Light as a true visual quantity : principles of measurement

Citation for published version (APA):
Roufs, J. A. J. (1978). *Light as a true visual quantity : principles of measurement*. (CIE publication; Vol. 41). Commission Internationale de l'Éclairage.

Document status and date:
Published: 01/01/1978

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 16. Nov. 2023

COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

LIGHT AS A TRUE VISUAL QUANTITY : PRINCIPLES OF MEASUREMENT

PUBLICATION CIE N° 41 (TC-1.4) 1978
BUREAU CENTRAL DE LA CIE
52, BOULEVARD MALESHERBES 75008 PARIS - FRANCE

LA COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE

La Commission Internationale de l'Eclairage (CIE) a pour mission la coopération et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Les Comités Nationaux qui la composent fonctionnent dans 30 pays et leurs membres consacrent leur temps et leurs capacités à la poursuite des objectifs de l'organisation.
De plus, des personnalités appartenant à 10 autres pays ont le statut d'Associés de la Commission.
Les objectifs de la CIE sont les suivants:

a) constituer un centre d'étude international pour toute matière relevant de la science et de l'art de l'éclairage;
b) stimuler l'étude de ces matières par tout moyen approprié;
c) assurer l'échange des informations sur l'éclairage entre les différents Pays;
d) préparer et publier des accords internationaux dans le domaine de l'éclairage.

Les travaux sont effectués par 26 Comités Techniques, chacun d'eux étant assigné à un Pays Membre de la Commission. Les sujets d'études s'étendent depuis les questions fondamentales, jusqu'à tous les types d'applications de l'éclairage.
Les rapports et guides établis par ces Comités Internationaux ne peuvent être dus qu'à une organisation telle que la CIE et sont acceptés dans le monde entier.
Tous les quatre ans une Session plénière passe en revue le travail des Comités Techniques et établit leurs projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. En tant que telle, elle occupe une position importante parmi les organisations internationales.

THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is an organization devoted to international cooperation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of 30 countries, each having a National Committee of individual members who devote their time and talent to the objectives of the organization. In addition, individuals from 10 other countries have Associate Member status.
The objectives of the CIE are:

a) to provide an international forum for all matters relating to the art and science of lighting;
b) to promote by all appropriate means the study of such matters;
c) to provide for the interchange of lighting information among the different countries;
d) to prepare and publish international agreements in the field of lighting.

The work of the CIE is carried on by 26 Technical Committees, each of which is assigned to a member country. These cover subjects ranging from those which involve basic and fundamental matters to all types of lighting applications. The reports and guides developed by these international committees are possible only through an organization such as the CIE and are accepted throughout the world.
A Plenary Session is held every four years at which the work of the committees is reviewed, reported and plans made for the future. The CIE is recognized as representing the authority on all aspects of light and lighting. As such it occupies an important position among international organizations.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Ihre Mitgliedschaft besteht aus 30 Ländern, wovon jedes ein Nationales Komitee besitzt, das sich aus einzelnen Mitgliedern zusammensetzt, die ihre Zeit und ihre Fähigkeiten den Zielen der Organisation widmen. Außerdem besitzen Einzelpersonen aus 10 anderen Ländern den Status von Assoziierten Mitgliedern.
Die Ziele der CIE sind:

a) ein internationales Forum auf allen Gebieten der Kunst und Wissenschaft der Lichttechnik zu bilden;
b) durch alle geeigneten Maßnahmen das Studium dieser Materie zu fördern;
c) für den Austausch von Informationen über die Lichttechnik unter den verschiedenen Ländern zu sorgen;
d) internationale Vereinbarungen auf dem Gebiet der Lichttechnik vorzubereiten und veröffentlichen.

Die Arbeit der CIE wird von 26 Technischen Komitees durchgeführt, wovon jedes einem Mitgliedsland zugeordnet ist. Diese Komitees bearbeiten Gebiete, mit grundlegendem und fundamentalem Inhalt bis zu allen Arten der Lichtanwendung. Die Berichte und Richtlinien, die von diesen international zusammengesetzten Komitees ausgearbeitet werden, sind nur durch eine Organisation wie die CIE möglich; sie werden von der ganzen Welt anerkannt.
Eine Tagung wird alle vier Jahre abgehalten, in der die Arbeiten der Komitees überprüft werden, in der hierüber berichtet wird und Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als die höchste Autorität angesehen, die alle Aspekte des Lichtes und der Beleuchtung vertritt. Auf diese Weise hat sie eine bedeutende Stellung unter den internationalen Organisationen inne.

This report has been prepared by the CIE Technical Committee 1.4 « Vision ». It represents the opinion of the majority of the Committee members who represent most member countries of the CIE. This report is recommended for future study and it is not an officially agreed CIE recommendation, approved by the National Committee of the member countries. It should be noted that recommendations in this report are advisory and not mandatory.

Ce rapport a été préparé par le Comité Technique CIE 1.4 « Vision ». Il a été approuvé par la majorité du Comité, dans lequel sont représentés la plupart des pays membres de la CIE, et il est recommandé pour une future étude. Il n'est pas une recommandation officielle de la CIE approuvée par les Comités Nationaux des pays membres. Il faut noter que toutes les recommandations de ce rapport sont conseillées et non obligatoires.

Dieser Bericht wurde vom Technischen Komitee 1.4. „ Sehen" der CIE ausgearbeitet. Er entspricht der Mehrheit der Meinungen des Komitees, in dem die meisten Mitgliedsländer der CIE vertreten sind und wird zum zukünftigen Studium empfohlen. Er ist keine offiziell anerkannte CIE-Empfehlung, die von den Nationalen Komitees der Mitgliedsländer anerkannt wurde. Es muß darauf hingewiesen werden, daß alle Empfehlungen dieses Berichts nur als Anleitung dienen und nicht verbindlich sind.

The following members of the Committee TC-1.4. took part in the preparation of the Technical Report :

Les membres suivants du Comité TC-1.4 ont participé à la préparation du rapport technique :

Die folgenden Mitarbeiter des Komitees TC-1.4 haben sich an der Ausarbeitung des Technischen Berichtes beteiligt :

Members

Membres

Mitglieder

E. MEYER	Afrique du Sud
W. ADRIAN	Allemagne
J. KINGSLEY	Australie
G. VERRIEST	Belgique
V. GAVRIISKI	Bulgarie
P. KAISER	Canada
E. KROGH	Danemark
M. AGUILAR	Espagne
J. KINNEY	Etats-Unis
P. LEHTINEN	Finlande
F. PARRA	France
D. PALMER	Grande-Bretagne
J. SCHANDA	Hongrie
A. TCHETCHIK	Israël
L. RONCHI	Italie
M. IKEDA	Japon
E. ALNAES	Norvège
J. ROUFS	Pays-Bas
S. KONARSKI	Pologne
A. IONESCU	Roumanie
T. KRAKAU	Suède
F. FANKHAUSER	Suisse
J. JOHN	Tchécoslovaquie
D. GLIGO	Yougoslavie

Summary

There are many methods available to photometrists by which visually meaningful assessments of light may be made. All are somewhat more complicated than the simple use of a physical photometer corrected to V (λ). In addition, all require some understanding of the visual system and how it works. However the advantages are sizeable : the assessment of light bears a logical relationship to how we perceive the light. The methods are summarized below.

For photopic vision, luminances of several $cd{\cdot}m^{-2}$ or higher, ordinary physical photometers corrected to V (λ) give visually accurate measures for small, centrally fixated lights of broad spectral composition. For all other applications a different luminous efficiency function should be employed. In order to utilize the appropriate function, one must either measure the spectral distribution of radiant power directly or correct the photocell's existing V (λ) curve to the appropriate luminous efficiency.

An alternate solution is to calculate a new quantity from ordinary luminance values and from CIE colorimetric measures according to mathematical formulae specifically developed for this purpose. This method is potentially the most useful since different formulae can be developed for different applications (for example, two degree or ten degree fields); at the same time it rests on established CIE quantities and no new measures need be developed.

For scotopic vision, assessment of radiant power is made with respect to the scotopic luminous efficiency function V′ (λ), either with a physical photometer appropriately corrected or by radiance measurement or visual photometry.

For mesopic photometry, the light should be assessed for both its photopic and its scotopic contributions. An estimate can be obtained by combining the simple photopic and scotopic luminances non-linearly or a more precise measure by utilizing three, or even better, four quantities, based on X_{10}, Y_{10}, Z_{10} and V′ (λ), in the final assessment.

Résumé

Les photométristes disposent d'un grand nombre de méthodes pour évaluer les effets visuels de la lumière. Elles sont toutes passablement plus compliquées que le simple usage d'un instrument de photométrie énergétique dont la réponse est corrigée pour tenir compte de la fonction V (λ). D'autre part, elles requièrent toutes une certaine compréhension du système visuel et de son fonctionnement. Toutefois, les avantages sont appréciables : il existe une relation logique entre l'évaluation ainsi obtenue et la façon dont nous percevons la lumière. Voici comment on peut résumer ces méthodes.

Pour la vision photopique (luminances supérieures ou égales à quelques $cd\ m^{-2}$) les photomètres énergétiques corrigés selon V (λ) donnent des mesures précises du point de vue visuel lorsqu'il s'agit de stimuli de petite dimension, observés en vision centrale et dont le spectre est largement étalé. Dans tous les autres cas, il convient d'avoir recours à une fonction d'efficacité lumineuse différente. Pour appliquer celle-ci il faut, soit déterminer directement la répartition spectrale du flux énergétique, soit appliquer une correction à la courbe V (λ) utilisée dans la cellule photo-électrique afin de tenir compte de l'efficacité lumineuse qui convient.

Une autre solution consiste à calculer une quantité nouvelle à partir des valeurs ordinaires de la luminance et des mesures colorimétriques de la CIE, en appliquant des formules mathématiques établies à cet effet. Cette méthode est celle qui offre le plus de possibilités puisque des formules appropriées peuvent être mises au point pour chacune des applications (par exemple, une pour les champs de 2° et une pour les champs de 10°) et que, néanmoins, elle reste basée sur les grandeurs CIE déjà établies sans qu'il soit nécessaire d'en introduire de nouvelles.

Pour la vision scotopique, l'évaluation est faite, soit à partir du flux énergétique en tenant compte de la fonction d'efficacité lumineuse scotopique V′ (λ), soit avec un photomètre énergétique convenablement corrigé, soit encore au moyen d'une mesure de luminance énergétique ou par photométrie visuelle.

Pour la photométrie mésopique, la lumière doit être évaluée tant en ce qui concerne ses effets photopiques que ses effets scotopiques. Il est alors possible d'obtenir une estimation, soit en combinant d'une façon non linéaire les luminances photopique et scotopique, soit, si l'on désire une évaluation plus précise, en combinant dans la formule finale trois ou, mieux encore, quatre quantités basées sur X_{10}, Y_{10}, Z_{10} et V′ (λ).

Zusammenfassung

Dem Photometriker stehen viele Methoden zur Verfügung, nach denen eine visuell sinnvolle Bewertung des Lichtes vorgenommen werden kann. Alle Methoden sind etwas komplizierter als nur die Anwendung eines V (λ) korrigierten physikalischen Photometers. Darüberhinaus erfordern alle einiges Verständnis des visuellen Systems und seiner Funktionsweise. Die Vorteile sind jedoch erheblich : Die Messung des Lichtes steht in logischem Zusammenhang mit der Augenphysiologie, d.h., wie wir das Licht wahrnehmen. Die Methoden sind unten zusammengestellt.

Für photopisches Sehen (Tagessehen), Leuchtdichten von mehreren cd/m² oder höher, liefern gewöhnliche V (λ) korrigierte physikalische Photometer visuell richtige Meßergebnisse für kleine zentral fixierte Lichter breiter spektraler Zusammensetzung. Für alle anderen Anwendungen sollte eine verschiedene spektrale Helligkeitsfunktion angewendet werden. Zur Anordnung der geeigneten Funktion muß man entweder die spektrale Verteilung der Strahlungsquelle direkt messen, oder die bestehende V (λ)-Kurve der Photozelle an die gültige spektrale Empfindlichkeit anpassen.

Eine andere Lösung besteht darin, eine neue Größe aus den gewöhnlichen Leuchtdichtewerten und farbmetrischen Größen der CIE nach speziell für diesen Zweck entwickelten Formeln zu berechnen.

Diese Methode ist möglicherweise die nützlichste, da verschiedene Formeln für verschiedene Anwendungszwecke entwickelt werden können (z.B. zwei Grad oder zehn Grad Felder); gleichzeitig ist sie auf den von der CIE aufgestellten Größen aufgebaut und es brauchen keine neuen entwickelt zu werden.

Für scotopisches Sehen (Nachtsehen) wird die Bewertung der Strahlungsleistung auf die spektrale Empfindlichkeitsfunktion V′ (λ) bezogen, entweder mit einem physikalischen Photometer, der entsprechend korrigiert ist oder durch Strahlungsmessung oder visueller Photometrie.

Für die mesopische Photometrie (Messungen im Dämmerungssehbereich) sollte das Licht nach beiden Arten, sowohl photopisch (V (λ)) als auch scotopisch (V′ (λ)) bewertet werden. Eine Abschätzung erhält man durch nichtlineare Addition der photopischen und scotopischen Leuchtdichteanteile oder zur endgültigen Bewertung durch Verwenden von deir oder noch besser vier Größen, die auf X_{10}, Y_{10}, Z_{10} und V′ (λ) basieren.

Table of contents

Chapter 1 PROBLEMS IN PHOTOMETRY

1.1. Introduction
1.2. The Problems of Photometry
1.2.1. Inadequacies in the original determination of V (λ).
1.2.2. Inappropriate uses of V (λ).
a) Problems introduced because an individual's luminous efficiency function differs from V (λ).
b) Problems due to a change of luminous efficiency function with luminance level.
c) Problems due to inappropriate viewing conditions.
1.2.3. Criteria for establishing V (λ).
1.3. The Size of the Discrepancies Introduced
1.4. Summary Tables of Some Examples of Discrepancies Introduced by Improper Measuring Techniques

Chapter 2 RECOMMENDED PROCEDURES FOR PROVISIONAL USE AND STUDY

2.1. Photopic Photometry (above several cd·m^{-2})
2.1.1. The appropriate luminous efficiency function.
a) Normal photometry.
b) Large-field photometry.
c) Photometry of narrow band or monochromatic sources.
d) Photometry for individuals markedly different than average.
e) Photometry for point sources.
f) Summary of the choice of appropriate luminous efficiency functions.
2.1.2. Means of measurement.
a) Radiance measures.
b) Physical photometry.
c) Visual photometry.
d) Mathematical models in photometry.
2.2. Scotopic Photometry (below about 10^{-3} cd·m^{-2})
2.3. Mesopic Photometry (between about 10^{-3} and 3 cd·m^{-2})

Chapter 3 METHODS FOR ASSESSING LUMINOUS EFFICIENCY FUNCTIONS

3.1. Methods
3.1.1. Flicker photometry.
3.1.2. Step-by-step brightness matching.
3.1.3. Direct heterochromatic brightness matching.
3.1.4. Absolute thresholds.
3.1.5. Increment thresholds.
3.1.6. Minimally distinct border.
3.1.7. Visual acuity.
3.1.8. Critical flicker frequency.
3.1.9. Colorimetry.
3.1.10. Other methods.

3.2. The Implications for Photometry
  3.2.1. Photopic, small field photometry.
    a) The model proposed by Guth.
  3.2.2. Large field models.
    a) Kokoschka's system for a total range of light levels.
    b) Trezona and Clarke's tetrachromatic model.
  3.2.3. The future of models in photometry.

REFERENCES

APPENDIXES

A. Luminous efficiency curve for a centrally-viewed, two degree field by heterochromatic brightness matching.
B. Luminous efficiency curve for a .7 to 1.0° centrally-viewed field by absolute threshold technique.

Chapter 1

Problems in photometry

1.1. INTRODUCTION

This report is dedicated to the measurement of light. To many who have been making light measurements for years, it may seem superfluous, and indeed it is for the vast majority of the applications around the world. However, there are many instances in which light is measured in the routine way, with light meters and photometers, and the values yielded bear little or no relationship to the visual impression.

The definition of light itself lies behind the problems encountered in photometry. The CIE provides two similar definitions[1] appropriate to the problem at hand : 1. Any radiation capable of causing a visual sensation directly. 2. Radiation capable of stimulating the organ of vision. In this document we will use a concept consistent with those defined by the CIE but somewhat more general. Light is radiant power weighted according to the spectral sensitivity of the human eye. The word weighted implies measurement and indeed photometry concerns the measurement of light. The mathematical expression associated with photometric measures of light is

$$L_v = K_m \int_{360}^{830} L_{e,\lambda}\, V(\lambda)\, d\lambda \tag{1}$$

where L_v = luminance (*) in cd·m^{-2}
$L_{e,\lambda}$ = spectral radiance in w·m^{-2} · sr^{-1} · nm^{-1}
$V(\lambda)$ = spectral luminous efficiency for photopic vision (**)
K_m = maximum spectral luminous efficacy (683 lumens per watt) (***).

The two definitions and this equation represent major and far-reaching accomplishments of the CIE. Without such a definition, the only means of specifying the physical stimulus for vision would be to give the entire radiant power distribution for the source in question.

This definition of light makes it an unusual quantity, something not completely physical, not psychological, but psychophysical. Its introduction was somewhat of an historical accident. Humans were using light and measuring it long before physicists learned that light was part of the radiant energy spectrum. The unit of measurement was the most common source — the candle — and the means of measuring was a visual brightness match using a standard candle. Since there was always a human doing the measuring, the spectral sensitivity of the human eye was already built into the procedure of measuring light. The CIE V (λ) curve thus became a bridge tying the existing art of photometry to the physicist's newly discovered science of electromagnetic energy.

Unfortunately, this definition of light brings disadvantages as well as advantages. Discrepancies occur in the assessment of light for a wide variety of reasons. This report will list these problems for which routine light measurement may vary; it gives the reasons for the error, discusses possible alternative means of assessing the light, and makes recommendations as to the proper procedure for each case.

(*) Luminance is the fundamental quantity considered throughout this document because it is the basic visual stimulus. It represents the " light-emitting " ability of an element of a surface, whether this be self-luminous or reflective. In the International System of Units (SI), it is measured in candelas per square metre, somewhat as if that number of standard candle flames were spread uniformly over a unit area containing the element in question. However, the considerations of this report apply to other measures of light as well, such as intensity and illuminance, since all are related to luminance by simple mathematical equations.

(**) Values are listed in Table 2.1 and depicted graphically in Figure 1.1.

(***) New value approved by The International Committee for Weights and Measures, Sept., 1977.

1.2. THE PROBLEMS OF PHOTOMETRY

The problems are roughly categorized below into three groups. First the V (λ) curve itself may be in error, not representing adequately the average observer. Second, the V (λ) curve may be used in situations for which it is inappropriate. (The most obvious example is the use of the photopic or daylight V (λ) curve for night vision, but there are many other instances of its misuse as well.) Finally, the assumption of linear additivity of the contributions of different wavelengths as expressed by equation (1) may be wrong. This problem arises because of the physiology of the visual system and requires understanding of when and why the additivity assumption fails.

1.2.1. Inadequacies in the original determination of V (λ).

It has been realized for many years that the weighting of the short wavelengths is too low; in 1951, Judd[2] published his correction and this has been used extensively where needed. Since the eye is so insensitive in general to the shorter wavelengths, and since they do not contribute heavily to the spectral powers of many light sources, most notably tungsten, the error involved is usually of slight importance. However, in measuring the luminance of monochromatic lights from 400 to around 450 nm or so, of bluish lights, or of sources with a larger proportion of short wavelengths, the contribution of these short wavelengths will be underevaluated and the measurement in error.

1.2.2. Inappropriate uses of V (λ).

Since the V (λ) curve is an integral part of the measurement of light, adequate measurement of light demands that the V (λ) curve is a reasonable assessment of the spectral sensitivity of human beings in the light being measured. In many situations, such as photopic levels of illumination, V (λ) does provide a reasonable assessment. This is particularly true of light from tungsten lamps. There are however many situations in which V (λ) values are *not* sufficiently representative of the luminous efficiency of the viewer and the following sections will enumerate these and the reasons for them.

a) Problems introduced because an individual's luminous efficiency function differs from V (λ).

There are, of course, a number of organisms, which, for genetic reasons, possess luminous efficiencies different from the standard CIE curve. Such a statement probably applies to most infrahuman animals, invalidating the use of V (λ) units for many experimental purposes with animals. However, this fact seems to be rather generally recognized; numerous investigators attempt to determine brightness equivalents behaviorally for their animal subjects before using light as an experimental variable.

Certain human beings are likewise equipped constitutionally with luminous efficiencies different from V (λ). Most notable are the protanopes, color defective individuals seriously insensitive to the longer wavelengths of radiation. Other color defective individuals, deuteranopes and tritanopes, may also display sensitivities distinct from the CIE function, but to a lesser extent[3]. Deviations from V (λ) may be also found among the elderly and in certain highly pigmented races.

Variations are also found in individuals with normal color vision. Because the CIE curve is an average of the data for a large number of individuals, it will rarely apply precisely to a given individual. This variation in the normal population is of little importance in most practical situations. There are, however, some instances requiring precise measurement for which it is necessary to specify the subject's own luminous efficiency function rather than use V (λ). [See ch. 3 for methods].

b) Problems due to a change of luminous efficiency function with luminance level.

There are many ways in which light units may be used inappropriately but by far the gravest problems are introduced when the level of illumination is not in the range of daylight or photopic vision (*). Under this condition, the photopic luminous efficiency function or V (λ) is usually employed even though the spectral sensitivity of the human eye has shifted toward the shorter wavelengths (Purkinje shift). The shorter wavelengths appear brighter than they are given credit for, while the long wavelengths are being overestimated for their light producing capabilities. The use of V (λ) values, when scotopic or night vision values apply,

---

(*) The lower level of photopic vision can only be approximated since many conditions, such as adaptation level, size and position of visual field, and the task of the individual, affect it. This approximation is indicated in the CIE definition of " at least several cd·m^{-2} ".

results in sizeable errors. For example, Illuminant C will be underestimated by some 2.5 times, while the measurement of a monochromatic light of 450 nm is too low by a factor of 30[4].

Fortunately, these problems were recognized a long time ago and a scotopic standard observer, V′ (λ), was standardized by the CIE in 1951[5, 6]. This curve should be used to evaluate the energy distributions at scotopic levels; the formula is completely analogous to that used for photopic luminance.

$$L'_v = K'_m \int_{360}^{780} L_{e,\lambda} V'(\lambda)\, d\lambda \qquad (2)$$

where L'_v = scotopic luminance in $cd \cdot m^{-2}$
$L_{e,\lambda}$ = spectral radiance in $w \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$
$V'(\lambda)$ = spectral luminous efficiency for scotopic vision (*)
K'_m = maximum spectral luminous efficacy (1,699 lumens per watt).

The technique is completely analogous to the use of V (λ) at high levels; physical photometers can be built with a spectral sensitivity curve matching the V′ (λ) values; and the result is, of course, in *scotopic* photometric units.

Between photopic and scotopic levels of luminance, there is a wide range, covering several log units, for which neither the V (λ) nor the V′ (λ) values are really suitable.

One possible solution to the question of mesopic photometry would be a series of standard luminous efficiency curves, each applicable to a different level. There are, however, many problems which accrue to this solution, since the range in between photopic and scotopic levels is characterized by a series of curves which shift irregularly from one extreme to the other. The amount of shift at a given luminance depends upon a large number of factors, such as the size and retinal position of the field and the adaptation level of the eye[7-13]. For example, as the luminance is raised above scotopic threshold the first change to take place is heightened sensitivity to the longer wavelengths. While this increase continues regularly for several log units, relative sensitivity to the short wavelengths remains essentially unchanged; the result is a progressive broadening of the luminous efficiency curves, until finally the shift in short wavelength sensitivity toward the photopic curve is realized at much higher luminances. Furthermore, the rate of change will depend markedly on the retinal area stimulated. If the foveal area is included, the changeover will be much more rapid than if only peripheral areas are stimulated.

c) Problems due to inappropriate viewing conditions.

Since the luminous efficiency function of the human eye is known to vary with a wide variety of viewing conditions, the assessment of radiant power can give accurate values only when the measured light corresponds to the conditions under which V (λ) was obtained. These conditions are, specifically, photopic levels of illumination, a small field size (2 to 3 degrees), a neutral background, and central fixation. One troublesome problem in this category is field size; frequently one wishes to measure large fields rather than small spots of light. Luminous efficiency functions for large fields show the eye to be more sensitive to short wavelengths than is indicated by V (λ); this means of course that the more short wavelength energy in a source, the greater will be the error in measuring a large field. The CIE has recognized this and provided a provisional V (λ) curve for a 10 degree field[14]. Fortunately beyond ten degrees, the luminous efficiency for a centrally fixated target does not change much with area.

Another troublesome problem is measuring point sources of light; here too, spectral sensitivity differs somewhat from V (λ) but no CIE standard currently exists.

1.2.3. Criteria for establishing V (λ).

A much more insidious problem arises from the fact that luminous efficiency functions depend upon the method of assessment. The goal of the CIE in defining light was to have a means of assessing the visual effects of radiation. Thus, the measurement of light should predict its brightness and its efficiency for seeing. The method used in the assessment of sensitivity to radiant power should be immaterial : the amount of radiant power necessary at each wavelength for some constant response could be determined and the constant response might be equal brightness to some standard, absolute threshold, equal visual acuity, etc. In fact, the results obtained depend markedly on the constant response selected to assess the monochromatic radiations.

(*) V′ (λ) values can be found in Table 2.1 and Figure 1.1.

Since luminous efficiency does vary with the method it is of considerable interest to know how the V (λ) function was obtained. The 1924 V (λ) (2°) was derived primarily from flicker photometry although some step-by-step brightness matching was involved also[15–17].

Flicker photometry requires the observer to adjust the quantity of a chromatic light which temporally alternates with a reference light, until minimum flicker is obtained. In the step-by-step brightness matching method the observer makes brightness matches between two wavelengths in a bipartite field. The two wavelengths are selected to be only a few namometers apart so that the colors almost look alike and the observer can concentrate on making a brightness match without appreciable color differences to complicate the task. These methods were used to determine the CIE V (λ) instead of heterochromatic brightness matching method for two main reasons. The first is that heterochromatic brightness matching yields generally much more variable data than does the step-by-step or minimum flicker method. Furthermore, it has been determined that the additivity law is not obeyed with heterochromatic brightness matching but is obeyed with flicker photometry (see below).

As noted above (Equation (1)), the CIE defines luminance of non-monochromatic light as the summation of the weighted spectral radiance of the component wavelengths. If, for example, one had a light which appeared yellow but indeed was made up of a mixture of red and green light, the luminance of the yellow light is defined as equal to the sum of the luminances of the red and green lights. Whether or not this additivity reflects its appearance to the eye depends upon how the weighting of the radiances to derive luminance is achieved [18–25]. If the weightings are achieved by means of the flicker method then additivity will be obtained. If the weightings are obtained by means of heterochromatic brightness matching then additivity will not be obtained.

This adherence or lack of adherence to the additivity law (Abney's law) can be described in another way. If, for example, one matched for brightness a green light to a given white light and then matched for brightness a red light to that same white light and finally mixed these two quantities of red and green light together one would find that the resulting yellow light would not match twice the amount of the original white light. Similar additivity failures are obtained when the experiment is performed using an absolute threshold criterion[26].

On the other hand, if one were to take the green light and adjust its radiance in order to obtain minimum flicker with an alternating reference white light and then take a red light and adjust its radiance for minimum flicker with that same reference white light, it would be found that when these amounts of red and green lights are mixed and then the white light is adjusted in order to obtain a minimum flicker with this mixture of red and green light one would require twice the amount of the original white light. That is to say the additivity law would hold for minimum flicker as a criterion[27].

It has also been determined that the additivity law holds for at least two other psychophysical criteria. Boynton and Kaiser[28] have shown that additivity holds when using the criterion of minimally distinct border. In this criterion the observer adjusts the brightness of a chromatic field which is precisely juxtaposed with a reference white field until the border between these two fields is minimally distinct. This would be done first with, for example, a red light and then a green and then when the quantities of the red and green lights are halved and mixed it would be found that the minimally distinct border would be maintained. Similarly, additivity is found to hold if luminous efficiency is measured with visual acuity as the criterion[29–31].

The conclusion from all these studies is that the method used to obtain luminous efficiency functions unfortunately influences the function that is obtained. Other possible measures as pupil size, reaction time, electroretinograms, cortical evoked responses, and increment thresholds, etc., are described in Chapter 3. One type of curve is obtained from flicker photometry, step-by-step matches, minimally distinct border and acuity. This curve is narrow, the weightings obtained are additive, and it is very similar in shape to Judd's modification of V (λ). Another type of curve with greater sensitivity at both the blue and red ends of the spectrum, particularly the blue, is obtained from direct heterochromatic brightness matching and threshold criteria; values obtained from these techniques are not additive.

Most of these effects have been recognized for years; in fact, the non-additivity problem has been named the Helmholtz-Kohlrausch effect[32]. The causes are only recently beginning to be understood. A possible explanation and the data supporting it are described in some detail in Chapter 2. Briefly, however, this explanation states that the output from cones feeds into two systems, one spectrally opponent or chromatic and the other one achromatic. Signals from the cones to the non-opponent achromatic system are combined linearly and activity at higher neural levels can be accurately predicted from the sum of the inputs. Signals from the cones to the opponent or chromatic system however are antagonistic in that activity within the red-green system (or the blue-yellow) is subtracted from one another. Thus, the specific luminous efficiency function obtained in a given experiment depends upon whether the method used taps the output of the achromatic system (flicker, minimum border, etc.) or the outputs of both the chromatic and achromatic systems (heterochromatic brightness matching, absolute foveal threshold, etc.)[26, 31, 33–36].

What this means for photometry is that the results based upon V (λ), the additive system, will not always be representative of the perceived brightness of the light. Generally speaking, neutral sources will appear equally bright when their luminances are the same; this occurs because the additional activity in the chromatic systems tends to cancel. Colors of equal luminance lying close to each other on the spectral locus will also appear equally bright. But, if two highly saturated lights relatively far apart in wavelength are of equal luminance they will rarely be equally bright. Since a relative luminous efficiency function obtained by heterochromatic brightness matching is broader than even Judd's modification of the CIE V (λ), equally luminous lights (using Judd's correction) would not always be equally bright. Similarly they may not be equally visible, using a threshold criterion.

1.3. THE SIZE OF THE DISCREPANCIES INTRODUCED

The preceding discussion has shown the many ways in which discrepancies are introduced into the measurement of light by using CIE V (λ) when some other luminous efficiency curve more appropriately assesses vision in a specific situation. In order to give the reader some idea of the magnitude of the problem, tables have been prepared for a variety of the problem areas[37]. In each case, the standard luminance, based on V (λ), is used as the norm and the " true " luminance is calculated using an appropriate luminous efficiency curve for the given conditions. The ratio of the latter value to this norm is given in the tables. The difference introduced through these various misapplications of V (λ) obviously varies from an infinitesimal amount to a sizeable quantity depending upon the specific conditions. For neutral sources, all differences are small, regardless of their cause; for monochromatic radiances, most differences are large. Thus most of the problems apply to the measurement of colored lights.

The readers can judge for themselves whether or not a given difference marks a significant departure from reality for his given application. For example, it may or may not be important to the user that a large field of 6,486 K has 1.1 times more light when assessed by a curve known to be more appropriate than CIE V (λ). However, the fact that a blue light emitting diode was underestimated by a factor of two compared with a yellow of equal luminance would be undoubtedly a problem for many applications. Chapter 2 is devoted to recommended techniques to circumvent each of these errors.

1.4. SUMMARY TABLES OF SOME EXAMPLES OF DISCREPANCIES INTRODUCED BY IMPROPER MEASURING TECHNIQUES

The values in these tables are ratios, calculated from

$$\frac{\int L_{e,\lambda}\, V^*(\lambda)\, d\lambda}{\int L_{e,\lambda}\, V(\lambda)\, d\lambda}$$

where V* refers to the curve, appropriate to the condition, found in the Tables at the end of Chapter 2.

Table 1.1. *The Relative Luminance of Different Color Temperature Sources Calculated for Subjects Whose Luminous Efficiencies are Constitutionally Different from the CIE Photopic Luminous Efficiency Function* (*), (**).

	Color Temperature		
Condition	2042 K	2998 K	6486 K
CIE light unit	1.000	1.000	1.000
Color-defective subjects			
Protanope	0.678	0.781	0.915
Deuteranope	1.008	0.960	0.901
Possible corrections to CIE curve			
10° field size	1.039	1.057	1.099
Judd's short wavelength correction	1.001	1.002	1.007

Table 1.2. *Relative Luminous Efficiencies for Various Color Temperature Sources in the Mesopic Region* (*), (**)

	Color Temperature		
Condition	2042 K	2998 K	6486 K
2° field			
3.4 $cd \cdot m^{-2}$ (1.0 ft-L)	1.000	1.000	1.000
0.34 $cd \cdot m^{-2}$ (0.1 ft-L)	1.000	1.002	1.024
0.034 $cd \cdot m^{-2}$ (0.01 ft-L)	1.000	1.059	1.201
10° field			
3.4 $cd \cdot m^{-2}$ (1.0 ft-L)	1.000	1.017	1.058
0.34 $cd \cdot m^{-2}$ (0.1 ft-L)	1.000	1.045	1.161
0.034 $cd \cdot m^{-2}$ (0.01 ft-L)	1.000	1.172	1.549
Scotopic threshold (CIE curve)	1.000	1.524	2.512

(*) All of the calculations have been made assuming additivity of luminance as a function of wavelength, an assumption which we have just seen does not hold for prediction of brightness. However, as noted in section 3, for neutral sources the errors introduced are small.

Table 1.3. *Relative Luminance of Different Wavelengths Calculated for Subjects whose Luminous Efficiencies are Constitutionally Different from the CIE Photopic Luminous Efficiency* (**)

	Wavelength (nm)			
Condition	450	520	580	650
CIE light unit	1.00	1.00	1.00	1.00
Color-defective subjects				
Protanope	2.10	1.27	0.70	0.09
Deuteranope	0.74	0.59	1.14	1.29
Possible corrections to CIE curve				
10° field size	2.36	1.07	1.00	1.01
Judd's short wavelength correction	1.23	1.00	1.00	1.00

Table 1.4. *Luminous Efficiencies for Various Spectral Sources in the Mesopic Region Calculated Relative to a Luminous Efficiency of* 1.0 *for* 2,042 *K* (**)

	Wavelength (nm)			
Condition	450	520	580	650
2° field				
3.4 cd·m^{-2} (1.0 ft-L)	1.00	1.00	1.00	1.00
0.34 cd·m^{-2} (0.1 ft-L)	1.65	1.00	1.00	1.00
0.034 cd·m^{-2} (0.01 ft-L)	7.23	1.13	0.78	1.09
10° field				
3.4 cd·m^{-2} (1.0 ft-L)	2.27	1.03	0.96	0.97
0.34 cd·m^{-2} (0.1 ft-L)	6.92	1.18	0.83	1.08
0.034 cd·m^{-2} (0.01 ft-L)	16.89	1.37	0.74	0.60
Scotopic threshold (CIE curve)	30.62	3.37	0.36	0.01

(**) All of the discrepancies referred to in these tables are based solely on the inappropriate use of V (λ) for assessing visual functions. The assumption is made that the photometer in use is properly calibrated to V (λ) and no attempt is made to predict errors arising from inaccurate calibrations. These can and do occur and we recommend that, for accurate measurement, photometers be checked for accuracy of spectral calibration by laboratories specialized to perform these measures.

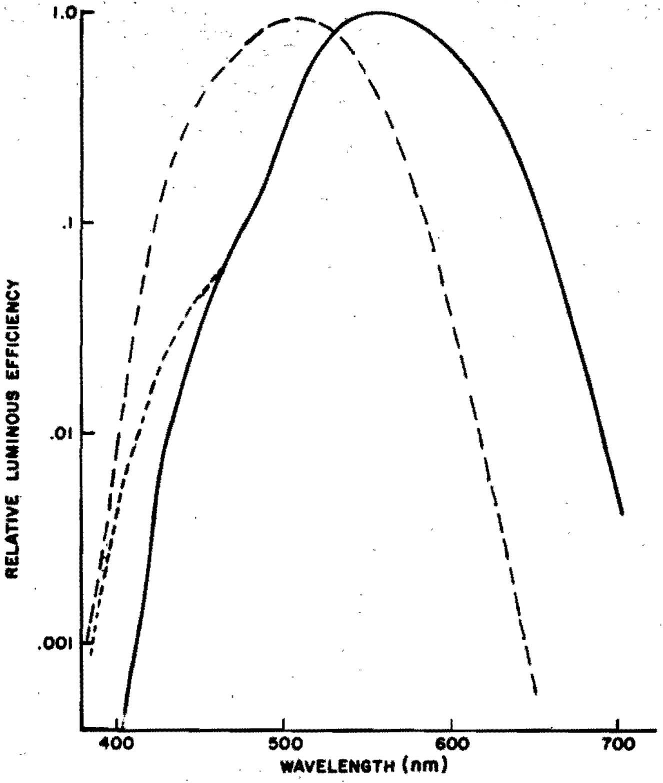

Fig. 1.1. — Luminous Efficiency Functions V′ (λ) —— ——; V (λ) ————; Judd's short wavelength correction — — —.

Chapter 2

Recommended procedures for provisional use and study

As pointed out in the introduction, the measurement of light, as defined by the CIE V (λ) curve, is subject to a variety of possible difficulties. In this chapter procedures for measuring light in a visually meaningful way are recommended for all conditions of photopic, scotopic, and mesopic photometry. If followed, useful assessment can be made of the quantity of light involved in various situations.

2.1. PHOTOPIC PHOTOMETRY (above several $cd{\cdot}m^{-2}$)

2.1.1. The appropriate luminous efficiency function.

a) Normal photometry.

This is the region where ordinary measurement techniques apply, that is where V (λ) (see Table 2.1.) values are generally acceptable. However there are many restrictions to the use of V (λ).

First, V (λ) should be applied only to cone vision and to centrally fixated fields. The level should be high, to inhibit the rods, and the field size restricted to about two degrees because of differences in cone population and in macular pigmentation with larger areas. For example, the luminance of the figures on dials in dimly-lit vehicle cockpits could well be specified by means of V (λ) because the observer would have to use his foveal cones to read the figures, even at low levels.

Second, the light being measured should have a broad band spectral power distribution, because, for the measurement of monochromatic or near-monochromatic sources, light measures based on V (λ) will not accurately predict brightness (*). This applies to any technique which yields additive measures : photometers, flicker photometry, or minimally-distinct border photometry. Even for neutral sources, the measures based upon V (λ) will theoretically not predict brightness since the luminances of different wavelengths are not strictly additive. With neutral sources, however, the extra chromatic activity induced by one portion of the spectrum is cancelled by another part and the resultant changes in brightness are generally minor. Thus for practical purposes, additivity failures can be ignored for neutral sources, unless very accurate measures are required[40]. An additional precaution is needed for accurate measures if the source, even though neutral, has a large proportion of short wavelength energy; then Judd's correction for V (λ) or that of Vos[41] should be employed (Table 2.1.).

If these two conditions are not met, the V (λ) function will not be adequate and other procedures should be followed.

b) Large-field photometry.

With large fields (**) or small fields viewed extrafoveally, the sensitivity of the eye in the blue spectral region is considerably increased, partly because of the reduced effect of the yellow macular pigment. This is in addition to the deficiencies of V (λ) in the blue, and so another curve becomes desirable. This is also logically demanded as the end-point of a system of mesopic photometry, which is essentially extrafoveal as it involves rod vision.

In 1964, the CIE recommended a large-field colorimetric system, with a Y_{10} (λ) function based on luminosity measurements (Table 2.2.). It was derived so as to pass through the values which Stiles

---

(*) The exception to this are wavelengths near 570 nm, the least saturated portion of the spectrum. The amount of discrepancy between luminance and brightness increases with the saturation of the light.[38, 39]

(**) There can be no exact limits specified since the change is a gradual one, but the CIE recommends Y_{10} be used for areas greater than four degrees. Recent data indicate that by far the largest changes in photopic spectral sensitivity occur between the fovea and 10° with only negligible changes from 10° outwards[13, 42, 43].

determined from 26 persons' flicker observations at three instrumental primary wavelengths. This curve is also a good fit for flicker matches in other parts fo the spectrum. The CIE has never formally recommended its use for photometry, but provisionally it may supplement V (λ) in appropriate conditions, e.g. for field sizes greater than 4° (*). Here again the problem of non-additivity occurs, just as it does in small-field photometry. Thus luminances calculated from a function for 10° will suffer the same problems as V (λ) itself : it will not accurately predict brightness. Again however for neutral sources the inaccuracies introduced are minor.

c) Photometry of narrow band or monochromatic sources.

Due to the inherent make-up of the visual system, measures of monochromatic sources based upon V (λ) will never accurately predict their brightness. There are two possible ways to circumvent this problem :

1) Use of a direct luminous efficiency curve.

Luminous efficiency curves derived by heterochromatic brightness matching show greater sensitivity in both the long and short wavelengths than V (λ). A typical set, compiled from seven different studies employing heterochromatic brightness matching, is given in Table 2.2. and Appendix A. This curve is recommended for provisional use until more data can be collected. Because of the inherent variability in heterochromatic curves, it is highly desirable that a final curve be based on a large number of subjects.

2) Use of a mathematical model in photometry.

An alternate suggestion for specifying luminances for light is available in a type of approach exemplified in a vector model[36]. This approach has the distinct advantage that no new luminosity curve is required; instead measures based on V (λ) and colorimetric functions form the basis of the system and these are converted mathematically to new luminance values which more accurately predict brightness. Various models are discussed at greater length below.

d) Photometry for individuals markedly different than average.

All of the photometric techniques discussed above are based upon data derived from large numbers of subjects and are meant to represent an average or normal individual. As mentioned previously, it is unlikely that these spectral sensitivities will agree precisely with that of a given individual. If individual is known to deviate from normal or if precise measures of light are needed for a specific individual, then curves other than the group average must be employed.

1) For color defective individuals.

Table 2.3. gives average luminous efficiency functions of deuteranopes and protanopes for conditions comparable to those of V (λ). The protanopic curve differs greatly from that of V (λ) in the long wavelengths; for other types of color defectives, the average luminous efficiency shows only slight deviations from normal. The actual curves in Table 2.3. are derived from theoretical calculations of Vos and Walraven[44] but they agree well with empirical data, such as those of Verriest's 25 protanopes and 25 deuteranopes[45].

2) For elderly individuals.

A second group of individuals known to deviate significantly from the norm are those in advancing years. This is due to changes in the light transmission of the ocular media with age and is manifest primarily in the loss of sensitivity to the short wavelengths. Verriest's data on individuals over 70 show a loss of sensitivity below 480 nm of approximately .1 log unit; the rest of the curve is unchanged[46]. Verriest's data were determined by flicker photometry but the same loss of relative sensitivity to the short wavelengths is manifest in data obtained by the step-by-step method[47] and by direct heterochromatic photometry[48].

3) For individuals of different races.

A logical extension of the changes in luminous efficiency function found in the elderly is the prediction that highly pigmented races might have functions differing significantly from V (λ). However, Ishak[49] found no large deviations from V (λ) among Egyptians and there is insufficient evidence at the present time to generalize.

(*) Data are currently being collected in several countries on luminous efficiency for a 10° field; the final decision on the most appropriate V_{10} function must await these results.

4) For specific individuals.

If two light sources or two wavelengths must be equated for a specific individual, then his luminous efficiency must be determined directly. This may be done by flicker photometry, step-by-step matches, the minimally distinct border technique, or by direct brightness matches. In selecting the technique, however, it is important to consider the application. If two different lights are to match in brightness, then direct brightness matching must be the technique employed; no other method will adequately assess this aspect of the lights. If however, the two lights must match in luminance for an individual, then flicker photometry or minimally distinct border technique may be used. In other words, all of the considerations and restrictions on the use of V (λ) mentioned above apply to the individual curves as well.

e) Photometry for point sources.

This is an area of practical importance but one for which few data are available. The most important unsolved questions concern the apparent brightness of monochromatic or near-monochromatic sources, as for example in looking at signal lights, approach and runway lights, or beacon lights from a distance. Many factors must be taken into account in attempting to predict perceived brightness : the background (whether dark or daylight, etc.); the position in the field (whether foveally or peripherally viewed); and whether the light is flashing or steady. Because of the paucity of data and the fact that what there is does not differ greatly from V $(\lambda)^{50-53}$, a recommendation other than V (λ) cannot be made until new data warrant it.

f) Summary of the choice of appropriate luminous efficiency functions.

In summary, luminances measured by ordinary methods – the use of a physical photometer corrected to V (λ) – will agree with the visual impression of their brightness only if certain precautions are followed. Thus the light to be measured must be at daylight levels of luminance, at least 3 $\mathrm{cd \cdot m^{-2}}$; it must be about two degrees in subtense; it must be a broad band radiator; it must be viewed foveally; and the luminous efficiency of the viewer must not differ greatly from that of the standard observer.

For other conditions, if luminance measures are to agree with visual impressions, curves other than the CIE standard observer must be used. These conditions include the use of large fields, the measurement of non-neutral lights, and the measurement of light at low intensities. The next section discusses procedures for use with the other conditions.

2.1.2. Means of measurement.

The procedures described above may be dichotomized into normal photometric techniques and all others. The normal photometric techniques employ V (λ) in the measures while the others require some other luminous efficiency function. Almost all light measuring devices on the market today – photometers, light meters, luminance meters, etc. – are based upon the V (λ) curve. The instruments are built so that their spectral sensitivities match (*), as closely as practicable, the CIE V (λ). If a different luminous efficiency function is needed, for whatever reason, this means that the existing devices must be modified or augmented. Since the output of the device is an integration of radiant power and spectral sensitivity, no simple correction is possible and a rather major change may be required. There are at least four courses of action that could be taken.

a) Radiance measures.

One could measure the spectral radiant power of the light and then integrate mathematically with respect to the appropriate luminous efficiency function, whether V (λ) or one of the others discussed above. This solution is perhaps the most general and basic; once the radiant power measurements are made, any curve may be applied and the light effectiveness calculated, without error, for a multitude of applications. Unfortunately, this solution is also the most difficult; few individuals with the exception of standardizing laboratories, are equipped to make spectral radiant power measures.

(*) Marked deviation may occur in individual instruments, particularly at the ends of the spectrum. It is always wise to have the calibration checked by a reliable laboratory if accurate luminance measures are required.

b) Physical photometry.

Perhaps the simplest, and most easily repeated measurement would be by means of a physical photometer. This would require some method, e.g. by adding filters, of adjusting the photo detector so that its sensitivity would be comparable with a curve other than V (λ). For example, a photocell could be adjusted so that its sensitivity would be comparable to Y_{10}.

c) Visual photometry.

A third alternative is the use of visual photometry. This would involve the observer making particular kinds of matches or adjusting a reference light in a particular way to meet the criterion of the test light in question. Many of these criteria have been discussed above. One can utilize flicker photometry, CFF, heterochromatic brightness matching, minimally distinct border, or visual acuity. With visual photometry one is operating automatically with the luminous efficiency of the observer and therefore no assumptions need be made relevant to the CIE function. The criterion adopted depends on the interests of the investigator. If it is desired that luminance type values are obtained then minimum flicker or minimally distinct border would be appropriate criteria[28, 54]. On the other hand, if one wishes to know about the subjective brightness (luminosity) then clearly heterochromatic brightness matching would be a more suitable method of evaluating the stimuli in question.

This solution also is a sensible and effective one. It, too, unfortunately has serious disadvantages : the scarcity of visual photometers, variability in readings, and the large individual differences.

d) Mathematical models in photometry.

Finally, there is an entirely different approach possible in the use of mathematical models. These models generally require measurement of several quantities; the quantities are then combined mathematically according to current knowledge of the underlying physiology of the eye (*). It is now well established, for example, that outer segments of the receptors contain photopigments responsible for quantum absorption. It is at this stage of the visual system that the trichromatic or Young-Helmholtz theory is applicable to color vision. The subsequent neural activity is more adequately described according to the Hering opponent processes theory. Briefly the Hering theory assumes two chromatic channels, red-green and blue-yellow and one achromatic channel, a black-white.

A number of theories[44, 62–65] – commonly called zone theories – have been based upon these concepts and used to explain various phenomena in color vision over the years. A recent one, that of S. L. Guth, has been developed specifically for the photometry of small, photopic fields[26, 36]. It is discussed here in some detail as an example of how such models may be employed in photometry.

Guth's model is a zone-type theory, which makes extensive use of Hering's ideas. Since chromatic channels operate as opponent mechanisms, Guth hypothesizes that neural activity channeled through them subtract rather than add. The black-white or luminance channel is not opponent and therefore behaves additively. Utilizing currently accepted visual physiology, Guth has been able to explain the failure of Abney's additivity law and the failure of the CIE V (λ) to predict the brightness of chromatic lights. The model derives a measure of light, called L**; the most important point for photometry is that this measure is derivable from the CIE XYZ system and thus requires no new standards but only mathematical manipulation of established functions.

The use of mathematical models can be expanded to all levels of illumination and to all field sizes by inclusion of a fourth measure, one of scotopic luminance or rod functioning. Such models also have the advantage of being well-founded upon underlying physiology and of being derivable from established CIE measures. In this case, however, four measures are required and they are V′ (λ) and the CIE XYZ system for a ten-degree field. Two such models have recently been proposed.

One of these, that of Trezona and Clarke[66, 67], is based upon a four color matching procedure, rather than the normal three used in colorimetry. The fourth primary takes account of rod functioning. Tetrachromatic matching procedures yield measures which are additive over a wide range of luminances.

(*) Extensive data have been amassed in recent years toward understanding the physiology of vision and color vision. See, for example, papers by Tomita et al.[55], Marks et al.[56], Brown and Wald[57], De Valois[58], Hubel and Wiesel[59], Padmos and Norren[60, 61]. These are only sample references; many others are available.

Another, that of Kokoschka[13, 68] is derived from data on luminous efficiency in the mesopic region. The four functions used in the model were derived by factor analysis from these data. They can be related to V′ (λ) and X_{10} Y_{10} Z_{10} and furthermore have been incorporated into an electronic instrument capable of making these measures.

None of these theories is as yet complete, with all the necessary data and mathematical formulations. However, all are described in greater detail in Chapter 3 since all have considerable merit as means to achieving a visually meaningful photometric system.

2.2. SCOTOPIC PHOTOMETRY (below about 10^{-3} cd·m^{-2})

At low light levels typical of night vision, only rods are operative and the peripheral retina must be employed to see, since there are no rods in the foveal center. The scotopic spectral luminous efficiency is quite different from that at daylight levels, being relatively more sensitive to the short wavelengths and less sensitive to the long[69, 70]. Since V (λ) values are not appropriate, the CIE, in 1951, established a standard observer for scotopic vision[5]. This curve, referred to as V′ (λ), is based upon the data of 70 persons under the age of 30. The values for 10 nm intervals are given in Table 2.1.; they are to be employed mathematically like the V (λ) function in accordance with equation (2).

Theoretically scotopic photometry is a simple procedure. Since the luminous efficiency is based upon the activity of only one type receptor, many of the problems inherent in photopic photometry do not occur. For example, luminance measures *do* adequately predict the apparent brightness of the stimulus and there are very few differences between individuals[71]. The V′ (λ) values are based upon sufficient, adequately determined data and suffer from few known defects. Scotopic light measures therefore are straightforward integrations of the radiant power and the scotopic V′ (λ) values.

However, once again the problem of the assessment of radiant power must be met. One solution is the construction of light measuring devices whose luminous efficiency function is that of the scotopic standard observer rather than the photopic. There are in fact a few devices on the market that utilize this principle and it is to be hoped that more will be built with the realization that photopic light meters should *not* be used at low levels.

Visual photometers can be used at scotopic levels of illumination because once again the appropriate sensitivity is obtained through the eyes of the operator. The technique however produces variable results since contrast sensitivity is poor in the periphery.

2.3. MESOPIC PHOTOMETRY (between about 10^{-3} and 3 cd·m^{-2})

The region referred to as mesopic encompasses several log units between purely photopic and scotopic light levels. This region is not adequately covered by either the photopic or scotopic systems of photometry since vision at these levels employs both rods and cones. There are many practical situations however, for which an adequate system of mesopic photometry is essential. For example, in highway lighting, the illumination is generally low, the area of interest is large, certainly greater than two degrees, and the illuminant may have a high blue content. Although all of these conditions invalidate the use of V (λ) values, they are generally used, probably because no other system is readily available.

Mesopic spectral sensitivity curves can be found in the literature for measuring light in this region[7–10, 72], but it is unlikely that they will provide a practical solution. One reason is that a battery of photocells and correcting filters would be required since mesopic luminous efficiency functions change so much with light level and with the size and position of the area to be measured. Equally important is the fact that the correct choice of filters cannot be known before the measurement is made, so the actual assessment of the light would have to be made by a process of iteration. The use of visual photometry in the mesopic region is a reasonable solution, since the appropriate luminous efficiency is used automatically. However, no available visual photometers have the necessary large field size and extensive range of adjustments.

Another approach recommended provisionally[73] is to measure the scotopic and 10° photopic luminances, S and P, with two detectors corrected to V′ (λ) and Y_{10} (λ) respectively, and combine them by means of a nonlinear formula which expresses the luminance L.

$$L = (MS + P^2)/(M + P) \tag{3}$$

(L, S, P, and M are in $cd \cdot m^{-2}$ and M has the value of 6×10^{-2} $cd \cdot m^{-2}$) (*).

This formula works within observational precision from the scotopic range well into the mesopic, although at higher levels the non-additivity associated with photopic matches becomes increasingly apparent[74–76].

As an example of the use of this procedure, consider two street lighting installations, one using yellow sodium and the other blue mercury lamps, both adjusted to produce the same luminance of the road, according to the usual type of daylight cell commonly employed by lighting engineers. Suppose the value in each case is .05 $cd \cdot m^{-2}$, a fairly low level which falls in the region of mesopic photometry as defined in this chapter. This means that the level is below that of photopic vision, the use of V (λ) is inappropriate, and the values are in error. Indeed, if one were to go out to look at the two installations, it would be obvious that the two were not equal, but that the mercury was brighter.

Measures with a photometer adjusted for scotopic spectral sensitivity, V′ (λ), would yield values of .01 $cd \cdot m^{-2}$ for the sodium and .07 $cd \cdot m^{-2}$ for the mercury. These scotopic measures are at least in accord with the visual impression, but now the mercury is overevaluated; it is not seven times as effective as the sodium. Using both the photopic and scotopic values in the formula given above results in .03 $cd \cdot m^{-2}$ for the sodium and .06 $cd \cdot m^{-2}$ for the mercury – reasonable values more representative of what the individual would see.

Examples : (All values in $cd \cdot m^{-2}$)

Low Pressure Sodium	Mercury
$L = \frac{.06\,(.01) + (.05)^2}{.06 + .05} = .028\ cd \cdot m^{-2}$	$L = \frac{.06\,(.07) + (.05)^2}{.06 + .05} = .061\ cd \cdot m^{-2}$

The formula by which the photopic and scotopic luminances are combined is an empirical one and must be considered a first approximation. The fit to experimental data can be improved considerably by additional terms[66, 77]. Kokoschka has proposed a system which more accurately predicts mesopic brightness; this is discussed in greater detail in Chapter 3.

To summarize the status of mesopic photometry, the use of V (λ) alone generally results in sizeable errors in the assessment of light. Inclusion of V′ (λ), as in the system described above, considerably improves the measurement and even greater accuracy can be obtained by the addition of a third and even fourth term. This is the purpose of Kokschka's formulation[78].

(*) If only photodetectors calibrated with respect to CIE V (λ) and V′ (λ) are available, then P may be estimated (ref. 74) to a good approximation as $P \simeq 0.96\ L_v + 0.04\ S$, where L_v is the CIE photopic luminance.

Table 2.1. *Spectral Luminous Efficiency for the Standard CIE Observer.*

λ nm	Photopic Vision $V(\lambda)$	Judd's 1951 Correction	Scotopic Vision $V'(\lambda)$
380	.000 039	.000 4	.000 589
390	.000 120	.001 5	.002 21
400	.000 396	.004 5	.009 29
410	.001 21	.009 3	.034 8
420	.004 00	.017 5	.096 6
430	.011 6	.027 3	.199 8
440	.023 0	.037 9	.328
450	.038 0	.046 8	.455
460	.060 0	.060 0	.567
470	.091 0	.091 0	.676
480	.129	Same as $V(\lambda)$	.793
490	.208		.904
500	.323		.982
510	.503		.997
520	.710		.935
530	.862		.811
540	.954		.650
550	.995		.481
560	.995		.329
570	.952		.208
580	.870		.121
590	.757		.065 5
600	.631		.033 2
610	.503		.015 9
620	.381		.007 37
630	.265		.003 34
640	.175		.001 50
650	.107		.000 677
660	.061 0		.000 313
670	.032 0		.000 148
680	.017 0		.000 071 5
690	.008 21		.000 035 3
700	.004 10		.000 017 8

Note : The tables list luminous efficiency values only from 380 to 700 in 10 nm steps. Complete values in 1 nm steps are available in ref. 79 and CIE Publication No. 18 (E-1.2) for photopic vision (from 380 to 830 nm) and in CIE Compte Rendu, 12th Session, Stockholm, 1951, Vol. III, pp. 32-40, for scotopic vision (from 380 to 780 nm).

Table 2.2. *Other Spectral Luminous Efficiencies*

λ nm	10 degree field	2 degree field heterochromatic brightness matching*
380	.000 014	
390	.000 283	
400	.002 00	.019
410	.008 8	.032
420	.021 4	.042
430	.038 7	.076
440	.062 1	.103
450	.089 5	.135
460	.128 2	.166
470	.185 2	.214
480	.253 6	.294
490	.339 1	.359
500	.460 8	.523
510	.606 7	.698
520	.761 8	.978
530	.875 2	1.103
540	.962 0	1.200
550	.991 8	1.179
560	.997 3	1.075
570	.955 6	1.000
580	.868 9	.967
590	.777 4	.965
600	.658 3	.895
510	.528 0	.782
620	.398 1	.651
630	.283 5	.494
640	.179 8	.357
650	.107 6	.184
660	.060 3	.093
670	.031 8	.049
680	.015 9	.028
690	.007 7	.014
700	.003 72	.007

(*) These values are weighted averages of data from seven studies in the literature. Details are found in Appendix A. The curve has been normalized at 570 nm; this is a departure from the usual procedure of normalizing at the peak of a relative luminous efficiency function. It has been done because the absolute luminous efficiency values determined by various methods converge at 570 nm.

Table 2.3. *Relative Luminous Efficiency for Dichromatic Subjects* (*).

λ nm	Protanope	Deuteranope
380	.000 33	.000 25
390	.001 32	.000 88
400	.004 68	.003 51
410	.012 6	.009 15
420	.030 3	.021 0
430	.047 4	.030 5
440	.065 0	.038 0
450	.079 3	.041 5
460	.099 8	.047 5
470	.142	.068 1
480	.197	.106
490	.272	.164
500	.399	.264
510	.597	.424
520	.809	.617
530	.941	.773
540	.997	.883
550	.987	.954
560	.923	.993
570	.807	.997
580	.651	.964
590	.477	.894
600	.318	.795
610	.193	.670
620	.110	.530
630	.058 3	.380
640	.029 6	.256
650	.014 4	.159
660	.007 13	.091 3
670	.003 35	.048 1
680	.001 67	.025 6
690	.000 79	.012 4
700	.000 39	.006 20

(*) Values are computed from the theoretical curves of J. J. Vos[41, 80]; the values are $(G + B)_{rel}$ for the protanope and $(R + B)_{rel}$ for the deuteranope.

Chapter 3

Methods for assessing luminous efficiency functions

This chapter reviews the various ways in which human spectral sensitivity has been assessed, either directly or indirectly. These methods apply primarily to photopic luminous efficiency since many of the problems do not occur in scotopic vision. These discussions will often cover the same points as previous chapters and some sections are repeated here for the sake of continuity.

3.1. METHODS

3.1.1. Flicker photometry.

The first method is perhaps the most common. Flicker photometry requires the observer to adjust the radiance of a colored light (*) which temporally alternates at a suitable frequency with a reference light until minimum amount of flicker is perceived[17, 81, 82]. This frequency of alternation should be selected to ensure color fusion and preferably should be optimal with respect to flicker sensitivity (**). The reciprocal of radiant power required for minimum flicker is then plotted as a function of wavelength. It is common practice to normalize these functions to unity at the maximum sensitivity. These curves are then called « relative luminous efficiency functions ».

3.1.2. Step-by-step brightness matching.

In the step-by-step brightness matching method, the observer makes brightness matches between two wavelengths in a bipartite field[17, 88]. Since the two wavelengths are only a few nanometers apart the colors appear very nearly alike, so the observer can concentrate on making a brightness match without appreciable color differences to complicate the task.. Again the reciprocal of the radiant power is plotted as a function of wavelength and normalized for a maximum of unity. Luminous efficiency functions obtained by this technique generally are intermediate to those found by flicker photometry and by direct heterochromatic brightness matching[17, 35, 88]. The size of the step used in the match is an important variable in determining whether the luminous efficiency function obtained is more like the flicker function or the heterochromatic brightness matching function.

3.1.3. Direct heterochromatic brightness matching.

Direct heterochromatic brightness matching requires the observer to adjust the radiance of a colored light to appear as bright as a reference light. When this is done the two differently colored lights will usually *not* be equal in luminance. The matching of brightness while ignoring color differences is a difficult task and results in variable data. (Indeed, for this reason, flicker photometry and the step-by-step method yield considerably more reliable data than does direct heterochromatic brightness matching at photopic levels[81].) However, this variability can be partially circumvented by using a large number of subjects and taking many trials on each to determine a more reliable estimate of the match.

Data obtained by minimum flicker and the step-by-step methods formed the basis of the original definition of CIE V (λ); these methods were used instead of heterochromatic brightness matching method for two main reasons. The first is that heterochromatic brightness matching generally yields

---

(*) All descriptions will be presented in terms of adjusting the colored, test light. Obviously the test lights could also be set for equal power and then the reference light could be adjusted to match each test light according to the criterion required by the method.

(**) The frequency at which flicker sensitivity is maximum depends upon the radiance[83-85] and the area[86, 87] of the reference light. A reasonable solution is to select a frequency just above color fusion.

much more variable data than does the step-by-step or minimum flicker method. Furthermore, it has been determined that the additivity law is not obeyed with heterochromatic brightness matching but is obeyed with flicker photometry.

As noted in Chapter 2, CIE luminance assumes that the total luminance of non-monochromatic light is the sum of the weighted radiances of the component wavelengths. Consequently, the additivity of luminances is demanded by the CIE definition. If, for example, one has a light which appears yellow but indeed is made up of a mixture of red and green light, the luminance of the yellow light is, by definition, equal to the sum of the luminances of the red and green lights. Whether or not this additivity is representative of the visual appearance depends upon how the weighting of the radiant power (luminous efficiency functions) to derive luminance is achieved. If the weightings are achieved by means of the flicker method then additivity will be obtained. If the weightings are obtained by means of heterochromatic brightness matching then additivity will not be obtained.

3.1.4. Absolute thresholds.

In this method, a determination is made of the least amount of energy at each wavelength necessary to see. This can be done with either foveal or peripheral vision and the curve thus obtained will be either photopic or scotopic, respectively. If a photopic function is desired, stimulation of only the cones is crucial and requires exact fixation and a small field of less than 1°. Since the rods are more sensitive, if they are allowed to participate, e.g. with larger fields at low levels, a shift in sensitivity towards the shorter end of the spectrum can be expected.

The threshold method has been in use since at least 1880 (*) and employed frequently over the years[90, 91]. Luminous efficiency functions determined by this method will also show additivity failures. If two wavelengths are each set to one half their threshold value and then added together, their mixture frequently will be below threshold. Guth et al.[26] present a plausible hypothesis to explain why the additivity law does not hold for heterochromatic brightness matching or threshold criterion. This explanation makes use of the chromatic responses' contribution to brightness; the latter involves cancellation of neural activity at the opponent processing stage of color vision processing.

3.1.5. Increment thresholds.

This method employs the same technique as absolute threshold with the exception that the test wavelengths are presented against a lighted background instead of a dark one. It thus has the advantage of allowing the determination of luminous efficiency functions for any type and level of adaptation, such as mesopic, suprathreshold or chromatic. It has been widely employed to investigate adaptive effects[61, 92–100]. Verriest has shown luminous efficiency functions determined by incremental thresholds, with achromatic backgrounds, yield data similar to the absolute measures; that is, the curve is wider and more irregular than V (λ)[96]. Additivity failures exist also with increment thresholds; this failure is adaptation dependent[101]. Similarly, wide, irregular spectral sensitivity curves under intense white adaptation are shown by Sperling and coworkers[102, 103]. These data may have important implications for outdoor lighting conditions in that they probably indicate large additivity failures.

3.1.6. Minimally distinct border.

The minimally distinct border method involves presenting a precisely juxtaposed bipartite field. Half the field contains a reference light, the other half the light of variable wavelength. The observer's task is to minimize the distinctness of the border between the fields by adjusting the radiance of the monochromatic light. In order to make this judgment easier for the subject, it is essential to use a lens which compensates for the chromatic aberration of the eye. This procedure is about as reliable as minimum flicker and also obeys the additivity rule [28, 35]. With this criterion the observer adjusts the brightness of a chromatic field which is precisely juxtaposed with a reference white field until the border between these two fields is minimally distinct. To test for additivity this would be done first with, for example, a red light and then a green and then when the quantities of the red and green lights are halved and mixed it would be found that the minimally distinct border would be maintained.

(*) See reference 89 for a review of the early literature.

3.1.7. Visual acuity.

Ives was one of the first to use spatial visual acuity as a criterion for assessing human spectral sensitivity[81]. In this method one uses constant sized acuity targets on backgrounds varying in dominant wavelength (e.g., gratings, Landolt C's). The radiant power of the background is adjusted until the distinguishing feature (grating or gap) is correctly identified. This radiant power is then plotted as a function of wavelength to yield the luminous efficiency function.

Guth and Graham have reported an additivity experiment where acuity with Landolt C's was the psychophysical criterion[29]. They found that additivity was obtained. Similar results have been found by Myers, Ingling, and Drum for grating targets[31]. Perhaps the same visual mechanism is mediating flicker, minimally distinct border, and acuity criteria.

3.1.8. Critical flicker frequency.

The criterion of constant threshold flicker has been used to derive luminous efficiency functions[81, 104]. In this technique a chromatic light is alternately presented with a dark field; the light and dark periods are generally of equal duration. With flicker frequency held constant, the observer adjusts the radiance of the chromatic light for just-detectable flicker. While there is some dependence on the choice of the constant flicker rate, the curves generated by this technique generally agree with those of flicker photometry and minimally distinct border. For a small foveally viewed stimulus, the luminous efficiency is very close to Judd's modifications of the CIE V (λ); for larger areas, and for more peripheral locations, the curves are broader in the short wavelengths than V (λ) as might be expected[105].

3.1.9. Colorimetry.

Luminous efficiency functions can be derived from data obtained in color matching experiments[79, 106]. The procedure requires two steps. First, the luminance of the primaries are determined by flicker photometry. Second the luminances of the primaries required in each of the color matches are added together. When these total luminances are obtained from color matching functions for an equal radiance spectrum, the result of the additions is a luminous efficiency function. The technique rests on the assumption of additivity and yields luminous efficiency functions similar to those of flicker photmetry[27].

3.1.10. Other methods.

A wide variety of other responses may be used to measure relative luminous efficiency. Although these methods are less direct assessments of luminous efficiency functions than the strictly visual measures, all will yield curves if some constant criteria is employed. Thus pupil diameter[107–114], reaction time [115] and electrophysiological measures [116–125] have been used and generally yield photopic or scotopic luminous efficiency functions under the appropriate conditions. However few additivity tests have been made.

3.2 THE IMPLICATIONS FOR PHOTOMETRY

These then are examples of methods by which the luminous efficiency functions of individuals may be determined. The ideal of an unique luminous efficiency function is not met, for the results obtained depend markedly upon the method used. The result is that definitions of light based upon one method will produce measures that do not agree with the visual impressions found by other methods. One possible way out of this impasse is to separate the concept of luminance from vision and use it simply as a physical quantity. This has in fact been the solution employed by many individuals: statements are made to the effect that luminance measures and impressions of brightness do not agree but there is no reason why they should; the former are objective, physical, repeatable measures which, according to this view are, only vaguely related by historical accident to the eye.

The opposite view is adopted by Technical Committee 1.4 who feel that the measurement of light should be meaningfully related to vision as was originally intended by the CIE. We further believe that some practicable methods do exist for bringing the two into agreement. Four such techniques were described in Chapter 2. Admittedly, all complicate the measure of light beyond current practice. However one of these, mathematical models in photometry, represents a potential solution for all the problems discussed above and its requirements for future instrumentation do not involve apparatus more complicated than the current physical photometers. For these reasons, various models and their implications for photometry are discussed in some detail below.

3.2.1. Photopic, small-field photometry.

a) The model proposed by Guth.

This model [26, 36] serves as an excellent example of the type of system possible within photometry; it is neither unique – there are many similar in the literature [44, 62, 63, 126] – nor adequate in its present form. However, it does represent an excellent beginning for an all inclusive system of photometry capable of providing a visually meaningful measure of light.

The model is based upon two important concepts. One is the current physiological theory of color vision which views it as mediated by three different kinds of cones at the retina whose output is fed into an opponent neural system. In the latter, activity in the red-green system is antagonistic or subtractive, as is activity in the blue-yellow system. The second major concept is that the results of luminous efficiency functions determined by all the different methods discussed above can be roughly grouped into two types. One of these is the narrow curve characteristic of V (λ) which manifests the property of additivity, and the second of which is a wider curve with heightened sensitivity at both the short and the long ends of the spectrum which gives non-additive results.

The model is called the ATD threshold model, the letters ATD standing for Achromatic, Tritanopic, and Deuteranopic. The A part of this model corresponds to the non-opponent black/white system. The T corresponds to part of the opponent system, namely the yellowish-red versus the bluish-green mechanism, or as some may wish to call it, the red versus green system, and the D is the violet versus the greenish-yellow mechanism or again as some may wish to call it, the blue versus yellow system.

The model is able to predict additivity failures, in addition to saturation functions, wavelength discrimination functions and equal lightness to luminance ratio contours. For the purpose of this report the most interesting part of the model is concerned with the quantity he calls L**. L** is related to the objective concept of brightness or more specifically the detectability of chromatic light. And herein lies the strength of his model. As noted above one of the major difficulties with CIE luminance is that it does not predict the brightness and detection perception of highly colored lights very well. L** purports to do this (at or near threshold) quite well.

Since detection responses are mediated by all systems, additivity failures due to opponent, subtractive effects are predicted, through vector addition. At the same time, flicker photometry relates only to the non-opponent system and is therefore additive[36].

Another important aspect of the model is that one can transform back and forth between his ATD threshold model and the CIE XYZ system. The computation of L** is accomplished as follows :

$$L^{**} = (A^2 + T^2 + D^2)^{1/2} \tag{4}$$

where at threshold :

$$\begin{aligned} A &= 0.000X + 0.954Y + 0.010Z \\ T &= 0.799X - 0.646Y - 0.167Z \\ D &= 0.000X - 0.058Y + 0.030Z \end{aligned}$$

L** can be computed if one knows Y, which is available from a photometric measurement and the chromaticity coordinates of the stimulus.

Equation (4) is given in terms of the tristimulus values (XYZ). This transformation can also be accomplished using the same coefficients and the spectral tristimulus values $(\bar{x}\bar{y}\bar{z})$ (*). This is sometimes useful for spectral lights because these values are readily accessible in colorimetric reference sources. If the spectral power distribution of a source is known, the spectral tristimulus values can be used to obtain the tristimulus values, XYZ, for use in equation (4) to obtain ATD and thus L**. Further, it should be recalled that $\bar{y}$ (λ) is equivalent to V (λ).

(*) Also called color matching functions or distribution coefficients.

There are several disadvantages at the present time with this approach. This particular model has been developed for foveal threshold data and is applicable only under these conditions. Suprathreshold, foveal models are obviously of importance and these require a new set of transformations from the X, Y, Z, data. The relative importance of the yellow-blue system must be greater at suprathreshold levels; Guth has suggested a set of suprathreshold transformations but extensive development and testing is still required.

3.2.2. Large field models.

Models based on the CIE XYZ system of colorimetry, such as Guth's, have the same restrictions as V (λ) regarding viewing conditions; that is, they apply only to foveal viewing for a small field of about two degrees. Other models must be developed for applications to larger fields and for a greater range of light levels than simply photopic. Fortunately, two such models have recently been proposed and are under development; these are discussed below.

a) Kokoschka's system for a total range of light levels.

This system is aimed at providing a means of photometry for the total range of light levels from scotopic to photopic. It is based upon empirically-determined, spectral sensitivity curves, obtained by direct heterochromatic brightness matching over a mesopic range of four log units for field sizes from 3 to 64 degrees[12, 13]. The experimental data were subjected to a factor analysis which revealed four components; physiologically these undoubtedly correspond to the outputs from three types of cones and the rods[78].

Thus the spectral sensitivity of the human eye performing a brightness match in the mesopic range of adaptation is viewed as a linear combination of three cone components and one rod component and the equivalent luminance for any radiant power distribution can be calculated from the CIE tristimulus values, $\bar{x}_{10}$, $\bar{y}_{10}$, $\bar{z}_{10}$, the CIE spectral luminous efficiency function, V′ (λ), for scotopic vision, and a set of four coefficients, F_x, F_y, F_z, and F_s, whose values depend upon luminance level. These coefficients, which are determined by the factor analysis, are available in two papers [68, 78]; however, the choice of the values to use depends upon the equivalent luminance itself. In order to solve this circular problem, an iterative computer solution is recommended, although other methods are available.

This system has the obvious advantages of being applicable throughout the range of change over from photopic to scotopic vision and of being based upon standard CIE functions. In addition, it has been used as the basis for a physical photometer using four inputs; since the Z input is quite small throughout the mesopic range, a simplified version of the physical photometer can be employed with three inputs[68].

b) Trezona and Clarke's tetrachromatic model.

Another system based upon four inputs is being developed from an entirely different basis; ie.tetrachromatic color matching [66, 67]. Since additivity failures are often encountered in large field, trichromatic color matching, the technique of a tetrachromatic, rod-balanced color match is being studied. The results to date indicate that the tetrachromatic match has general properties : uniqueness, generality for all spectral and nonspectral colors, additivity, and invariance with respect to luminance level, and thus could form the basis for general systems of colorimetry and photometry.

A complete 10° system of colorimetry and photometry is being developed on these principles. It is envisaged in the form of a computer program, which consists of two parts of which the first is tetrachromatic. In this part the absolute spectral power distribution reaching the eye will be weighted by the tetrachromatic color matching functions to derive the tetrastimulus values. All predictions of mixtures take place at this stage. The second part is non-additive and deals with emergence from the tetrachromatic system into a system of three variables for color specification and/or of one variable for its (newly defined) photometric value.

For the second stage, functions (yet to be determined) will be provided to give the output derived from the particular tetrachromatic stimulus values. These functions, 3 for colorimetry and 1 for photometry, can be determined experimentally by fitting them to matches made over a four dimensional sampling at discrete intervals in the tetrastimulus space. The system of general photometry could be either the flicker type (photometrically additive in photopic conditions) or of the heterochromatic brightness matching type (non-additive). However, both systems could be incorporated as alternative forms of output. Interfacing between these outputs and industrial requirements is under consideration.

3.2.3. The future of models in photometry.

It is the considered opinion of TC-1.4 that models represent an excellent solution to the present and future problems that photometry faces. We urge investigators to study and test these models and to provide the necessary data for improving them. In fact, one of the goals of this report is to stimulate such research.

All the models described herein are still in the development stage. Guth's model needs more accurate transformations for suprathreshold levels of luminance; Kokoschka's needs to be extended to the higher photopic levels where additivity failures may be encountered; and Clarke and Trezona's is still being constructed. Furthermore, all of these models need to be validated by thorough investigation.

All these models are more complicated than the CIE method of determining luminance because they require the transformation from the CIE system to obtain the final measures. However, the current availability of computers and computing calculators for the serious visual scientist or photometrist makes such transformations very simple. With the advent of new light weight, solid-state calculators, these transformations are now possible in all field conditions where existing photometric equipment can be used.

There are many advantages to such systems. Models can be much more closely allied to the subjective impression, detectability and brightness than is the CIE luminance. They also have advantages in being grounded in basic physiological and theoretical formulations of color vision and are relatively consistent with a number of visual phenomena which were discussed above. Finally, and of major importance, these systems can be realized at the present time, using standard efficiency functions : the CIE colorimetric standard observers for either 2° or 10°.

References

1. CIE, International Lighting Vocabulary, 3rd Edition; Publication #17, 1970 (Bureau Central de la CIE, Paris 1970) p. 2 item #45-04-025, and p. 111 item #45-25-125.
2. CIE, Compte Rendu, 12th Session, Stockholm, 1951 (Central Bureau of CIE, New York, 1951) Vol. I, Tech. Committee No. 7, Colorimetry and Artificial Daylight. pp. 7 (1-52).
3. Hsia, Y. and C. H. Graham. In *Vision and Visual Perception,* C. H. Graham, Ed. (John Wiley & Sons, Inc., New York 1965) pp. 402-403.
4. Kinney, J. A. S. Calculated effect of the color temperature of the stimulus on scotopic thresholds. J. Opt. Soc. Am. 46, 1093, 1956.
5. CIE, Compte Rendu, 12th Session, Stockholm, 1951 (Central Bureau of CIE, New York, 1951) Vol. III, pp. 32-40.
6. Barbrow, L. E. International Commission on Illumination, J. Opt. Soc. Am. 41, 734-738, 1951.
7. Walters, H. V. and W. D. Wright. The spectral sensitivity of the fovea and extrafovea in the Purkinje range. Proc. Roy. Soc., B, 131, 340-361, 1943.
8. Kinney, J. A. S. Sensitivity of the eye to spectral radiation at scotopic and mesopic intensity levels. J. Opt. Soc. Am. 45, 507-514, 1955.
9. Kinney, J. A. S. Comparison of scotopic, mesopic, and photopic spectral sensitivity curves. J. Opt. Soc. Am., 48, 185-190, 1958.
10. Kinney, J. A. S. Effect of field size and position on mesopic spectral sensitivity. J. Opt. Soc. Am. 54, 671-677, 1964.
11. Grigorovici, R., I. Aricescu-Savopol. Luminosity and chromaticity in the mesopic range. J. Opt. Soc. Am. 48, 891-898, 1958.
12. Kokoschka, S. Spektrale Hellempfindlichkeit und äquivalente Leuchtdichte zentraler Gesichtsfelder im mesopischen Bereich. CIE, Compte Rendu, 17th Session, Barcelona, 1971 (Central Bureau of the CIE, Paris, 1972) pp. 153-154.
13. Kokoschka, S. and W. Adrian. Influence of field size on the spectral sensitivity of the eye in the photopic and mesopic range. Paper presented at the ARVO meeting, April 1974.
14. CIE, Compte Rendu, 14th Session, Bruxelles, 1959 (Central Bureau of CIE, Paris, 1960) Vol. A, p. 95.
15. CIE, Recueil des Travaux et Compte Rendu, 6th Session, Geneva, 1924 (Cambridge University Press, London, 1926) Principales décisions, p. 67; Report of the national committee of the USA, pp. 232-238.
16. CIE, Recueil des Travaux et Compte Rendu, 8th Session, 1931 (Cambridge University Press, London, 1932) Official Recommendations, p. 19, 25, 26.
17. Le Grand, Y. *Light, Colour and Vision* (Chapman & Hall, Ltd., London, 1968).
18. Dresler, A. The non-additivity of hetero-chromatic brightness. Trans. Ill. Eng. Soc. 28, 141, 1953.
19. Chapanis, A. and R. M. Halsey. Luminance of equally bright colors. J. Opt. Soc. Am. 45, 1-6, 1955.
20. Sanders, C. L. and G. Wyszecki. L/Y ratios in terms of CIE-chromaticity coordinates. J. Opt. Soc. Am. 48, 389-392, 1958.
21. Federov, N. T. The additivity of spectral heterochromatic luminance in connection with revision of standard spectral mixture. Compte Rendu, CIE, 1957, Paper 31.
22. Yurov, S. G. The question of the metrics of brightness. In *Visual Problems of Colour*, Vol. I, pp. 195-208 (London, Her Majesty's Stationery Office, 1958).
23. Guth, S. L., J. V. Alexander, J. I. Chumbly, C. B. Gillman, and M. M. Patterson. Factors affecting luminance additivity at threshold among normal and color-blind subjects and elaborations of a trichromatic-opponent colors theory. Vision Res. 8, 913-928, 1968.
24. Volkenshtein, A. A. Addition of low luminances. Svetotechnika, 1, 1958.
25. Volkenshtein, A. A. Addition of small luminances. J. Tech. Phys. 25, 1100, 1955.
26. Guth, S. L., N. J. Donley, and R. T. Marrocco. On luminance additivity and related topics. Vision Res. 9, 537-575, 1969.
27. Sperling, H. G. In *Visual Problems of Colour*, Vol. I, pp. 250-277 (London, Her Majesty's Stationery Office, 1958).

28. Boynton, R. M. and P. K. Kaiser. Vision : the additivity law made to work for heterochromatic photometry with bipartite fields. Science, 161, 366-368, 1968.
29. Guth, S. L. and B. V. Graham. Heterochromatic additivity and the acuity response. Vision Res. 15, 317-319, 1975.
30. Graham, B. V. and S. L. Guth. Red-plus-green heterochromatic additivity as applied to the acuity response. J. Opt. Soc. Am. 60, 1573 (A), 1970.
31. Myers, K. J., C. R. Ingling, Jr., and B. A. Drum. Brightness additivity for a grating target. Vision Res. 13, 1165-1173, 1973.
32. Judd, D. B. Measurement of light and color. Illum. Eng., 53, 61-71, 1958.
33. Kaiser, P. K. Luminance and brightness. Appl. Optics, 10, 2768-2770, 1971.
34. Kaiser, P. K. Minimally distinct border as a preferred psychophysical criterion in visual heterochromatic photometry. J. Opt. Soc. Am. 61, 966-971, 1971.
35. Wagner, G. and R. M. Boynton. Comparison of four methods of heterochromatic photometry. J. Opt. Soc. Am. 62, 1508-1515, 1972.
36. Guth, S. L. and H. R. Lodge. Heterochromatic additivity, foveal spectral sensitivity, and a new color model. J. Opt. Soc. Am. 63, 450-462, 1973.
37. Kinney, J. A. S. Degree of applicability and consequence of inappropriate uses of units of light. Appl. Optics, 6, 1473-1477, 1967.
38. Sanders, C. L. and G. Wyszecki. Correlate for brightness in terms of CIE color matching data. CIE, Compte Rendu, 15th Session, Vienna, 1963 (Central Bureau of CIE, Paris, 1964) Vol. B, pp. 221-230.
39. Kaiser, P. K. and P. Smith. The luminance of equally bright colors. CIE, Compte Rendu, 17th Session, Barcelona, 1971 (Central Bureau of CIE, Paris, 1972) Vol. 21A, pp. 143-144.
40. Guild, J. Comments made at the Symposium No. 8. In *Visual Problems of Colour*, Vol. I, p. 337 (London, Her Majesty's Stationery Office, 1958.
41. Vos, J. J. Tabulated characteristics of a proposed 2° fundamental observer. Institute for Perception TNO, Rep. No. IZF 1975-9, Sept. 1975.
42. Wooten, B. R., K. Fuld, and L. Spillmann. Photopic spectral sensitivity of the peripheral retina. J. Opt. Soc. Am. 65, 334-343, 1975.
43. Graham, B. V., R. Holland, and D. L. Sparks. Relative spectral sensitivity to short wavelength light in the peripheral visual field. Vision Res. 15, 313-316, 1975.
44. Vos, J. J. and P. L. Walraven. On the derivation of the foveal receptor primaries. Vision Res. 11, 799-818, 1971.
45. Verriest, G. Les courbes spectrales photopiques d'efficacité lumineuse relative dans les déficiences congénitales de la vision des couleurs. Vision Res. 11, 1407-1434, 1971.
46. Verriest, G. Variations in the photopic relative spectral luminous efficiency curve for normal subjects. Nouv. Rev. d'Optique Applique, 1, 107-126, 1970.
47. Rudduck, K. H. Effects of age upon colour vision II. Changes with age of light transmission in the ocular media. Vision Res. 5, 47-58, 1965.
48. Harrington, R. E. Effect of color temperature on apparent brightness. J. Opt. Soc. Am. 44, 113-116, 1954.
49. Ishak, I. G. H. The photopic luminosity curve for a group of fifteen Egyptian trichromats. J. Opt. Soc. Am. 42, 529-534, 1952.
50. Sperling, H. G. and Y. Hsia. Some comparisons among spectral sensitivity data obtained in different retinal locations and with two sizes of foveal stimulus. J. Opt. Soc. Am. 47, 707-713, 1957.
51. Thomson, L. C. The spectral sensitivity of the central fovea. J. Physiol. (Lond.) 112, 114-132, 1951.
52. Bedford, R. E. and G. W. Wyszecki. Luminosity functions for various field sizes and levels of retinal illuminance. J. Opt. Soc. Am. 48, 406-411, 1958.
53. Blackwell, H. R. and J. H. Taylor. Variations in spectral sensitivity within the human fovea. Institute for Research in Vision, Ohio State University, Ann Arbor, Michigan. Final report on ERI Project 2455, Bureau of Ships, Department of the Navy, Contract No. Nobs-72038, Washington, D. C. June 1958.
54. Kaiser, P. K., P. Herzberg, and R. M. Boynton. Chromatic border distinctness and its relation to saturation. Vision Res. 11, 953-968, 1971.
55. Tomita, T., A. Kaneko, M. Murakami, and E. L. Pautler. Spectral response curves of single cones in the carp. Vision Res. 7, 519-531, 1967.
56. Marks, W. B., W. H. Dobelle, and E. F. MacNichol, Jr. Visual pigments of single primate cones. Science, 143, 1181-1183, 1964.

57. Brown, P. K. and G. Wald. Visual pigments in single rods and cones in the human retina. Science, 144, 45-52, 1964.
58. De Valois, R. L. Analysis and coding of color vision in the primate visual system. Cold Springs Harbor Symposia on Quantitative Biology, 30, 567-579, 1965.
59. Hubel, D. H. and T. N. Wiesel. Receptive fields and functional architecture of monkey striate cortex. J. Physiol. (Lond.) 195, 215-243, 1968.
60. Padmos, P. and D. V. Norren. Cone systems interaction in single neurons of the lateral geniculate nucleus of the macaque. Vision Res. 15, 617-619, 1975.
61. Padmos, P. and D. V. Norren. Increment spectral sensitivity and colour discrimination in the primate, studied by means of graded potentials from the striate cortex. Vision Res. 15, 1103-1113, 1975.
62. Jameson, D. and L. M. Hurvich. Opponent chromatic induction : experimental evaluation and theoretical account. J. Opt. Soc. Am. 51, 46-53, 1961.
63. Hurvich, L. M. and D. Jameson. Some quantitative aspects of an opponentcolors theory. IV. A psychological color specification system. J. Opt. Soc. Am. 46, 416-421, 1956.
64. Walraven, P. L. On the mechanisms of colour vision. Thesis Utrecht. Ed. Inst. for Perception RVO/TNO 1962.
65. Walraven, P. L. and M. A. Bouman. Fluctuation theory of colour discrimination of normal trichromats. Vision Res. 6, 567-586, 1966.
66. Trezona, P. W. Additivity in the tetrachromatic system. Vision Res. 14, 1291-1301, 1974.
67. Clarke, F. J. J. and P. W. Trezona. Towards general systems of colorimetry and photometry based on the tetrachromatic colour match. CIE, 18th Session, London 1975.
68. Kokoschka, S. and H.-W. Bodmann. Ein konsistentes System zur photometrischen Strahlungsbewertung im gesamten Adaptionsbereich. CIE, 18th Session, London, 1975.
69. Crawford, B. H. The scotopic visibility functions. Proc. Phys. Soc. B. 62, 321, 1949.
70. Le Grand, Y. Comité d'études sur la lumière et la vision, rapport du secrétariat. CIE, Compte Rendu, 12th Session, Stockholm 1951, Vol. I, pp. 4 (1-31) (New York, Bureau Central CIE 1951).
71. Pirenne, M. H. Spectral luminous efficiency of radiation. In *The Eye Vol. 2 the Visual Process* (New York, Academic Press 1962), pp. 65-91.
72. CIE, Compte Rendu, 15th Session, Vienna 1963 (Central Bureau of CIE, Paris, 1964) p. 216.
73. CIE, Compte Rendu, 17th Session, Barcelona, 1971 (Central Bureau of CIE, Paris, 1972), p. 151.
74. Palmer, D. A. Standard observer for large-field photometry at any level. J. Opt. Soc. Am. 58, 1296-1299, 1968.
75. Palmer, D. A. A system of mesopic photometry. Nature 209, 276-281, 1966.
76. Palmer, D. A. The definition of a standard observer for mesopic photometry. Vision Res. 7, 619-628, 1967.
77. Palmer, D. A. Personal communication.
78. Kokoschka, S. Untersuchungen zur mesopischen Strahlungsbewertung. Die Farbe, 21, 39-112, 1972.
79. Wyszecki, G. and W. S. Stiles. *Color Science* (New York : John Wiley and Sons 1967) pp. 507-508.
80. Vos, J. J. Colorimetric and photometric properties of a 2° fundamental observer. Institute for Perception-TNO, Report No. 12F 1974-12, 1974.
81. Ives, F. Studies in the photometry of lights of different colors. Philisophical Magazine 24, 149-188, 352-370, 744, 845, 1912.
82. Walsh, J. W. T. *Photometry* (London, Constable & Co. Ltd, 1926) p. 505.
83. De Lange, H. Attenuation characteristics and phase-shift characteristics of the human fovea-cortex systems in relation to flicker fusion phenomena. Thesis Delft 1957.
84. Kelly, D. M. Visual responses to time-dependent stimuli I. Amplitude sensitivity measurements. J. Opt. Soc. Am. 51, 422-429, 1961.
85. Roufs, J. A. J. Dynamic properties of Vision I. Experimental relationships between flicker and flash thresholds. Vision Res. 12, 261-278, 1972.
86. Gon, J. J. Denier van der. Gezichtsscherpte, een fysisch-fysiologische studie. Thesis Amsterdam 1959.
87. Roufs, J. A. J. and H. J. Meulenbrugge. The quantitative relation between flash threshold and the flicker fusion boundary for centrally fixated fields. IPO, Ann. Progr. Report, 133-139, 1967.
88. Gibson, K. S. and E. P. T. Tyndall. Visibility of radiant energy. Bur. of Standards Scientific Papers 19, 131-191, 1923.
89. Coblentz, W. W. and W. B. Emerson. Relative sensibility of the average eye to light of different colours and some practical applications to radiation problems. Bull. Bur. Stand. 14, 167-237, 1917.

90. König, A. Ges. Abhandlungen, Pflügers Ann. der Phys. 9, 185, 1902.
91. Hsia, Y. and C. H. Graham. Spectral sensitivity of the cones in the dark adapted human eye. Proc. Nat'l Acad. Sciences 38, 80-85, 1952.
92. Stiles, W. S. and B. H. Crawford. The liminal brightness increment as a function of wave-length for different conditions of the foveal and parafoveal retina. Proc. Roy. Soc. (Lond.) B 113, 496-530, 1933.
93. Stiles, W. S. The directional sensitivity of the retina and the spectral sensitivity of the rods and cones. Proc. Roy. Soc. (Lond.) B 127, 64-105, 1939.
94. Wald, G. and P. K. Brown. Human color vision and color blindness. Cold Spring Harbor Symposia on Quantitative Biology, 30, 345-361, 1965.
95. Verriest, G. and M. Szmigielski. Variation spectrale du seuil d'éclairement rétinien énergétique pour des contrastes positifs maculaires. Rev. Opt. (Paris) 45, 293-312, 1966.
96. Verriest, G. and H. Kandemir. Normal spectral increment thresholds on a white background. Die Farbe 23, 3-16, 1974.
97. Stiles, W. S. Increment thresholds and mechanisms of colour vision. Docum. Ophthal. 3, 138-165, 1949.
98. Stiles, W. S. The determination of the spectral sensitivities of the retinal mechanisms by sensory methods. Ned. Tijdschr. Natuurk. 15, 125-146, 1949.
99. Stiles, W. S. Colour vision : the approach through increment threshold sensitivity. Proc. nat. Acad. Sci. (Wash.) 75, 100-114, 1959.
100. Enoch, J. M. The two-color threshold technique of Stiles and derived component color mechanisms. In *Handbook of Sensory Physiology Vol. VII/4 Visual Physchophysics* (edited by D. Jameson and L. M. Hurvich) (New York, Springer-Verlag, 1972) pp. 537-567.
101. Boynton, R. M., M. Ikeda, and W. S. Stiles. Interactions among chromatic mechanisms as inferred from positive and negative increment thresholds. Vision Res. 4, 87-117, 1964.
102. Sperling, H. G. and R. S. Harwerth. Red-green cone interactions in the increment-threshold spectral sensitivity of primates. Science, 172, 180-184, 1971.
103. Sidley, N. A. and H. G. Sperling. Photopic spectral sensitivity in the rhesus monkey. J. Opt. Soc. Am. 57, 816-818, 1967.
104. Bornstein, M. N. and L. E. Marks. Photopic luminosity measured by the method of critical frequency. Vision Res. 12, 2023-2034, 1972.
105. Bornstein, M. H. Spectral sensitivity of the modulation-sensitive mechanism of vision : Effects of field size and retinal locus. Vision Res. 15, 865-869, 1975.
106. Wright, W. D. *Researches on Normal and Defective Colour Vision* (St. Louis, C. V. Mosby Co. 1947), pp. 107-143.
107. Bartlett, N. R. Thresholds as dependent on some energy relations and characteristics of the subject. In *Vision and Visual Perception* (edited by C. H. Graham) (New York, Wiley & Sons, 1965) pp. 164-165.
108. Davson, H. *The Eye Vol. III. Muscular Mechanisms* (New York, Academic Press, 1962) p. 239.
109. Laurens, H. Studies on the relative physiological value of spectral lights III. The pupillomotor effects of wave-lengths of equal energy content. Am. J. Physiol. 64, 97-119, 1923.
110. Adrian, W. Pupil size and wavelength of light of equivalent luminance. Tagungsbericht Internationale Farbtagung COLOR 69, Stockholm 1969.
111. Bouma, H. Receptive systems mediating certain reactions on the pupil of the human eye. Thesis, Eindhoven, 1965.
112. Alpern, M. and F. W. Campbell. The spectral sensitivity of the consensual light reflex. J. Physiol. (Lond.) 164, 478-507, 1962.
113. Alexandridis, E. and E. R. Koeppe. Die spektrale Empfindlichkeit der für den Pupillenlichtreflex verantwortlichen Photoreceptoren beim Menschen. Albrecht von Graefes Arch Klin. Ophthalmol. 177, 136-151, 1969.
114. Hedin, A. Pupillary spectral sensitivity in normals and color defectives. Proc. 3rd Intern. Symp. Colour Vision Deficiencies, Amsterdam, 1975.
115. Lit, A., R. H. Young and M. Shaffer. Simple time reaction as a function of luminance for various wavelengths. Percept. & Psychophysics 10, 397-399, 1971.
116. Armington, J. C. Spectral sensitivity of simultaneous electroretinograms and occipital responses. Clinical Electroretinography, Vision Res. Suppl. 1, 225-233, 1966.
117. De Voe, R. H., H. Ripps, and H. G. Vaughan, Jr. Cortical responses to stimulation of the human fovea. Vision Res. 8, 135-147, 1968.

118. Riggs, L. and B. R. Wooten. Electrical measures and psychophysical data in human vision. In *Handbook of Sensory Physiology, Vol. VII/4 Visual Psychophysics.* D. Jameson and L. M. Hurvich (Eds.), (New York, Springer-Verlag 1972).
119. Biersdorf, W. R. Purkinje shift in the human electroretinogram. Am. J. Ophthal. 64, 757-760, 1967.
120. Wooten, B. R. Photopic and scotopic contribution to the human visually evoked cortical potential. Vision Res. 12, 1647-1660, 1972.
121. Regan, D. Evoked potentials and colour vision. 7th ISCERG Symposium, Istanbul, 1969.
122. Regan, D. Objective method of measuring the relative spectral-luminosity curve in man. J. Opt. Soc. Am. 60, 857-859, 1970.
123. Regan, D. Evoked potentials to changes in the chromatic contrast and luminance contrast of checkerboard stimulus patterns. ISCERG Symposium, Brighton, 1971.
124. Regan, D. Electrophysiological evidence for colour channels in human pattern vision. Nature 250, 437-439, 1974.
125. Regan, D. Recent advances in electrical recording from the human brain. Nature, 253, 401-407, 1975.
126. Ingling, C. R., B. Tsou, and T. Nosek. A transformation of color space with photometric properties. Paper presented at annual meeting of Association for Research in Vision and Ophthalmology, Sarasota, Florida, 1973.

Appendix A

Luminous efficiency curve for a centrally-viewed, two degree field by heterochromatic brightness matching

Data listed in Table A.1 have been compiled from the following seven studies :

1) Bedford, R. E. and G. W. Wyszecki. Luminosity functions for various field sizes and levels of retinal illuminance. J. Opt. Soc. Am. 48, 406-411, 1958.
2) Comerford, J. P. and P. K. Kaiser. Luminous efficiency functions by heterochromatic brightness matching. J. Opt. Soc. Am. 65, 466-468, 1975.
3) Guth, S. L. and H. R. Lodge. Heterochromatic additivity, foveal spectral sensitivity, and a new color model. J. Opt. Soc. Am. 63, 450-462, 1973.
4) Kinney, J. A. S. Effect of field size and position on mesopic spectral sensitivity. J. Opt. Soc. Am. 54, 671-677, 1964.
5) Sperling, H. G. An experimental investigation of the relationship between colour mixture and luminous efficiency. In *Visual Problems of Colour,* Vol. 1, Her Majesty's Stationery Office, 1958.
6) Sperling, H. G. and W. G. Lewis. Some comparisons between foveal spectral sensitivity data obtained at high brightness and absolute threshold. J. Opt. Soc. Am. 49, 983-989, 1959.
7) Wagner, G. and R. M. Boynton. Comparison of four methods of heterochromatic photometry. J. Opt. Soc. Am. 62, 1508-1515, 1972.

All studies employed heterochromatic brightness matching in a centrally viewed field of 1 to 2° size. The mean values from each study are listed in Appendix Table A.1 and shown in Figure A.1, together with the mean and the CIE values. While there is considerable variability among the 7 studies, note that almost every individual data point is above the CIE curve.

The data represent a weighted average, based on the total number of subjects. For most of the curve, this $N = 31$ (from 450 through 650 nm). Data points were obtained from tables, if available, and if not, from graphic material, with the aid of magnifying glass and ruler. Interpolation from figures was done if actual 10 unit nm values were not employed experimentally.

An additional comparison is shown in Figure A.2, among the heterochromatic brightness matching function, Guth's $V^{**}(\lambda)$, and the CIE $V(\lambda)$. The major difference is between $V(\lambda)$ and the other two curves.

Appendix Table A.1. *Luminous efficiency function by heterochromatic brightness matching.*

Study	Bedford & Wyszecki	Comerford & Kaiser	Guth & Lodge	Kinney	Sperling	Sperling & Lewis	Wagner & Boynton	N	Weighted $\bar{X}$
No of Ss	4	5	5	4	6	3	4		
400	.003						.034	8	.019
10	.008		.025				.064	13	.032
20	.020	.052	.037		.036	.012	.094	27	.042
30	.038	.124	.057		.064	.064	.104	27	.076
40	.050	.161	.078		.080	.076	.167	27	.103
450	.074	.187	.10	.19	.088	.080	.229	31	.135
60	.104	.210	.13	.21	.112	.092	.312	31	.166
70	.148	.258	.18	.23	.172	.130	.375	31	.214
80	.250	.378	.23	.29	.206	.168	.542	31	.294
90	.300	.464	.38	.37	.231	.166	.583	31	.359
500	.420	.603	.60	.56	.368	.412	.709	31	.523
10	.560	.809	.82	.74	.542	.58	.823	31	.698
20	.880	1.090	1.17	1.1	.775	.847	.979	31	.978
30	1.02	1.136	1.31	1.25	.961	.947	1.07	31	1.103
40	1.1	1.238	1.44	1.24	1.15	1.06	1.08	31	1.200
550	1.08	1.308	1.24	1.23	1.186	1.07	1.06	31	1.179
60	1.02	1.118	1.11	1.06	1.115	1.05	1.01	31	1.075
70	1.00	1.000	1.0	1.0	1.00	1.0	1.00	31	1.000
80	1.06	.962	.90	1.02	.907	.947	1.01	31	.967
90	.94	.951	.89	1.06	.945	.962	1.04	31	.965
600	.86	.941	.89	.89	.814	.886	1.01	31	.895
10	.68	.910	.77	.72	.658	.801	.969	31	.782
20	.50	.792	.64	.56	.511	.702	.904	31	.651
30	.38	.556	.48	.45	.346	.495	.813	31	.494
40	.23	.439	.36	.35	.235	.298	.614	31	.357
650	.136	.294	.20	.27	.145	.113	.099	31	.184
60	.076	.159			.070	.084	.070	22	.093
70	.038	.085			.039	.024		18	.049
80	.024	.045			.021	.018		18	.028
90	.013	.021			.021	.005		18	.014
700	.005	.011			.004			15	.007

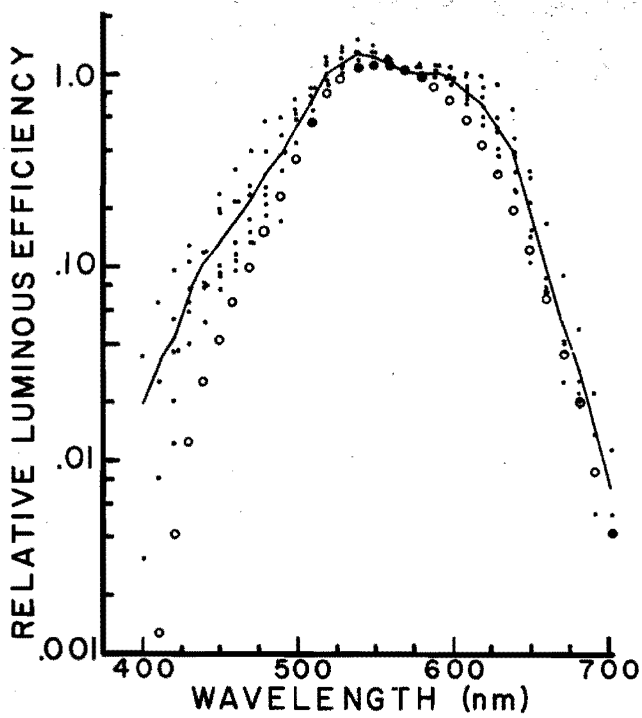

Fig. A.1. – Luminous Efficiency Functions. Comparison among Brightness Matching [————]; V** (λ) [●], and CIE V (λ) [o].

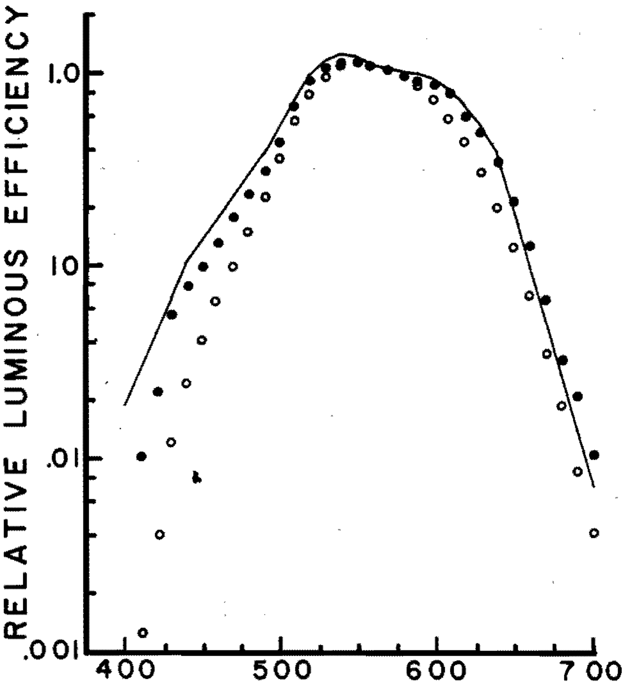

Fig. A.2. – Luminous Efficiency Functions. Heterochromatic Brightness Matching [● = mean of individual studies; ———— overall mean] compared to CIE V (λ) [o].

Appendix B

Luminous efficiency curve for a .7 to 1.0° centrally-viewed field by absolute threshold technique

Data listed in Appendix Table B.1 have been compiled from the following studies :

1) Guth, S. L. and H. R. Lodge. Heterochromatic additivity, foveal spectral sensitivity, and a new color model. J. Opt. Soc. Am. 63, 450-462, 1973.
2) Hsia, Y. and C. H. Graham. Spectral sensitivity of the cones in the dark adapted human eye. Proceedings of the National Academy of Sciences, 38, 80-85, 1952.
3) Hurvich, L. M. and D. Jameson. Spectral sensitivity of the fovea. I. Neutral adaptation. J. Opt. Soc. Am. 43, 485-494, 1953.
4) Sperling, H. G. and Y. Hsia. Some comparisons among spectral sensitivity data obtained in different retinal locations and with two sizes of foveal stimulus. J. Opt. Soc. Am. 47, 707-713, 1957.
5) Sperling, H. G. and W. G. Lewis. Some comparisons between foveal spectral sensitivity data obtained at high brightness and absolute threshold. J. Opt. Soc. Am. 49, 983-989, 1959.

All studies employed a threshold technique for a foveally viewed field of less than 1° (about 3/4 degree). The mean values of the individual studies are given in Appendix Table B.1. The overall mean, weighted for the total number of subjects in each study, is shown in Fig. B. 1, together with the average curve for brightness matching. While the threshold curve has more pronounced irregularities than does the brightness matching curve, overall sensitivities of the two are similar.

Since all of these curves are based upon relatively small numbers of subjects, we believe that the differences among threshold, brightness matching, and V** (λ) are small compared to the differences between them and *V* (λ). We thus recommend that the values of Table 2.2 of the main report (also Table A.1 Appendix) be used for either application until more data are available.

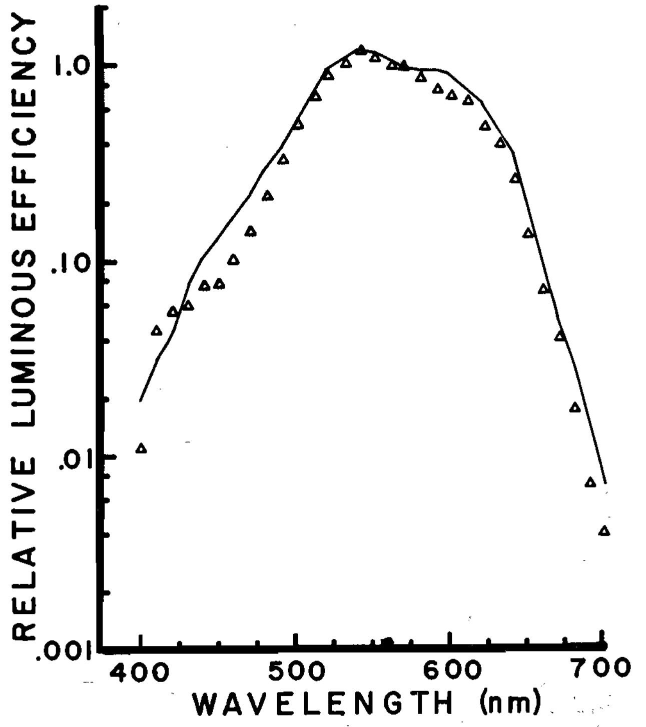

Fig. B.1. – Luminous Efficiency Functions. Absolute threshold [Δ] compared to mean of brightness matching [– – – –[.

Appendix Table B.1. *Luminous efficiency function by threshold technique.*

Study	Guth & Lodge	Hsia & Graham	Hurvich & Jameson	Sperling & Hsia	Sperling & Lewis	N	Weighted $\bar{X}$
No. of Ss	5	5	2	7	3		
400		.013	.011			7	.012
10		.026	.025		.089	10	.045
20	.045	.032	.031	.021	.089	19	.056
30	.070	.052	.050	.038	.107	19	.062
40	.094	.058	.055	.051	.109	19	.074
450	.103	.045	.062	.065	.114	19	.077
60	.123	.091	.081	.087	.118	19	.102
70	.186	.129	.106	.142	.134	19	.145
80	.247	.204	.168	.194	.330	19	.229
90	.381	.363	.255	.282	.432	19	.350
500	.598	.513	.373	.468	.573	19	.520
10	.825	.724	.540	.709	.855	19	.749
20	1.13	.912	.733	.934	1.02	19	.972
30	1.24	1.15	.845	.892	1.11	19	1.08
40	1.34	1.29	1.03	1.29	1.14	19	1.25
550	1.19	1.28	1.06	1.12	1.11	19	1.17
60	1.03	1.07	1.03	.934	1.09	19	1.03
70	1.00	1.00	1.00	1.00	1.00	19	1.00
80	.928	.813	.975	.794	.932	19	.875
90	.825	.646	.870	.676	1.05	19	.787
600	.732	.513	.733	.709	1.05	19	.720
10	.690	.576	.565	.709	.886	19	.676
20	.567	.457	.429	.550	.739	19	.504
30	.41	.323	.360	.380	.682	19	.419
40	.289	.204	.217	.194	.522	19	.276
650		.129	.118	.148	.182	13	.144
60		.058	.062	.063	.105	13	.071
70		.036	.031	.042	.061	13	.042
80		.018	.012	.021	.034	13	.018
90		.008	.006		.007	10	.007
700		.004	.004	.004		10	.004

Imprimerie Bayeusaine, 14401 Bayeux — 2441
Imprimé en France
4e trimestre 1978