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COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE
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TECHNICAL REPORT

TESTING OF SUPPLEMENTARY SYSTEMS OF PHOTOMETRY

CIE 141 - 2001

UDC: 535.24
535.241.44

Descriptor: Photometry
Luminance (brightness)

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This Technical Report has been prepared by CIE Technical Committee 1-21 of Division 1 “Vision and Colour” and has been approved by the Board of Administration of the Commission Internationale de l’Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

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FOREWORD

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TESTING OF SUPPLEMENTARY SYSTEMS OF PHOTOMETRY

SUMMARY

This report contains the most recent versions of 10 photometric systems (4 for 2° and 6 for 10° fields) which have been proposed to CIE Division 1 as methods of assessing the relative brightness of lights across the entire range of human visual sensitivity. To provide quantitative tests of these systems, each system has been applied to several sets of data submitted by independent laboratories employing different stimulus sets and different experimental procedures for heterochromatic brightness matching (HCBM). Furthermore, each system was applied to data obtained in HCBM experiments performed by 6 research groups using the same coloured samples under very similar experimental conditions. These numerical tests were primarily intended to see the equality of equivalent luminances for brightness-matched stimuli but not to test the absolute level of scaling for brightness. This report describes the results of these quantitative tests; it makes no recommendation for a new CIE system.

EVALUATION DES SYSTEMES PHOTOMETRIQUES SUPPLEMENTAIRES

RESUME

Ce rapport contient les plus récentes versions des systèmes photométriques (4 pour des champs de 2° et 6 pour les champs de 10°), qui ont été proposés à la Division 1 comme méthodes d'évaluation de la luminosité relative de lumières, pour tout le domaine de sensibilité visuelle humaine. Pour donner des résultats de tests numériques de ces systèmes, chacun d'eux a été essayé sur plusieurs ensembles de stimulus et diverses procédures expérimentales de comparaison de luminosités hétérochromes (HCBM). En outre, chaque système a été appliqué aux données obtenues dans des expériences de HCBM réalisées par 6 groupes de recherches, utilisant les mêmes échantillons colorés initialement envisagés pour apprécier l'égalité des luminances équivalentes pour les stimulus égalisés en luminosité, mais pas pour apprécier le niveau absolu de l'échelle de luminosité. Ce rapport décrit les résultats de ces essais quantitatifs; il ne donne pas de recommandation pour un nouveau système CIE de photométrie.

PRÜFUNG ZUSÄTZLICHER PHOTOMETRISCHER SYSTEME

ZUSAMMENFASSUNG

Dieser Bericht enthält die neuesten Versionen über 10 photometrische Systeme (4 für 2° und 6 für 10° Gesichtsfeldgrößen), die der CIE Division 1 als Methoden vorgeschlagen wurden, mit deren Hilfe die Relativhelligkeit von Lichtern im Gesamtbereich der menschlichen visuellen Empfindlichkeit bewertet werden kann. Um quantitative Vergleiche dieser Systeme durchführen zu können, wurde jedes mit verschiedenen Datensätzen getestet. Diese waren von unabhängigen Laboratorien zur Verfügung gestellt worden, die unterschiedliche Reizdatensätze und unterschiedliche Verfahren des heterochromen Abgleichs der Eindrucksshelligkeit (HCBM = heterochromatic brightness matching) angewandt haben. Darüber hinaus wurde jedes System mit Datensätzen getestet, die 6 verschiedene Forschungsgruppen in HCBM-Experimenten erhalten hatten unter Zugrundelegung der gleichen Farbwahl und sehr ähnlicher experimenteller Bedingungen. Diese numerischen Tests sollten vorrangig erkennen lassen, ob die äquivalenten Leuchtdichten der nach der Eindrucksshelligkeit abgeglichenen Reize gleich waren. Sie sollten aber nicht das absolute Niveau der Skalierung der Eindrucksshelligkeit untersuchen. Dieser Bericht beschreibt die Ergebnisse dieser quantitativen Tests; er enthält keine Empfehlung für ein neues CIE System.

1. INTRODUCTION

Photometric luminance, defined within the current CIE photometric system, does not correlate well with the perception of brightness for coloured objects or lights. The discrepancy between luminance and brightness also manifests itself as an additivity failure; the apparent brightness of two or more monochromatic sources combined together is frequently different from the sum of their luminances. In photopic vision, the combined effect is commonly less than the sum of the luminances, so that additivity fails on the side of sub-additivity. Current colour theories explain this phenomenon (the Helmholtz-Kohlrausch effect) in terms of cone-cone interaction; saturated colours produce a "chromatic contribution" to the physiological brightness signal.

Failures in the direction of super-additivity also occur, in which the combined effect of two or more sources is greater than the sum of their luminances. Because this phenomenon is found at mesopic luminance levels, it is presumably due to rod-cone interactions. The shift from cone to rod spectral sensitivity with declining luminance makes bluish lights gain in brightness relative to reddish lights. In scotopic vision, this Purkinje shift is complete, and additivity failures tend to disappear.

Recognizing these discrepancies between brightness and luminance, Division 1 has appointed technical committees (TCs) over the past 15 years to survey the problems of heterochromatic brightness matching (HCBM) and to work toward developing a new photometric system for the assessment of brightness. The first of these TCs were the following:

- TC1-01 Mesopic photometry (Chaired by J. A. S. Kinney)
- TC1-02 Luminous efficiency functions (Chaired by M. Ikeda)
- TC1-03 Models of heterochromatic brightness matching (Chaired by P. K. Kaiser)

TC1-01 provided an excellent summary of the mesopic photometry systems available by the late 1980s (CIE, 1989), preparing the way for TC1-21. TC1-02 established spectral luminous efficiency functions based on brightness for a point source, for a 2° field, and for a 10° field (CIE, 1988). These luminous efficiency functions have served as reference data in photometry and also in further research on HCBM. Physiological models of brightness matching were investigated by TC1-03 (CIE, 1986).

In response to these TC activities, several research groups have proposed photometric systems based on HCBM. Division 1 undertook evaluation of those systems, looking toward the future development of an international standard that provides satisfactory brightness measures at all luminance levels.

TC1-21, "Testing of supplementary systems of photometry," was established at the 21st Quadrennial Session of the CIE at Venice in 1987. This TC was directed to test the proposed systems quantitatively by applying them to existing data from HCBM experiments. Its task is to report how well each system predicts the data. However, its scope does not extend to recommending any one system for establishment as a CIE standard.

The present report gives the numerical data and the procedures used for testing. Considering the predictability of brightness relationships of coloured objects or lights is one of the major functions in photometry, the present testing was designed to test how well each proposed system can describe the equality of brightness for a brightness-matched pair obtained by HCBM experiments.

Chapter 1 addresses the problems that current CIE photometric system has and the objectives of TC1-21 to solve them. Chapter 2 summarizes the currently proposed photometric systems based on HCBM, updating the report of TC1-01 (CIE, 1989) and adding newly proposed systems. For each system, the chapter presents the procedures used to calculate a "system equivalent luminance" as a measure of brightness specified on a particular reference stimulus, together with a calculation example. Chapter 3 describes the data sets selected for testing the systems together with the procedure for testing. Chapter 4 reports the system equivalent luminances obtained when the proposed photometric systems were applied to these data sets. Chapter 5 reports quantitative results on the application of these systems to a new data set, obtained with common stimuli and experimental conditions in 6 laboratories from 4 countries, which was prepared by TC1-21 for its workshop at the CIE 22nd Session at Melbourne in 1991. Chapter 6 describes the relationship between these quantitative tests and the problem of brightness scaling. Chapter 7 presents conclusions.

To be in line with the intended scope of TC1-21, this report does not include a recommendation for a new CIE photometric system based on HCBM. This task is left to a new technical committee (TC 1-37, Supplementary System of Photometry) together with the qualitative investigation of the systems.

2. PHOTOMETRIC SYSTEMS FOR ASSESSING THE BRIGHTNESS OF OBJECTS AND LIGHTS

Photometric systems for evaluating the brightness of lights depend primarily upon data obtained when observers are required to match a test sample and a reference stimulus for brightness. The brightness of a test sample is defined in terms of the luminance of a matching reference stimulus. That is, brightness is measured as an "equivalent luminance," namely, the luminance of the reference stimulus that appears equal to the test sample in brightness. Different systems are generally based upon different data sets, often with quite different choices of reference stimulus. According to the resolution of CIE Division 1 at the CIE 23rd Session, the term "equivalent luminance" is regarded formally as the luminance referred to the 540 THz (nearly 555 nm) stimulus. The equivalent luminance based on reference stimuli other than 555 nm will, therefore, be described as "system equivalent luminance, L_{seq} " in this report.

Table 2.1 Photometric systems based on heterochromatic brightness matching

2° systems	Specifications
Ware-Cowan (1983)	Polynomial function of chromaticity (x,y) for B/L ratio
Guth et al. (1973, 1980)	Vector luminance of chromatic and achromatic responses
Yaguchi-Ikeda (1980, 1983, 1984)	Nonlinear vector luminance
Nakano (1988, 1992)	Log-linear combination of cone-receptor responses
10° systems	
Palmer 1 st (1968)	Linear combination of L_{10} and L
Palmer 2 nd (1981)	Non-linear combination of L_{10} and L
Sagawa-Takeichi (1987, 1992a)	Geometric weighted mean of L' and [L +chromatic response], iterative calculation
Nakano-Ikeda (1986, 1988, 1992)	[Geometric weighted mean of L_{10} and L]+chromatic response
Kokoschka-Bodmann (1975, 1980, 1991)	[Linear combination of X_{10} , Y_{10} , Z_{10} , and L]+ chromatic response, iterative calculation
Trezona (1983a, 1987, 1989)	Hyperbolic tangent function with polynomial functions of tetrastimulus values X_{10} , Y_{10} , Z_{10} , and V
*Ashizawa et al. (1985, 1989, 1991)	Hyperbolic tangent function for lightness of object colour

* The Ashizawa et al. system is a system for equivalent lightness of object colours and cannot be directly applied to the present system equivalent luminance calculation.

Table 2.1 summarizes the systems currently proposed to the CIE. All of these systems are based upon data from HCBM experiments, and in most of these experiments luminance levels varied from the photopic through the mesopic range. Because of the greater prominence of cone vision in foveal small fields, the systems will be presented in two groups. Four of the systems are based on data from brightness matches of 2° fields; these systems address themselves primarily to the problem of chromatic contribution and sub-additivity arising from cone-cone interactions at photopic levels. The other six systems, based on data from 10° fields, consider the effects of both cone-cone and rod-cone interactions; these systems are intended to apply at photopic, mesopic, and scotopic levels.

Table 2.1 provides a brief description of each system. More extensive descriptions, together with a sample of calculation, follow in the next sections of this chapter.

2.1 Systems for 2° fields

2.1.1 Ware-Cowan system

In photopic vision, the brightness of coloured lights can be described in terms of a brightness-to-luminance (B/L) ratio, in which L represents the photopic luminance of the test sample and B represents the photopic luminance of its brightness-matched reference stimulus (Kinney, 1983). The Ware-Cowan system extends this principle to give a formula to describe the B/L ratio as a function of chromaticity.

Ware and Cowan began by selecting from the published literature more than 50 experiments using HCBM with 2° fields and meeting certain other criteria (Ware & Cowan, 1983). Using the published data from these experiments, they derived a factor c for converting log luminance L to log apparent brightness B ; thus, the B/L ratio is given by 10^c . The conversion factor c is computed as a polynomial function of the sample's x,y -chromaticity coordinates. In Fig. 2.1, a block diagram of this system is shown, B is represented by L_{seq} , which will be used throughout this report to designate system equivalent luminance.

Ware and Cowan present the results of their system as a set of equal B/L contours drawn in the CIE 1931 chromaticity diagram (see Appendix Fig. A.2.1). The B/L ratio is 1,0 at Illuminant D65 which is the reference stimulus of the system.

The Ware-Cowan system is simple and easy to use. It is intended for application to small fields where cone vision predominates. As an empirical formula, it does not attempt to describe any physiological processes in the visual system. This system was recommended for trial use by the former technical committee, TC1-03 (CIE TC1-03, 1986).

Calculation:

1. From the CIE 2° chromaticity coordinates x and y , calculate c .

$$c = 0,256 - 0,184y - 2,527xy + 4,656x^3y + 4,657xy^4 \quad \text{for } y > 0,02 \quad (2.1)$$

For $y \leq 0,02$ obtain c from its dominant wavelength by referring additional data as shown in Appendix Fig. A.2.1.

2. Determine system equivalent luminance, L_{seq} .

$$L_{\text{seq}} = L \cdot 10^c \quad (2.2)$$

Example: (Sample: Munsell Color Chip 10B5/10 at 10 cd/m²)¹

1. From the sample data shown in Appendix 1,

$$x = 0,205 \text{ and } y = 0,245$$

2. From Equation (2.1),

$$c = 0,0973$$

3. From Equation (2.2),

$$L_{\text{seq}} = 10 \cdot 10^{0,0973} = 12,5 \text{ cd/m}^2 \text{ of the D65 reference stimulus}$$

¹ Munsell Color Chip 10B5/10 serves as the test sample for all the sample calculations. It is illuminated by a fluorescent lamp EDL-50 to achieve a luminance of 10 cd/m² (a photopic condition) or 0,01 cd/m² (a mesopic condition). Appendix 1 presents colorimetric and photometric data for such a sample.

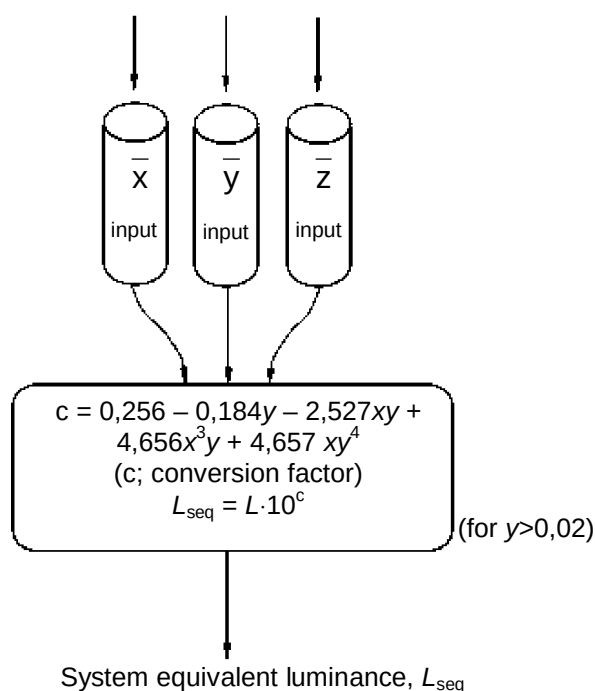


Fig. 2.1 Ware - Cowan system

2.1.2 Guth et al system

Guth's system takes its origin from the concept of "vector luminance," proposed by S.L. Guth and his colleagues as part of their theory of colour vision (Guth, 1973; Guth, 1980). Figure 2.2 shows a block diagram of this system. Tristimulus values X' , Y' , and Z' , based on Judd's modification of the $V(\lambda)$ function, serve as inputs. These values are converted to A (achromatic component), T (tritanopic chromatic component) and D (deutanopic chromatic component) in the manner specified in the Guth group's colour vision model. The values of A , T and D are then treated as coordinates in a Euclidean three-dimensional space and combined as a geometric average to obtain the vector luminance, here called system equivalent luminance L_{seq} . The conversion factors from $X'Y'Z'$ to ATD are normalized so as to make the quantity $(A^2 + T^2 + D^2)^{1/2} = 1$ at the 545 nm monochromatic stimulus which is the reference stimulus of the Guth's system.

Calculation:

1. Determine X' , Y' and Z' for the sample, using Judd's modified $V_M(\lambda)$ function.
2. Calculate A , T and D .

$$\begin{bmatrix} A \\ T \\ D \end{bmatrix} = \begin{bmatrix} 0 & 0,9341 & 0 \\ 0,7401 & -0,6801 & 0,1567 \\ -0,0061 & -0,0212 & 0,0314 \end{bmatrix} \cdot \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} \quad (2.3)$$

3. Determine the sample's system equivalent luminance, referred to the 545 nm monochromatic stimulus.

$$L_{seq} = (A^2 + T^2 + D^2)^{1/2} \quad (2.4)$$

Example: (Sample: Munsell Color Chip 10B5/10 at 10 cd/m²)

1. From Appendix 1,

$$Y' = (L_{Judd}/L)Y = 10,10$$

$$X' = (x'/y')Y' = 8,189$$

$$Z' = ((1-x'-y')/y')Y' = 20,71$$

2. From Equation (2.3),

$$A = 9,434 \quad T = -4,054 \quad D = 0,3862$$

3. From Equation (2.4)

$$L_{\text{seq}} = 10,27 \text{ cd/m}^2 \text{ of the 545 nm reference stimulus}$$

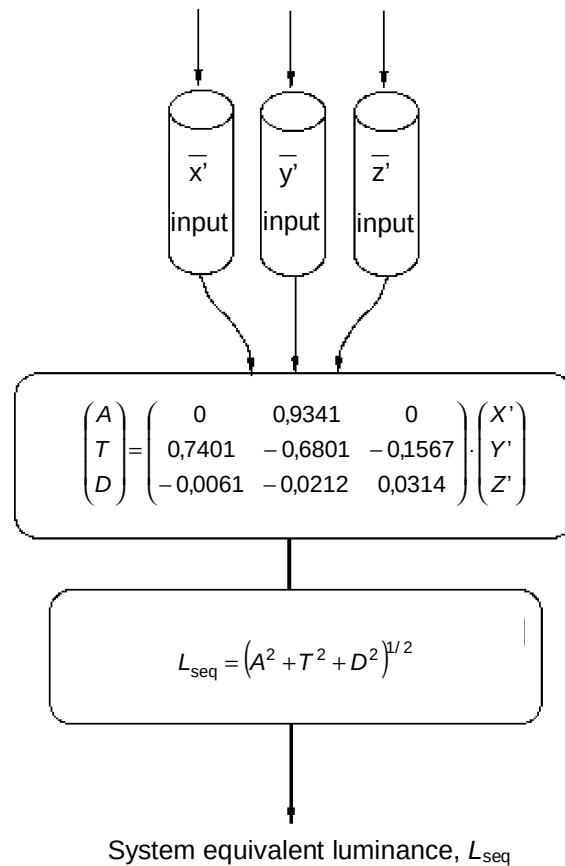


Fig. 2.2 Guth et al. system

2.1.3 Yaguchi-Ikeda System

The Yaguchi-Ikeda system is a modification of the Guth system in which new exponents are provided for the two chromatic signals. Figure 2.3 shows a block diagram of this system. Factors, C_1 and C_2 , represent the two chromatic signals (Yaguchi, 1984). Yaguchi found that his brightness-additivity data (Yaguchi, 1980, 1983) require the introduction of different exponents into the equation for deriving system equivalent luminance, L_{seq} . As a result, calculation of L_{seq} becomes somewhat more complex. The reference stimulus of this system is a white light ($x=0,38$; $y=0,33$) as B/L ratio is normalized to 1,0 at this white light.

Calculation:

1. Determine X' , Y' , and Z' for the sample, using Judd's modification of the $V(\lambda)$ function.
2. Calculate A , C_1 , and C_2 , (2.5)
3. Using numerical estimation, find a value of L_{seq} which satisfies the following equation.

$$(A/L_{\text{seq}})^2 + (C_1/L_{\text{seq}})^{1,28} + (C_2/L_{\text{seq}})^{0,72} = 1 \quad (2.6)$$

Example: (Sample: Munsell Color Chip 10B5/10 at 10 cd/m²)

1. From Appendix 1,

$$Y' = (L_{\text{Judd}}/L)Y = 10,10$$

$$X' = (x'/y')Y' = 8,189$$

$$Z' = [(1-x'-y')/y']Y' = 20,71$$

2. From Equation 2.5

$$A = 10,10 \quad C_1 = -4,457 \quad C_2 = -0,3582$$

3. Estimate L_{seq} and evaluate Equation (2.6). Taking $L_{\text{seq}} = 12,4$

$$(10,10/12,4)^2 + (-4,457/12,4)^{1,28} + (-0,3582/12,4)^{0,72} = 1,0113 > 1$$

4. Increase the estimate, and evaluate Equation (2.6) again. Taking $L_{\text{seq}} = 12,5$

$$(10,10/12,5)^2 + (-4,457/12,5)^{1,28} + (-0,3582/12,5)^{0,72} = 0,9975 < 1$$

5. Interpolate to find an L_{seq} value which satisfies Equation (2.6)

$$L_{\text{seq}} = 12,48 \text{ cd/m}^2 \text{ of a white reference stimulus}$$

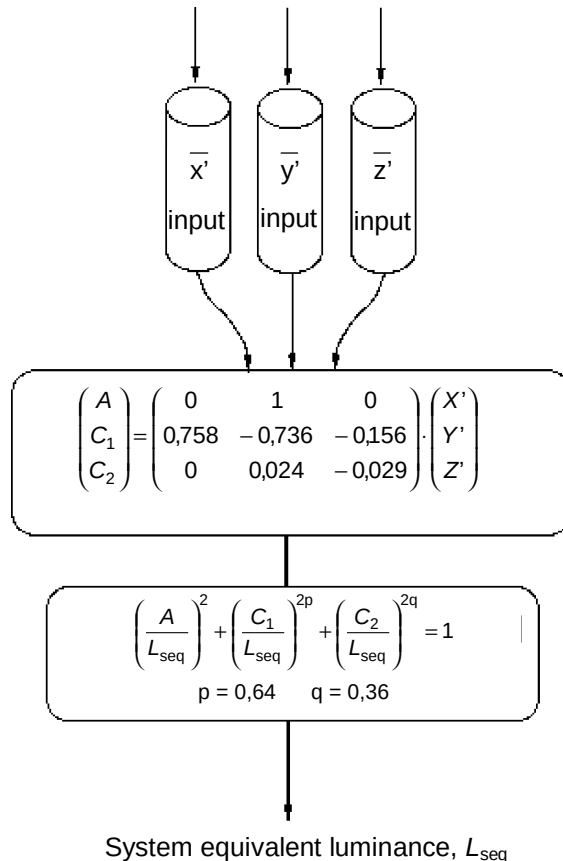


Fig. 2.3 Yaguchi - Ikeda system

2.1.4 Nakano system

The Nakano system is based on a model of brightness perception proposed by Y. Nakano (Nakano, 1988; Nakano, 1992), in which the physiological brightness signal results from a log linear combination of the three cone receptor signals. The system has been expanded to include the scotopic luminous efficiency function, using principles developed for a 10° field in the Nakano-Ikeda system (Nakano, 1986) discussed below in Section 2.2.4.

Figure 2.4 shows a block diagram of the system. As inputs, the system uses CIE photopic luminance L , a measure of scotopic luminance L' , and CIE 1931 x, y -chromaticity coordinates. A conversion factor c converts sample luminance to system equivalent luminance of a reference stimulus; c is derived from photopic and scotopic components. The photopic conversion factor p is obtained from x and y through the model (Nakano, 1988); the scotopic conversion factor s is obtained through the scotopic to photopic luminance ratio L'/L .

This system models the physiological mechanisms of human brightness perception. Its calculation requires several steps. The reference stimulus of this system is illuminant D65.

Calculation:

1. Obtain photopic luminance L and a quantity proportional to scotopic luminance L_s by the following equations:

$$L = 683 \cdot \int L_{e,\lambda}(\lambda) \cdot V(\lambda) d\lambda \quad (2.7)$$

$$L_s = 689,7 \cdot \int L_{e,\lambda}(\lambda) \cdot V'(\lambda) d\lambda \quad (2.8)$$

where $L_{e,\lambda}(\lambda)$ is the spectral radiance of the test light within the interval $d\lambda$. Note that L corresponds exactly to the CIE definition of photopic luminance, whereas L_s represents only a portion (689,7/1700) of CIE scotopic luminance. The CIE definition of scotopic luminance sets maximum scotopic luminous efficiency at 1700 scotopic lumens/watt.

2. Calculate ξ , η , ζ .

$$\begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} = \begin{bmatrix} 0,40024 & 0,70760 & -0,0801 \\ -0,22630 & 1,16532 & 0,04570 \\ 0,00000 & 0,00000 & 0,91822 \end{bmatrix} \cdot \begin{bmatrix} \frac{x}{y} \\ 1 \\ \frac{1-x-y}{y} \end{bmatrix} \quad (2.9)$$

3. Calculate α , β and γ .

$$\begin{aligned} \alpha &= 0,374 \xi / (\xi + \eta + \zeta) + 0,002(\eta - \zeta)\xi \\ \beta &= 0,374 \eta / (\xi + \eta + \zeta) + 0,002(\zeta - \xi)\eta \\ \gamma &= 0,374 \zeta / (\xi + \eta + \zeta) + 0,002(\xi - \eta)\zeta \end{aligned} \quad (2.10)$$

4. Calculate F_{L-M} and F_{M-L} , and determine F .

$$F_{L-M} = (1,015 + \alpha) \ln(\xi + 1) + (-0,389 + \beta) \ln(\eta + 1) + (0,000 + \gamma) \ln(\zeta + 1) \quad (2.11)$$

$$F_{M-L} = (-0,537 + \alpha) \ln(\xi + 1) + (1,341 + \beta) \ln(\eta + 1) + (-0,178 + \gamma) \ln(\zeta + 1) \quad (2.12)$$

$$F = \max(F_{L-M}, F_{M-L}) \quad (2.13)$$

5. Find the scotopic factor s and photopic factor p .

$$s = L_s / L \quad (2.14)$$

$$p = \exp(F) - 1 \quad (2.15)$$

6. Calculate the conversion factor c .

$$c = [0,026 / (L + 0,026)] \log s + [L / (L + 0,032)] \log p \quad (2.16)$$

7. Calculate system equivalent luminance.

$$L_{seq} = L \cdot 10^c \quad (2.17)$$

Example: (Sample: Munsell Color Chip 10B5/10 at 10 cd/m²)

1. Since Equation (2.7) is the definition of CIE luminance for a 2° field, and from Appendix 1,

$$L = 10$$

2. Since Equation 2.8 is 689,7/1700 of scotopic luminance, and scotopic luminance is 4,411 · L ,

$$L_s = (689,7/1700) \cdot 44,11 = 17,90$$

3. With $x = 0,205$ and $y = 0,245$ (Appendix 1), calculate ξ , η and ζ from Equation (2.9),

$$\xi = 0,8611 \quad \eta = 1,0786 \quad \zeta = 2,061$$

4. From Equation 2.10,

$$\alpha = 0,0788 \quad \beta = 0,1034 \quad \gamma = 0,1918$$

5. From Equations (2.11), (2.12), and (2.13),

$$F_{L-M} = 0,6850$$

$$F_{M-L} = 0,7877$$

$$F = 0,7877$$

6. From Equations (2.14) and (2.15),

$$s = 1,791$$

$$p = 1,198$$

7. From Equation (2.16),

$$c = 0,07895$$

8. From Equation (2.17),

$$L_{seq} = 10 \cdot 10^{0,07895} = 11,99 \text{ cd/m}^2 \text{ of the D65 reference stimulus}$$

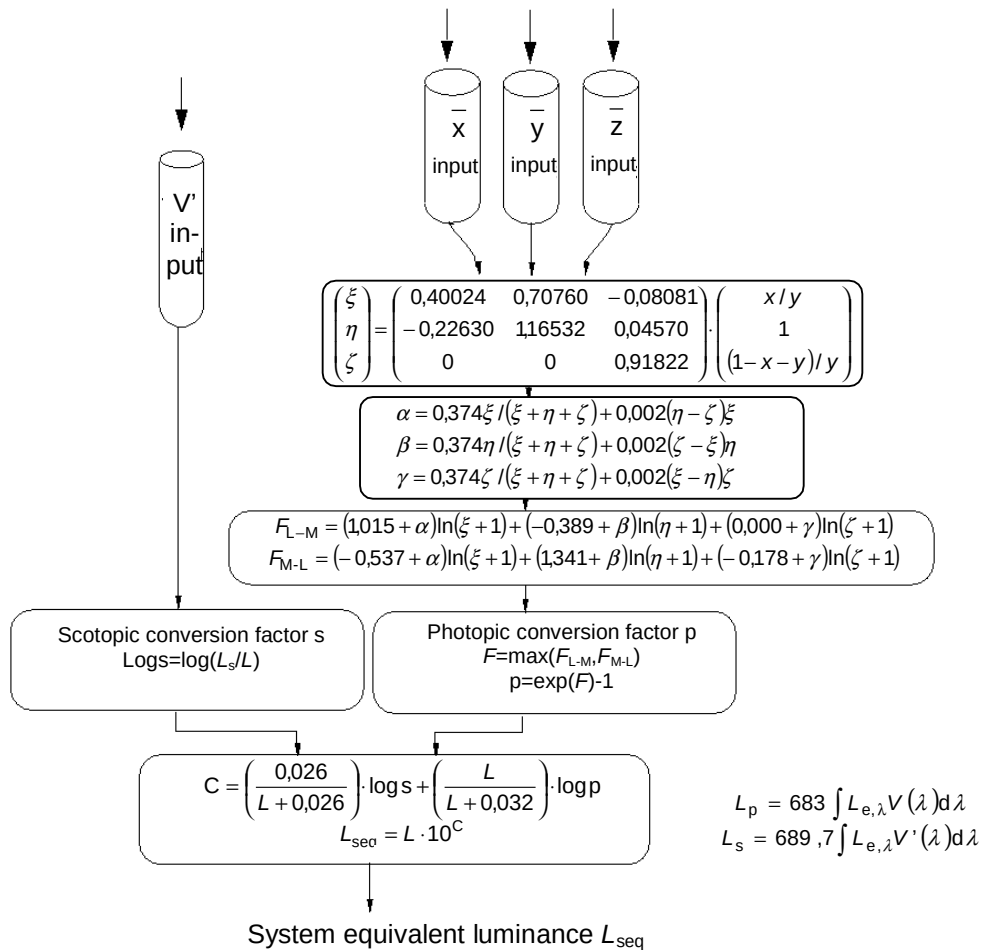


Fig. 2.4 Nakano system

2.2 Systems for 10° fields

2.2.1 Palmer's first system

D. A. Palmer made the earliest suggestion for a system of mesopic photometry (Palmer, 1968). He derived a system equivalent luminance by combining CIE scotopic luminance with a photopic large field luminance based on CIE 1964 $y_{10}(\lambda)$. If scotopic luminance is represented by L' and photopic luminance by L_{10} ,

$$L_{seq} = (L' M + L_{10}^2) / (L_{10} + M),$$

where M is a parameter in units of cd/m^2 . If this equation is written in a different form,

$$L_{\text{seq}} = aL' + (1-a)L_{10}$$

where $a = M / (L_{10} + M)$, it becomes clear that system equivalent luminance is a weighted mean of scotopic luminance and large-field photopic luminance. The weighting factor a , called the adaptation coefficient, depends upon photopic luminance. In this system, Palmer specifies a value of $0,04 \text{ cd/m}^2$ for M . His database was obtained by HCBM to a tungsten light at 2042 K, the former CIE standard for defining equivalent luminance (CIE, 1989).

Palmer's first system, shown in Fig. 2.5, is simple and easy to use. It is designed to reflect the increasing effect of rod activity as illumination declines. It does not attempt to address the chromatic contribution to brightness at photopic levels. The reference stimulus of this system is the Planckian radiator at 2042 K.

Calculation:

1. Using $L_{10} = Y_{10} = 683 \int L_{e,\lambda}(\lambda) y_{10}(\lambda) d\lambda$, calculate the adaptation coefficient

$$a = [M / (L_{10} + M)] = [0,04 / (L_{10} + 0,04)] \quad (2.18)$$

2. Calculate L_{seq} .

$$L_{\text{seq}} = aL' + (1-a)L_{10} \quad (2.19)$$

Example: (Sample: Munsell Color Chip 10B5/10 at $0,01 \text{ cd/m}^2$)

1. From Appendix 1,

$$L_{10} = L \cdot 1,197 = 0,01197$$

$$L' = L \cdot 4,411 = 0,04411$$

2. From Equation (2.18),

$$a = 0,770$$

3. From Equation (2.19),

$$L_{\text{seq}} = 0,0367 \text{ cd/m}^2 \text{ of a reference stimulus of Planckian radiator at 2042K.}$$

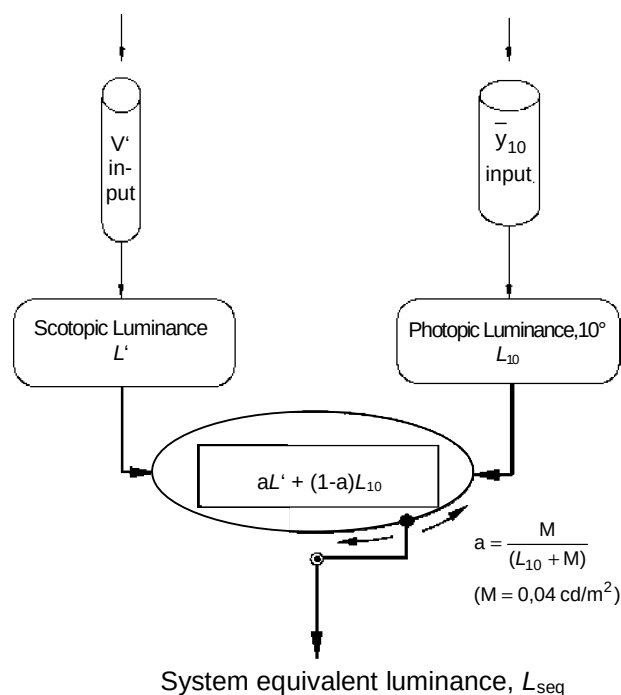


Fig. 2.5 Palmer 1st system

2.2.2 Palmer's second system

Palmer revised his first system to improve the fit to his own HCBM data (Palmer, 1981). Figure 2.6 diagrams the second system. This system employs the same inputs as Palmer's first system, but in the newer system the system equivalent luminance becomes a nonlinear function of L_{10} and L' . The adaptation coefficient a has disappeared, and the parameter M takes a new value: $0,06 \text{ cd/m}^2$.

Although Palmer's second system appears complex, "it is actually a quadratic solution to a simple relationship depicting the relative contributions of the rods and cones to mesopic brightness" (CIE 1989, p. 5). This system is also derived from brightness matches between a tungsten reference at 2042 K and test lights varying in intensity, chromaticity, and purity. The value of L_{seq} should therefore be understood as the luminance of a 2042 K tungsten light that would appear equally as bright as the test stimulus.

Calculation:

1. Using $L_{10} = Y_{10} = 683 \int L_{e,\lambda}(\lambda) y_{10}(\lambda) d\lambda$, calculate system equivalent luminance.

$$L_{\text{seq}} = (ML)^{1/2} + L_{10} + M/2 - \{M[(ML)^{1/2} + L_{10} + M/4]\}^{1/2} \quad (2.20)$$

where $M = 0,06 \text{ cd/m}^2$

Example: (Sample: Munsell Color Chip 10B5/10 at $0,01 \text{ cd/m}^2$)

1. From Appendix 1,

$$L_{10} = L \cdot 1,197 = 0,01197$$

$$L' = L \cdot 4,411 = 0,04411$$

2. From Equation (2.20),

$$L_{\text{seq}} = 0,0248 \text{ cd/m}^2 \text{ of a 2042 K Planckian radiator reference stimulus}$$

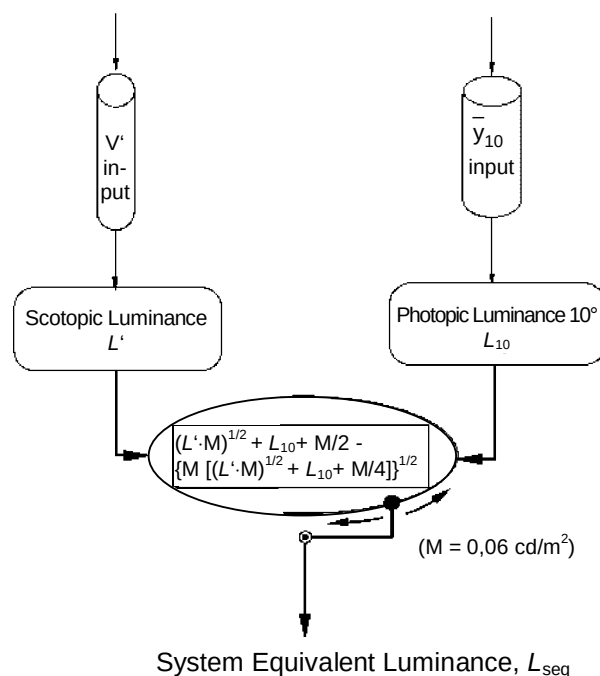


Fig. 2.6 Palmer 2nd system

2.2.3 Sagawa-Takeichi system

The Sagawa-Takeichi system also combines photopic and scotopic contributions to determine system equivalent luminance of a test sample. However, working from CIE photopic and scotopic luminance, the Sagawa-Takeichi system first determines two components of system

equivalent luminance, $L_{\text{seq,p}}$ and $L_{\text{seq,s}}$, which represent the photopic and scotopic contributions to L_{seq} . L_{seq} is a weighted geometric mean of these two components.

Photopic system equivalent luminance $L_{\text{seq,p}}$ makes use of the Ware-Cowan conversion factor c (see Section 2.1.1), with a modification intended to improve its application to 10 degree fields. Scotopic system equivalent luminance is taken to be a constant multiple of CIE scotopic luminance. An adaptation coefficient a serves as weighting factor in combining the photopic and scotopic components; its numerical value can be determined from the table in Appendix 3.

Since the value of a depends upon system equivalent luminance, determination of L_{seq} requires an iterative procedure. Figure 2.8 illustrates a graphical method to assist in this determination. Since L_{seq} is derived by a method based on spectral luminous efficiency functions normalized at 570 nm, the reference stimulus for the Sagawa-Takeichi system is the 570 nm monochromatic stimulus (Sagawa, 1986, 1987, 1992a).

Calculation:

1. Using CIE 1931 photopic luminance L and x,y -chromaticity coordinates, calculate photopic system equivalent luminance.

$$L_{\text{seq,p}} = L \cdot 10^{c'}, \quad (2.21)$$

$$c' = 2(c + 0,047) \quad (2.22)$$

where c is the Ware-Cowan conversion factor defined in Equation (2.1).

2. Using CIE scotopic luminance L' , calculate scotopic system equivalent luminance.

$$L_{\text{seq,s}} = 1,84 L' \quad (2.23)$$

3. On a graph of the values (L_{seq}, a) shown in Appendix 3, draw a straight line between the points representing $(L_{\text{seq,p}}, 0)$ and $(L_{\text{seq,s}}, 1)$. Take the intersection of this line with the function (L_{seq}, a) as the value L_{seq} .

Example: (Sample: Munsell Color Chip 10B5/10 at 0,01 cd/m²)

1. From Equation (2.1), using 2° x,y -coordinates,

$$c = 0,0973$$

2. From Equation (2.21),

$$c' = 2(c + 0,047) = 0,2886$$

3. From Equation (2.22) and (2.23),

$$L_{\text{seq,p}} = 0,01 \cdot 10^{c'} = 0,01944$$

$$L_{\text{seq,s}} = 1,84L' = 0,08116$$

4. Draw a straight line between points $(0,01944, 0)$ and $(0,08116, 1)$ in a graph of (L_{seq}, a) , as shown in Fig. 2.8. Find the intersection of this line with the (L_{seq}, a) function (defined in Appendix 3):

$$L_{\text{seq}} = 0,036 \text{ cd/m}^2 \text{ of the 570 nm reference stimulus}$$

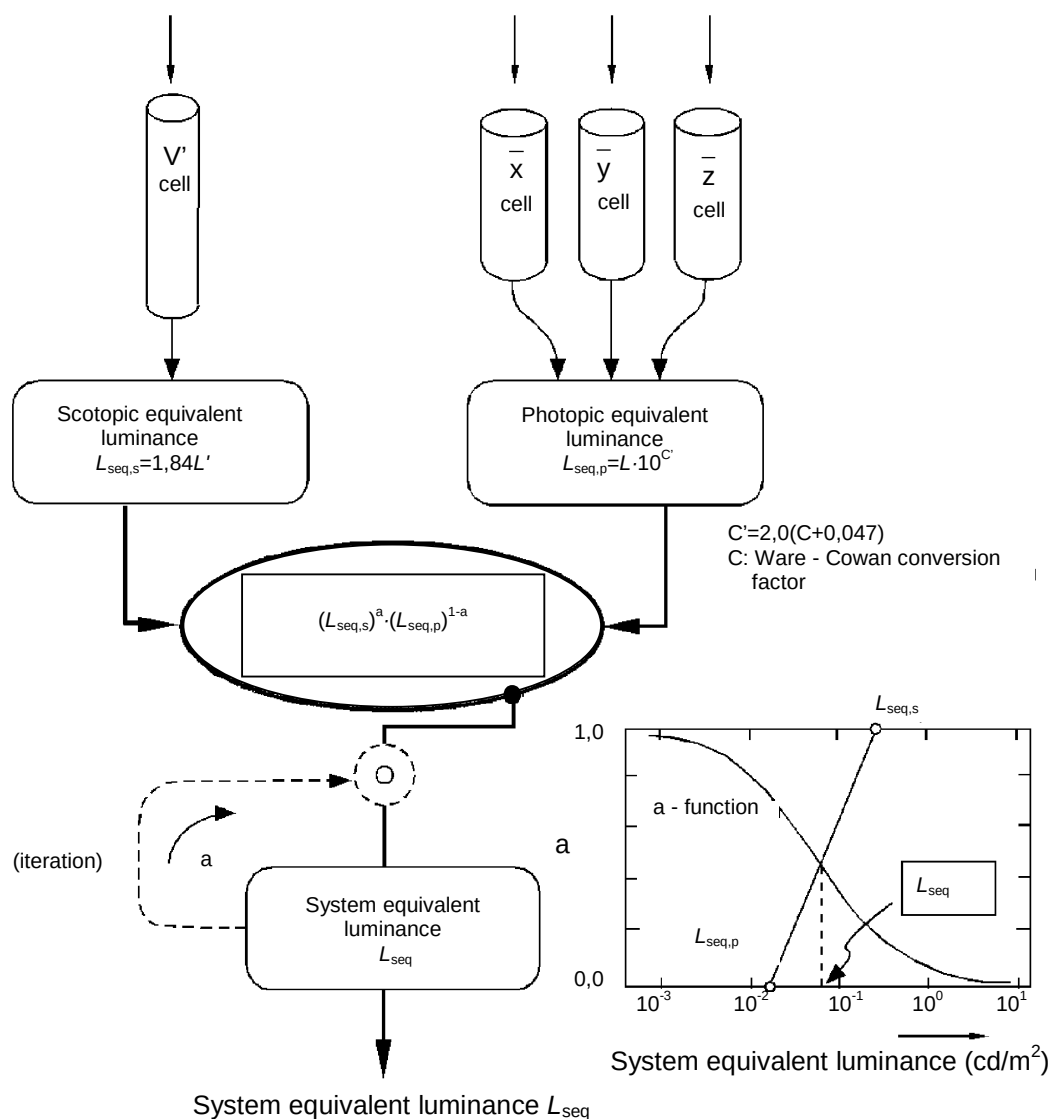


Fig. 2.7 Sagawa - Takeichi system

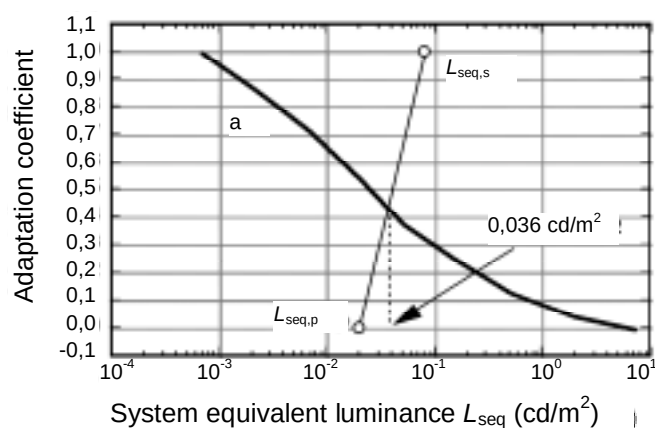


Fig. 2.8 Worksheet of Sagawa - Takeichi system

2.2.4 Nakano-Ikeda System

The Nakano-Ikeda system parallels the Nakano 2° system (Section 2.1.4), changing the parameters to make them suitable for a 10° field. Except for these parameters, Fig. 2.9 for the Nakano-Ikeda system is identical with Fig. 2.4 for the Nakano 2° system. As in the Nakano 2° system, this 10° system determines a factor converting luminance to brightness, and the conversion factor contains photopic and scotopic components whose relative weighting depends upon luminance (Nakano, 1992). The reference stimulus of this system is illuminant D65.

Calculation:

1. Obtain a quantity proportional to 10° photopic luminance, L_p , and a quantity proportional to scotopic luminance, L_s , by the following equations.

$$L_p = 621,1 \cdot \int L_{e,\lambda}(\lambda) \cdot y_{10}(\lambda) d\lambda \quad (2.24)$$

$$L_s = 689,7 \cdot \int L_{e,\lambda}(\lambda) \cdot V'(\lambda) d\lambda \quad (2.25)$$

Note that the L_p equation deviates from the equation for L in Section 2.1.4 by using 621,1 (instead of 683) as multiplier and $y_{10}(\lambda)$ (instead of $y(\lambda)$). Thus, L_p is proportional to Y_{10} . As in Section 2.1.4, L_s represents only a portion (689,7/1700) of CIE scotopic luminance.

2. Using the CIE1964 x , y -chromaticity coordinates x_{10} and y_{10} , calculate ξ , η , and ζ .

$$\begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} = \begin{bmatrix} 0,38355 & 0,73268 & -0,08977 \\ -0,24931 & 1,20294 & 0,03116 \\ -0,00063 & 0,00163 & 0,93097 \end{bmatrix} \cdot \begin{bmatrix} \frac{x_{10}}{y_{10}} \\ 1 \\ \frac{1-x_{10}-y_{10}}{y_{10}} \end{bmatrix} \quad (2.26)$$

3. Calculate α , β , and γ .

$$\begin{aligned} \alpha &= 0,374 \xi / (\xi + \eta + \zeta) + 0,002(\eta - \zeta)\xi \\ \beta &= 0,374 \eta / (\xi + \eta + \zeta) + 0,002(\zeta - \xi)\eta \\ \gamma &= 0,374 \zeta / (\xi + \eta + \zeta) + 0,002(\xi - \eta)\zeta \end{aligned} \quad (2.27)$$

4. Calculate F_{L-M} and F_{M-L} , and determine F .

$$F_{L-M} = (1,015 + \alpha) \ln(\xi + 1) + (-0,389 + \beta) \ln(\eta + 1) + (0,000 + \gamma) \ln(\zeta + 1) \quad (2.28)$$

$$F_{M-L} = (-0,537 + \alpha) \ln(\xi + 1) + (1,341 + \beta) \ln(\eta + 1) + (-0,178 + \gamma) \ln(\zeta + 1) \quad (2.29)$$

$$F = \max(F_{L-M}, F_{M-L}) \quad (2.30)$$

5. Find the scotopic factor s and photopic factor p .

$$s = L_s / L_p \quad (2.31)$$

$$p = \exp(F) - 1 \quad (2.32)$$

6. Determine the conversion factor c .

$$c = [0,026 / (L_p + 0,026)] \log s + [L_p / (L_p + 0,032)] \log p \quad (2.33)$$

7. Find system equivalent luminance L_{seq} .

$$L_{seq} = L_p \cdot 10^c \quad (2.34)$$

Example: (Sample: Munsell Color Chip 10B5/10 at 0,01 cd/m²)

1. From Equations (2.24) and (2.25),

$$L_p = 0,01089$$

$$L_s = 0,01790$$

2. From Equation (2.26),

$$\xi = 0,8496 \quad \eta = 1,0731 \quad \zeta = 1,8422$$

3. From Equation (2.27),

$$\alpha = 0,08309 \quad \beta = 0,1087 \quad \gamma = 0,1822$$

4. From Equations (2.28) through (2.30),

$$F_{L-M} = 0,6613 \quad F_{M-L} = 0,7822 \quad \text{therefore } F = 0,7822$$

5. From Equations (2.31) and (2.32),

$$s = 1,644$$

$$p = 1,1863$$

6. From Equation (2.33),

$$c = 0,1714$$

7. From Equation (2.34),

$$L_{\text{seq}} = 0,0162 \text{ cd/m}^2 \text{ of the D65 reference stimulus}$$

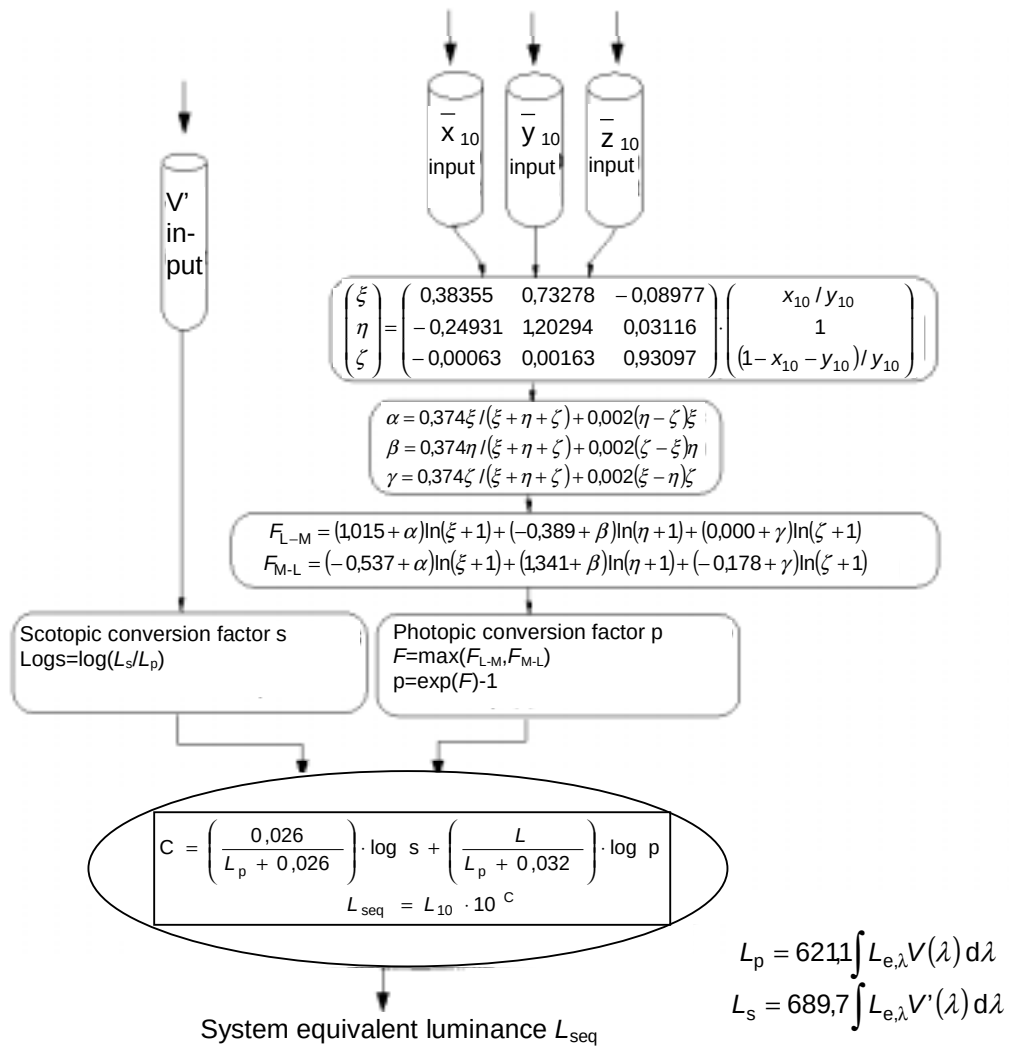


Fig. 2.9 Nakano - Ikeda system

2.2.5 Kokoschka-Bodmann system

The Kokoschka-Bodmann system is based on a linear weighted sum of four components, namely, the sample's tristimulus values for a 10° field and its scotopic luminance (Kokoschka & Bodmann, 1975). These four components can be considered as reflecting the activity of three types of cone receptors and of the rods. Figure 2.10 diagrams the system.

F -coefficients used as weighting factors are dependent upon system equivalent luminance, L_{seq} . Their numerical values, originally determined from HCBM data, can be calculated by using the table in Appendix 4. Since the F -coefficients enter into the calculation of L_{seq} , determination of L_{seq} requires an iterative procedure. Figure 2.11 provides a worksheet to assist in this determination.

As originally proposed in 1975, the system did not incorporate the chromatic contribution to brightness; consequently, its L_{seq} values approximated L_{10} at photopic levels. To deal with the Helmholtz-Kohlrausch effect, the system has recently been revised by addition of a modifier, f . The value of f depends upon chromaticity through an equation parallel to the Ware-Cowan empirical formula for the conversion factor c (Ware & Cowan 1983). However, the Kokoschka-Bodmann version is based on CIE 1964 large-field chromaticity coordinates x_{10}, y_{10} instead of the CIE 1931 x, y -coordinates. The resulting value of f_0 is then passed through an equation based on the Ikeda-Ashizawa adaptation coefficient function. This function (Ikeda & Ashizawa, 1991) describes the chromatic contribution as increasing linearly with log luminance from 0 at 0,001 cd/m² to a maximum value, defined by the Ware-Cowan conversion factor, at 100 cd/m².

Although the Kokoschka system is based on HCBM experiments in which the reference stimulus was a monochromatic field at 530 nm, the F -coefficients found in Appendix 4 and the equation defining L_{seq} are based on a derivation (Kokoschka & Bodmann, 1975) in which platinum at 2045 K serves as the reference.

Calculation:

1. Determine the CIE 1964 tristimulus values, X_{10} , Y_{10} , Z_{10} , and CIE scotopic luminance, L' , for the sample.
2. Calculate L_{est} (estimated L_{seq}) for two or three of the L_{seq} levels represented in the table of F -coefficients (Appendix 4), choosing a region near the level equal to Y_{10} for the sample. Use the equation.

$$L_{\text{est}} = F_x X_{10} + F_y Y_{10} + F_z Z_{10} + F_s L' \quad (2.35)$$

In most cases, Equation (2.35) will be found to yield a value of L_{est} that differs from the value of L_{seq} corresponding to these F -coefficients in the table.

3. Interpolate between the levels represented in the table, using iteration or a graphical method (see Figure 2.11), to find the set of L_{seq} values and F -coefficients for which Equation (2.35) will give $L_{\text{est}} = L_{\text{seq}}$

4. Calculate the chromatic correction factor f .

$$f = 1 + (f_0 - 1)(0,6 + 0,2 \log L_{10}) \quad (2.36)$$

using the following equations to define f_0 :

$$f_0 = 10^{c^*} \quad (2.37)$$

$$c^* = c_{10} + 0,067 \quad \text{and} \quad (2.38)$$

$$c_{10} = 0,256 - 0,184 y_{10} - 2,527 x_{10} y_{10} + 4,656 x_{10}^3 y_{10} + 4,657 x_{10} y_{10}^4 \quad (2.39)$$

Equation (2.39) will be recognized as identical with the Ware-Cowan equation for the conversion factor c , except for the change to CIE 1964 chromaticity coordinates.

5. Use the chromatic correction factor to correct L_{est} , obtained in step 3:

$$L_{\text{seq}} = L_{\text{est}} \cdot f \quad (2.40)$$

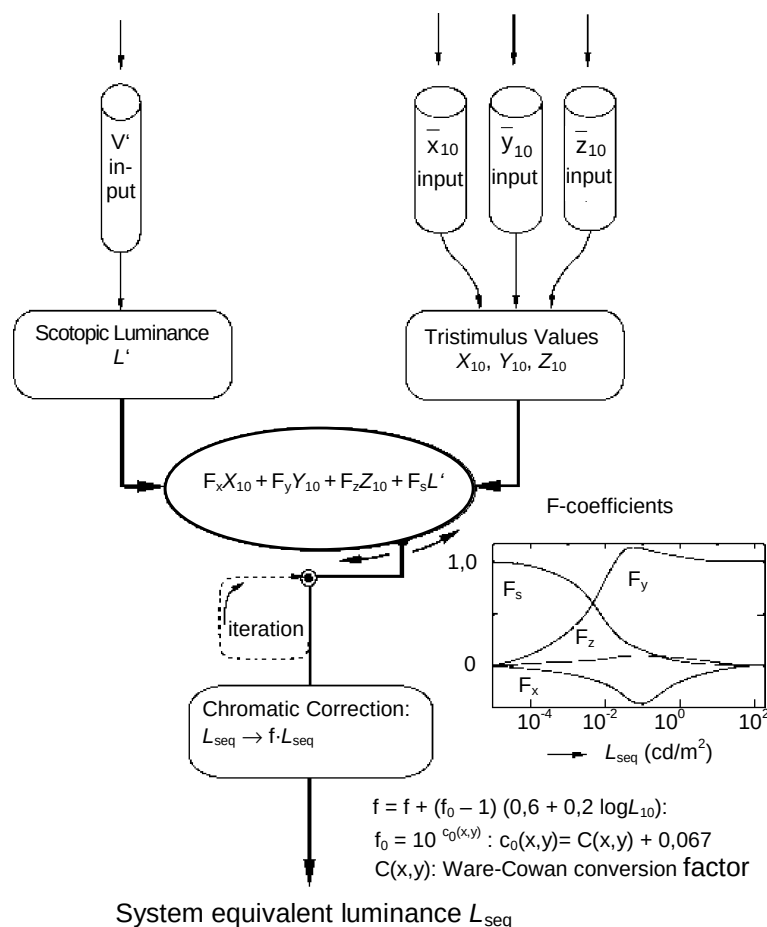


Fig. 2.10 Kokoschka - Bodmann system

Example: (Sample: Munsell Color Chip 10B5/10 at 0,01 cd/m²)

1. From $x_{10} = 0,205$, $y_{10} = 0,267$ and $L = 0,01$ cd/m² (Appendix 1)

$$Y_{10} = (L_{10} / L) L = 1,197 \cdot 0,01 = 0,01197$$

$$X_{10} = (x_{10} / y_{10}) Y_{10} = 0,00919$$

$$Z_{10} = ((1 - x_{10} - y_{10}) / y_{10}) Y_{10} = 0,02367$$

$$L' = (L' / L) L = 4,411 \cdot 0,01 = 0,04411$$

2. From the table in Appendix 4, choose levels of L_{seq} near the value of Y_{10} , and determine the corresponding values of L_{est} by Equation (2.35). (See Fig. 2.11.)

For all three L_{seq} values in Fig. 2.11, Equation (2.35) yields a value of L_{est} which differs from L_{seq} . However, the F -coefficients (from Appendix 4) for $L_{seq} = 0,0175$ yield $L_{est} > L_{seq}$ while those for $L_{seq} = 0,0288$ yield $L_{est} < L_{seq}$. By linear interpolation within the table, a set of L_{seq} and F -coefficient values can be found lying about 0,4 of the distance between the lines $L_{seq} = 0,0175$ and $L_{seq} = 0,0288$ and having the following interpolated values.

L_{seq}	F_x	$F_x X_{10}$	F	$F_y Y_{10}$	F_z	$F_z Z_{10}$	F_s	$F_s L'$	L_{est}
0,022	-0,269	-0,00247	1,10	0,01317	0,0484	0,00115	0,225	0,01007	0,02192

Since $L_{seq} = L_{est}$ for this choice of L_{seq} , the value $L_{est} = 0,022$ is carried forward.

When a computer is used, this solution is easily found by iteration. Otherwise, the three values of L_{est} and L_{seq} may be plotted as in Figure 2.11, showing the way in which L_{est} varies with L_{seq} in this region. The point at which $L_{est} = L_{seq}$ can then be read from the graph.

3. To correct for any chromatic contribution, use Equations (2.37) through (2.39) to determine

$$c_{10} = 0,0841$$

$$c^* = 0,1511$$

$$f_0 = 1,416$$

4. From Equation (2.36)

$$f = 1 + (0,416)(0,6 + (0,2 \cdot (-1,92191))) = 1,090$$

5. From Equation (2.40)

$$L_{\text{seq}} = f \cdot L_{\text{est}} = 0,0240 \text{ cd/m}^2 \text{ of a platinum reference stimulus at 2045 K}$$

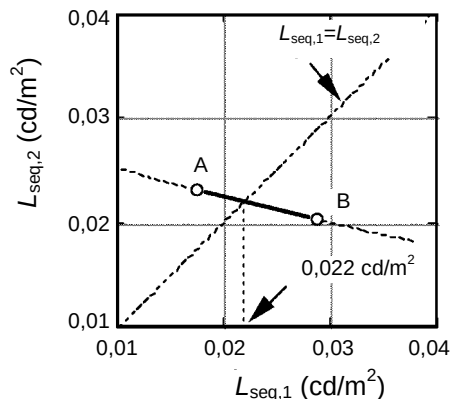


Fig. 2.11 Worksheet of Kokoschka - Bodmann system

2.2.6 Trezona system

P. W. Trezona has developed her system from the concept of tetrachromatic colorimetry, in which four monochromatic primaries are combined to obtain matches for monochromatic lights that will remain valid at scotopic as well as photopic luminance levels (Trezona 1973). Above the scotopic level, test and comparison fields must match in both brightness and chromaticity; at the scotopic level, only apparent brightness need be considered. For a colorimetry that will remain valid at both levels, Trezona argues that four components must be used. She makes a similar argument in developing a photometry that will remain valid across photopic, mesopic, and scotopic levels. Figure 2.12 sketches her photometric system.

Using a 588 nm monochromatic matching field, Trezona has traced the decline in brightness of individual test lights as retinal illuminance is reduced from above +2 to below -2 log radiometric trolands. In each set of observations, log radiometric trolands that matched to the test light declines linearly with log retinal illuminance in two regions, a photopic region where the decline parallels the prediction from $V(\lambda)$, but may not coincide with it, and a scotopic region where it coincides with the prediction from $V'(\lambda)$. These two linear limbs have unit slope; between them, her data show a smooth transition. The entire function, drawn in units of radiometric millitrolands, can be described by a hyperbolic tangent function.

The Trezona system describes this function, for each test object or light, by determining the position of the two linear portions and the limits of the transitional region; these positions differ from one test sample to another. Since the linear portions have unit slope, their positions can be defined by their intercept with the axis for reference light in log unit ($\log L_{e,\text{ref}}$ in Fig. 2.12); parameters a and b designate the scotopic and photopic intercepts, respectively. Parameters S and P designate the points at which the transitional region first deviates by 0,05 log units (about 10 percent) from the adjacent scotopic or photopic limb. Using four inputs based on CIE 1964 colour-matching functions and the $V'(\lambda)$ function, the system determines the appropriate hyperbolic tangent function so that an equivalent luminance L_{seq} can be calculated for any test sample. Although her data were obtained with a 588 nm reference stimulus, the Trezona system in its present form produces a L_{seq} interpretable as the luminance of a 555 nm light which will appear equally as bright as the test

sample. Trezona has adopted the 555 nm reference in order to tie her system to the new 1979 definition of the candela.

The constants for the Trezona equations which appeared in the report of TC1-01 (CIE, 1989) have been revised to reflect additional empirical data, but the forms of these equations remain essentially the same. A computer program is available (Trezona, 1990) to assist users with the computations.

Calculation:

1. Using radiometric data from the sample, determine the four tetrastimulus values.

$$\begin{aligned} X_t &= \frac{\int L_{e,\lambda}(\lambda) x_{10}(\lambda) d\lambda}{\int L_{e,\lambda}(\lambda) d\lambda} \\ Y_t &= \frac{\int L_{e,\lambda}(\lambda) y_{10}(\lambda) d\lambda}{\int L_{e,\lambda}(\lambda) d\lambda} \\ Z_t &= \frac{\int L_{e,\lambda}(\lambda) z_{10}(\lambda) d\lambda}{\int L_{e,\lambda}(\lambda) d\lambda} \\ V'_t &= \frac{\int L_{e,\lambda}(\lambda) V'(\lambda) d\lambda}{\int L_{e,\lambda}(\lambda) d\lambda} \end{aligned} \quad (2.41)$$

2. Use these tetrastimulus values to determine the scotopic and photopic limits, S and P ,

$$\begin{aligned} S' = & -1,2834 + 0,1242 X_t / Y_t + 0,1207 Z_t / Y_t - 1,3919 V'_t / Y_t - 0,1507 X_t^2 / Y_t^2 \\ & - 0,0190 X_t Z_t / Y_t^2 + 0,0156 Z_t^2 / Y_t^2 - 0,1166 Z_t V'_t / Y_t^2 + 0,3301 V_t'^2 / Y_t^2 + \\ & 0,1493 V'_t X_t / Y_t^2 \end{aligned} \quad (2.42)$$

$$S = S' - \log Y_t \quad (2.43)$$

$$\begin{aligned} P' = & +0,4423 - 0,7054 X_t / Y_t - 0,1100 Z_t / Y_t - 0,1099 V'_t / Y_t + 0,2020 X_t^2 / Y_t^2 + \\ & 0,0341 X_t Z_t / Y_t^2 - 0,0188 Z_t^2 / Y_t^2 + 0,0017 Z_t V'_t / Y_t^2 + 0,0519 V_t'^2 / Y_t^2 + \\ & 0,3458 V'_t X_t / Y_t^2 \end{aligned} \quad (2.44)$$

$$P = P' - \log Y_t \quad (2.45)$$

3. Use the CIE 1964 x_{10} , y_{10} coordinates to determine the intercepts a and b of the log linear limbs of the function for the scotopic and photopic regions, respectively,

$$a = \log V'_t + 1,1278 \quad (2.46)$$

$$b' = 0,325 - 0,184 y_{10} - 2,527 x_{10} y_{10} + 4,656 x_{10}^3 y_{10} + 4,657 x_{10} y_{10}^4 \quad (2.47)$$

$$b = b' + \log Y_t \quad (2.48)$$

4. Using a , b , S , and P , find the parameters d and m which define the hyperbolic tangent function in the transitional region.

$$d = (S + P) / 2 \quad (2.49)$$

$$m = 2 \tanh^{-1} [1 - 0,1 / (a - b)] / (P - S) \quad (2.50)$$

5. Convert $\log Y_{10}$ (in $\log \text{cd/m}^2$) for the sample into N_p (in $\log$ photopic trolands) by linear interpolation within the conversion table in Appendix 5.

6. Convert N_p (log photopic trolands) into N (log radiometric trolands):

$$N = N_p + 0,1656 - \log Y_t \quad (2.51)$$

7. Calculate the value M in log radiometric trolands of the 555 nm reference stimulus that will match the sample's apparent brightness.

$$M = N + (a+b) / 2 - [(a-b) / 2] \tanh[m(N-d)] \quad (2.52)$$

8. Convert M (log radiometric trolands) into R (log photopic trolands).

$$R = M - 0,4148 + 0,3172 \{ \tanh 1,845(M + 0,489) \} - 0,1660 \quad (2.53)$$

9. Using conversion table (Appendix 5), convert R into $\log \text{cd/m}^2$ to obtain $\log L_{\text{seq}}$.

Example: (Sample: Munsell Color Chip 10B5/10 at 0,01 cd/m²)

1. Appendix 1 provides the tetrastimulus values for the sample,

$$X_t = 0,267 \quad Y_t = 0,349 \quad Z_t = 0,691 \quad V_t = 0,510$$

2. From Equations (2.42) through (2.45),

$$S' = -2,514 \quad S = -2,0569$$

$$P' = 0,1281 \quad P = 0,5853$$

3. From Equations (2.46) through (2.48),

$$a = 0,8405 \quad b' = 0,1531 \quad b = -0,3041$$

4. From Equations (2.49) and (2.50),

$$d = -0,7358 \quad m = 1,168$$

5. Converting $\log L_{10}$ to log radiometric trolands (Appendix 5),

$$\log L_{10} = -1,922 \quad (\log \text{cd/m}^2)$$

$$N_p = -0,3506 \quad (\log \text{photopic trolands})$$

6. From Equation (2.51),

$$N = N_p + 0,1656 - \log(0,349) = 0,2722 \quad (\log \text{radiometric trolands})$$

7. From Equation (2.52),

$$M = N + [0,8405 + (-0,3041)] / 2 - [0,8405 - (-0,3041)] \tanh [1,168 \times (N + 0,7358)] \\ = 0,0674 \quad (\log \text{radiometric trolands})$$

8. From Equation (2.53),

$$R = 0,2722 - 0,4148 + 0,3172 \{ \tanh 1,845(0,2722 + 0,489) \} - 0,1660 = -0,2684 \quad (\log \text{photopic trolands})$$

9. Convert R in log photopic trolands to L_{seq} in cd/m^2 (Appendix 5),

$$\log L_{\text{seq}} = -1,833 \quad \log \text{cd/m}^2$$

$$L_{\text{seq}} = 0,0147 \text{ cd/m}^2 \text{ of a 555 nm reference stimulus}$$

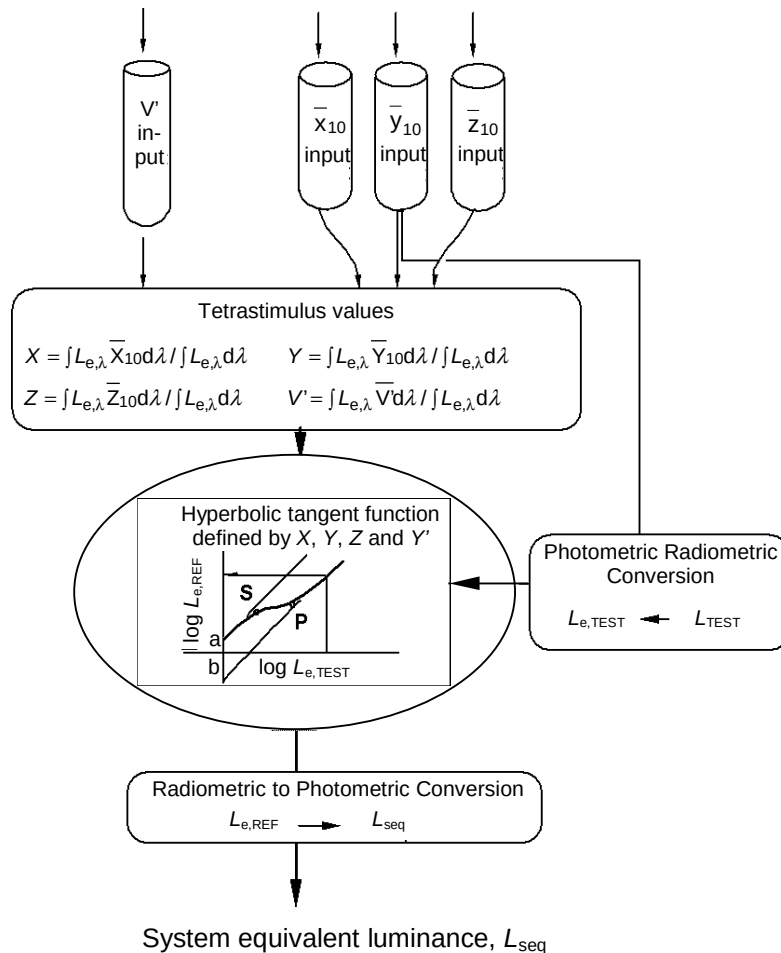


Fig. 2.12 Trezona system

2.2.7 Other systems

In addition to above proposed systems, Ashizawa and Ikeda have proposed a system to give equivalent lightness for object colours (Ashizawa, 1985; Ikeda, 1991). This system is designed in the same concept of the 10° systems working for a wide range of visual sensitivity including scotopic vision. Because of difficulties of applying the system directly to the brightness matching data obtained in luminous modes, the system is not included in the present numerical testing. The system is fully described in Appendix 6.

3. TEST DATA AND PROCEDURES

3.1 Data sources

Data for testing the proposed photometry systems were selected from reports of experiments using direct brightness matching (HCBM) with more than one observer. These data were obtained with a wide variety of test stimuli, including spectral and non-spectral lights, and under several different viewing conditions, including both aperture-mode and object-mode. No data were used unless each test stimulus could be fully specified either as a spectral power distribution or as a complete set of CIE colorimetric and photometric quantities (2°, 10°, and Judd-modified tristimulus values; scotopic luminance; and tetrastimulus values).

Table 3.1 summarizes the data sets which have been used for this report, giving the number of test stimuli, type of light, field size, number of observers, and luminance levels studied. Some of the data sets have been published in full; others were obtained by personal communication with the experimenters. Appendix 8 provides the chromaticity coordinates for