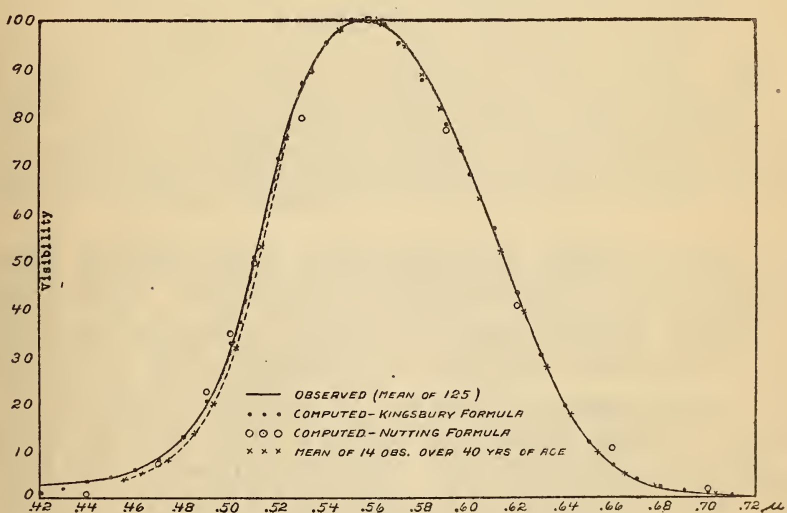

FIG. 15.—*Comparison of observed and computed data; also the effect of age upon visibility*

examined was between 22 and 32 years, and the question has been raised whether the average curve of those persons who were above 40 years of age is markedly different from that of the younger subjects. The present investigation contains 14 subjects who were 40 or more years of age. Their average visibility curve is given in Fig. 15.

Of this number, the grouping of the visibility curves is as follows: 1 wide, 1 blue sensitive, 2 green sensitive, 4 normal, and 6 sub-blue sensitive. This group is conspicuous for its lack of red sensitives and its large number of subnormal blue sensitives. From this large number of subjects (which is half of the total number examined, see Table 3, who have a low sensibility in the blue) it would appear as though the effect of age should be considered in deciding upon an average visibility curve in the blue and violet part of the spectrum.

It would be of interest to study a group of observers whose occupation requires working under artificial light of a definite color (e. g., in photographic work, such as the manufacture of photographic materials) to determine whether prolonged exclusion of parts of the visible spectrum has any effect upon the visibility curve.

V. THE VISIBILITY CURVE OF THE AVERAGE EYE

The visibility data of the average eye is based upon the mean value of the observations of 125 subjects given in Table 1. Two of these subjects confused colors, but their visibility curves do not differ much from the curves of the red-sensitive observers, some of which did not show color blindness by the Nagel color-card test. The omission of these two observers would lower the average visibility curve, at most, by less than 0.3 per cent in the red.

In order to simplify the computations, three correction factors were omitted in computing the individual curves. These correction factors, therefore, are to be applied to the average curve. The most important correction to be applied is due to the selectivity of the response of the eye for energy of different wave lengths. In other words, a correction is to be made for change in slope of the visibility curve. For this purpose, for the intensities used, the response of the retina for a stimulus of a given (color) wave length and for the adjacent wave lengths comprised in the slit image may be taken proportional to the intensity of the stimulus as shown in Fig. 2. Furthermore, for any given intensity the response of the retina is proportional to the mean visibility of the energy passing through the observing slit. The visibility curve, therefore, is to be corrected for change in slope by applying a slit-width correction similar to the Runge [49] formula used in spectral radiation, but with this difference that the function involved is visibility (V_λ) instead of radiation (E_λ). In other words, the Runge formula is applied in the form

$$V(\lambda) - 1/6\ V'(\lambda) + \ldots \qquad (1)$$

This correction is most effective in the sharp bends in the visibility curve.

A correction is applied also to make the zero of the scale reading correspond with the minimum light transmission through the crossed Nicol prisms. This correction, amounting to 0°.1, was determined at the start, and therefore might have been incorporated with other data used in reducing the various visibility curves.

A further correction[65] is applied to eliminate the effect of spectroscopic field light (scattered light) which is perceptible in the extreme blue and red ends of the visible spectrum. As discussed elsewhere in this paper, this scattered radiation has no effect upon the radiation measurements, but it has a measurable effect upon the visual measurements in the red end of the spectrum.

This correction to the visual measurements was determined by making the visibility observations with and without absorption screens of blue, Crookes's sage-green, and Corning signal-red glasses. The transmissions of these glasses were accurately determined by means of a photoelectric cell, a spectrophotometer and a spectroradiometer, in which care had been taken to screen off the scattered radiation.

In the blue (0.45 to 0.48μ), and in the green, (0.52μ), the visibility measurements were not affected by absorbing the scattered light. But in the red the visibility measurements required a correction which increased quite uniformly from 1 per cent at 0.65μ to 28 per cent at 0.75μ.

The visibility curve, Fig. 14, resulting from making these corrections differs but little from the uncorrected curve. These data are given at the bottom of Table 1. In Table 5 these data are given for the even wave lengths, read from the visibility curve.

TABLE 5

Average Visibility for Even Wave Lengths

Wave length	Average visibility	Wave length	Average visibility	Wave length	Average visibility	Wave length	Average visibility
μ		μ		μ		μ	
0.400	0.010	0.490	0.194	0.580	0.898	0.670	0.0338
.410	.017	.500	.316	.590	.800	.680	.0178
.420	.024	.510	.503	.600	.687	.690	.0085
.430	.029	.520	.710	.610	.557	.700	.0040
.440	.033	.530	.862	.620	.427	.710	.00203
.450	.041	.540	.954	.630	.302	.720	.00097
.460	.056	.550	.994	.640	.194	.730	.00048
.470	.083	.560	.998	.650	.115	.740	.00028
.480	.125	.570	.968	.660	.0645	.750	.00020

It is relevant to add a few remarks in regard to the energy measurements. In view of the difficulties involved in eliminating stray light, etc., the present writers have adopted the radiation measurements made with the apparatus used in the present investigation, because they agree with the measurements [40] made with two other kinds of spectroradiometers, one of which (the mirror spectrometer) is perfectly achromatic and is free from stray light introduced by the lenses. In view of the fact that our visibility curves differed in the red and in the blue, Dr. Nutting very kindly submitted the acetylene burner used in his visibility measurements. The energy distribution was found the same as in the burner used in the present work, instead of agreeing with the standard spectral-energy curve of acetylene previously published,[40a] which was much higher in the red. From data submitted it appeared that the energy measurements were in coincidence at 0.51μ and 0.56μ, but from 1 to 3 per cent too high (all within experimental errors and possible stray radiation between these two points, which depressed the visibility curve below the present curve by amounts varying from 1 to 3 per cent). Making this correction brings the two visibility curves in exact coincidence throughout the curve on the short wave-length side of the maximum. Applying the spectral-energy distribution of acetylene recently determined, instead of the older determinations (which applied to a flat flame viewed edgewise), which were much higher in red, the visibility curve is raised to close coincidence with the present curve. (See Fig. 14.) The slight difference at 0.60μ to 0.62μ may be due to the large number of very green sensitive subjects found in Nutting's work.[a] The present visibility curve would be still higher in the red if this investigation had been terminated after the examination of the first 24 individuals, of whom about one-fourth were red sensitive.

As indicated in Table 4, the visibility curve of about 110 subjects is in very close agreement with the average curve of the 125 subjects in the blue and the green and differs from it by less than 1 per cent in the yellow and the red.

The visibility curve obtained by Ives,[23] Fig. 14, is somewhat higher in the blue and lower in the red. No direct-energy measurements were made, the energy distribution having been obtained by computation on the assumption that the source (a tungsten lamp) had a certain temperature. The maximum of the curve is

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[a] No white surrounding field was used, as was done in the present work.

shifted to the blue just as though the temperature of the lamp had been higher than it was supposed to be, thus giving relatively more energy in the blue than in the red. In other words, the energy distribution that was applied to the measurements may have been too low in the blue and too high in the red. Aside from this possible cause of disagreement in the visibility curves, one must consider also the total number of subjects examined. The present curve, between wave lengths 0.49μ and 0.69μ, is based upon six times as many subjects as had been previously examined for establishing the average visibility curve. Between wave lengths 0.43μ and 0.49μ the present curve is based upon from 30 to 36 observers (only one observer, W. W. C., made measurements to 0.40μ) and beyond 0.69μ it is based upon measurements made by 39 observers. In the violet these data are somewhat higher than observed by Nutting,[27] and in the red they are higher than the values published by Hyde and Forsythe.[19] (See Table 6.) In the present investigation the aim has been to obtain an accurate average visibility curve, of a large group of observers, between 0.48μ and 0.70μ. Owing to stray light, the extreme violet end of the spectrum should be further investigated; eliminating stray light by means of absorption screens or by placing two spectroscopes in series.

TABLE 6

Comparison of Different Data for the Red End of the Spectrum

Wave lengths	Coblentz and Emerson	Hyde and Forsythe	Nutting	Ives	König
0.620μ	220.0	252.0	227.0	221.0	189.0
.630	156.0	164.0	164.0	156.0	143.0
.640	100.0	100.0	100.0	100.0	100.0
.650	59.3	58.0	62.0	59.0	61.0
.660	33.2	30.0	34.0	^{a}39.0	33.0
.670	17.4	15.7	18.6	^{a}25.0	15.0
.680	9.2	7.6	8.0	^{a}15.0	....
.690	4.4	3.8	$4._7$	....	....
.700	2.06	1.87	$1._3$	....	....
.710	1.04	.91	....	....	....
.720	.50	.45	....	....	....
.730	.25	.22	....	....	....
.740	.14	$.11_1$	....	....	....
.750	$.10_2$	$.05_5$	....	....	....
.760	....	$.02_9$	....	....	....
.770	....	$.01_4$	....	....	....

^{a} Extrapolated values.

The question has been raised as to whether the visibility curve would be modified by using light stimuli in which the energy distribution is normal, e. g., using a grating spectrum. In the blue the length of spectrum (in wave lengths) comprised within a given slit width is only one-fifth[40] that included in the same slit opening when observations were made in the red. However, in either case (prismatic or normal spectrum) the retinal impression is the mean visibility of the light passing through the slit, and in order to eliminate this effect a correction is applied to the observed visibility curve as already described.

As a result of an extensive investigation of the transmission of certain blue and yellow solutions as determined visually and by means of a physical photometer, Ives and Kingsbury[50] concluded that the solution of salts used to produce a transmission curve which coincides with the visibility curve of the average eye would have to be modified so as to produce a higher transmission in the red than was indicated by the average visibility curves of Ives and of Nutting then at hand. The data pertaining to their luminosity-curve solution (*I* and *K*) are plotted in Fig. 14. It is interesting to note that their predicted curve coincides very closely (especially in the red) with the average visibility curve obtained in the present investigation.

The transmission of the ocular media, especially the yellow spot, is highly selective in the blue and violet. In a recent communication Troland[51] applied a correction to the visibility curves published by Nutting in order to eliminate this selective absorption. This correction produces a very symmetrical curve. Applying a similar correction to the energy measurements in order to eliminate this selective absorption, the present average visibility curve is changed into a very symmetrical form, as indicated by the dotted curve in Fig. 14. The uncorrected curve represents the visibility of radiation impinging upon the average eye, no attempt being made to localize the effect within the eye. Correcting for selective absorption traces the stimulus to the retina, and this corrected curve represents the retinal visibility curve of the average eye. As mentioned by Troland, the marked symmetry of this (cone) visibility curve leads to the inference that luminosity is due to a single photochemical process in the retina.

As already mentioned, the present visibility curve is higher in the red than previously observed, but it is in agreement with what is to be expected by other tests. Hence, while the present visibility curve, as a whole, disagrees with previous determinations, it approaches closely (especially in the red) to what is to be expected as the result of other tests in which the spectral visibility of radiation is indirectly involved.

VI. SOME PRACTICAL APPLICATIONS TO RADIATION PROBLEMS

It is important to obtain a mathematical equation of the curve of the relative visibility of radiation of the average eye, with which equation it is possible to relate visual sensation, "light," with radiant energy, especially with the energy radiated from a black body, the constants of which are fairly well established.

1. A VISIBILITY OF RADIATION EQUATION

During the past few years various mathematical equations have been proposed by Goldhammer,[37] Hertzsprung,[38] Nutting,[39] and Kingsbury [47] to express the visibility of radiation of the average eye as a function of an equal-energy spectrum. While such an equation would be of value (1) in defining the visibility curve, (2) in computing radiant efficiencies and the mechanical equivalent of light, etc., unfortunately, in the present state of our knowledge of the processes involved in visual consciousness, such a mathematical equation must necessarily be empirical.

The simple visibility equation

$$V_\lambda = V_m R^n e^{n(1-R)} \tag{2}$$

has been used by Goldhammer,[37] Nutting,[27] and others. In this equation $R = \lambda_{max} \div \lambda$ and the parameter V_m is the ratio of the candle or lumen to the watt at $\lambda = \lambda_{max}$. As used by Nutting $n = 181$ and $\lambda_m = 0.555\mu$. In order to fit the computed curve to the observed curve, the constants used in the present work are $\lambda_m = 0.558\mu$ and $n = 170$. This gives a curve which, as shown in Fig. 15, does not fit the observations very closely except in the yellow and the blue. In view of the fact that there were no indications that such a simple equation could fit the present observations, the three-term formula proposed by Kingsbury [47] was modified by changing some of the constants and adding a fourth term. The formula, which is a modification of equation (2), is:

$$V_\lambda = 0.999(R_1 e^{(1-R_1)})^{200} + 0.035(R_2 e^{(1-R_2)})^{400} \tag{3}$$
$$+ 0.130(R_3 e^{(1-R_3)})^{1000} + 0.084(R_4 e^{(1-R_4)})^{2000}$$

In this formula $R_1 = \frac{0.556}{\lambda}$, $R_2 = \frac{0.455}{\lambda}$, $R_3 = \frac{0.610}{\lambda}$, and $R_4 = \frac{0.525}{\lambda}$.

A fifth term $R_5 = 0.58 \div \lambda$, and a large exponent, say, $n = 5000$, would bring exact coincidence between the observed and computed data at $\lambda = 0.58\mu$. As shown in Fig. 15 and Table 7, between the wave lengths $\lambda = 0.45\mu$ and $\lambda = 0.66\mu$ the observed and the computed data are in agreement within 2 to 3 per cent, which is about as accurate as the visibility observations, including the energy measurements. In Table 7 the second column gives the computed data for the first term of equation (3) and the sixth column gives the summation of all the terms.

TABLE 7

Comparison of Observed and Computed Data Using the Modified Kingsbury Formula

Wave length λ	First term of equation	Second term of equation	Third term of equation	Fourth term of equation	Sum of all Σ	Observed	△ Per cent from observed
0.400	0.000	0.001			0.001	0.010	− 90.0
0.410	.000	.004			.004	.017	− 76.0
0.420	.000	.009			.009	.024	− 62.0
0.430	.001	.018			.019	.029	− 34.0
0.440	.003	.028			.031	.033	− 6.1
0.450	.008	.034			.042	.041	+ 2.4
0.460	.022	.034			.056	.056	0.0
0.470	.050	.028			.078	.083	− 6.0
0.480	.103	.020		0.000	.125	.125	0.0
0.490	.189	.012		$.000_6$	.201	.194	+ 3.6
0.500	.311	.006		.007	.324	.316	+ 2.5
0.510	.463	.003		.036	.502	.503	− 0.2
0.520	.632	.001		.077	.710	.710	0.0
0.530	.791	.000		.077	.868	.862	+ 0.7
0.540	.916		0.000	.038	.954	.954	0.0
0.550	.987		$.000_5$	.010	.997	.994	+ 0.3
0.560	.994		.003	.001	.998	.998	0.0
0.570	.939		.012	.000	.951	.968	− 1.8
0.580	.839		.036		.875	.898	− 1.4
0.590	.708		.074		.782	.800	− 2.2
0.600	.567		.113		.680	.687	− 1.0
0.610	.434		.130		.564	.557	+ 1.3
0.620	.318		.114		.432	.427	+ 1.2
0.630	.223		.078		.301	.302	− 0.3
0.640	.151		.042		.193	.194	− 0.5
0.650	.098		.018		.116	.115	+ 0.9
0.660	.0619		.0063		.0682	.0645	+ 5.7
0.670	.0379		.0018		.0397	.0338	+ 17.4
0.680	.0224		.0004		.0228	.0178	+ 28.1
0.690	.0130		.0001		.0131	.0085	+ 54.2
0.700	.0073		.0000		.0073	.0040	+ 82.5
0.710	.0040				.0040	.00203	+ 97.0
0.720	.0021				.0021	.00097	+116.5
0.730	.0011				.0011	.00048	+129.0
0.740	.0006				.0006	.00028	+114.0
0.750	.0003				.0003	.00020	+ 50.0

2. THE MINIMUM RADIATION VISUALLY PERCEPTIBLE

Calculations have been made of the minimum energy required to excite the retina to visual perception. Evidently the minimum energy required will depend upon surrounding conditions. For example, a sixth-magnitude star is considered the limit of vision in viewing stars. When the eye is adapted to complete darkness its sensibility is much greater than when viewing a star.

Assuming that a sixth-magnitude star is the limit of visibility (at sea level) of the central retina and that the pupillary opening is 3 mm in diameter, Drude[57] calculated that the eye would respond to 12×10^{-8} meter candles, i. e., a sixth-magnitude star is as bright as a Hefner flame at 11 000 meters. The total radiation[56] from a Hefner flame is 26×10^{-6} g-cal. per cm^2 per second (29×10^{-6} for a sperm candle) at 1 m. The radiant luminous efficiency[54] of the sperm candle is 0.0024, so that for the Hefner flame it is about 0.0027. This gives a value of 7×10^{-8} g-cal. (or 29×10^{-8} watt) per cm^2 per second for the luminous energy density at 1 m. For a pupillary opening of 3 mm and a candle at 11 000 meters the light intercepted by the eye would be ($29 \times 10^{-8} \times 0.07 \div 11\ 000^2 =$) 1.7×10^{-16} watt $= 1.7 \times 10^{-9}$ erg. per cm.^{2}

The sensitivity of the eye may be estimated also from direct measurements[55] of the heat from stars. The calibration of the radiometer was 1 mm deflection $= 34 \times 10^{-14}$ g-cal. per cm^2 per minute $= 85.5 \times 10^{-16}$ watt per cm^2 per second. The sixth-magnitude stars gave deflections of 0.5 mm for blue stars to 1.5 mm for red stars (say, 1 mm on an average), depending upon their color. From measurements made on the transmission of stellar radiation through a cell of water the radiant luminous efficiency may be 0.2 (0.1 for red stars to 0.4 for blue stars). Hence, the luminous energy intercepted by a pupillary opening of 0.07 cm^2 is ($85.5 \times 10^{-16} \times 0.2 \times 0.07 =$) 1.2×10^{-16} watt or 1.2×10^{-9} erg., which is in agreement with the preceding computation.

Another method of estimating the minimum radiation which is visually perceptible is to use data on the mechanical equivalent of light, viz, 1 lumen per cm$^2 = 1.6 \times 10^{-7}$ watt per cm.^{2} A pupil opening of 3 mm will intercept ($0.07 \times 1.6 \times 10^{-7} =$) 1.1×10^{-8} watt and for 1.2×10^{-8} meter candle this amounts to 1.3×10^{-16} watt or 1.3×10^{-9} erg.

These computations show the extraordinary sensibility of the eye as compared with a radiometer, which had to be combined with a 3-foot reflecting mirror in order to attain the same sensibility.[a] The ratio of the area of the mirror to the radiometric receiver was 1 to 7 000 000. In other words, the eye is 7 000 000 times as sensitive as the radiometer receiver used two years ago to measure heat from stars. Recent improvements in the radiometer[58] reduce this value to about $\frac{1}{300\,000}$ as sensitive as the eye.

As a further illustration of the extraordinary sensibility of the eye, the above calculations show that it responds to visually perceptible energy of the order of 1.3×10^{-16} watt (3×10^{-14} g-cal. per minute), at which rate it would take 60 million years to raise the temperature of 1 gram of water 1°.[b]

Since writing this paper Dr. Burns has called our attention to a very interesting paper by H. D. Curtis[61] on the limits of unaided vision. One difficulty of making the test of star visibility is in finding the position of the star, after which it is comparatively easy to recognize it. Another difficulty arises from the fact that the background of the sky is not perfectly dark. Given as artificial aids the direction in which the object lies and the screening off of the light of the sky (by looking through a long tube), Curtis could easily see stars of the 7.5 to 8.0 magnitude, but stars of the 8.3 to 8.5 magnitude were seen with difficulty. This means brightnesses one-fifth to one-sixth as great as used in the above calculations. The pupillary aperture would be 6 to 7 mm. Using these values, the above computations give about 8×10^{-10} erg., which is a reasonable estimate of the sensibility of the eye.

VIII. SUMMARY

The object of the present investigation was the determination of the spectral visibility of radiation curve of the average eye, as based upon a large group of observers. The total number of persons subjected to test was 130, of which number 7 were known to be color blind.

One of the most important measurements involved in the work was the radiometric evaluation of the light stimulus, which was a cylindrical acetylene flame. The distribution of energy in the spectrum of the acetylene flame was determined with great care.

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[a] To be exact, this comparison should be made in terms of the "light" instead of the total radiation from a star. Assuming a stellar luminous efficiency of 20 per cent, it would require a 7-foot mirror to attain the sensibility comparable with that of the eye.

[b] Since writing the above section of this paper a discussion of this same subject has been published by Ives.[59] He used a more probable pupil opening of 6 mm and Russel's[60] value of 1 meter candle = −14.18 stellar magnitude. This gives a somewhat higher value than the above, viz, 3.8×10^{-9} erg. per cm.^{2} Using a 6-mm pupil the present computations would be increased fourfold.

As this paper goes to the press, a paper by Russel[62] has appeared in which the data by Ives[57] are recalculated on the basis of the observations of star visibility by Curtis[61] and recent measurements of the aperture (8.5 mm) of the pupil by Stevenson.[63] His calculations of 7.7×10^{-10} erg., for the minimum energy perceptible, is in agreement with the present calculations. This rate of energy reception by the eye corresponds to about 200 elementary quanta of radiation per second, or 1 g-cal. in 1700 million years.

The spectral-energy curve determined with the spectroradiometer used in the present investigation was found in agreement with similar measurements made with two other instruments of an entirely different type of construction.

The methods employed in obtaining the spectral-visibility curve were photometric. The complete visibility curve extending from 0.46μ to 0.74μ was determined with a flicker photometer by comparing the various spectral colors with a standard incandescent lamp. Similar measurements were made at five points in the spectrum using the equality-of-brightness method of photometry, the object being to determine whether there is a systematic difference in the measurements made by these two methods of photometry.

It was found that the various observers experienced little or no difficulty in making the photometric comparisons when using the flicker photometer. On the other hand, only a few observers were able to make accurate settings with the equality-of-brightness photometer, especially in the blue and in the red. This difficulty of forming a judgment of equality of brightness which is not influenced by differences in color seemed to be aggravated by the feeling that such a comparison had no meaning. In the yellow (0.5876μ) about as many observers overestimated as underestimated in making the equality-of-brightness settings as compared with the flicker photometer, and the magnitude of these variations (0 to 50 per cent) were within reasonable limits. On the other hand, when comparing less saturated colors, in the blue and in the red ends of the visible spectrum, a greater number of observers overestimated than underestimated their equality-of-brightness settings. Furthermore, the magnitude of this overestimation varied from 5 to 500 per cent. For the same observer these measurements varied greatly from day to day, whereas his flicker measurements were repeated to within several per cent. Because of these erratic settings the data do not appear to be convincing evidence that the visibility curve determined with the equality-of-brightness photometer differs from the visibility curve obtained with the flicker photometer.

From the data obtained on 14 observers above 40 years of age, it appears that age has a perceptible effect upon the spectral-visibility curve.

The same visibility curves were obtained for the right and left eye of a given observer.

The spectral-visibility curves of no two persons appear to be exactly alike, although there are some which are closely alike. When a spectral-visibility curve does not coincide with the average, there is usually a marked departure from the average visibility in a given spectral region. This gives rise to (1) wide visibility curves with the maximum shifted toward the red, i. e., "red sensitive," (2) narrow curves with a sharp maximum in the green, and (3) curves with the maximum shifted toward the violet. A fourth group of observers has the average visibility in the red and yellow, but has a low sensibility in the blue, while a fifth group has the average sensibility in the blue but has a low sensibility in either the yellow or the red or throughout this entire region of the spectrum.

The data available indicate that 60 per cent of the cases examined fall into three quite evenly divided groups (i. e., 20 per cent roughly estimated, in each group) which are either (1) red sensitive, (2) blue sensitive, or (3) average. Similarly, 30 per cent of the cases examined are quite evenly divided into three groups which fall below the average sensibility in either (1) the red, (2) in the blue, or (3) in both the red and the blue, thus giving rise to an apparently high sensibility in the green. One person in about 20 has a very wide visibility curve as compared with the average.

The point of maximum visibility is very different for different observers. The maximum visibility of the average of 125 subjects is at $\lambda = 0.5576\mu$. Correcting the visibility curve of the average eye for selective transmission of the ocular media including the yellow spot, produces a quite symmetrical curve with a maximum $\lambda = 0.556\mu$.

The present results are in agreement with previous conclusions that the effect of a light stimulus upon the color sense is quite independent of its effect upon the brightness sense. Subjects were found who were normal with respect to color sensation, but who were abnormally sensitive to brightness sensation. The abnormal color sense of so-called color-blind subjects is associated with an abnormal visibility curve.

Tabulated data are given of the visibility of radiation of the average eye as a function of an equal-energy spectrum. A mathematical equation is given of the average visibility curve.

Calculations are given showing that the eye responds to light having an intensity of less than 8×10^{-17} watt, or 8×10^{-10} erg.

WASHINGTON, October 16, 1916.

APPENDIXES

APPENDIX 1.—ON DIFFUSE LIGHT AND SPECTRAL-ENERGY MEASUREMENTS

During the past 10 years repeated attempts have been made to measure the scattered light superposed upon the spectrum under investigation. The invariable result was to find that, provided proper precautions had been taken to prevent reflection of the ends of the spectrum from the sides of the telescope tube and thence upon the radiometer, the effect of scattered radiations ("field light") upon the spectral-radiation measurements was quite uniform and neglible [a] in the visible spectrum.

When using a mirror spectrometer, one test was to attempt to measure the energy in the spectrum at 0.32μ, where the reflecting power of silver is practically zero. Hence the energy measured at this point in the spectrum is due to diffuse radiation. Another test was to attempt to measure the residual energy in the yellow and green part of the spectrum after transmission through Schott's red glass, which is completely opaque to these radiations. The results of these tests indicated that the correction for stray light in the region from the violet to the red was less than 1 part in 300.

In view of the fact that the crucial part of the present investigation has been the energy measurements, this question was recently investigated anew in order to establish beyond all reaonable doubt the accuracy of the radiometric evaluation of the light stimulus.

Before describing the present tests for diffuse light, it is of interest to describe the construction of the radiometric attachment to the spectroscope used in the present investigation.

Until very recently the spectroscopes obtained on the market were not properly constructed to prevent light from being reflected from the side of the telescope tube and from the beveled edges of the slit jaws.

In the present instrument the knife-edge jaws which form the slit are placed with the flat side toward the incident light.[b] The knife edge is curved to fit the image of the slit of the collimating telescope. These slits and the inside of the tube are painted with lampblack, after which the knife edges are wiped smooth with a thin wedge of wood. The inside of the telescope tube was entirely free from springs and attachments to the slits such as are to be found in some instruments. The radiometer end of the telescope tube was about 3 cm in diameter. Hence, when used without diaphragms, one end of the spectrum falls upon the side of the tube when the other end is on the slit. When the blue end of the spectrum was on the slit, enough red light was reflected from the side of the tube into the radiometer slit to increase the true value in the blue by 5 to 50 per cent.

Suitable diaphragms gradually decreasing in opening as they approached the slit prevented reflections from the side of the telescope tube. These diaphragms were painted with lampblack (reflecting power 3 per cent), then smoked by holding them in the flame of a sperm candle. The diffuse reflecting power of soot deposited by holding the plate in the candle flame is very small—as low as 0.5 per cent.[c]

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[a] Coblentz, this Bulletin, **10**, p. 53; 1913.
[b] Coblentz, Journal Franklin Institute, **175**, p. 151; 1913.
[c] Coblentz, this Bulletin, **9**, p. 301; 1913.

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This manner of construction of the receiver end of a spectroradiometer has been employed for a number of years, thus eliminating the possibility of reflection from the side of the telescope tube,[a] and hence reducing the scattered light to the unavoidable "field light", which comes from the prism and lenses. In certain kind of investigations (e. g., transmission spectra) this field light can be reduced by inserting absorption screens. In very exact measurements of spectral-energy distributions it would be more practicable to use two spectroscopes in series.

The diffuse light in the spectroscope used in the foregoing investigation was determined by measuring (with a thermopile) the transmission through a sample of Schott's "monochromatic" red glass (No. 2745; thickness=3.5 mm), which is opaque to radiation of wave lengths less than 0.6μ.

In the first determination of the transmission of red glass the source of light was the acetylene flame used in the visibility measurements. At $\lambda=0.604\mu$, where this glass is not entirely opaque, the transmission was about 0.6 per cent, but throughout the remainder of the spectrum from the yellow ($\lambda=0.5876\mu$) to the blue no radiation transmitted through the red glass could be detected. The sensitivity of the thermopile and meteorological conditions were such that a deflection of 1 part in 130 could have been detected.

In the second determination of the diffuse radiation transmitted through this red glass the source of radiation was a Nernst glower. The intensity in the yellow was more than 30 times as great as in the acetylene flame. The amount of diffuse radiation varied quite uniformly from 3.8 per cent at 0.59μ to 6 per cent at 0.50μ, and from this point the transmission increased rapidly to 18 per cent at 0.42μ. This result was at variance with all previous tests, and in view of the fact that the Nernst glower has far more infra-red radiation than the acetylene flame in the region of the spectrum[b] from 0.7μ to 2μ it was evident that the diffuse radiation was chiefly infra-red radiation.

This test, therefore, was repeated, using a 1-cm cell of a 3 per cent solution of cupric chloride in addition to the red glass. The cupric-chloride solution is practically opaque to the infra-red[c] beyond 0.8μ and has a high transmission throughout the visible spectrum.

Using this combination to eliminate the infra-red radiations, the transmission was found to be about 0.5 per cent at 0.604μ, as observed with the acetylene flame. At $\lambda=0.5876\mu$ the transmission (which is due entirely to diffuse radiation) was found to be 0.3 to 0.4 per cent, while at 0.50μ the (transmission) diffuse radiation amounted to 0.1 to 0.2 per cent. At this point the total deflection was 102 mm and the readings could be made to 0.1 to 0.2 mm; i. e., the observations were read to 1 to 2 parts in 1000. At 0.45μ the diffuse radiation was of the order of 1 part in 300. The test with the Nernst glower is, therefore, in entire agreement with that on the acetylene flame, showing that the radiometric correction for diffuse radiation (which is also of low visibility) is entirely negligible in this work.

As used in the visibility measurements the diffuse light was even less than observed in these tests. This is due to the selection of the part of the optical system which showed the least diffuse light and the "ghost" spectra visible along the axis of the lenses. In view of these facts the data, uncorrected radiometrically for diffuse reflection, are published as given in the foregoing pages.

As already mentioned, the difference between the visibility curve obtained by Nutting and the one obtained in the present work seems to be due chiefly to the

[a] Ives, Phys. Rev., 6, p. 339, 1915, and Souder, Phys. Rev., 8, p. 310, 1916, comment on the great amount of diffuse light which vitiated their spectral-radiation measurements in the blue. Nothing is mentioned, however, concerning the provision of diaphragms to prevent reflection of the spectrum from the side of the telescope tube.

[b] Coblentz, this Bulletin, 7, p. 265; 1911. The present investigation differed from the previous ones in that a Zeiss uncemented triple achromatic lens was used to focus an image of the flame or the glower on the spectrometer slit.

[c] Coblentz, This Bulletin, 7, p. 655; 1911; 9, p. 110, 1912.

difference in our determinations of the distribution of energy in the spectrum of the acetylene flame, especially in the region of 0.59μ to 0.72μ. The spectral-energy measurements, therefore, were verified once more before publishing these data. In the first series of measurements the spectral-energy curve was found to coincide within 1 per cent with the previous measurements in the spectrum from 0.6μ to 0.72μ.

To make this test more crucial, the work was repeated by concentrating our efforts upon measurements at two selected points in the spectrum. At the first point, $\lambda=0.604\mu$, the energy curves used by Nutting and by the writers are in close coincidence, while at $\lambda=0.717\mu$ the energy curve used by Nutting is from 12 to 14 per cent higher than the curve used in the present work. The ratio of the spectral radiation at $\lambda=0.717\mu$ to the radiation at $\lambda=0.604\mu$ should be 3.75 to 3.8 if the former curve is correct. On the other hand, the energy curve used in the present investigation indicates this ratio to be 3.36 to 3.39. Accordingly, a day was spent in making measurements on this ratio. By so doing, the slow change in galvanometer sensitivity which ocurs when determining the complete spectrum was eliminated. In all, six sets of measurements, involving 236 readings, were made. The mean value of the six sets was (3.38, 3.32, 3.41, 3.43, 3.35, 3.36) 3.37, which indicates an exact agreement of the present energy measurements with our previous determinations. The most crucial part of the present investigation has been verified after a lapse of almost a year, and hence there appears to be no reason for further withholding these data from publication.

Washington, November 21, 1916.

APPENDIX 2.—A SCREEN WHICH TRANSMITS RADIATIONS PROPORTIONAL TO THE AVERAGE VISIBILITY CURVE [a]

In certain investigations it is often desirable to use a screen which is opaque to all the infra-red and ultra-violet radiations and which transmits the visible radiations in proportion to the visibility curve of the average eye. Such a screen would be especially useful in a physical photometer, in radiant luminous-efficiency measurements, etc.

The transmission of light through a solution of certain inorganic salts in water forms a convenient and quite accurate copy of the visibility curve of the average eye. Various combinations of salts have been proposed, the most recent being by Ives and Kingsbury.[b] As already mentioned, the concentration of salts recommended by these two investigators gives a transmission curve which coincides very closely with the visibility curve of the average eye except in the green. The object of the present paper is to describe a modification of the above solution which gives a transmission screen which coincides more closely with the visibility curve of the average eye. The lack of coincidence in the blue is of minor importance.

This solution has the following composition:

Cupric chloride ($CuCl_2.2H_2O$)	grams	5.7
Cobalt ammonium sulphate [$Co(NH_4)_2(SO_4)_2.6H_2O$]	do	1.2
Potassium chromate (K_2CrO_4)	do	0.16
Nitric acid (HNO_3)	do	0.123
Water (H_2O)	mols (cc)	100

The salts were analyzed for purity. The nitric acid is expressed as 100 per cent acid (equivalent to 1.3 cc nitric acid, specific gravity 1.05 at 15°/4°).

This solution is to be used in a glass cell 1 cm in thickness with uncolored glass windows. An additional cell of water 3 to 4 cm in thickness is to be used to absorb

[a] These data were obtained in collaboration with Mr. A. N. Finn of the chemical division, who prepared the solutions, and Mr. H. J. McNicholas, who made the spectrophotometric settings.

[b] Ives and Kingsbury, Phy. Rev., (2) 6, p. 319, 1915.

the infra-red rays.[a] To reduce reflection losses these two cells may be placed in contact with a film of glycerin intervening, the edges being covered with paraffin. The maximum transmission of this (double) cell was found to be 61 per cent at 20° C.

The transmission of the separate constituents was determined, and from this the proper concentrations for matching the visibility curve were estimated. In view of the fact that the "computed" and "observed" transmissions at 20° C. are in exact agreement for the mixture of the salts (see Fig. 16) they can be used in a single cell, although one would naturally expect to use the constituents in separate cells. The visibility curve is 1.2 per cent larger than the superposed (at 0.56μ) transmission curve of the screen between λ=0.44μ and λ=0.72μ.

Washington, January 9, 1917.

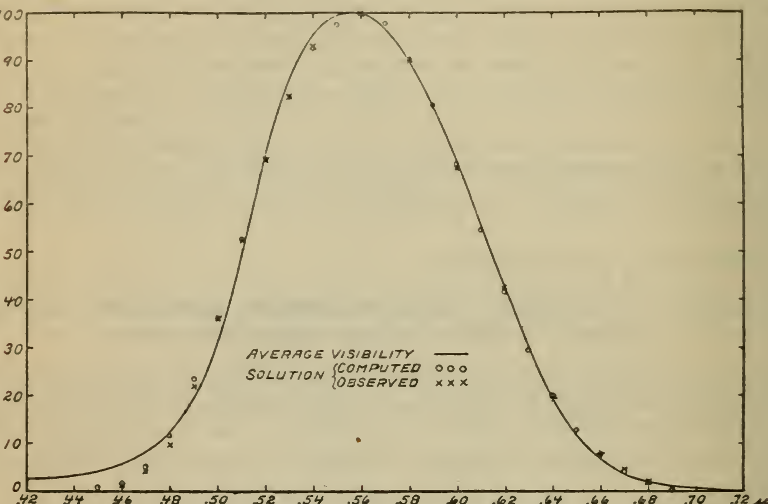

Fig. 16.—*Comparison of average visibility curve with that of the proposed transmission screen*

APPENDIX 3.—TEST OF A PHYSICAL PHOTOMETER

As already mentioned in the beginning of this paper, an important application of the visibility data is in physical photometry.[b] In a previous investigation of a physical photometer it was found that very satisfactory results could be obtained.[c] It was, therefore, of interest to repeat the test, using the luminosity screen described in Appendix 2. In view of the fact that the linear thermopile which was used in the present test was exposed to the air, conditions were not as favorable as in the previous experiments. However, the data obtained indicate that with this instrument accurate measurements can be easily and quickly made. The present test was made upon a standard vacuum tungsten lamp obtained from the photometry division of this Bureau. The lamp was operated at the currents specified to give 1.02 and 1.23 watts per candle, respectively, under which conditions the ratio of the luminous intensities (candlepowers [d]) was =1.405.

In the first series of measurements of these intensities, determined radiometrically, the maximum galvanometer deflection was only 15 mm and the ratio was =1.418, or

[a] This Bulletin, 7, p. 655, 1911; 9, p. 110, 1912; Journal Franklin Inst., 180, p. 355; 1915.

[b] Ives, Trans. Illum. Eng. Soc., 10, p. 101, 1915; Ives and Kingsbury, Phys. Rev., 7, p. 319; 1915.

[c] Coblentz, Jour. Franklin Inst., 180, p. 355; 181, p. 233; 1916.

[d] In accordance with the Middlekauff-Skogland equation, this Bulletin, 11, p. 483, 1915.

a difference of 1 per cent, which is smaller than the errors of observation. In the second series of measurements, made some hours later with the lamp closer to the thermopile (maximum deflection 450 mm) and with more favorable meteorological conditions, the ratio of the radiometric intensities was =1.401. This is a difference of only 0.3 per cent between the photometric and the radiometric determinations. Using a vacuum thermopile the galvanometer reading would have been steadier and a higher precision would have been attainable.

WASHINGTON, January 24, 1917.

APPENDIX 4.—ON COLOR PERCEPTION VERSUS BRIGHTNESS PERCEPTION

As already mentioned in the main part of this paper, an abnormal color sense is associated with an abnormal brightness-sensibility curve, but the converse does not seem to be true. While, of course, many subjects must be tested in order to thoroughly

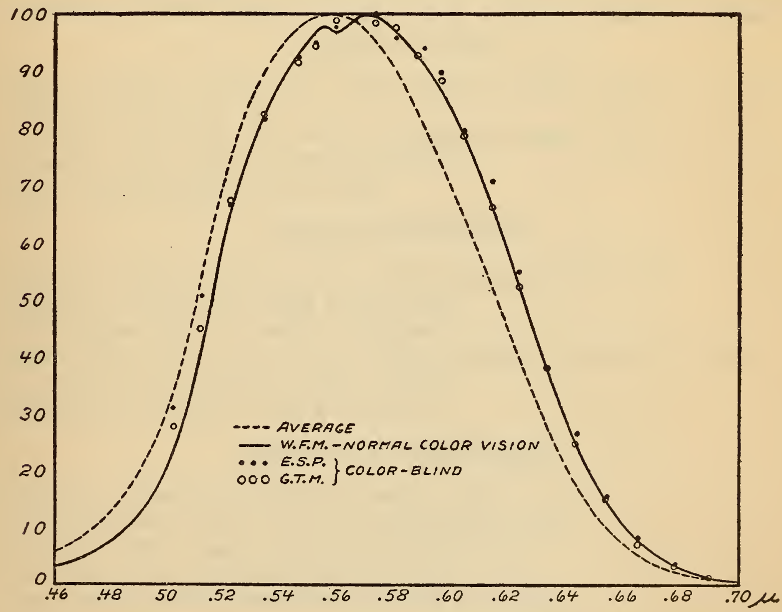

FIG. 17.—*Curve illustrating abnormal color sense as compared with brightness sense*

establish this fact, it is of interest to record further data on the color vison of one subject (W. F. M.), who is abnormally sensitive in the red, but who shows no signs of color blindness by the most crucial tests thus far used.[a]

In the present examination for color blindness each eye was examined separately, the other being blindfolded. The first test made with the Stilling and the Nagel color cards gave no indications of color blindness.

The second test was one devised by Drs. Dunlap and Loring, who consider it better than the Holmgren yarn test. This test consists in classifying a large number of yarns with a set of 11 yarns (red, yellow, green, blue, blue-purple, gray, pink, brown, green-blue, red-purple, and yellow-green) of low color saturation. The subject showed no color confusion in making this classification.

[a] These tests were made in the psychological laboratory of John Hopkins University. The writers wish to acknowledge their indebtedness to Drs. Dunlap and Loring for their courtesy in making these tests.

In the perimeter test (not completed) nothing unusual was found in the color perception of the peripheral retina.

In the spectrometer test the subject named the colors correctly throughout the spectrum.

In the tobacco-scotoma test, the fovea was explored with a colored object (red or green) 17 mm. in diameter, at a distance of 3 meters. There were no indications of a color-blind spot in the fovea.

From this brief summary of the results of the tests for color blindness it is quite evident that the color sense of this subject is quite different from that of other subjects who showed color blindness when examined by much simpler tests, e. g., the Nagel color-card test.

The sensibility curves of these two types of color perception are given in Fig. 17. This is an excellent illustration of abnormal color sense accompanied by abnormal brightness sense, and the converse example, which shows that abnormal brightness sensibility does not necessarily indicate abnormal color perception.

WASHINGTON, March 10, 1917.

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