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Mesopic Photometry: History, Special Problems and Practical Solutions

Foreword

The following members of TC 1-01, Mesopic Photometry, took part in the preparation of this technical report. The committee comes under CIE Division 1, Vision and Colour.

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Mesopic Photometry: History, Special Problems and Practical Solutions

ABSTRACT

This report is a summary of information concerning the measurement of light at levels between those of photopic vision, where $V(\lambda)$ applies, and scotopic vision, for which $V'(\lambda)$ is used. There is currently no official CIE system recommended for measuring light at these mesopic levels. Consequently many people use photopic photometers, a fact which results in improper evaluation of the light from many of the newer sources of illumination.

This report contains a history of CIE suggestions, a discussion of the special problems involved, and descriptions of five current systems proposed for evaluation, together with examples of the calculations required.

Photométrie mésopique: Historique, problèmes spécifiques et solutions pratiques

RÉSUMÉ

Ce rapport est un résumé de connaissances relatives à la mesure de la lumière aux niveaux intermédiaires entre ceux de la vision photopique, pour lesquels la relation $V(\lambda)$ est applicable et ceux de la vision scotopique, pour lesquels la relation $V'(\lambda)$ est utilisable.

Il n'existe pas de méthode officielle CIE recommandée généralement pour mesurer la lumière à ces niveaux mésopiques. En conséquence, beaucoup de personnes font usage de photomètres photopiques, ce qui conduit à une évaluation incorrecte de la lumière émise par de nombreuses sources nouvelles d'éclairage.

Ce rapport contient: un historique des suggestions faites par la CIE, une discussion sur les problèmes spécifiques posés et la description de cinq méthodes courantes proposées pour l'évaluation de la lumière, ainsi que des exemples des calculs qu'elles impliquent

Mesopic Photometry: Geschichte, spezielle Probleme und praktische Lösungen

ZUSAMMENFASSUNG

Dieser Bericht enthält eine Zusammenfassung des Wissens über die Photometrie im Adaptationsbereich zwischen photopischem Sehen, wo die Funktion $V(\lambda)$ gilt, und skotopischem Sehen, wo die Funktion $V'(\lambda)$ angewendet wird. Für diesen mesopischen Adaptationsbereich gibt es derzeit kein offizielles CIE-System der Photometrie. Folglich werden oft Photometer für das photopische Sehen verwendet, mit dem Ergebnis, daß das Licht von vielen neueren Lichtquellen falsch bewertet wird.

Dieser Bericht enthält eine Übersicht über die bisherigen CIE-Vorschläge, eine Diskussion der spezifischen Problematik und eine Beschreibung von fünf derzeitigen Systemen, die zur Erprobung vorgeschlagen werden, zusammen mit Beispielen für die notwendigen Berechnungen.

1 INTRODUCTION

The goal of this report is to summarize the information that is currently available on the measurement of light at mesopic levels of intensity. Mesopic refers to light levels covering a range of several log units, which are neither completely photopic (for which the use of $V(\lambda)$ may be appropriate) nor scotopic (for which $V'(\lambda)$ should be employed). This covers an approximate range of luminance from some hundredths or less of a cd/m^2 to at least several cd/m^2 . There is no official CIE method available for assessing lights at these levels, although there is a long history of CIE involvement in this area and a number of different methods have been suggested for trial at different periods of time.

A major reason for the lack of a system of mesopic photometry is the extreme complexity of the subject. In keeping with standard CIE definitions of light, it is desirable that the measured quantities not be arbitrary, such as values of radiant power, but rather they should be meaningfully related to vision. Thus a greater luminance must refer to a more effective stimulus for vision than a lesser luminance. For photopic vision, this is achieved by integrating the radiant power distribution with $V(\lambda)$ and for scotopic vision, with $V'(\lambda)$. For mesopic vision, no one luminous efficiency curve will suffice but rather there are a whole family of curves, which change both in shape and in maximum sensitivity, as the light level is reduced from photopic to scotopic (Wright, 1946; Kinney, 1955; 1958).

Since mesopic, by definition, includes both rod and cone vision, it shares all the problems of photopic photometry. From photopic vision, one can expect additivity failures, a lack of equivalence between brightness and luminance, and two general types of luminous efficiency curve dependent upon the visual criteria employed. Many of these problems have been addressed in the report, *Light as a True Visual Quantity, Principles of Measurement* by TC 1.4, Vision (CIE, 1978), and will not be repeated here. Mesopic photometry gains further complexity from the combination of the photopic and scotopic systems, with the appropriate luminous efficiency curve dependent upon the size and configuration of the area of stimulation. All of these, together with the important problem of individual differences in sensitivity, must be addressed in any complete system of mesopic light measurement.

1.1 Early Attempts at Measurement in the Mesopic Range

There are a number of solutions possible to the question of how radiant power should be evaluated in the mesopic range of intensities. The most obvious is to derive luminous efficiency or visibility functions for monochromatic lights in the mesopic range and to evaluate the radiant power distribution of the light under test by integration in a way completely analogous to that used for photopic and scotopic luminance. This was the first system to be proposed for trial by the CIE; many mesopic luminous efficiency curves were available in the literature and a representative set was standardized for use with the spectral power distribution of a source (CIE, 1964).

Such a technique, because of additivity failures, gives only a first order approximation of the effectiveness of the radiation for vision (except for monochromatic lights, for which it is necessarily exact). Furthermore it is not a convenient method; one must measure the spectral power distribution of the source in question and then apply the appropriate curve. The alternative, a battery of photocells and correcting filters to simulate the spectral sensitivity of the mesopic observer, is cumbersome. Even if one had the instrumentation available to assess the power distribution, the choice of filters or curves cannot be known until the measurement is made, so that the actual assessment of the light would have to be done by a process of iteration.

The use of visual photometry together with the concept of equivalent luminance is another possible technique. This too was suggested by a technical group of the CIE. (CIE, 1964; 1968). A photometric match was to be made between the unknown source and a given standard (in this case, a light source of 2042 K of a specific size and configuration); the unknown is then given the 'equivalent luminance' of the standard that it matches. This technique is theoretically valuable since it can be used for the specification of any distribution of energy at any light level. Again the procedure did not meet with acceptance: visual photometry had been superseded by instrumental photometry. Furthermore, even if the user could be educated as to the value of the visual method (the appropriate spectral sensitivity curve is automatically employed), there were no visual photometers available with the necessary large field size and extensive range of adjustments.

A different type of approach was suggested by Palmer at the CIE meeting in Washington in 1967, that of a non-linear average of photopic and scotopic luminances. Since these two represent the limits, between which the unknown mesopic luminance must lie, an average of the two, weighted toward the photopic or the scotopic value, whichever is closer to the mesopic level being measured, should provide a reasonable value (Palmer, 1966; 1967; 1968). Several empirical formulae have been tested since then in an attempt to find the best predictor; the tests consist of brightness matches made between a variety of

different lights at mesopic levels (Palmer, 1974). In addition, several investigators from Japan have proposed various formulae for combining photopic and scotopic measurements to predict mesopic effectiveness.

Another approach is exemplified by the work of Kokoschka (1972b), which uses four variables rather than just two, the four being X_{10} , Y_{10} , Z_{10} (tristimulus values from the CIE 1964 color matching functions) and the scotopic function. The system was based upon empirically determined spectral sensitivity curves over a mesopic range of four log units; these data were subjected to a factor analysis which revealed four factors and it was an easy step to assume that they represented the activity of the three cones and the rods (Kokoschka, 1972a; Kokoschka and Adrian, 1974).

The system of Trezona (1970; 1974; Clarke and Trezona, 1975) likewise is based upon the use of four variables, the inputs of the three cones and the rods; this system however was derived from tetrachromatic colour matching functions. Since a system based upon the independent contributions of the various cones and the rods need not assume that they respond together, it in principle offers the greatest degree of accuracy.

1.2 The Current Status

Since there is today no system recommended by the CIE for mesopic photometry, common practice employs ordinary photopic photometers for the measurement of light at mesopic levels. Unfortunately, many of these instruments have a range of response that extends well into the mesopic region, thus facilitating their use. The most important problem in this practice is the shift in the luminous efficiency of the eye toward the short wavelengths as the light level is reduced. If we use an ordinary light meter, bluish lights will be brighter and more effective for vision than they are given credit for, while yellowish and reddish lights will be over-evaluated for their light-producing capabilities.

A number of examples of the size of the errors introduced by using a photopic photometer to measure luminance in the mesopic region were given in TC 1.4's report (CIE, 1978). The values are the discrepancy between the actual perceived equivalent luminance (calculated using an appropriate luminous efficiency curve for the given conditions) and the measured luminance using a photopic photometer employing $V(\lambda)$. These discrepancies vary greatly with the spectral energy distribution of the source in question, from relatively minor errors for sources on the Planckian locus to factors of ten and greater for highly colored sources at lower mesopic levels. For example, at low mesopic levels, below 0.1 cd/m^2 , a bluish light could be 10 times as effective as an ordinary tungsten source when the two measure exactly the same photopically.

Low pressure sodium provides an excellent example. The spectral power is concentrated near 589 nm, wavelengths to which the photopic eye is relatively sensitive; if measured with a photopic light meter, this sensitivity is reflected in relatively high readings. With a decrease in light to mesopic levels, the sensitivity of the eye is dramatically reduced; the resultant appearance is much dimmer than expected from the photopic values. Even greater discrepancies can be found in the measurement of red lights such as are employed in ship or plane control-rooms.

Although a great deal of information concerning the measurement of luminance at mesopic levels was amassed during the two decades following the first proposals by technical groups of the CIE, it was unfortunately true, in 1983, that the complexities of the situation still precluded an official recommendation in the immediate future. It was therefore decided at the meeting in Amsterdam to set up a technical committee whose sole purpose would be to prepare a technical report on the determination of mesopic luminances with descriptions of the problems and techniques proposed for study.

It is the hope of this committee that the presentation of a technical report which describes in detail techniques by which luminance can currently be measured will put a stop to the unquestioning use of photopic meters in mesopia. The techniques to be described herein use equipment that is available today; that is, they either rest on measures of photopic and scotopic luminance for which meters are available or on tristimulus or chromaticity values and scotopic luminance measures, again for which techniques are currently available. There is thus no need to wait for further developments before they can be tried.

While there are many unanswered questions and remaining problems, each of the techniques described herein will provide a better measurement of mesopic luminance than does the current practice of employing photopic devices. The experience obtained should allow an officially recommended system for the CIE in the near future.

2 PROBLEM AREAS IN MESOPIC PHOTOMETRY

2.1 Failure of Additivity

The measurement of light for both photopic and scotopic vision, as defined by the CIE, assumes additivity; that is, the total luminance of a non-monochromatic light is the summation of the weighted spectral radiations of the component wavelengths. This important property permits the use of one number to assess the light-giving quality of any radiant energy distribution and for many applications it works very well. Thus different spectral radiance distributions which have equal luminance will provide an equal stimulus for vision, will permit equal legibility of alphanumerics (Guth and Graham, 1975), visibility of borders (Kaiser, 1971) and, in many cases, will look equally bright (CIE, 1978). It also works well in truly scotopic vision, where the weighting function is $V'(\lambda)$, because only one species of receptor is involved.

However, in photopic vision, a failure of additivity frequently is found; if, for example, two or more monochromatic stimuli are added together and compared in brightness with some standard, the combined effect is frequently less than the sum of the luminances of the components. This phenomenon is referred to as sub-additivity and is due mainly to cone-cone interactions. It is also called the Helmholtz-Kohlrausch effect.

In mesopic vision, one would expect similar additivity failures whenever the cone component is large, but there are additional complications. There is another way in which additivity fails: the combined effect may also be *more* than the sum of the components (supra-additivity). At low levels, supra-additivity can be found and this is presumably due to cone-rod interaction (Crawford and Palmer, 1985; Nakano and Ikeda, 1986). At intermediate levels, complex hybrid forms may arise (Yaguchi, 1986). A mesopic system ideally should take into account all of these effects.

2.2 The Lack of Equivalence between Brightness and Luminance

The example of the subadditivity cited above for photopic vision was the appearance or the brightness of the light (the Helmholtz-Kohlrausch effect); this is one of the most notable failures of additivity. Colored lights of equal luminance, particularly monochromatic or highly saturated, often do not appear equally bright. This effect has been well known for more than 30 years (Dresler, 1953; Chapanis and Halsey, 1955; Sanders and Wysecki, 1958). Luminous efficiency functions determined by heterochromatic brightness matching are higher at the ends of the spectrum than is $V(\lambda)$ and do not display additive properties (Kaiser and Wysecki, 1978; Yaguchi and Ikeda, 1981; Ikeda et al., 1982). The implications of these facts for color theory and measurement have been pointed out by many authors (Guth et al., 1969; Kinney, 1975; CIE, 1978).

Methods are now available for determining the luminances that will yield equally bright appearing colored lights in photopic vision. For example, one can simply apply a brightness/luminance ratio (Kinney, 1983) to the measured luminance of monochromatic or near-monochromatic lights to obtain a rough estimate of their brightness. A more comprehensive solution (Ware and Cowan, 1984; Kaiser, 1986) is available for lights of any spectral power distribution; it requires only the measurement of luminance and of the CIE chromaticity coordinates of colors, whose values are then put in a polynomial function which predicts their brightness under certain specific observing conditions.

In mesopic vision there are few data which describe brightness/luminance relations at different light levels. However, Ashizawa et al. (1983; 1985) have recently collected data on changes in the appearance of reflecting samples. Brightness matches were made between a number of clothing samples and a reference gray scale (Munsell) at illuminance levels from photopic through mesopic. As the overall illuminance on them was reduced, each of the colored samples behaved differently, some gaining in brightness relative to the gray scale and other losing. For some colors, complex interactions occurred, with loss in brightness followed by a gain. A schematic analysis of the data is given in Figure 1. First, all of the colors decreased in brightness, relative to gray, as the illuminance was decreased at low photopic levels; this is illustrated by curve C in the figure. At further low illuminances, a rod contribution is evident, whose shape (1, 2, or 3) depends upon the relative amount of rod response produced in the sample and in the reference gray scale. If the response is larger in the sample, curve 1 will result; if smaller, curve 3, etc. These components change almost continually and gradually when the illuminance level is altered. Again, an ideal system of photometry should take into account all these possible ramifications. It should be noted that even this complex scheme may be an oversimplification, since all the cone responses are shown to be operating together.

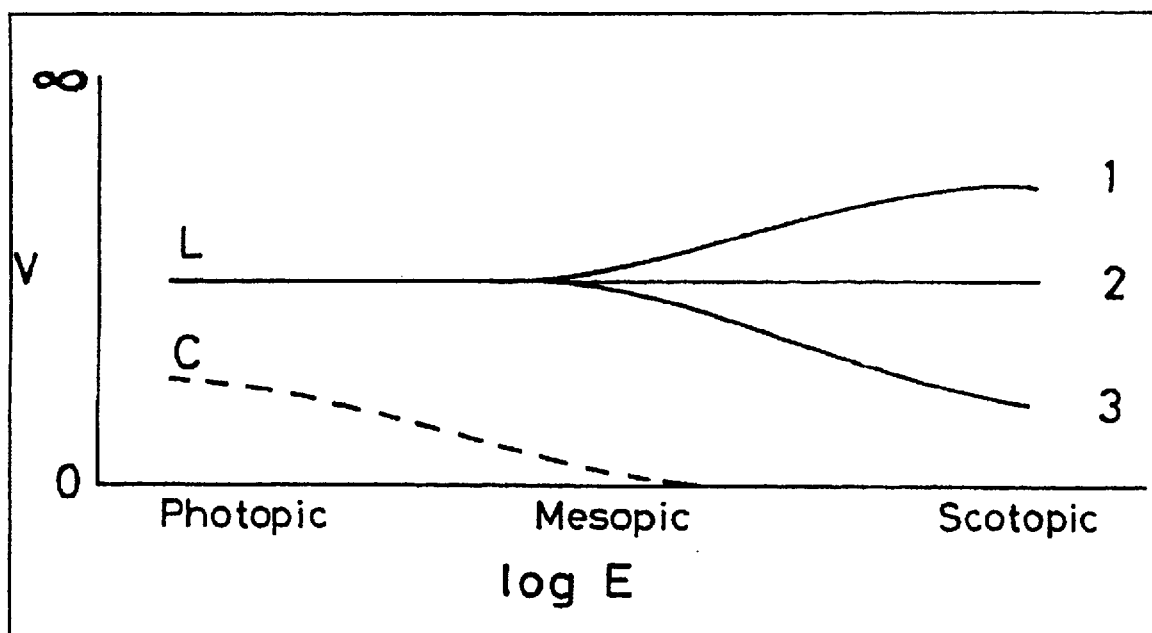


Fig. 1: Theoretical functions, as specified by the Munsell value (V), for three types of achromatic components, $L = 1, 2$ and 3 and the chromatic component C . (From Ashizawa et al., 1985.)

One might expect that the complications due to the failure of additivity would become less of a problem as the light level is lowered and the response is more of a function of the rods alone. On the other hand, a major advantage of the CIE definition of light for photopic vision - that additivity holds for acuity and thus adequately describes much of our important cone visual functioning - may be lost at mesopic levels. Here, there is often not enough light by which to read and thus other aspects of vision, such as visual-motor locomotion, become more important. The extent to which these functions show additivity is not known, but it is likely that the appearance of the light is important.

2.3 Individual Differences in Sensitivity

There are always differences in spectral sensitivity among individuals; $V(\lambda)$ and $V'(\lambda)$ are of course the average of a large group of subjects. While early data on mesopic spectral sensitivity were usually collected on only a few subjects, recent investigations have greatly improved the situation. Sagawa and Takeichi (1983; 1986) for example reported spectral sensitivity functions for 24 observers in a ten degree field at nine light levels between 0.01 and 100 photopic trolands. Individual differences are largest in the middle of the mesopic range, from 32 to 0.32 trolands and least at the two lowest levels, 0.032 and 0.01 troland. Additional data on 26 Chinese observers have recently been received from Dazhi, Xinjia, and Xiaju at the National Institute of Metrology in Beijing.

In addition to a normal range of individual differences, investigators are reporting fundamental differences in function among people, particularly when a large field of ten degrees is employed. Palmer (1985) published spectral sensitivity curves by heterochromatic brightness matching to a white standard in a ten degree field. His subjects seemed to fall into distinct groups: out of 24 subjects, 12 had luminous efficiency curves that were more or less additive and resembled the CIE $\bar{y}_{10}(\lambda)$ color matching function. Another group of 8 subjects had curves that were double peaked, similar to the heterochromatic brightness curve for two degrees (CIE 1978; 1987), and marked by large additivity failures. The other four subjects had functions intermediate between the two main groups. While these data were collected at photopic levels (1000 trolands), there is evidence that the differences may be found among subjects at mesopic levels; Ikeda and Nakano (1986) find similar differences between their subjects, one evidencing additivity at 100 and at 10 trolands, while the other did not.

Because of the importance of individual differences for mesopic photometry and for modeling of the visual system in general, the individual data should be made available to interested investigators. Therefore, the individual results for the 24 subjects of Sagawa and Takeichi (1983; 1986) and the 26 subjects of Dazhi et al. have been deposited at the Central Bureau of the CIE. They can be obtained by writing. The individual data for Palmer's 12 subjects are to be found in the published article (1985). Additional data will be added as they become available.

3 CURRENT SYSTEMS

In the work reported here, all of the investigators have employed brightness matching to some extent in the derivation of their systems of mesopic photometry. This is not meant to imply that other visual criteria could not be used, but rather that it is this aspect of light, its appearance, that changes most at mesopic levels.

The units of measurement employed by the various systems are, whenever possible, those of the CIE in accord with standard CIE definitions or their nearest equivalent. Thus luminance is measured in cd/m^2 with photopic values based upon $V(\lambda)$ and scotopic values upon $V'(\lambda)$. However the requirements of mesopic photometry necessitate measures for a large field and many systems utilize $\bar{y}_{10}(\lambda)$ in place of $V(\lambda)$. (See Appendix 6.1.) Likewise, trolands can be changed to employ $\bar{y}_{10}(\lambda)$ rather than $V(\lambda)$ as the luminance base and thus become trolands for a ten degree field. Equivalent luminance, L_{eq} , also is used in accord with CIE definition, although the specific standard used to match the unknown source may differ in different systems. Whenever non-standard units are employed, their basis is explicitly stated. Since some of the systems have been based upon data collected with an artificial pupil, a conversion from trolands to photopic luminance is given in Appendix 6.3.

The systems are organized according to the distinction, described earlier, between the different types: first those systems based upon the measurement of both photopic and scotopic luminance, and second, those that use four variables to represent the three types of cones and the rods.

The systems of Ikeda, Palmer, and Sagawa all utilize measures of photopic and scotopic luminance and compute a mesopic value from the two. While fundamentally similar, the systems differ in detail, particularly in the choice of luminous efficiency functions which are employed to assess the photopic and scotopic contributions. Palmer's formulae are empirical and have been revised several times over the years in an effort to obtain better predictive power. The latest version appears complex, but it is actually a quadratic solution to a simple relationship depicting the relative contributions of the rods and cones to mesopic brightness. The formulae of Ikeda and of Sagawa utilize coefficients that vary with the overall retinal illuminance level and describe the relative photopic and scotopic contributions at each level. Each of these systems is well developed and has reached the stage at which it can be tested empirically. Formulae, luminous efficiency functions, and examples are thus given so that readers may test and compare them.

The four-variable systems are those of Trezona and of Kokoschka. These systems have four independent factors dependent upon retinal illuminance level rather than just two. They differ in the type of mesopic data upon which they were based, the foundation of Trezona's system being a tetrachromatic treatment of brightness and Kokoschka's spectral sensitivity functions.

All of the systems give adequate prediction of mesopic luminous efficiency functions and thus of the brightness of monochromatic light. The ability to reproduce mesopic luminous efficiency functions, in fact, has never been a problem for the analysis of mesopic vision. A successful attempt was made as early as 1953 by Bridgman simply by adjusting the relative positions of supposedly pure rod and pure cone curves. More recently, excellent fits of mesopic luminous efficiency functions have been published by Palmer (1976), Ikeda and Shimozono (1981), Sagawa and Takeichi (1986) etc. The more stringent test however is the prediction of the brightness of complex radiations (wavelength mixtures, white light, Planckian radiators, non-Planckian sources etc), because all of these involve problems of additivity, both sub and supra. Palmer's section of this report describes tests of the ability of his and of several other systems to predict the appearance of some complex radiations.

3.1 Systems Utilizing Two Variables

Two variable systems are of two types, those employing adaptation coefficients that vary with the light level and those based upon measures of photopic and scotopic luminance. The first system using adaptation coefficients was described by Ikeda and Shimozono (1981); theoretical luminous efficiency functions were expressed by the formula:

$$\log St(\lambda) = a \log SR(\lambda) + b \log Sc(\lambda) + c \quad (1)$$

where $St(\lambda)$ is the theoretical luminous efficiency function
 $SR(\lambda)$ is a rod efficiency curve similar to $V'(\lambda)$
 $Sc(\lambda)$ is a cone efficiency function determined by direct brightness matching.

The constants a and b are adaptation coefficients depicted in Figure 2 which vary depending upon the overall retinal illuminance level. Since the constant c is almost zero and $a + b = 1$, equation (1) can be rewritten as:

$$\log S_T(\lambda) = a \log S_R(\lambda) + (1 - a) \log S_C(\lambda) \quad (2)$$

Sagawa and Takeichi (1983) improved the fit of the theoretical curves to the actual data by modifying the coefficient a (the contribution of the scotopic function) so that it has a different value for the shorter and the longer wavelengths.

From this point on, the systems devised by the two groups of researchers vary. Although both Ikeda and Sagawa utilize the formula of the weighted sum of the scotopic and photopic functions, each expressed in log units, their newest research has emphasized different aspects of mesopic photometry. Consequently, the numerical values for the adaptation coefficient, a , can vary.

3.1.1 The Method Devised by Ikeda and Colleagues

The problem attacked by Ikeda is that of the failure of additivity of mesopic luminances. This was described above and it was noted that both subadditivity and supra-additivity have been found depending upon the spectral composition of the light (Guth and Lodge 1973; Yaguchi and Ikeda 1983). In addition to additivity failures attributed to cone interactions, other problems may be due to rod/cone interactions in mesopic vision. Ikeda notes that the equations described above already suggest a failure of rod and cone additivity, since the efficiencies are added logarithmically rather than linearly.

In order to test for additivity failures, Stiles summation index (Boynton, Ikeda and Stiles, 1964) was used; in this system two stimuli, λ_1 and λ_2 , are presented in mixtures of various radiance ratios and the mixture is matched in brightness to a white reference. For example, 470nm and 580nm may be mixed in various ratios from all of one to all of the other, and a brightness match made for each ratio. The proportion of each wavelength, relative to its radiance when presented alone (p_1 for wavelength λ_1 and p_2 for wavelength λ_2), is then determined for each of the matches.

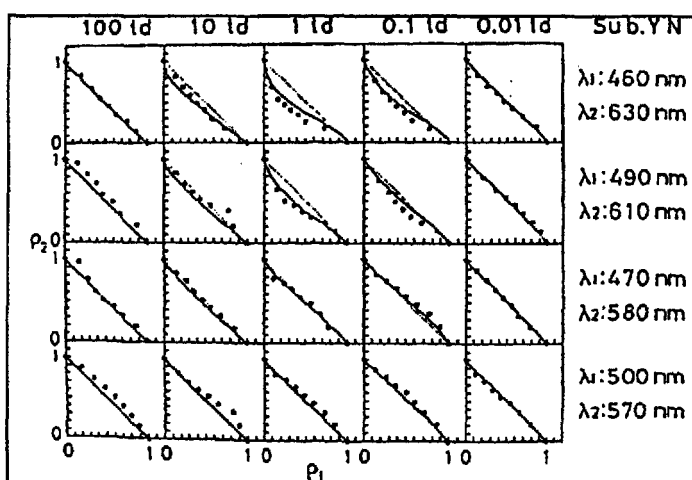


FIG.3: The functions for p_1 versus p_2 for five illuminance levels (columns) and for four pairs of wavelengths (rows). Filled circles are data points, continuous lines are the theoretical curves, and dotted lines represent complete additivity, for Subject YN. (From Nakano and Ikeda 1986.)

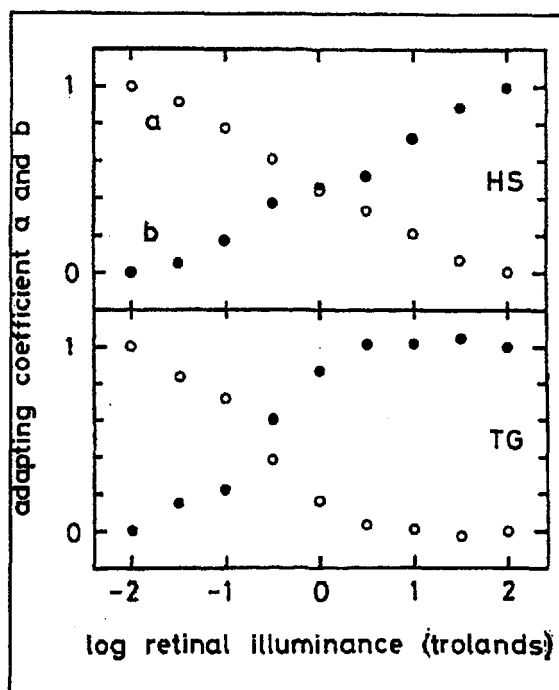


Fig.2: Adapting coefficients, a (open circles) and b (filled circles) as a function of the retinal illuminance level from subjects HS (top) and TG (bottom). (From Ikeda and Shimozono 1981.)

Additivity holds if $p_1 + p_2 = 1$. It fails in the direction of subadditivity if $p_1 + p_2 > 1$ and in the direction of supra-additivity if $p_1 + p_2 < 1$.

Nakano and Ikeda (1986) have made these tests on four wavelength combinations in a bipartite ten degree field at each of five luminance levels of the white reference from 100 to 0.01 trolands, the 100 Td level representing photopic vision and the 0.01, nearly complete scotopic vision. The results for two subjects are shown in Figures 3 and 4 and interestingly, the two subjects behave differently at photopic levels.

Subject YN (Figure 3) shows linear additivity for all combinations at the 100 Td level; the experimental points almost fall upon the straight lines connecting (1,0) and (0,1) shown by the dotted lines. It is true even for the combination, 490 nm and 610 nm, which normally gives