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ON THE MEASUREMENT OF VISUAL STIMULATION INTENSITIES

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I. INTRODUCTION

It must probably be admitted that there are few fields of science in which definite quantitative results are obtainable, which have been more carelessly cultivated than that of visual psycho-physiology. The literature of visual research is truly monumental, the ascertained qualitative facts are legion, and yet the laws of vision are few and vague. The conditioning cause of our present chaotic conception of visual response is undoubtedly the failure of the majority of investigators in this realm to pay attention to details, chiefly, their failure to measure in absolute units the conditions and results of their experiments. As a consequence, the conditions are not reproducible, and the results can be employed in the support of almost any hypothesis, at the experimenter's pleasure.

The essentials for the standardization and accurate description of the work in vision have been available to intelligent students of the subject for a century, but only quite recently have these essentials been developed to a form in which they are readily applicable. There are now a number of workers on vision in this country whose methods can be described as exact and scientific. Much of this development—on the photometric side at least—has been the out, come of the technical demands of illuminating engineering-and the debate over many methodological details is still far from arriving at a definite conclusion.

The conditions of stimulation for any experiment in monocular vision are unequivocally determined if the 'energy distribution curve' (*cf.* Fig. 1) is known for the total radiation falling upon each sensitive element of the retina. Since the visual receptors, proper, lie in the external strata of the retina, the state of affairs outside the eye is of importance only in so far as it determines that within the eye. The mode of this determination is not simple for any of the dimensions of the visual stimulus.

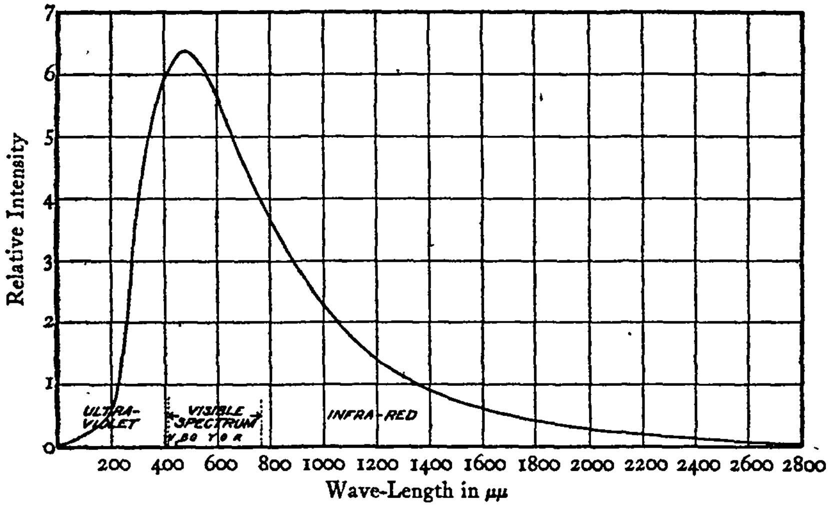

FIG. 1. Energy Distribution Curve of the Radiation from a "Black Body" at 6200° Absolute. The ordinates of this curve represent the 'specific radiant power density' for each wave-length, *i. e.*, they are proportional to the energy per unit wave-length, passing through a given surface in the path of the radiation, in a given time. The area enclosed between the curve and the axis of the abscissæ, is proportional to the 'total radiant power density.' (See note 1.) This distribution curve is closely similar to that of sunlight, and the sensation produced by such radiation would be approximately 'white.' It will be noticed that more than half of the energy lies outside of the visible spectrum. A thermopile will measure all of this energy, while a photometer can deal only with that lying in the visible spectrum.

It is the purpose of the present article to give special consideration only to the general dimension of stimulation intensity. The discussion will be divided into three more or less independent parts, the first dealing with the significance and usefulness of photometric as compared with radiometric measurements, the second considering the problem of the proper method for general photometry, and the third dealing with the influence of pupillary size upon visual stimulus intensity. The final object of the paper is the definition and justification of a standard unit of visual stimulus intensity, the *photon*. Little will be said which is essentially new, but in this field, at the present time, there is small danger that repetition will become over-emphasis.

II. Radiometry Versus Photometry in the Measurements of Stimulus Intensities

It no longer savors of originality to point out that the term 'intensity' has been employed in a very indefinite way by writers in psycho-physiological optics. It has been purposively so employed in the title of the present article. For a technical analysis of various possible meanings of the word, the reader is referred to a footnote,[1] which explains

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[1] Rand (Psychol. Mongr., No. 62, 12) says: "This term [intensity] has been employed at various times to indicate (*a*) the energy of a beam of spectral light homogeneous as to color; (*b*) the white-value of a color; (*c*) the saturation of a color; and (*d*) the energy of light-waves reflected from a pigment surface as conditioned by the general illumination of the visual field." Further (p. 20) "The terminology which we propose to use . . . may be outlined as follows: *Intensity of stimulus* will be used to indicate the energy of light-waves coming to the eye. *Intensity of sensation*, or apparent intensity, will be used as its correlative subjective term. So used, it will signify merely energy or voluminousness of sensation and will have no reference whatever to the white-value of a color. . . . The terms *brightness* and *white-value* will be used interchangeably to indicate the lightness or darkness of a color."

Rand's system of intensity terms appears to be not less confused than that of previous workers. The fact is that practically every intensity term in vision has been employed at one time or another to denote the meanings of every other intensity term, so that any definite nomenclature must be more or less arbitrary. In the present paper the following classification will be utilized.

Intensity will be employed as a generic term to stand for any one of the group of allied dimensions which we are here discussing. The simplest method of defining these dimensions for the purposes of visual physiology is to consider them with direct reference to the retinal image.

From this point of view they are (1) the *total radiant power density*, or the number of ergs of radiant energy of all wave-lengths, striking the retina, per unit area, per unit time. This is the integral of the energy distribution curve for unit time and area, and is what would be measured by a surface thermopile (at the retina).

somewhat in detail the concepts to be used in the ensuing discussion.

One reason why the generalized visual stimulus is difficult to deal with lies in its extreme complexity. Physically speaking there is no such thing as 'homogeneous' light,[1] or a visual stimulus of a single wave-length. Homogeneity is a relative term only, since every light, no matter how 'pure,' must occupy a finite range of the spectrum, and hence must be constituted by an infinite number of wave-lengths, each

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(2) *Specific radiant power density* or the number of ergs per unit wave-length of any single wave-length, striking the retina per unit area, per unit time. This is the value of the ordinate of the distribution curve for any given wave-length, or is the value of the derivative of the complete radiant power density with respect to the wave-length, for a given wave-length.

(3) *Retinal illumination*, or the luminous flux density at the retina, the number of *lumens* of *light* impinging upon the retina per unit area. This may be either *total* or *specific*, according as lights of all wave-lengths or of one wave-length, respectively, are considered. In the latter case the measure will be in lumens per unit wave-length.

(4) *Photometric brightness*, or the luminous intensity per unit projected area of any stimulus surface measured by the standard method of photometry, including only a surface of dimensions negligibly small in comparison with the distance to the observer. This, also, may be *total* or *specific* and, for a constant pupil, would be proportional to the retinal illumination, or *vice versa*. Photometric brightness is an external measure depending on the eye only for the relative values given to light of differing wave-lengths. It is measured in candles per unit area, or in lamberts.

(5) *Luminosity*, or apparent brightness; which is a wholly psychological variable, probably depending upon the degree of stimulation of the retina by given radiation. It cannot be expressed in any physical units, although equality of luminosities furnishes the basis for all photometric equations made by direct comparison. For a wide range of intensities, photometric brightness is independent of the absolute value of the retinal illumination, but the luminosity depends directly upon this quantity, and also upon the general state of sensitivity of the visual system.

(6) *Flicker value*, or the photometric brightness of any stimulus surface, as determined by the standard method of flicker photometry.

In order to avoid the introduction of odious technical terms into the text of the article, *total energy* will be employed as a synonym for 'total radiant power density,' and *specific (radiant) intensity* for 'specific radiant power density.' This amounts merely to a neglect of the fact that radiation has a definite energy density in space and is in motion.

A recent summary of photometric terminology is that of the 1915 Report of the Committee on Nomenclature and Standards of the Illuminating Engineering Society, *Trans. Illum. Eng. Soc.*, 1915, 10, 642–651. See also Rosa, E. B., 'Photometric Units and Nomenclature,' *Bull. Bur. of Stand.*, 1911, 6, 543–573.

[1] Exception might be taken to this statement on the basis of the modern 'quantum' theory of radiation, but such an exception is hardly relevant to the purposes of the present discussion.

with its own specific intensity. Only when the range is very short can we legitimately choose the average wavelength as representative of the whole range, and employ the total energy as the intensity measure. In all other cases we must either divide up the spectrum of the stimulus into a finite number of 'small ranges' of this sort, and state the total energy of each, or we must specify the function (or energy distribution curve) connecting specific (radiant) intensity with wave-length.

An important corollary of the above is that, physically, there is no such generic entity as 'white light,' a conception which is of so much importance in visual physiology. We might define white light physically as light, the energy distribution curve of which approximates that of solar radiation, or possibly that of the radiation from a so-called 'black body' at some definite temperature (see Fig. 1). However, the distribution curves of such types of radiation would be merely isolated examples, out of an infinite number of similar curves, having no essential peculiarities. A *uniform distribution* of energy over the visible spectrum would give rise to a sensation of (unsaturated) purple and not of white.

Another fertile cause of confusion in the discussion of the intensity relations of visual stimuli, is the double or compound meaning of the word 'light.'[1] Light, on the one hand, is a form of radiation, or moving electromagnetic energy, and on the other hand, is a quality of experience, or one dimension—at least—of visual sensation. According to current definitions, light-intensity—measured in lumens—is equal to radiant power—measured in watts—*multiplied by the relative luminosity producing capacity of the given radiation for the normal eye.*[2] This relative luminous capacity, 'stimulus coefficient,' or 'visibility,' is determined by a photometric equation of the given radiation to a standard, the radiant power of the standard being known or, at least, constant. Light, itself, is thus technically neither radiation nor visual

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[1] *Cf.* Nutting, P. G., 'The Luminous Equivalent of Radiation,' *Bull. Bur. Stand.*, 5, 261–264, 1908. Also Cobb, P. W., 'Photometric Considerations Pertaining to Visual Stimuli,' *Psychol. Rev.*, 23, 72, 1916.

[2] *Cf.* Cobb, *loc. cit.*, pp. 87–88.

sensation but is a mathematical concept based upon both of these variables. When we speak of light we imply both radiation and sensation; but both radiation and visual luminosity can exist without any light existing. Light is measured by photometry, radiation by radiometry.

Any mass of radiation moving through space has a definite energy density—contains a definite number of ergs per cubic centimeter—and when this radiation falls upon a surface there is a definite flux of energy into that surface. The total intensity of such a flux on a unit area, can be completely specified in terms of ergs per second—or some other *unit of mechanical power* such as the watt. If the energy is wholly absorbed, and is converted only into heat, the power can be measured by calorimetric methods, *i. e.*, by ascertaining the rise in temperature of the absorbing body, the mass and specific heat of which are known. In practice, this is done, although not easily, with the help of a bolometer, a thermopile or a similar device. Determinations of this sort, when made for successive small wave-length ranges over the entire range of wave-lengths in the stimulus, would make possible an exact specification of the intensity, and would thus render the conditions of the experiment quite reproducible.

Two distinct, but closely related problems are involved in the control of visual stimulation intensities. The first is that of the equation of intensities, while the second concerns the establishment of a definite relation between at least one member of a set of such equations, and an *absolute* and reproducible *standard of intensity.*

In the study of visual response we are interested to determine the manner in which the various dimensions of the response depend upon each other and upon those of the stimulus. This dependency is complex in such a way that it can be represented symbolically by a polyvariable function, like $r = f(w, i, s, \cdots)$ where r is some one dimension of the response, and $w, i, s, \cdots$ are other dimensions, either of the response or of the stimulus. To determine the form of this complex function experimentally it is necessary to hold all of the variables on the right-hand side of the equation constant, except one, and then to subject this one to variation. For example, to determine the effect of stimulus intensity, we may take any constant wave-length and try our experiment with different values of the intensity, or to find the influence of wave-length, we may select a definite intensity and vary the wave-length. In this latter procedure we are obliged to *equate* the intensities of the qualitatively different lights which we use.

For establishing such an equality of intensity the two general alternatives of photometry and radiometry are open. If the first method is employed the equation will be one of brightness; with the second method it will be one of radiant power (per unit area). The specific interpretation which is made of the term intensity will thus depend upon the method adopted.

The relation between the two types of equations should be borne carefully in mind. In the first place, when all other conditions are the same for the two equated stimuli—*i. e.*, for the same wave-length constitution, state of adaptation, position in the visual field, contrast, etc.—a photometric equation implies a radiometric equation. On the other hand, when the two stimuli are not similarly conditioned, in general this implication will not hold, and when the difference is one of wave-length a photometric equation may entail a relation between the radiometric intensity of one stimulus and that of the other, such that the quotient of these two intensities can have values ranging between zero and infinity, according to the relative positions of the two groups of wave-lengths in the spectrum.

Another point of importance is that, for certain standard and fairly representative conditions, the function—visibility curve—connecting radiant energy for equal photometric brightness, with wave-length has been accurately determined for the average or normal eye. This being the case, it is possible, for these conditions, to deduce one measure from the other; and the eye can be regarded as a selective radiometer having a known calibration curve. Conversely, Ives and Kingsbury[1] have carried out extensive experiments on a so-called 'physical photometer' or 'artificial eye' in which an absorbing solution, or equivalent arrangement, having a selective transmission corresponding closely to the normal visibility curve, is placed between the light source and a thermopile. The results obtained, although radiometrically determined, are actually proportional to the photometric brightness of the stimuli measured. The visibility (or stimulus) coefficient, which is plotted—as a function of wave-length—in Fig. 2, is directly proportional to the quotient obtained by dividing the photometric measure by the corresponding radiometric measure.

The average visibility function may now be considered a reliable technical asset of the investigator in vision.[2] Strictly

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[1] Ives, H. E., and Kingsbury, E. F., 'Physical Photometry with a Thermopile Artificial Eye,' *Phys. Rev.*, 1915 (2), 6, 319–334. Also, Ives, H. E., 'A Precision Artificial Eye,' *ibid.*, pp. 334–346.

[2] Average 'visibility curves' for normal cone vision and flicker photometry have been determined by Ives, Nutting, Bender and others. Ives employed 18 observers and later 25 more. Nutting used 21 in all. The relative visibilities (brightness/relative energy) of various parts of the spectrum, as found by these two investigators, are given in the following table:

Wave-Length $\mu\mu$	400	410	420	430	440	450	460	470	480	490
(Nutting)	.002	.003	.008	.012	.023	.038	.066	.105	.157	.227
(Ives)	—	—	—	—	.029	.047	.073	.107	.154	.235

Wave-Length	500	510	520	530	540	550	560	570	580	590
(Nutting)	.330	.477	.671	.835	.944	.995	.993	.944	.851	.735
(Ives)	.363	.596	.794	.912	.977	1.000	.990	.948	.875	.763

Wave-Length	600	610	620	630	640	650	660	670	680	690
(Nutting)	.605	.468	.342	.247	.151	.094	.051	.028	.012	.007
(Ives)	.635	.509	.387	.272	.175	.104	.068	.044	.026	—

Wave-Length	700	710	720	730	740	750	760
(Nutting)	.002						
(Hyde and Forsythe)	.00282	.00137	.00068	.00033	.00017	.00008	.00003

Wave-Length	770
(Hyde and Forsythe)	.000015

Nutting's results are plotted in Fig. 2.

The values from 700 to 770 $\mu\mu$ are calculated from Hyde, E. P., and Forsythe, W. E., 'The Visibility of Radiation in the Red End of the Visible Spectrum,' *Astrophys. Journ.*, 1915, 42, 285–294. Nutting's results appear in his paper, 'The Visibility of Radiation,' *Trans. Illum. Eng. Soc.*, 1914, 9, 633–643; also in the *Phil. Mag.*, 1915,

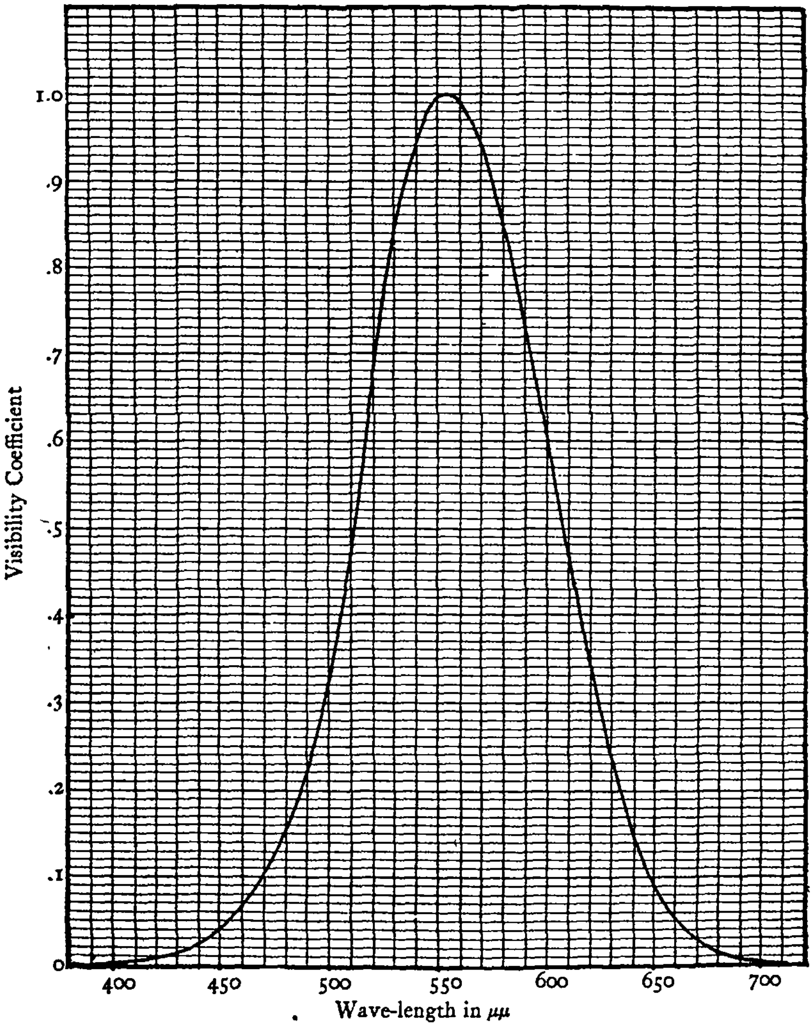

FIG. 2. The Visibility Curve According to Nutting. This curve is an accurate plot of the visibility values given below, representing the average results obtained from 21 subjects. If the photometric intensity of any 'homogeneous' visual stimulus is divided by the appropriate visibility coefficient (read off from the curve), and multiplied by the 'mechanical equivalent of light' (.00132 watts per lumen), the resulting value will be the radiometric intensity of the stimulus. By the converse procedure radiometric intensities can be changed into photometric values. Nutting's data were obtained by flicker photometry, and at a standard intensity of about 75 photons (see text).

speaking there will be a special visibility curve for each individual, for each species, for each absolute intensity of illumination of the retina, for each position on the retina, for each state of adaptation (whether general or specific) and for each method of photometry. However, comparison of the curves for different conditions does not, in general, reveal 'order of magnitude' discrepancies. It is very probable that the modal visibility curve for a given visual type is

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(6) 29, 301. See also: Ives, H. E., 'The Spectral Luminosity Curve of the Average Eye,' *Phil. Mag.*, 1912 (6), 24, 853–864; and Bender, H., 'Untersuchung am Lummer-Pringsheimschen Spektralflickerphotometer,' *Ann. d. Phys.*, 1914 (4), 45, 105–144.

According to Nutting, the equation of the visibility curve is

$$V = V_m R^a e^{a(1-R)} = V_m v_\lambda, \tag{1}$$

where $R = \lambda_{\text{max}}/\lambda$, λ_{max} being the wave-length for the maximum ordinate of the curve, approximately 555, and λ the wave-length for which the visibility is to be calculated. $a = 181$; V_m is the visibility at the maximum and e is the base of the natural system of logarithms. V_m is the ratio of the lumen to the watt (unit of power) at the wave-length having maximum visibility, the reciprocal of the so-called mechanical equivalent of light, for this wave-length. Since the problem of making an accurate determination of the mechanical equivalent of light has only recently been attacked, there is still considerable lack of agreement between authorities, as to its value. Nutting (*loc. cit.*) finds .00120 watts per lumen; Ives ('Luminous Efficiency,' *Electrical World*, 1911, 57, 1565–1568), calculating certain data of Nernst's, gets .00125. Ives, Coblentz. and Kingsbury ('The Mechanical Equivalent of Light,' *Phys. Rev.*, 1915, (2), 5, 269–294) give .00159; Langmuir ('The Characteristics of Tungsten Filaments as Functions of Temperature,' *Phys. Rev.*, 1916 (2), 6, 302–330), .00121; and Hyde, Cady, and Forsythe ('The Candle Power of the Black Body and the Mechanical Equivalent of Light,' *Jour. of the Franklin Inst.*, 1916, 181, 420–421), .00132. The last value, which was calculated on the basis of Nutting's visibility data, was obtained from especially satisfactory data.

The value of the expression, $R^a e^{a(1-R)}$, in Nutting's equation should be equal, for a given wave-length, to the corresponding value in the table, *i. e.*, it gives the relative visibility, or visibility coefficient, of the selected wave-length, the visibility at the maximum being taken as unity. When multiplied by V_m (757), the values in the table, or those obtained from the curve in Fig. 2, or from the equation, will yield the visibility in absolute terms, *i. e.*, in lumens per watt.

The lumen is the unit of luminous flux, and the candle-power of any light source in a given direction is equal to the number of lumens emitted by it per unit solid angle, in this direction. In visual psycho-physiology, however, we are concerned immediately, only with units of brightness, which involve the distribution of candle-power over a surface. Brightness is expressed in lumens per unit solid angle per unit area of radiating surface. Accordingly, the reduction of visual stimulus values from photometric to radiometric terms, means the conversion of *candles per square meter*, to *watts per steradian per square meter*. This latter quantity will be proportional, other things equal, to the energy impinging upon the retina, per unit time, per unit area.

practically independent of everything except the degree of participation, in the response, of rod process as compared with cone process. The problem of separating the effects contributed by these two distinct visual mechanisms, under all conditions, is one upon which further important advances are still possible. The standard visibility values now refer properly only to the normal, trichromatic, cone process.

Ultimately the technical definition of photometric brightness will probably be such that the brightness of any visual stimulus differing in quality from the standard will be determined only by its radiant power, and by the standard 'average visibility' of the given radiation. This standard specific visibility value will be determined by finding the mean values for a large number of normal human individuals under conditions most favorable for photometric comparison, and representing the most common circumstances of vision. On such a basis, with tested normal observers working[1] under the

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To accomplish this reduction, the photometric value of the stimulus, expressed in candles per square meter, must be divided by the absolute visibility of the radiation constituting the stimulus. Thus, if b is the brightness measure in question, and v_λ is the proper visibility coefficient (obtained from the table or from the plot), we have, for watts/(steradian × square meter):

$$w = \frac{b}{V_m v_\lambda} = L\frac{b}{v_\lambda} = .00132\, b/v_\lambda, \tag{2}$$

where L is the mechanical equivalent of light. The same quantity, expressed in *ergs*/(second × steradian × square meter), would be

$$w' = 1.32 \times 10^4\, b/v_\lambda, \tag{3}$$

since one watt is equal to 10^7 ergs per second. The radiometric intensity of the radiation striking the retina can be calculated from w or w', by multiplying either of these quantities by a factor, the magnitude of which is determined by the size of the pupil, the focal length of the eye, and other ocular variables (*vide infra*).

[1] In order to select observers whose color vision approximates the established averages, H. E. Ives has devised color filters intended to provide a simple and effective test of the normality of any individual. See his papers, 'On the Choice of a Group of Observers for Heterochromatic Measurements,' *Trans. Illum. Eng. Soc.*, 1915, 10, 203–209; 'Experiments with Colored Absorbing Solutions for Use in Heterochromatic Photometry,' *ibid.*, 1914, 9, 795–814; 'Additional Experiments on Colored Absorbing Solutions for Use in Heterochromatic Photometry,' *ibid.*, 1915, 10, 253–259; 'A Method of Correcting Abnormal Color Vision and Its Application to Flicker Photometry,' *ibid.*, 1915, 10, 259–271. The Ives-Kingsbury test filters were employed by Crittenden and Richtmyer in their recent extensive investigations of flicker photometry.

specific standard conditions visual photometry can be construed as a special, convenient method of radiometry.

Ferree and Rand[1] claim that for the purposes of scientific physiological optics, the intensity of visual stimuli should be measured, and equated, in radiometric and not generally in photometric terms. If this is taken to mean that, at least with present methods, the ultimate basis of standardization of intensity measures is radiometric, the claim may be admitted. If, on the other hand, it is meant that direct radiometry is required in the psychological laboratory, for the immediate control of visual stimulus intensities, and that photometric measurements and equations should be rejected, we must certainly dispute the contention.

It would even be possible to argue that the radiometric treatment of the intensity of the stimulus is not only technically difficult, and perhaps lacking in immediate interest for the majority of problems, but is arbitrary. To measure radiation in terms of energy is to determine how much heat it can generate. Why not consider radiation in its immediately interesting context, and try to discover how much luminosity, or visual brightness, it can generate? In other words, let us replace the thermopile by a retina, and find the law of distribution of brightness in the spectrum of the stimulus which we are using. Then we shall be able to select visual stimuli of different wave-length, but of equal brightness.

From a strictly physical point of view the argument that the standardization of visual stimuli in terms of the temperature effect of the radiation is of no more fundamental significance than its standardization in terms of brightness, cannot be considered valid. In the first place, if we measure radiation intensity in terms of energy, and employ ideal instruments, our results will be independent of the instruments themselves; every radiocalorimeter which will absorb

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[1] See Rand, G., 'The Factors that Influence the Sensitivity of the Retina to Color, etc.,' *Psychol. Mongr.*, No. 62, 32–40, 1913. Also: Ferree, C. E., and Rand, G., 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. J. of Psychol.*, 23, 328–333.

all of the radiation and convert it all into heat will give us the same measure, and the measure can never be greater than this. In the case of the retina and brightness, however, everything depends on the instruments, and there is, so far as we are aware, no maximally efficient instrument. In general, the energy of a physiological response is not derived from the stimulus, but is merely released by it. Only an almost infinitesimal fraction of the total gamut of electromagnetic waves is capable of producing any brightness at all. There is nothing inherently distinctive about this fraction, either, so that, strictly speaking, its brightness, or its luminosity, is a property of the eye and its appendages rather than of the radiation itself.

Moreover, a measure of brightness cannot be regarded as being in absolute units unless it is referred to a definite radiant power (by use of the standard visibility values). It may be possible, ultimately, to measure the intensity of physiological —and even psychological—response in absolute units, but there is no established technique for doing this at present, so far as the results of photometry are concerned. If it were certain, or even likely, that this response intensity was the same for all individuals for a given intensity of the photometric standard, the response to the standard could be adopted as an absolute norm. As matters stand it can only be regarded as a relative norm.

In spite of all these objections, however, it is the writer's opinion that, in general, the photometric equation of intensities is preferable to the radiometric. This opinion has both a theoretical and a practical basis. The latter consists primarily in the extreme difficulty of making reliable radiometric measurements, as compared with the ease with which photometric equations are established, especially when the flicker method (*vide infra*) is employed. Radiometric and photometric measurements have, in general, about the same precision, somewhat better than one per cent. However, radiometers measure indiscriminately the energy of all types of radiation, whether visible or not, so that unless great care is taken to eliminate infra-red and ultra-violet rays, the results are apt to be wholly misleading, considered as estimations of stimulus intensity, since these special rays are not visual stimuli.[1] Closely related with this is the fact that stimuli equated in energy over the whole spectrum will have a brightness so disproportionate as, in many cases, to make their visual comparison almost impossible. For example, under these conditions, a stimulus of wave-length 550 $\mu\mu$ would be about ten thousand times brighter than one of wave-length 750 $\mu\mu$. One of these stimuli might be just at the threshold, and the other would then be dazzlingly bright.

The purely practical difficulties of radiometry can be conquered by a careful technique. However, considering the interconvertibility of photometric and radiometric measurements, when the former are made by normal observers, it would seem unnecessary for the psychologist to trouble himself with these delicate procedures. *Moreover, whether the observers are normal or abnormal, there are certain theoretical advantages possessed by photometric equations, which cannot be ascribed to radiometric equations.*

Visual response consists of a series of stages or phases following each other in time, each phase having a number of more or less independent dimensions, the exact values in which, however, are determined primarily by the values of corresponding dimensions in the preceding stage. These stages, in their temporal order are, roughly: (1) visual object, (2) radiation from the object entering the eye, (3) the retinal image, (4) the receptor process, (5) the neural stimulation, (6) the afferent impulse, (7) the adjustor (or central) process, (8) the efferent impulse, (9) the effector process. In addition to these, and a function of some, and perhaps all, of the stages, there is: (*a*) visual experience. The values of the variables in each stage at any moment may be regarded as mathematical functions of the values of the variables in preceding stages at earlier moments.

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[1] This statement may perhaps be questioned as applied rigorously to the ultraviolet, but it is the infra-red rays which are most bothersome in the radiometric measurements of visible radiation.

Now for the theoretical analysis of the total process of vision, which must be regarded as the ultimate scientific aim, the problem of the interrelation of what may be called the internal *factors* of the response (succeeding and including the receptor process), is probably of more importance, and is certainly far more difficult, than that of determining the relation between the stimulus variables (1 to 3) and certain internal factors. To separate the effects of the various variables in any internal stage of the response, certain of these variables, directly, should be held constant while others are subjected to change. It must be true that any two stimuli which produce the same effect upon a retinal receptor will have an equal value for all succeeding stages of the response. This will probably hold approximately, also, when the similarity of effect applies to only one dimension of the receptor process, if the subsequent influence of this dimension is considered in isolation from that of the others. The known facts provide us with some guarantee that photometric equations do establish such an equivalency—approximately—for the general dimension of intensity of the response, whereas there is no doubt whatsoever that stimulus energy equations fail in this respect.[1]

Such photometric equations would be relatively independent of specific, individual, and momentary variations in the sensitivity of the visual system, and hence would correct automatically for these variations, provided, of course, that the equations are made by the subject for whom the measured lights are later to be employed as further stimuli. Among themselves a system of intensity measures based upon photometry by *individuals selected at random*, must of course be considered as constructed with reference to any one subject's absolute sensibility to the standard of luminous intensity, as a norm.

However, when photometric equations are made by a

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[1] The exact physiological nature of response intensities, apart from experienced *luminosity*—or other sensory attributes—remains, of course, somewhat vague. It may be a question of equality of reaction velocities, equality of energy released or absorbed per second, or—what is more likely—the concentration of certain ions in the respector cells.

tested, normal observer,[1] they refer back automatically to radiation intensities as a basis, since photometric values obtained under standard conditions must be equal to the corresponding radiometric values, multiplied by the appropriate visibility factor. Consequently, the radiant power of stimuli of wave-length constitution different from that of the standard light can be obtained by dividing the photometric quantity by the factor in question. If a normal observer is not to be found, methods can be applied for correcting the measurements so that they will coincide approximately with the normal.[2]

It is perfectly obvious, of course, that certain problems—such as those of visibility—involving the relationship between the receptor process and the stimulus, must be settled on the basis of direct energy measurements. Our contention here—in summary—is merely that such problems form a relatively small part of the whole group of questions faced by the psycho-physiologist in vision, and that for the remaining group, energy equations will yield results difficult, if not impossible, of interpretation.[3] Moreover, the existence at present of reliable determinations of visibility and of standard methods for applying them to photometric results makes radiometric and photometric measurements largely interconvertible. The simple technique of photometry recommends it to the psychologist, and at the same time permits him to express the conditions of his observations in such a manner that they can be interpreted and reproduced by others.[4]

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[1] The appropriate tests have been described by Ives. See the references above.

[2] See Ives, *Trans. Illum. Eng. Soc.*, 1915, 10, 259–271. Also Crittenden, E. C., and Richtmyer, F. K., 'An "Average Eye" for Heterochromatic Photometry, and a Comparison of a Flicker and an Equality-of-Brightness Photometer. *Trans. Illum. Eng. Soc.*, 1916, 11, 331–372.

[3] In the writer's estimation, the questions raised primarily by Ferree and Rand, *viz.*, the peripheral limits of color sensitivity in the retina, fall mainly in the group where energy equations will complicate, rather than simplify the investigation. *Cf.* Baird, J. W., 'The Phenomena of Indirect Color Vision,' *Psychol. Review*, 1914, 21, 70–79.

[4] It should be borne in mind that ordinary direct radiometry, as carried out by means of a thermopile or bolometer, yields relative energy measures, only. The technique of absolute radiometric measurements, or radiocalorimetry, is even more difficult than that of relative methods.

III. THE PROBLEM OF HETEROCHROMATIC PHOTOMETRY, AND THE JUSTIFICATION OF THE FLICKER PHOTOMETER

If the procedure of photometry involved in general only the equation of stimuli having the same energy distribution curve in the spectrum and hence the same color, the problem would be a very simple one. As a matter of fact, it is very seldom that two visual stimuli to be equated have the same distribution curve, and this, of course, is never the case when the main conditions which we have been considering above are in question, for under such conditions radiometry and photometry are *equivalent* methods. Moreover, photometry in general is color photometry, since none of our light sources are strictly 'white' and even sunlight varies in hue.

The problem of the proper method for the equation, in respect to brightness, of two lights of different color, has been under discussion for many years, but has never received more attention than is being devoted to it at the present day. This problem is partly experimental and partly logical, and more progress has been made on the experimental than on the logical side of the question. The latter aspect of the problem concerns primarily the definition of 'equal brightness,' and the establishment of a scientific criterion for choosing a satisfactory method of heterochromatic photometry.[1]

The term 'brightness' may now be regarded as having been definitely appropriated by the photometrician to designate that aspect of illumination questions which has immediate reference to the effect of a given stimulus on a given eye. The brightness of an illuminated surface depends upon a point of view. When lights of different colors are compared the brightness must also depend upon the visibility curve of the eye, and this visibility curve will not, in general, be the same for different methods of heterochromatic photometry. *It would seem advisable to employ the term brightness to express*

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[1] The criteria have been considered by Ives, *Phil. Mag.*, 1912 (6), 24, 153–157. An excellent discussion of the problem of heterochromatic photometry will be found in M. Luckiesh, 'Color and Its Applications,' 1915, Chap. IX. This book contains much useful data for the investigator of vision.

the photometric value obtained for any visual stimulus by the standard method of photometry. For example, if we adopt the flicker method as our standard procedure the flicker value of a visual stimulus will be its brightness.[1]

Ordinary or direct comparison photometry is based upon an equation of luminosities. The criterion of 'equal luminosity' is not ambiguous when the lights to be compared are of the same color (hue and saturation) since in this case the task of the photometrician is merely to find two amounts of radiation which produce entirely similar sensations. However, when the two radiations are such as to condition a noticeable difference in color, it is necessary to discriminate inspectively between the experiential dimensions of hue and saturation, on the one hand, and that of *luminosity* on the other.

Now there seems to be a general psychological law that the distinctness of any experiential (or qualitative) dimension changes in parallel with the degree of similarity of two compared experiences in all other dimensions. For example, if luminosity, hue and saturation are three dimensions of a visual sensation (*per se*) the threshold for the perception of a difference in luminosity between two sensations will be greater the greater the concomitant differences in hue or saturation, or both. This principle may depend upon a weakening of our powers of discrimination or it may indicate that the dimensions, as such, are to a certain degree mutually dependent and unreliable. In other words, the meaning of the term 'equal luminosity' may become *ambiguous* in proportion as two compared sensations differ in color.[2]

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[1] Since the flicker value and direct comparison value of a given colored light do not, in general, agree, this definition would mean, on the basis of flicker photometry, that equally bright lights do not always generate equal luminosities. This usage of 'brightness' of course conflicts with some traditional phrases, such as 'equality of brightness,' but is in line with the modern development of photometric nomenclature.

[2] This conception may perhaps be expressed by saying that a system of ideal Cartesian axes for the determination of values in these dimensions would not be a set of mutually perpendicular *lines* intersecting in a single point, but would consist of a group of (perhaps truncated) *cones*, with their axes perpendicular and with their apices meeting at the origin of coördinates. This would mean that all differences in luminosity, hue, saturation, tint, etc., are to a certain extent indeterminate, and that

The hypothesis that in heterochromatic comparisons of luminosity it is not essentially the process of judgment but rather the conception of the dimension of luminosity itself which is uncertain, surely represents the psychological facts of the case very well. Relations exist which can be judged categorically as *differences* in luminosity, but it is never possible to make a categorical judgment of *equality* of luminosity. The truthful judgment is always: "I cannot tell whether they are equal in luminosity or not." Langfeld[1] and others have shown that the results obtained by heterochromatic comparison depend radically upon the 'attitude of the observer,' or upon the 'criterion' for equality of luminosity which is adopted. This 'criterion' would amount, on our theory, to a redefinition of the term 'luminosity' for the special comparison involved.

The existence of this uncertainty as to the meaning of the term 'equal luminosity' for lights of different color should lead one to conclude that equality of luminosity, and consequently the method of direct photometric comparison, cannot be regarded as furnishing a satisfactory test of equality of brightness for such lights. The uncertainty of course makes itself evident objectively in the lack of precision of photometric measurements made by this method, and in the lack of agreement between different normal observers.

this indetermination becomes greater in any given dimension the greater the established differences in other dimensions. The facts are such that this hypothesis involves us in fewer serious assumptions than one which refers the difficulty to a fallibility of the discriminative function.

If we adopt the hypothesis in question, it follows that the term 'equal luminosity' necessarily becomes more and more ambiguous the greater the difference in hue and saturation, between two compared sensations. In other words, 'equal luminosity' cannot represent any definite condition of affairs, except the absence of 'unequal luminosity,' a requirement which could be satisfied in many different ways. On this basis, since the photometric equation of brightnesses depends upon the equation of sensory luminosities, the ordinary procedure of 'direct comparison,' or 'equality of brightness,' photometry would tell us unequivocally when two brightnesses were unequal, but not unequivocally when they were equal.

Recent experiments by the writer show that with large color differences between compared visual fields, the just noticeable difference in brightness may exceed 20 per cent. See 'The Heterochromatic Brightness Discrimination Threshold,' *Journal of the Franklin Inst.*, 1916, 182, 112–115.

[1] Langfeld, J. S., 'Ueber die Heterochrome Helligkeitsvergleichung,' *Zeitschr. f. Psychol.*, 1909, 53, 113–179.

If we reject the method of direct comparison we must cast about for another procedure which measures approximately the same quantities, but which depends upon more definite psychological criteria, and possesses a better objective precision. A large number of careful experiments, due primarily to H. E. Ives,[1] have proved unquestionably that *flicker photometry* satisfies this requirement. It has been shown by Ives that (1) "the flicker method is more sensitive than the equality of brightness method, where different coloured lights are compared," and that (2) "the results by the flicker method are more reproducible than those by the equality of brightness."[2] Crittenden and Richtmyer, in recent work, find the mean variation of the results of 114 observers by the 'equality of brightness' method to be 1.9 per cent. and by the flicker method .6 per cent. for the same stimuli. They say: "With regard to certainty of measurement the flicker photometer shows a decided advantage even with small color differences. With more experienced observers, specially selected, this advantage would probably be materially reduced, but would not be entirely lost, because even when an observer makes consistent settings on the equality photometer the relation of his settings to those of the normal observer is uncertain. . . . with the flicker any observer of fair ability can make definite sets even with large color differences whereas on the Lummer-Brodhun ['equality of brightness'] photometer it is only the exceptional observer who can do so. . . . The flicker photometer affords a means of relatively precise comparison between lights of all degrees of color difference, and makes possible the use of test readings for which average values, which should be highly reproducible, can be established."

Ferree and Rand[4] have attacked the flicker method on

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[1] Ives, H. E., 'Studies in the Photometry of Lights of Different Colours,' *Phil. Mag.*, 1912 (6), 24, 149–189, 352–370, 744–751, 845–864. See also the recent elaborate investigations, with 114 subjects by Crittenden, E. C., and Richtmyer, F. K., 'An "Average Eye" for Heterochromatic Photometry, and a Comparison of a Flicker and an Equality-of-Brightness Photometer.' *Trans. Illum. Eng. Soc.*, 1916, 11, 331–367.

[2] *Loc. cit.*, p. 177.

[3] Ferree, C. E., and Rand, G., 'A Preliminary Study of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Colors,' *Psychol. Rev.*, 1915, 32, 110–163.

the ground that the results which it yields disagree with those of the 'equality of brightness' procedure. They explain the discrepancy in terms of the different rates of growth and decay of sensation for the different colors. This criticism of the use of the flicker method—and the considerations on which it is based are not new[1]—presupposes that the object of a method of photometry is to measure light in terms of equated luminosities, and that to justify the flicker procedure, it is necessary to prove that the *flicker value* of a light agrees within the limits of precision of the measurements with its value as determined by direct comparison. It is one thesis of the present article that this presupposition is arbitrary and scientifically questionable.

In the first place, it must be admitted that an acceptable method of photometry must yield results which agree *approximately* with those of the 'equality of brightness' procedure; the disagreement should certainly at no point be greater than a single order of magnitude. The reason for this requirement is to be found in our conviction that luminosity is closely proportional to the intensity of the response, and to the utility of the radiation, the variables in which we are fundamentally interested. However to require accurate agreement between the two sets of results would be unreasonable, first, because of the relative ambiguity of 'equality of luminosity,' and secondly, because it is improbable that luminosity or any other property of the response which we may select as a basis for establishing a photometric balance, can be considered immediately indicative of all phases of the intensity of the response, without correction for the special conditions of its utilization.

Ferree and Rand do not claim to be pioneers in the proof that the results of the flicker method and that of direct comparison do not agree. Ives[2] found that the curves showing the distribution of brightness in the spectrum, as determined by the two methods, differed in a number of very

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[1] See Luckiesh, M., 'On the Growth and Decay of Color Sensations in Flicker Photometry,' *Phys. Rev.*, 1914 (2), 4, 4–6.

[2] *Loc. cit.*, pp. 177–178.

definite ways. However, in general these differences were small. Crittenden and Richtmyer say: "In regard to relative results there appears to be no room for doubt that for sources having relatively high intensity at the blue end of the spectrum the values given by the flicker photometer as here used depart appreciably from those obtained with the Lummer-Brodhun as used in common practise, the difference being of the order of 2 per cent. at the higher efficiencies reached by the present gas-filled lamps."[2]

Considering the probable complexity of the processes of growth and decay of color sensation it would indeed be surprising if the results obtained by the flicker photometer depended directly, without correction, upon the luminosity value of a light. Very interesting theoretical studies on this question have been made by Ives and Kingsbury.[2] Successive contrast must also introduce complications,[3] just as simultaneous contrast must influence the results of direct com-

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[2] The same authors continue: "It is, however, hardly proper to assume that the results obtained by either photometer are 'right' and anything different is 'wrong'; the equality-of-brightness method of measurement is undoubtedly more closely related to the way in which the light is used, but it is by no means established that the method correctly indicates the relative usefulness of two kinds of light. It must be recognized that there is no one definite 'correct' ratio between the intensities of two lights of different color. . . . The specification of conditions of measurements must be more or less arbitrary, and the results obtained cannot be expected to be an exact indication of the value of different kinds of light under different conditions. Before we shall know much about the relative usefulness of different kinds of light much more experimental work must be done; an important requisite for such investigations or any others involving the comparison of the intensity of lights by very different color is a method which will enable different experimenters to make consistent measurements of the quantity which must serve as a basis for the comparison of their results. The usual equality-of-brightness method of comparison certainly does not fulfill this requirement; the flicker photometer at present is the most promising method available." "Comparison of actual tests made in the routine work of the laboratory shows that even with relatively small color differences a given accuracy of reproduction of results requires several times as many measurements with the equality-of-brightness or the contrast photometer as with the flicker; moreover the tests considered were made by observers who had had much experience with the contrast photometer and very little with the flicker."

[2] Ives, H. E., and Kingsbury, E. F., 'The Theory of the Flicker Photometer,' *Phil. Mag.*, 1914 (6), 28, 708–728. This article represents clearly the correct way to attack visual problems, and contains concepts of fundamental importance for a large number of visual phenomena.

[3] Cf. Luckiesh, *lec. cit.* p. 6–8.

parison.[1] The theory of the flicker photometer as developed by Ives and Kingsbury, indicates that its results should approach asymptotically those of the direct comparison method as the intensity of stimulation increases. This deduction is in harmony with fact.

The essential point to be established, however, is this: the one necessary requirement of a method of measurement is that it shall permit the accurate reproduction of experimental conditions. As shown by the work of Ives and other modern students of the problem of heterochromatic photometry, this requirement is met by the flicker method, and not by any other procedure which has been adequately tested.[2] As a consequence, we are forced at present to accept the flicker method as our standard procedure, and to define photometric brightness in terms of its results regardless of the fact that these results differ somewhat from those obtained by the criterion of equal luminosity.

It is possible that we shall ultimately find some reliable method for measuring directly what may be called the *true response intensity*, for a specified stage of the response. The exact functional connection between this quantity and flicker value can then be determined, so that the true intensity can be deduced from the flicker value. Possibly the nature and magnitude of this correction can be deduced from the theory of the flicker photometer. For many purposes, however, the conversion of true physiological intensity would prove useless, since a knowledge of the laws connecting other properties of stimuli, *e. g.*, such as acuity values, with flicker value should be as serviceable as a knowledge of the relation between these properties and true intensity. For theoretical purposes, of course, equations of true intensity are highly desirable, but it is by no means certain that the method of direct com-

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[1] See Bell, L., 'Some Factors in Heterochromatic Photometry,' *Electrical World*, 1912, 59, 201–203.

[2] Ferree ('A New Method of Heterochromatic Photometry,' JOURNAL OF EXP. PSYCHOL., 1916, 1, 1–13) has recently proposed a new procedure for which he claims remarkable accuracy. Since the method is a peculiar one, not immediately suggestive of reliability, it will have to be more carefully investigated before it can be taken seriously.

parison would not demand corrections, in this respect, as great as those required by flicker. Moreover the flicker results furnish a reliable measure upon which to base such a correction, which cannot be said of the results obtained by direct comparison.

As already pointed out, the general problem of photometry is that of establishing heterochromatic equations, since color differences are the rule rather than the exception, for the lights which need to be compared. However, when the color difference is less than some critical amount, the method of direct comparison becomes more sensitive than that of flicker. But, as color difference disappears, the results of the flicker procedure approach identity with those of direct comparison, so that for lights differing only slightly in color from the standard it is immaterial whether we define photometric brightness in terms of flicker or of equal luminosity values, and in such case—as in general—we will naturally employ the method which is the most reliable.

IV. The Influence of the Pupil on the Intensity of the Visual Stimulus, and the Definition of a Standard Unit for Specifying the Intensity of Visual Stimulation

In a previous article[1] the writer has emphasized the importance of the artificial pupil in the control of the intensity of visual stimuli. The actual visual stimulus is the retinal image, and the illumination which this image represents is always proportional to the area of the pupillary opening. The normal range of variation of pupillary area is from 1 to about 16, so that neglect to control the size of the pupil would introduce a factor of uncertainty into our measurements of the intensity of the visual stimulus—or our equations of response energies—perhaps as great as 1,600 per cent. This is not large compared with the range of external illuminations, but it is enormous compared with accuracy with which intensities can be determined by photometry.

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[1] Troland, L. T., 'The Theory and Practise of the Artificial Pupil,' *Psychol. Rev.*, 1915, 22, 167–177.

All careful workers in vision have recognized this fact, and have taken pains to keep the pupil opening constant, and to state the pupillary diameter as one of the conditions of their experiments. This is true of Ives's studies on the flicker photometer, of Nutting's determination of the visibility function, and of the earlier careful measurements of König on visibility and difference threshold. There may be some problems in vision for which the *order of magnitude* of the intensity alone is of importance, but with entire neglect of the pupillary size we cannot even insure a knowledge of the exact order of magnitude of the retinal illumination. In the present state of visual science it is not safe to assume that a determination of the order of magnitude of the intensity, or an establishment of intensity equations to a first order of approximation, is generally adequate.

It is perhaps needless to say that these considerations apply with equal force both to radiometrically and photometrically determined intensities.

When the pupil size is known it is convenient to express the intensity conditions in terms of unit pupil area. This is done by both Ives and Nutting in the researches already referred to. In an extensive monograph on the laws of color adaptation, yet to be published, the present writer has expressed his intensity measures throughout in terms of a unit involving the pupillary area, and has proposed that this unit, called the *photon,* be adopted as the standard means of specifying the photometric intensity of visual stimulation conditions.

The definition of such a unit involves a number of independent considerations. The first of these concerns the mode of expressing what may be termed the *external intensity* of the stimulus. As a rule this external intensity is given, in descriptions of visual work, in terms of *meter-candles.* This is, of course, a mistake, since the meter-candle is a unit of *illumination, i. e.,* it measures the light *falling upon* a surface, whereas for purposes of visual experimentation, it is the light (density) *leaving* the surface *in the direction of the eye* which, alone, is of importance. To deduce this quantity from the illumination it is necessary to know the coefficient of reflection, and the diffusing power of the surface. The quantity in question is called the *photometric brightness* of the surface in the given direction, and is measured in candles per unit area, or in *lamberts*. It is the only external photometric quantity which is of importance to the visual physiologist, since it is the brightness which determines the illumination of the retinal image.

It would be supererogatory to discuss this question of the measurement of the external intensity of the stimulus further in this paper, since it has been thoroughly treated in the recent and extremely useful article by Cobb, already referred to.[1] Suffice it to say that the first step is to determine this intensity in (let us say) candles per square meter, from the exact point of view to be employed by the subject in the experiment.

This determination should be made by a normal subject under standard conditions (or else corrected to the normal) and, in general, by the use of a flicker photometer. The photometer should be of the Whitman disk type, in which the alternation consists of an instantaneous substitution of the measured light for the standard at any one point of the retina, and in which the periods of presentation of the standard and the measured light are equal. Moreover, the speed of the photometer should be adjusted so as to give maximum sensibility, *i. e.*, should not be increased beyond the point at which color-flicker just disappears.[2]

The photometric equation should be established with the eye centered in front of an artificial pupil sufficiently small to prevent oscillations of the natural pupil from cutting off any of the light.[3] This pupil may be of any shape, provided its area is known, and in the standard case its axis should coincide with the line of sight. For stimuli produced by simple transmission or reflection arrangements, the circular pupil is preferable, while for spectral stimuli in which an

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[1] *Psychol. Rev.*, 1916, 23, 71-89.

[2] The writer is at present making careful measurements of this critical speed for the spectral colors at various intensities, and with standard lights of various colors. See *Journal of the Franklin Inst.*, 1916, 181, 553-555.

[3] See the writer's article on the artificial pupil.

image of a slit is thrown upon the eye, a square, or otherwise rectangular, opening is more convenient and reliable. In the case of a slit image it is not necessary—in determining the photon value—that the image should fill the pupil, provided the light from the standard fills it. To establish a photometric equation the two retinal illuminations must always have the same brightness, and any increase in the effective pupil area for one will thus automatically be compensated for by an inversely proportional decrease in the external intensity needed for the equation.

Let us suppose that the measured brightness is b candles per square meter, and that the area of the pupil is p square millimeters. Then if r is the illumination of the corresponding retinal image (in meter-candles), we have

$$r = jpb, \tag{4}$$

where j is a factor depending upon the reflection, absorption and scattering of light in the eye, upon the angle of incidence of the rays with reference to the line of sight, and upon other influences to be considered below.

Suppose, now, that in an ideal case both p and b are equal, separately, to unity. Obviously in this case the value of the product, pb, will also be unity. For a given value of j this condition represents a definite retinal illumination, which will be duplicated whenever pb has the value of unity, whether or not the individual components have this value. Let us arbitrarily select this convenient intensity, for certain standard conditions, to be specified more in detail below, as the unit of physiological stimulus intensity, which may be known as the *photon*.

It should be clear from the above that if the intensity conditions of stimulation in visual experiments are expressed in photons they are unequivocally determined and can be directly compared, regardless of the actual pupillary size which was used, or the actual external brightness. To obtain this photon measure approximately it is only necessary to multiply the photometrically ascertained brightness—in candles per square meter—by the area of the pupil—calculated in square millimeters.

In order to determine accurately the physiological intensity of a stimulus surface under any desired condition, it is necessary to correct for variations in the factor j. The value of this factor may be regarded as summing up the

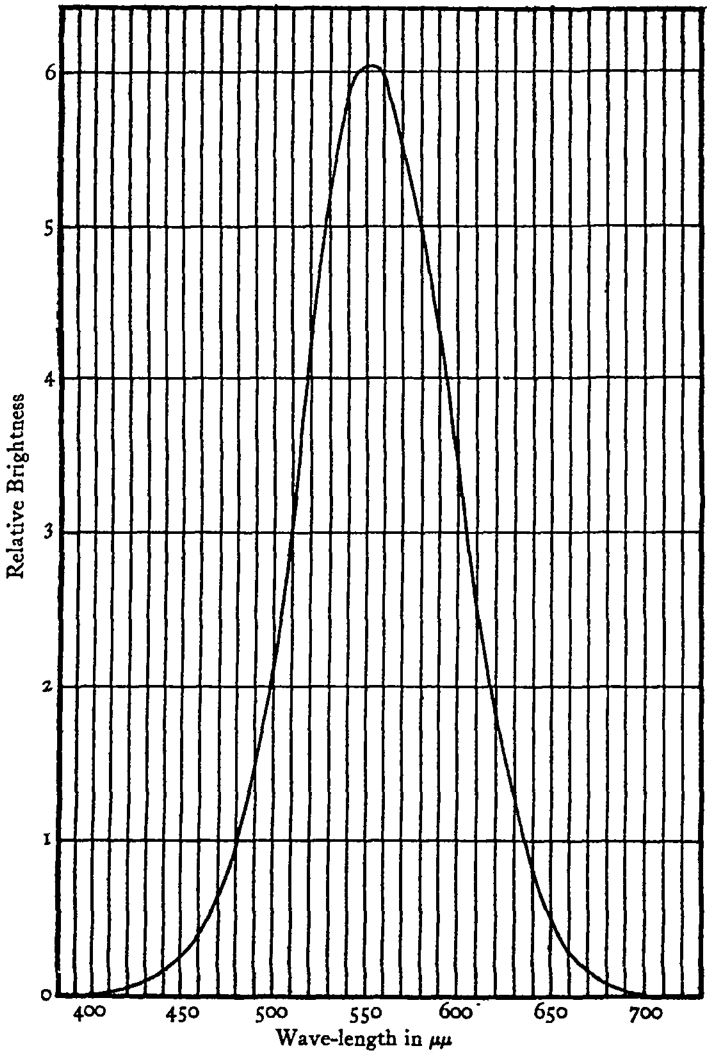

FIG. 3. Brightness Distribution Curve of the Light from a "Black Body" at 6200° Absolute. This curve was obtained theoretically by multiplying each ordinate of Fig. 1 by the corresponding ordinate of Fig. 2. It will be seen that it is practically identical in form with the visibility curve.

influence upon retinal illumination of variables other than the external brightness and the area of the pupil. The most important of these variables are the angle made by the direction of the stimulus surface with the line of sight, and the distance of the artificial pupil from the nodal point of the eye.

If ϕ is the angle in question (see Fig. 4) and the plane of the pupil is perpendicular to the line of sight, j must contain the factor: cos ϕ. On the assumption that intensity differences less than one per cent. may be neglected, the influence of angle can be disregarded, unless ϕ is greater than 8°, since the cosine of 8.1° is .9900. In the paper already referred to, the writer has estimated that the limiting angle for the use of the ordinary artificial pupil is about 53°. The cosine of 53° is .6018, the reduction in the physiological intensity of a stimulus viewed at this angle therefore amounting to about 40 per cent. of its value for direct vision.

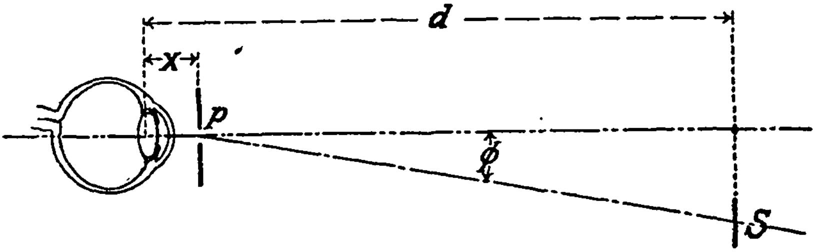

FIG. 4. The Influence of the Position of a Stimulus Surface and Artificial Pupil on the Intensity of the Retinal Image. See the text.

For larger angles than this it is still possible to use the principle of the artificial pupil by means of an optical train which forms a sharp image of a small diaphragm within the natural pupil. This device has been employed by Cobb,[1] although not for peripheral stimulation. In an arrangement of this sort the area of the effective pupil depends entirely upon that of the diaphragm, the image of which falls within the natural pupil, but may be considered equivalent to the

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[1] Cobb, P. W., 'The Influence of Illumination of the Eye on Visual Acuity,' *Amer. Journ. of Physiol.*, 1911, 29, 87.

pupillary area which was employed in photometering the light. In this case—provided, of course, the image clears the iris—there is no cosine effect.

It is possible to avoid the cosine correction in the use of the ordinary artificial pupil if the pupil is placed normal to the line passing through center of the stimulus surface and the nodal point of the eye, provided the surface in question is small. However, such an arrangement of the pupil presents no practical advantages, but only difficulties.

There is, of course, also a cosine effect when the natural pupil is employed, although it cannot be calculated directly from the external visual angle of the rays, on account of the refraction which occurs at the cornea. This tends to reduce slightly the average angle at which the rays strike the natural pupil, so that the reduction of intensity will not become appreciable at so small an external visual angle as with the artificial pupil.

In addition, for both natural and artificial pupils, there are other influences affecting the retinal illumination. The loss of light by reflection at the various refracting surfaces of the eyes increases with the angle at which the light impinges upon them. Besides this, the light strikes peripheral regions of the retina obliquely to the surface. Both of these effects reduce the peripheral retinal illumination. The peripheral regions, however, are reached by the light after passing through a somewhat thinner layer of absorbing material than is the case for the central regions, which would involve a slight relative increase in the illumination.[1] All of these factors would have to be taken into consideration in determining an accurate value for the physiological intensity of stimulation in the extreme periphery, although they can safely be neglected for fixated fields of 20° or smaller.

If the *photon* should be adopted as the universal unit for expressing the intensity of retinal stimulation it would of course be necessary to reduce the intensity to terms of this unit even when an artificial pupil is not used. This can be

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[1] This is not by any means a complete catalogue of the factors influencing the intensity of the light which gets to the retinal receptors, but it will probably suffice for the present discussion of approximations.

accomplished, approximately, by multiplying the photometric brightness of the stimulus by the average apparent size of the natural pupil—the so-called *Eintrittspupille.*

Analysis shows that the illumination of the retinal image is not wholly independent of the distance between the artificial pupil and the eye. In general the illumination of the retinal image is nearly independent of the distance of the *object* from the eye.[2] This is a result of the fact that the area of the image changes in close proportion to the total light flux entering the pupil from the object. However, when the eye moves relatively to an artificial pupil, and the object is stationary with respect to the pupil, this compensation does not occur, since the total flux remains the same, while the area of the image alters.

If f is the focal length of the eye, d the distance of the stimulus surface from the nodal point of the eye, and x the distance between the artificial pupil and the nodal point of the eye, we can argue as follows. Take S as the area of the (small) stimulus surface, and b, as its brightness. Then the area of the retinal image will be Sf^2/d^2, and if p is the area of the artificial pupil, the total flux passing through it will be $Sbp/(d - x)^2$. Consequently, the illumination of the image must be proportional to

$$\frac{bpd^2}{f^2(d - x)^2}.$$

It is seen that if x is small compared with d its influence can be neglected.

Assuming that the effect of x upon the retinal illumination must be less than one per cent. to be negligible, we may solve the equation: $d^2/(d - x)^2 - 1 = 1/100$ to determine how small x must be made in order that its influence can safely be neglected. We find: $x = d/201.5$, or the distance between the nodal point of the eye and the artificial pupil must be less than 1/200th of the distance between the nodal point

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[1] See Cobb, *Psychol. Rev.*, 1916, 23, 80–81. This proof does not hold accurately for objects close to the eye, since the area of the retinal image depends on the distance from the object to the nodal point of the eye, while the total flux of light contributing to the illumination of the image depends on its distance from a plane between the iris and the cornea, the nodal point of the 'reduced eye' lying posterior to the iris.

and the stimulus surface in order that its influence shall be negligible. Accordingly, it is necessary to adopt some standard position for the pupil. Optically, the natural position would be at the nodal point of the eye, since if the pupil were at this point, the retinal illumination would be independent of the distance of the stimulus surface. However, the natural pupil ordinarily lies about 2.7 mm. anterior to the nodal point and an artificial pupil can hardly be placed nearer than 10 mm. to it, or about 4 mm. from the cornea.

On account of the general necessity for correction—whatever the standard position adopted—it seems advisable to choose the plane of the nodal point of the eye, although no pupil ever does actually take this position. On this basis, the photon value is given with considerable accuracy by the equation:

$$i = \frac{pbd^2}{(d - x)^2} \cos \phi, \tag{5}$$

the significance of the variables being as already defined.

Of course, the above discussion must be considered only as approximative, but formula (5) will suffice for most purposes.

The following formal definition may be given of the *photon*, and of *the physiological intensity of a visual stimulus.* A *photon* is that intensity of illumination upon the retina of the eye which accompanies the direct fixation, with adequate accommodation, of a stimulus of small area, the photometric brightness of which, as determined by the standard flicker comparison and a normal subject, is one candle per square meter, when the area of the externally effective pupil, considered as lying in the nodal plane of the eye, is one square millimeter. The *physiological intensity of a visual stimulus* is its intensity expressed in photons. The photon is a unit of illumination, and hence has an absolute value in meter-candles.[1]

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[1] The numerical magnitude of the photon, in meter-candles, and also its reduction to energy units will be considered by the writer in a further paper. It will obviously be subject to some variation from individual to individual.

V. SUMMARY

The present paper is a somewhat discursive study of certain very general questions with regard to the measurement of the intensity of visual stimuli. The writer hopes that as a review of facts, as well as of problems, the paper will prove itself useful to the psychologist.

The various meanings of the term intensity are discussed, and the fundamental significance of photometric and radiometric measurements is considered, together with the relations which hold between radiant energy and light. Recent important empirical studies of these questions are summarized. On the basis of these facts and a theory as to the probable physiological significance of photometric equations, it is claimed that in general such equations will be more useful to the student of visual psycho-physiology than will radiometric equations.

The fundamental presuppositions of a method of photometry are then taken under consideration, and on the basis of recent very careful studies of the method of flicker, it is claimed that this method should be adopted, at least tentatively, as the standard photometric procedure, whenever two compared lights show a color difference.

A third aspect of the problem concerns the influence of pupillary size and other factors besides the external brightness of the stimulus, upon the illumination of the retinal image. In a preliminary discussion of this question, new considerations with reference to the use of the artificial pupil are presented, and the *photon*, defined as a unit of *physiological stimulus intensity*, is offered as a basis for the general standardization of conditions of visual experimentation, with regard to intensity.

This paper is written primarily for the experimental psychologist, rather than for the photometrician or illuminating engineer, but at the same time discusses fundamental problems of general interest.

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