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

CIE COLLECTION 1999

Vision and Colour

Physical Measurement of Light and Radiation

Contents:

- 135/1 Research note: Disability glare
 - 135/2 Research note: Colour rendering, TC 1-33 closing remarks
 - 135/3 CIE TC 1-45 report: Supplement 1 - 1999 to CIE 51 - 1981, Virtual metamers for assessing the quality of simulators of CIE illuminant D50
 - 135/4 Research note: Reporter's report: Some recent developments in colour difference evaluation
 - 135/5 Research note: Reporter's report: Visual adaptation to complex luminance distribution
 - 135/6 Chairman's report: 45°/0° Spectral reflectance factors of pressed polytetrafluoroethylene (PTFE) powder
- Abridged abstracts of CIE Publications prepared within Divisions 1 and 2

CIE 135 - 1999

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Diffuse reflectance

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The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in 37 countries and one geographical area and of 10 individual members.

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3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
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La Commission Internationale de l'Éclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant 37 pays plus un territoire géographique, et de 10 membres individuels.

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1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
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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. Die Mitgliedschaft besteht aus den Nationalen Komitees in 37 Ländern und einem geographischen Gebiet und aus 10 persönlichen Mitgliedern.

Die Ziele der CIE sind :

1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
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Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.

Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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1	February 2000	Page 25: In Table 1, Row 1, Last column (Wavelength 555, Metamers set 5): the corrected value is 0,119

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The Reports in this publication have been prepared by various CIE Technical Committees and Reporters within Division 1 "Vision and Colour" and Division 2 "Physical Measurement of Light and Radiation". The Research Notes in this publication were submitted by the Director of Division 1 after refereeing by two experts in the field of the Note, both of whom supported publication. The Division Director has also provided the accompanying statement on the relevance of the Note to the work of the CIE. The reports draw on current knowledge and experience within the specific field of light and lighting described, and are intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of the reports is advisory and not mandatory. The latest CIE proceedings, CIE NEWS, future issues in the "CIE Collection" Series or publication listing should be consulted regarding possible subsequent amendments.

Les rapports ont été préparé par différents Comités Techniques et Rapporteurs de la CIE la Division 1 "Vision et couleur" et la Division 2 "Mesures physiques de la lumière et des radiations". Les Notes de Recherches contenues dans cette publication ont été soumises par le Directeur de la division 1, après revue et approbation par deux experts dans le domaine de la note. Le Directeur de division a également fourni une déclaration d'accompagnement sur la pertinence de la Note pour le travail de la CIE. Les rapports traitent des connaissances courantes et de l'expérience dans le domaine spécifique indiqué de la lumière et de l'éclairage, et il est établi pour l'usage des membres de la CIE et autres groupements intéressés. Il faut cependant noter que les rapports sont indicatifs et non obligatoires. Pour connaître d'éventuels amendements, consulter les plus récents comptes rendus de la CIE, CIE NEWS, éditions futures de la série "CIE Collection" ou les listes de publications de la CIE.

Die Berichte wurden von verschiedenen Technischen Komitees der CIE in Division 1 'Sehen und Farbe' sowie in Division 2 'Physikalische Messungen von Licht und Strahlung' ausgearbeitet. Die Forschungsberichte in dieser Publikation wurden vom Direktor der Division 1 unterbreitet, nachdem sie von zwei Experten auf dem Gebiet des Berichtes geprüft und für publikationsreif befunden wurden. Der Divisionsdirektor lieferte auch einen begleitenden Kommentar über die Bedeutung des Berichtes für die Arbeit der CIE. Die Berichte behandeln den derzeitigen Stand des Wissens und der Erfahrung auf dem Gebiet Licht und Beleuchtung; sie sind zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, daß die Berichte Empfehlungen und keine Vorschriften sind. Die neuesten CIE-Tagungsberichte, das CIE NEWS, zukünftige Ausgaben in der Serie "CIE Collection" oder die Publikationsliste sollten im Hinblick auf mögliche spätere Änderungen zu Rate gezogen werden.

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Research Note

Note: This report was prepared by J.J. Vos, the chairman of TC1-18 Disability Glare and T.J.T.P. van den Berg. It contains a disability glare formula on the basis of Stiles-Holladay Formula with an extension of angular domain and an age-related effect in the formula. Although the committee was not in full approval of the report, Division 1 regarded it - after the revisions of the referees - as containing useful information for the further development of the disability glare formula and therefore it should be published in the CIE collection as a research note. It would be a base for the future recommendation on the CIE Glare Formula with further discussions and possible modifications.

REPORT ON DISABILITY GLARE

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REPORT ON DISABILITY GLARE**SUMMARY**

On the basis of a preceding theoretical analysis of experimental data on disability glare published in CIE Collection (Vos and Van den Berg, 1997 [14]), resulting in a complete glare equation covering the full 0° to 100° glare angle range, three simplified glare equations are presented, each of them defined for a more restricted glare angle domain. This ensemble of three equations together is recommended to define a CIE Standard Glare Observer; the most simple one, the Age Adapted Stiles-Holladay Equation, will suffice for most circumstances of daily practice.

RAPPORT SUR L'ÉBLOUISSEMENT PERTURBATEUR**RÉSUMÉ**

A la base d'une analyse précédente théorique des données expérimentelles sur l'éblouissement, publiée en CIE Collection (Vos et Van den Berg, 1997 [14]), aboutissant sur une équation complète de l'éblouissement pour le domaine angulaire entier de 0° à 100°, trois équations simplifiées sont présentées, chacune d'elle pour un domaine de validité angulaire spécifique. Cet ensemble de trois équations est recommandé pour définir un observateur standard CIE d'éblouissement; l'équation la plus simple, l'équation Stiles-Holladay adaptée à l'âge, suffira pour la majorité des circonstances d'usage courant.

BERICHT ÜBER PHYSIOLOGISCHE BLENDUNG**ZUSAMMENFASSUNG**

Auf Grund einer vorhergehenden theoretischen Analyse von experimentellen Blendungsdaten, veröffentlicht in CIE Collection (Vos und Van den Berg, 1997 [14]), und resultierend in einer vollständigen Blendungsformel für den ganzen Winkelbereich zwischen 0° und 100°, werden drei vereinfachte Formeln präsentiert, jede gültig in einem spezifischen Blendungswinkelbereich. Dieses Ensemble von drei Formeln wird empfohlen um einen CIE Standardblendungsbeobachter zu definieren; die einfachste Formel, die Alter-adaptierte Stiles-Holladay Formel, wird in den meisten Anwendungsumständen genügen.

1. INTRODUCTION

In the 1920s and 1930s in particular Holladay [3,4] and Stiles [8,9], the latter later together with Crawford [10], led the foundations for a well defined knowledge of disability glare. Their combined experimental results were brought in into CIE at its Scheveningen meeting in 1939 [7]. There they launched empirical description

$$L_{eq} / E_{gl} = 10 / \theta^2 \quad (1)$$

with L_{eq} = equivalent veiling luminance, in cd/m^2 ;
 E_{gl} = glare illuminance at the eye, in lux;
 θ = glare angle, in degrees.

even though never formally adopted by CIE and never attributed with an angular validity domain, became the canonized description of disability glare phenomenology, now generally known as the Stiles-Holladay glare formula.

Apparently, this situation was not felt entirely satisfactory, and as a follow up of the general discussion on Division 1 topics at the Amsterdam CIE meeting in 1983, and of a since published State of the Art paper by Vos [13], CIE decided, in 1986, that a Technical Committee (TC1-18) should be established with the task

to recommend a revised Stiles-Holladay formula which could be named: the CIE standard observer disability glare formula 1986; and to recommend a study on the relation between glare and age.

In this committee, several discussion papers were circulated, but due to a general lack of response from its membership, CIE decided to dissolve the committee and to charge the present authors with the task to write recommendations to CIE on a personal account. The present report is the result.

In the next four sections the considerations are sketched underlying the complete glare equation that was taken as a starting point. It is a summary survey only, intended to make the train of thoughts understandable. The full derivation is to be found in ref [14]. In section 6 three simplified versions are presented, each of which can be considered an adequate description within its specified glare angle domain. In section 7 these three simplified versions are formally recommended to CIE as Standard Glare Equations. Section 8, finally, gives a short discussion of the practical significance of these recommendations and indicates needs for further experimental research.

2. CONSIDERATIONS

The 1984 State of the Art survey paper [13] was taken as a starting point. In this paper the Stiles-Holladay course was taken as the generally accepted course in the 'glare domain proper' (roughly beyond 5°), and it was shown that this course needed corrections in the 0° to 5° domain. Furthermore it tentatively postulated an age (A) dependency by introducing an age dependent multiplication factor (AF)

$$AF = 1 + [A/70]^4 \quad (2)$$

Since then several shortcomings in this State of the Art paper (which will be henceforth quoted by that name) have emerged which necessitated further adjustments:

- The formula given in the State of the Art paper is not analytical at $\theta = 0^\circ$; consequently, it did not allow analytical transformation to a Modulation Transfer Function.
- The central part of the glare function was based on optical spread functions, whereas visual spread functions would have been a more appropriate choice.
- New experimental evidence made clear that, for glare angles beyond about 20° , the $1/\theta^2$ course is too steep, and that a gradual reduction in steepness towards a $1/\theta$ course, roughly, would be a more realistic description.
- New experimental evidence made clear that, in particular at large glare angles, ocular pigmentation should be taken into account as parameter.

Evidently, then, the description of the glare equation in the State of the Art paper needed to be modified. These modifications were not simply a matter of drawing new lines through better data, though, since large angle scatter data were scarce. Therefore, semi-theoretical extrapolation had to fill experimental gaps. Since the underlying detailed analysis would interfere with the conciseness and readability required for a CIE report, it was decided to publish

that detailed justification of the choices made in ref [14] and to only shortly summarise these considerations in this formal report.

3. THE SMALL ANGLE PART (POINT SPREAD FUNCTION PROPER)

The small angle part, in the minutes of arc domain, of the glare function is usually called the Point Spread Function (PSF) proper. In the State of the Art paper its shape was taken from Campbell and Gubisch's [2] optical spread function as determined by funduscopy. However, IJspeert et al. [6] have correctly criticised this choice as the glare function essentially is a psychophysical function, describing how subjects perceive the veiling luminance. They therefore turned to Campbell and Green's [1] earlier data on the visual point spread function. Moreover they described it in a mathematically better way than the trial and error formula of the State of the Art paper. It was decided to follow IJspeert et al.'s [6] line of thinking and so to adopt their description¹ of the small angle part of the glare function, i.e.:

$$\left[L_{eq} / E_g \right]_{PSFproper} = \frac{9,7 \cdot 10^6}{\left[1 + (\theta / 0,0046)^2 \right]^{1,5}} + \frac{1,56 \cdot 10^5}{\left[1 + (\theta / 0,045)^2 \right]^{1,5}} \quad [sr^{-1}] \quad (3)$$

In fact, the spread function varies with pupil size. Since the small angle part is not very important in situations of actual glare, and since, moreover, pupil size is seldom known in situations of daily life, it was decided to work with this average course (equ. 3), valid roughly for a four mm pupil size. Further it should be noted that this description applies to the foveal image. Farther off the fovea the quality will generally decrease.

The above formula translates into the Modulation Transfer Function

$$MTF = 0,39 \cdot e^{-0,029q} + 0,61 \cdot e^{-0,28q} \quad (4)$$

with q = spatial frequency in cycles per degree.

4. THE LARGE ANGLE PART (GLARE FUNCTION PROPER)

In the State of the Art paper the $1/\theta^2$ course in the very large angle domain was adopted from Stiles and Crawford's [10] classic work. However, since then IJspeert et al. [5] have produced considerable evidence for a more gradual fall off beyond about 10° . The apparent controversy induced Vos and Van den Berg [14] to a deeper analysis of data on and mechanisms of large angle scattering. The experimental controversy could be virtually eliminated because the Stiles and Crawford data, when corrected for the perspective narrowing of the pupil, roughly showed the same deviating trend from $1/\theta^2$. Furthermore, both the large angle dependency and the dependency on eye pigmentation could be reasonably well understood on the basis of a significant contribution of scattering at the ocular fundus to the entoptic straylight veil by Van den Berg et al. [11]. A mostly small contribution of light entering via the iris and sclera could further complement the picture. This so obtained convergence of experimental evidence and theoretical analysis confirmed the reality of the upward deviations from the classic $1/\theta^2$ course. The theoretical analysis, then, allowed for a reasonably reliable extrapolation into domains of glare angle and pigmentation not thoroughly covered by experimental data. For young adults it reads:

$$\left[L_{eq} / E_g \right]_{glare\ function\ proper} = \left[\frac{390}{1 + (\theta / 0,1)^2} + 2,7 \cdot 10^{-8} \cdot \theta^2 \right] + p \cdot \left[\frac{1300}{\left[1 + (\theta / 0,1)^2 \right]^{1,5}} + \frac{0,84}{\left[1 + (\theta / 0,1)^2 \right]^{0,5}} + 2,5 \cdot 10^{-3} \right] \quad [sr^{-1}] \quad (5)$$

with p = a pigmentation factor ($p = 0$ for very dark eyes, $p = 0,5$ for brown eyes, and $p = 1,0$ for blue-green caucasians).

¹ In fact, by applying IJspeert et al.'s [6] eqs (3) and (4) to the first two terms only, and using the parameters of the next page.

In this formula the first part can be attributed to cornea and lens scattering, and the second part to scattering at the fundus and to light entering the eye via the ocular wall.

5. AGE DEPENDENCE

A new factor analysis, by Van den Berg [12], of the earlier obtained age dependence data led Vos and Van den Berg [14] to a differentiated attribution of the age dependency of the various components of ocular scatter:

$$\begin{aligned} [L_{eq} / E_{gl}]_{glare\ function\ proper} = & \left[1 + 1,5 \cdot (A/70)^4 \right] \cdot \left[\frac{390}{1 + (\theta/0,1)^2} + 2,7 \cdot 10^{-8} \cdot \theta^2 \right] + \\ & + \left[0,6 + (A/70)^4 \right] \cdot p \cdot \left[\frac{2200}{[1 + (\theta/0,1)^2]^{1,5}} + \frac{1,4}{[1 + (\theta/0,1)^2]^{0,5}} \right] + 2,5 \cdot 10^{-3} \cdot p \quad [sr^{-1}] \end{aligned} \quad (6)$$

Of course it should be realised that the variation within each age group is considerable, so that the formulated dependency indicates an average trend only. Therefore, the semi-theoretical equ. (6) allows some simplification in practice:

$$\begin{aligned} [L_{eq} / E_{gl}]_{glare\ function\ proper} = & \left[1 + 1,6 \cdot (A/70)^4 \right] \cdot \\ & \cdot \left[\frac{400}{1 + (\theta/0,1)^2} + 3 \cdot 10^{-8} \cdot \theta^2 \right] + p \cdot \left[\frac{1300}{[1 + (\theta/0,1)^2]^{1,5}} + \frac{0,8}{[1 + (\theta/0,1)^2]^{0,5}} \right] + \\ & + 2,5 \cdot 10^{-3} \cdot p \quad [sr^{-1}] \end{aligned} \quad (7)$$

This increase in general glare level with age can only be obtained at the cost of the amount of light in the central PSF lobe. As a result, the total glare function proposed by Vos and Van den Berg [14] but somewhat simplified reads:

$$\begin{aligned} [L_{eq} / E_{gl}]_{total} = & \left[1 - 0,08 \cdot (A/70)^4 \right] \cdot \left[\frac{9,2 \cdot 10^6}{[1 + (\theta/0,0046)^2]^{1,5}} + \frac{1,5 \cdot 10^5}{[1 + (\theta/0,045)^2]^{1,5}} \right] + \\ & + \left[1 + 1,6 \cdot (A/70)^4 \right] \cdot \left\{ \left[\frac{400}{1 + (\theta/0,1)^2} + 3 \cdot 10^{-8} \cdot \theta^2 \right] + p \cdot \left[\frac{1300}{[1 + (\theta/0,1)^2]^{1,5}} + \frac{0,8}{[1 + (\theta/0,1)^2]^{0,5}} \right] \right\} + \\ & + 2,5 \cdot 10^{-3} \cdot p \quad [sr^{-1}] \end{aligned} \quad (8)$$

Equ. (8) is considered to give the best mathematical description of the foveal visual point spread function at the present state of knowledge. Fig.1 gives a few examples of curves calculated with this equation. The hatched area indicates the domain of experimental spread in IJspeert et al.'s [5] field study. Even a single glance at equ. (8), though, suffices to conclude that it is far too complicated - and unnecessary complex - to define a 'Standard Disability Glare Observer' for CIE purposes. Therefore, equ. (8) will be used in the next section as a starting point to define a few purely empirical simplified versions.

6. SIMPLIFIED VERSIONS

In this section we will start with the most simplified version, based on the hard core of the Stiles-Holladay relation, and then gradually turn to the more complicated versions by adding terms. The numerical values in these formulas are based on best fit considerations.

6.1 The age adapted Stiles-Holladay glare formula

The most simple version of a disability glare formula seems to be the classic Stiles-Holladay equation in which the constant is multiplied by an age factor AF . Taking for that the expression

$$AF = 1 + [A/70]^4 \quad (2)$$

as proposed in the State of the Art paper and confirmed by IJspeert et al.[5] one obtains

$$\left[L_{eq} / E_{gl} \right]_{S-H, age ad.} = \left\{ 1 + [A/70]^4 \right\} \cdot 10 / \theta^2 \quad (9)$$

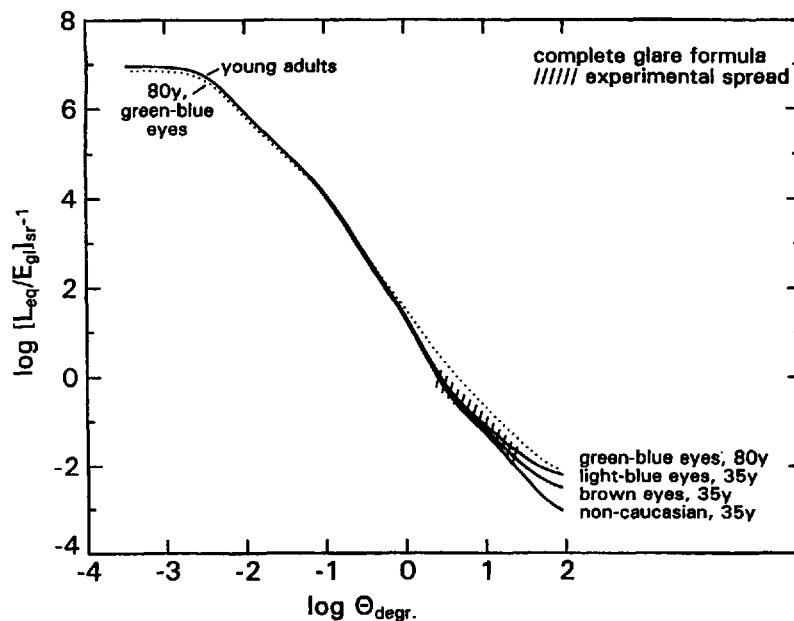


Fig.1. Calculated disability glare functions for four age/pigmentation conditions from Vos and Van den Berg [14]. The hatched zone indicates the individual spread from IJspeert et al. [5]

This angular relation is shown for ages $A=35$ and $A=80$ year in Fig.2, superimposed on the pattern of curves of Fig.1. Not surprisingly, after so many years of good service, the old Stiles-Holladay equation, marked by the y-symbols, follows a nice middle road through the set of calculated curves even up to the largest glare angles. The slope, though, is only reasonably correct in the, roughly, 3° to 30° domain. Within that domain it can be regarded as a justified simplification of disability glare behaviour and as a confirmation of a long standing practice.

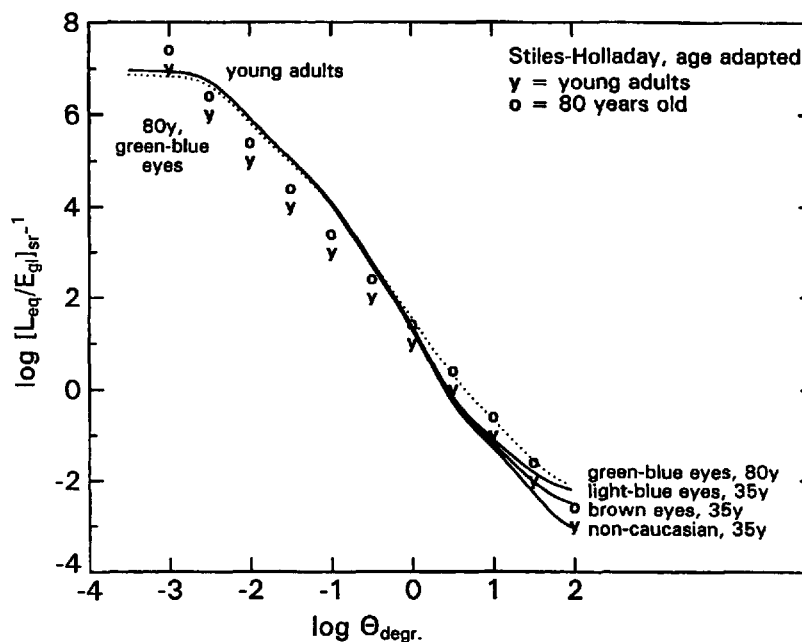


Fig.2. The calculated curve pattern of Fig.1, superimposed with the Age Adapted Stiles-Holladay Equation indicated by y's (for young adults, 35 years old) and o's (for 80 year olds). The course marked by the y's is the classic Stiles-Holladay relation. The validity domain of this age adapted equation runs from 3° to 30° .

6.2. The simplified glare equation

As it is evident that the Stiles-Holladay equation falls short in particular below 1° , a reduced version of equ. (8) may serve as a simplified glare equation in a more extended angular domain:

$$[L_{eq}/E_{gl}]_{simpl.} = 10/\theta^3 + \{1 + [A/62,5]^4\} \cdot 5/\theta^2 \quad (10)$$

This angular relation is shown for two ages in fig.3, superimposed again on the pattern of curves of Fig.1. The validity of this description stretches roughly from $0,1^\circ$ to 30° .

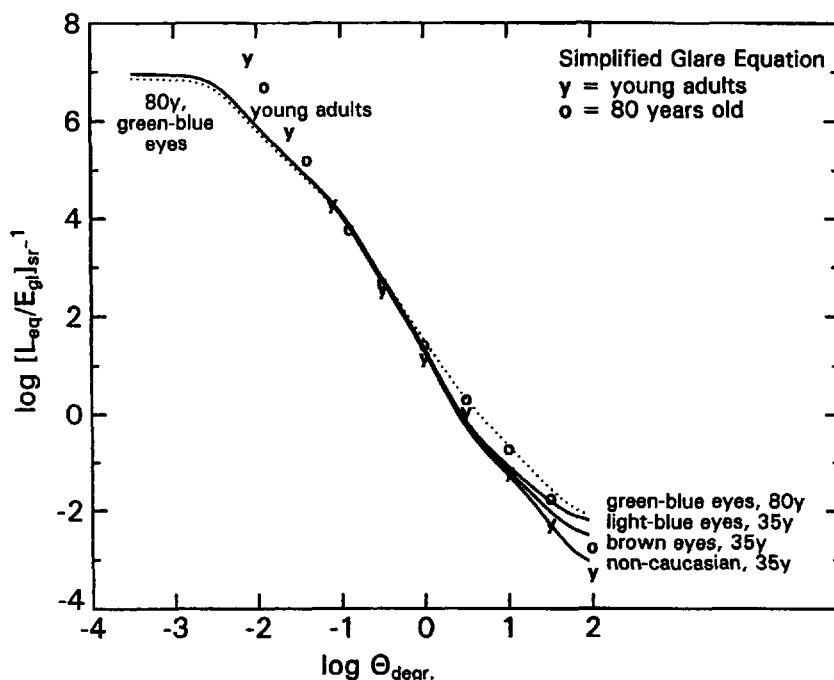


Fig. 3. The calculated curve pattern of Fig.1, superimposed with the Simplified Glare Equation, indicated by y's (for young adults, 35 years old) and o's (for 80 year olds). The validity domain of this simplified glare equation runs from $0,1^\circ$ to 30° .

6.3. The general glare equation

To also cover the very large angle domain, more terms of equ. (8) should be taken into account, albeit, again, in a reduced version:

$$[L_{eq}/E_{gl}]_{gen.} = 10/\theta^3 + [5/\theta^2 + 0,1 \cdot p/\theta] \cdot \{1 + [A/62,5]^4\} + 2,5 \cdot 10^{-3} \cdot p \quad (11)$$

This angular relation is shown in Fig. 4 for two ages and two pigmentation levels, again superimposed on the pattern of curves of Fig.1. The validity domain now stretches from $0,1^\circ$ all the way up to the very limit of the field of view, somewhere around 100° .

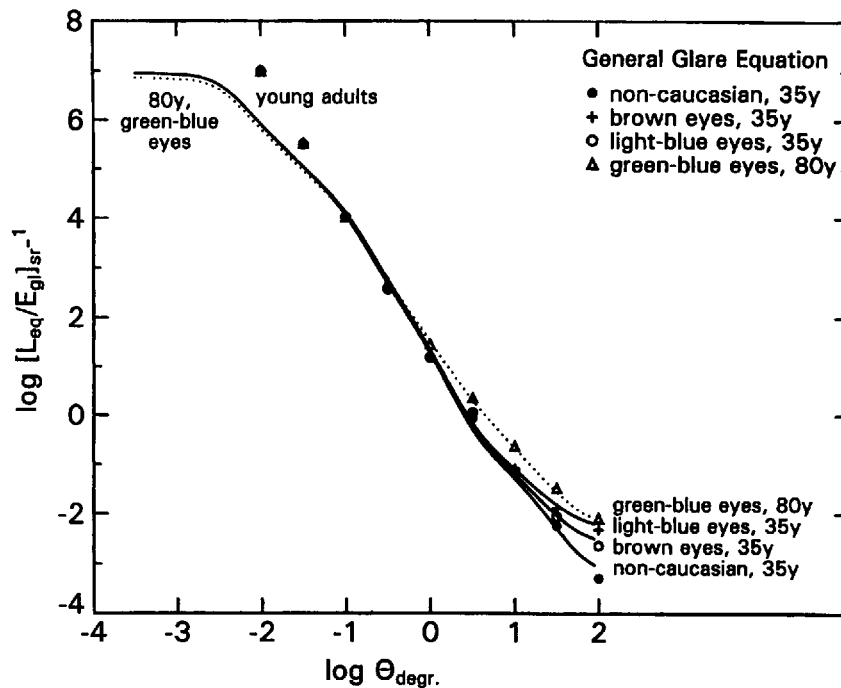


Fig. 4. The calculated curve pattern of Fig. 1, superimposed with the General Glare Equation, indicated by ●'s, ○'s, + 's and △'s for three age/pigmentation combinations. The validity domain of this general glare equation runs from 0,1° to 100°.

Only when the very small glare angle domain should be covered as well, the full equ. (8) ought to be used. Then, however, it is not customary anymore to speak of glare, but rather of the foveal point spread function. Moreover, glare situations are usually characterised by foveal vision in the presence of extrafoveal glare sources, and in those situations the very central part of that spread function was noted to be broader than of the foveal spread function. This, in fact, justifies the name *General Glare Equation* as it applies to the full range of ecological glare situations.

In this section minor indications of wavelength dependence have been disregarded, considering that application will mainly concern white glare light.

7. RECOMMENDATIONS

Summarising, the following set of three glare formulas for white glare light is recommended:

the **Age Adapted Stiles-Holladay Glare Equation**

$$\left[L_{eq} / E_{gl} \right]_{S-H, age ad.} = \left\{ 1 + [A/70]^4 \right\} \cdot 10 / \theta^2 \quad (9)$$

for the domain $3^\circ < \theta < 30^\circ$

the **Simplified Glare Equation**

$$\left[L_{eq} / E_{gl} \right]_{simpl.} = 10 / \theta^3 + \left\{ 1 + [A/62,5]^4 \right\} \cdot 5 / \theta^2 \quad (10)$$

for the domain $0,1^\circ < \theta < 30^\circ$

the **General Glare Equation**

$$\left[L_{eq} / E_{gl} \right]_{gen.} = 10 / \theta^3 + \left[5 / \theta^2 + 0,1 \cdot p / \theta \right] \cdot \left\{ 1 + [A/62,5]^4 \right\} + 2,5 \cdot 10^{-3} \cdot p \quad (11)$$

for the domain $0,1^\circ < \theta < 100^\circ$

In all these three versions of the disability glare equation the glare angle θ is expressed in degrees, the age A in years, whereas the pigmentation factor p ranges from 0 for very dark eyes, via 0,5 for brown eyes and 1,0 for blue-green eyes up to 1,2 for blue eyes. The equivalent

veiling luminance L_{eq} is expressed in cd/m^2 and the glare intensity E_{gl} in lux at the place of the pupil. Consequently, L_{eq}/E_{gl} reads in sr^{-1} .

8. DISCUSSION

By opting for three versions an attempt was made to avoid needless complexity and to maintain maximum adherence to existing practice. As an example one may take a rather common situation of glare by street lighting. Then, the use of equ. (9) is justified since, for $\theta > 30^\circ$ street lights will be shielded from sight by the limits of the wind screen, whereas for $\theta < 3^\circ$ street lights will usually be shielded from sight by the cut off of the luminaires.

For a street light with lateral intensity I [cd] positioned at R m remote from the line of sight, the inverse quadratic attenuation law reads

$$E_{gl} = I \cdot [(\pi \cdot \theta) / (180 \cdot R)]^2 = 0,0003 \cdot I \cdot (\theta / R)^2$$

so that, with equ. (9),

$$L_{eq} = 0,003 \cdot \frac{I}{R^2} \cdot [1 + (A/70)^4]$$

i.e. independent of θ . That means that, for a row of N of these lights, parallel to the line of sight, one can just add their candlepowers to calculate their joint equivalent veiling glare:

$$L_{eq} = 0,003 \cdot N \cdot \frac{I}{R^2} \cdot [1 + (A/70)^4]$$

This derivation illustrates the ease of using the most simple version, the Age Adapted Stiles-Holladay equation, and yet have the age factor included. The latter is of particular importance, now there seems to be consensus that lighting installations should be tuned to the need of the aged, rather than the habitual young adult.

Returning to the frame of reference formulated by CIE and reproduced in the Introduction, it is concluded

that a revision of the Stiles-Holladay formula is proposed in the sense that a choice of three revisions is given, depending on the angular domain of application;

that it is recommended to grant them all CIE observer status and to specify the most simple one by 'Stiles-Holladay, age adapted' in honor of the founding fathers; and to specify the next two by 'Simplified' and 'General', respectively;

that, in view of all presently available evidence, a special further study on the relation between glare and age has no high priority anymore from the point of view of illuminating engineering;

that, in view of the necessarily a bit speculative character of the glare function beyond about 30° further studies are recommended of the glare function in the large angle domain.

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CIE 135/2 - 1999

Research Note

Note: This report was prepared by J. Schanda, the chairman of TC1-33 Colour rendering as a chairman's report to archive the materials of discussions to develop a new CIE colour rendering index. Unfortunately the committee could not reach to a final conclusion and closed. It was regarded that the discussions in the committee achieved valuable results and should be documented for the future discussions on this subject. Division 1 therefore decided to publish the report with the suggestions of the referees who reviewed the report.

COLOUR RENDERING, CIE TC 1-33 CLOSING REMARKS*J Schanda,*

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COLOUR RENDERING, CIE TC 1-33 CLOSING REMARKS**SUMMARY**

The CIE "Test method to calculate a colour rendering index" has a long and complicated history. After first publishing a method in 1965 and updating it in 1974, it was soon realised that further amendments would be necessary. A TC worked on the subject in the 1980s, but had to be closed without any definite recommendation due to disagreements among the TC Members. A second trial was started after the 1991 Quadrennial Meeting. This TC worked – under various chairmen – for about six years, but again it had to be closed without producing a definite recommendation, although this time TC Members agreed in a number of questions.

This report summarizes those items where TC Members could agree and highlights also those questions where no consensus could be reached. To the latter category two groups of questions belong: items where it is hoped that CIE will come up very soon with further recommendations that should be incorporated in a colour rendering calculation (e.g. new chromatic adaptation transformation) and items where a political decision of the lamp manufacturers is needed, as a change in the calculation method necessarily will favour one lamp spectrum compared to that of another.

The present closing remarks document summarizes the items discussed by the TC during the past decade, states those items where a consensus could be formed and pinpoints questions where further research is needed to reach consensus.

RENDU DES COULEURS, CIE TC 1-33 REMARQUES FINALES**RESUME**

La "Méthode de calcul d'un indice de rendu des couleurs" CIE, possède une histoire longue et complexe. Après qu'une méthode ait été publiée d'abord en 1965, et mise à jour en 1974, il apparut rapidement que de nouvelles modifications seraient nécessaires. Un comité technique travailla sur le sujet dans les années 1980, mais dut être arrêté sans conclusions nettes du fait de désaccords parmi les membres du comité. Une deuxième tentative débuta après la réunion plénière de la CIE en 1991. Ce comité technique travailla avec divers présidents - pendant six ans environ, mais dut s'arrêter de nouveau sans arriver à une recommandation précise, bien que les membres du comité se soient, cette fois, accordés sur nombre de points.

Ce rapport résume les sujets sur lesquels les membres du comité pourraient réaliser un accord et met également en vedette ceux sur lesquels aucun consensus ne pourrait être obtenu. A cette dernière catégorie appartiennent deux groupes de sujets: ceux pour lesquels on espère que la CIE établira très rapidement de nouvelles recommandations qui pourraient être introduites dans un calcul de rendu de couleur (par exemple une nouvelle transformation d'adaptation chromatique) et ceux pour lesquels une décision politique des fabricants de

lampes est nécessaire, car un changement dans la méthode de calcul favorisera nécessairement un certain spectre de lampe au détriment d'un autre.

Le document de remarques finales actuel résume les sujets discutés par le comité technique durant la dernière décennie, établit les sujets pour lesquels un accord pourrait être trouvé et souligne les questions pour lesquelles de nouvelles investigations sont nécessaires afin d'atteindre un consensus.

FARBWIEDERGABE, CIE TC 1-33 SCHLUSSBEMERKUNGEN

ZUSAMMENFASSUNG

Die CIE "Test-Methode zur Berechnung des Farbwiedergabe-Index" hat eine lange und komplizierte Geschichte. Nach der ersten Veröffentlichung in 1965 und einer neuen in 1974 wurde bald erkannt, daß weitere Ergänzungen notwendig sind. Ein Technisches Komitee (TC) hat auf diesem Gebiet in der 80er Jahren gearbeitet, mußte jedoch ohne konkrete Empfehlung geschlossen werden, da sehr unterschiedliche Meinungen unter den TC-Mitgliedern bestanden.

Ein zweiter Versuch wurde nach der CIE-Tagung 1991 gestartet. Dieses TC arbeitete unter verschiedenen Vorsitzenden während 6 Jahren, und erneut mußte es ohne konkrete Ergebnisse geschlossen werden, obwohl die TC-Mitglieder sich in einigen Punkten einigen konnten. Der vorliegende Bericht zählt die Punkte auf, worüber unter den TC-Mitgliedern Einigung erzielt wurde, und nennt die Punkte, für die eine Einigung nicht erzielt werden konnte. Zur letzten Gruppe gehören zwei Probleme: Gebiete, wo die CIE sehr bald Empfehlungen verabschieden wird, die in die Berechnung des Farbwiedergabe-Index einfließen (z. B. neue Farbumstimmungstransformation) und Empfehlungen, wo eine politische Entscheidung der Lampenhersteller notwendig ist. Eine Änderung der Berechnungsmethode wird notwendigerweise ein Lampenspektrum, verglichen mit einem anderen, bevorzugen.

Die gegenwärtigen Schlußbemerkungen fassen die Punkte zusammen, die in der letzten Dekade im TC diskutiert wurden. Sie benennen solche Punkte, die eine Übereinstimmung erlauben, und heben die Punkte hervor, wo eine zusätzliche Forschung notwendig ist, um eine Übereinstimmung zu erreichen.

1. INTRODUCTION

Colour rendering of an illuminant is the effect of the illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant (see [i]). The CIE standardised a method of colour rendering index calculation based on test samples in 1965 [ii] and modified it slightly in 1974 [iii] (see also Appendix 1 for details of developing the CIE Test method to calculate a colour rendering index).

The CIE Test Method is a purely calculation method, no visual observations are needed in its application. In this method first a reference illuminant has to be selected. The colour appearance produced by using this reference illuminant will be the yardstick to which the colour appearance produced by the illumination with the test illuminant (or test lamp) will be compared. The selection of the reference illuminant is done by choosing a daylight or a blackbody illuminant whose correlated colour temperature equals that of the test lamp. If the test lamp has a correlated colour temperature above 5000 K, then a daylight illuminant is used; if it is below 5000 K, then a blackbody illuminant is used.

The CIE Test Method defines, as a next step, eight basic coloured test samples and six supplementary test samples. Tristimulus values for each test sample have to be calculated using the test lamp spectral power distribution and the reference illuminant spectral power distribution.

A von Kries chromatic adaptation transformation is used to bridge the difference between the test lamp and the reference illuminant chromaticities.

The final steps are the calculation of the colour difference between the tristimulus values obtained on each sample after the chromatic adaptation transformation has been

performed, illuminated once with the test lamp and then with the reference illuminant and the transformation of the colour differences into colour rendering indexes.

Since the introduction of the above calculation model, a number of new recommendations have been introduced. The two most important ones are the following:

- In 1976, two new colour spaces have been adopted: CIELAB and CIELUV [iv].
- In 1994, a new chromatic adaptation transformation has been introduced [v].

The Colorimetric Committee of the CIE soon realised this discrepancy and established a Technical Committee to deal with the question, under the chair of Ms. Halstead. The committee hoped, however, that better methods of chromatic adaptation transformation and colour appearance would soon be introduced, and decided to suspend its activity at the CIE Session in Venice (1987).

By the 1991 Quadrennial meeting, the colour appearance committee (TC 1-13) was closed, but a new committee was formed (TC 1-34) to monitor further progress on the subject. Two further TCs were formed on "Prediction of corresponding colours" (TC 1-32) and "Colour rendering" (TC 1-33), the latter under the chairmanship of Wolfgang Walter. It was assumed that this TC would develop a new method of determining colour rendering based on the work of the other two TCs. The Terms of Reference of TC 1-33 was formulated as

"Study indices for evaluation of colour rendering properties of light sources based on a colour appearance model. Prepare a report on a proposed method that will replace CIE Publication No. 13.2. (This report has the potential to become a standard.)"

Due to the fact that the progress of the colour appearance committee slowed down, later the second sentence of the Terms of Reference of TC 1-33 was changed to:

"Prepare a technical report on a proposed method that will replace CIE publication 13.2, this model shall be consistent with all the official recommendations on colorimetry."

In 1994, the chairman had to resign due to a new job engagement, and the author of the present report was asked to take over.

2. WORK OF TC 1-33

2.1 Test samples

The CIE Test Method [iii] used 8 + 6 Munsell test samples; these are not available anymore². Although the method can be used by purely mathematical methods, the committee thought that it would be advantageous to be able to test the results by visual inspection of real samples. Based on a world-wide inquiry the TC came to the conclusion that the original Munsell Test Samples do not cover the colour gamut sufficiently and opted for the nowadays readily available set of Macbeth ColorChecker test samples [vi]. This is a set of 18 coloured and six achromatic samples used in photography. The committee selected eight samples of this set and for the very important skin tones agreed on a typical Caucasian and Oriental complexion reflectance spectra. (The ColorChecker skin tone samples are metameric to real skin spectra and it was felt that it would be better to use real human complexion spectra).

Figure 1 shows the chromaticities of the eight ColorChecker samples and of the two complexion colours in an a^*, b^* diagram for D65 illumination. Test Sample Numbers (TCS) are shown followed by the L^* value of the sample. As seen the chromatic samples span a reasonable surface in a^*, b^* . Table 1 tabulates the Test Colour Samples, their equivalent Macbeth ColorChecker numbers and approximate Munsell notations. Appendix 2 contains the spectral radiance factors of the samples. The TC accepted the change from the original Munsell samples to the ColorChecker plus complexion colours, and subsequent drafts used these test sample spectra.

² The Bundesanstalt für Materialprüfung (BAM) produces test samples since 1978 up to now and sells complete test colour sets with their spectral and colorimetric measures.

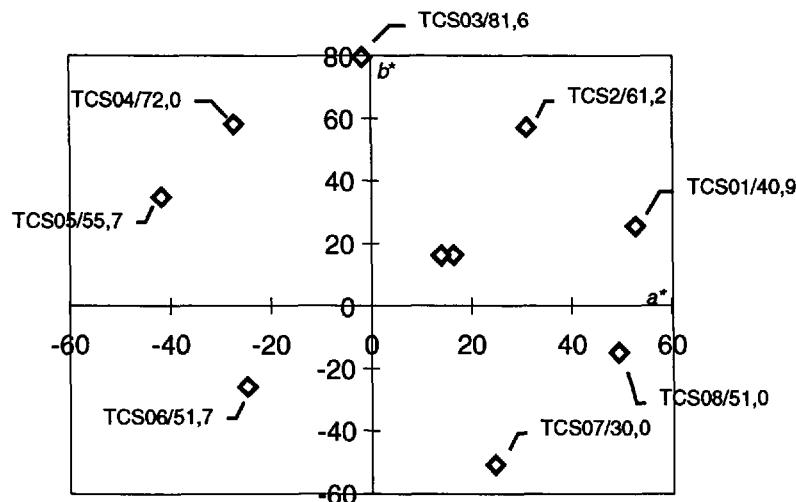


Fig. 1. $L^*a^*b^*$ values for Standard Illuminant D65 of the 10 test samples agreed by TC 1-33 to be used in colour rendering calculations.

Table 1. Test colour samples TCS01 to TCS10 recommended by TC 1-33.

TCS	Macbeth Color Checker No.	Munsell notation	TCS	Macbeth Color Checker No.	Munsell notation
TCS01	MCC 15	5.0R 4/12	TCS06	MCC 18	5.0B 5/8
TCS02	MCC 7	5.0YR 6/11	TCS07	MCC 13	7.5PB 2.90/12.75
TCS03	MCC 16	5.0Y 8/11.1	TCS08	MCC 17	2.5RP 5/12
TCS04	MCC 11	5.0GY 7.08/9.1	TCS09	Caucasian skin colour	
TCS05	MCC 14	0.1G 5.38/9.65	TCS10	Oriental skin colour	

2.2 Reference illuminant

The next problem the committee was faced with was the question of what reference illuminant should be used. The traditional system uses the concept of correlated colour temperature to select the reference illuminant. But the correlated colour temperature concept is based on the now outdated CIE 1960 UCS u, v diagram, by stating that the correlated colour temperature has to be calculated by finding the smallest chromaticity difference between the test lamp locus and a Planckian radiator on the $u', 2v/3$ diagram (the 1960 v co-ordinate value is the same as the $2v/3$ values). It was felt that a new colour space should be used for this purpose. This is an interesting item of competence: some members in TC 1-33 thought that this should be the subject of a TC dealing with colour per se, as e.g. TC 1-48. While in the colorimetric committee (CIE TC 1-48) members were of the opinion that in colorimetry itself the concept of correlated colour temperature is not needed, application TCs (e.g. TC 1-33) should deal with its definition.

First, the committee agreed to abandon the concept of equal correlated colour temperature between test and reference illuminant completely and suggested to use one of those target chromaticities IEC (International Electrotechnical Commission) is using in defining the target chromaticities for fluorescent lamps [vii] and high pressure discharge lamps [viii]. Six reference illuminants were selected. The fundamental idea behind this was that by providing such a choice, one could abandon the concept of correlated colour temperature completely, and could use that reference illuminant whose chromaticity lies nearest to the chromaticity of the test lamp in CIELAB space. It was hoped that by using the new CIE chromatic adaptation formula, the problem could be solved. Some of the TC Members were of the opinion that in practical illuminating engineering, it is more appropriate to use one of these target illuminants, because in preparing the design, this has to be specified, and the actual source has to be compared to one of these targets.

Table 2. Illuminants, their correlated colour temperature and chromaticity co-ordinates first recommended as reference illuminants.

Illuminant	(correlated) colour temperature	chromaticity co-ordinates	
		x_R	y_R
D65 CIE daylight	6500K	0,3128	0,3292
D50 CIE daylight	5000K	0,3457	0,3586
P4200 black-body	4200K	0,3720	0,3714
P3450 black-body	3450K	0,4081	0,3921
P2950 black-body	2950K	0,4405	0,4053
P2700 black-body	2700K	0,4599	0,4106

Unfortunately, later some other TC Members objected to this solution as it gave slightly lower colour rendering indices for some of the lamps they produced, compared to a method when the reference illuminant had the same correlated colour temperature as the test source.

Thus alternative methods were considered to enable the exclusion of the outdated uv-chromaticity diagram in calculating the correlated colour temperature of the reference illuminant. One possibility was to use the u',v' -chromaticity chart, the other to calculate the smallest colour difference between test lamp and reference illuminant in CIELAB space.

The views of the committee members differed on this item so gravely that this was one issue where no consensus for a new method could be obtained.

2.3 Chromatic adaptation

Since, in 1994, the CIE introduced a new chromatic adaptation transformation formula [v], the use of this formula for colour rendering was recommended. Both from test lamp chromaticity and from reference illuminant chromaticity transformation into a D65 based colour space was suggested, as the CIELAB space has been most thoroughly tested under D65 illumination. The CIE chromatic adaptation formula described in CIE 109 – 1994 uses two parameters: depending on the illumination level under which the experiments are performed. The TC recommended the use of 1000 lux, and to select as a parameter depending on the reflection factor of the background, the value of 0,20. Since suspending the work of TC 1-33, CIE published a colour appearance model [ix] that contains the so called “Bradford-transformation” to cope with chromatic adaptation applications. Thus should the colour rendering work be continued, this transformation could be applied.

2.4 Colour difference calculation

TC Members generally agreed that in a new method, CIELAB space should be used to calculate colour difference between the Test Colour Samples illuminated once by the test lamp and then by the reference illuminant, both transformed to D65 illuminant by the chromatic adaptation transformation mentioned in the previous paragraph.

It was discussed in the committee whether one should apply the ΔE_{94} formula [x] or not, but it was felt that the colour differences in colour rendering calculations are larger than the colour differences for which the ΔE_{94} formula was designed.

2.5 Colour rendering indices

The second item where it was impossible to find a compromise among the opinion of the committee members was the calculation of the colour rendering indices (R_i) from the colour differences. Some members argued for a linear relationship, as in the current method, some others would have favoured a method where one special colour rendering index would result in large values that would put some lamps at a disadvantage. The majority of members voted for the use of an inverse linear relationship between ΔE_i and R_i , similarly to the current method:

$$R_i = 100 - c \cdot \Delta E_i^* \quad (1)$$

The general colour rendering index would then be calculated as the arithmetic mean of the 10 special colour rendering indices:

$$R96_a = \frac{1}{10} \sum_{i=1}^{10} R96_i \quad (2)$$

Much discussion evolved on determining the constant c in equation 1. In the original CIE publication [ii], the transition was made in such a form that the warm white fluorescent lamp had a general colour rendering index of 50. In the current method [iii], this value shifted to 51. Thus one alternative considered by the committee was to select the constant c in such a form that the warm white fluorescent lamp shall again have an R_a value of 50 to 51.

An other alternative was not to keep the R_a value of the warm white fluorescent lamp constant, but to keep the average of a large number of present day popular lamp R_a values constant. The committee asked National Committees and major lamp manufacturers to supply representative spectra. Based on the 107 spectra received, the chairman calculated the c value that would keep the average of the R_a values of these lamps constant.

For the method, where the six IEC target chromaticities were used as reference illuminants, the calculation resulted in*:

$$c(R96_a(c)) = 3,248 \quad (3)$$

when the nearest daylight/black-body chromaticity in CIELAB space is used:

$$c(R96(TCC/LAB)_a) = 3,032 \quad (4)$$

Figure 2 compares the different methods: As seen the major trend is similar, there are only a very few lamps where the two methods provide significantly different results.

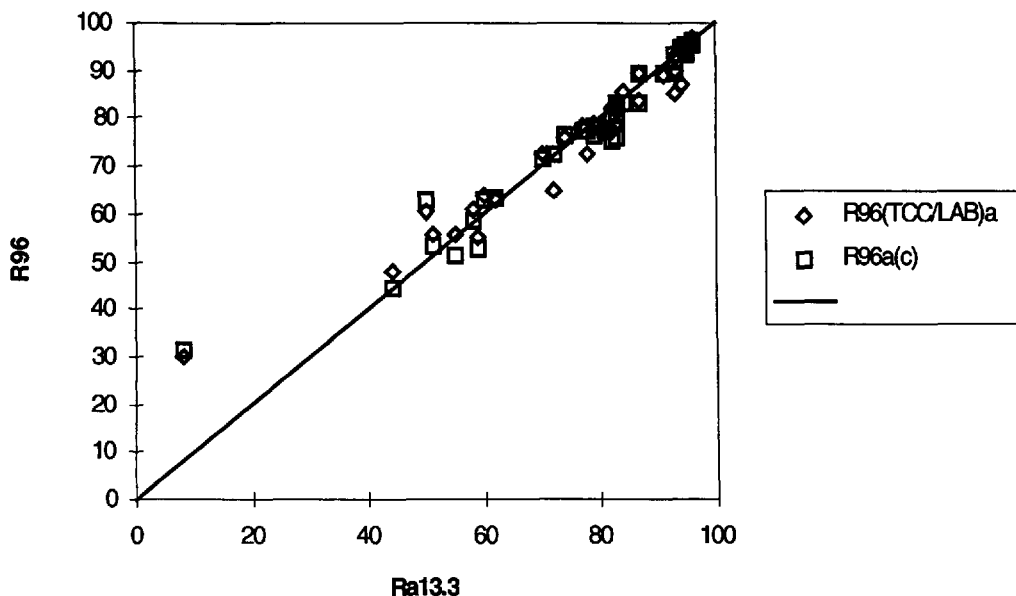


Figure 2. Correlation chart depicting the $R_a(96)$ values.

A further question - more of a political nature than of technical character - was whether all 107 spectral power distributions submitted by the National Committees should be used in determining the constant c , or only lamps with the highest colour rendering index, i.e. lamps with $R_a(13.3)$ higher than 85 should be considered.

* To distinguish among the different R_a values the following labels were used:
 $R96_a(c)$ denotes the R_a value calculated using the IEC target reference chromaticities;
 $R96(TCC/LAB)$ denotes the R_a value calculated using the reference illuminant in CIELAB space;
 $R_a(13.3)$ denotes the R_a value calculated using the current method.

Between 1994 and 1997 seven drafts were prepared, subsequently modifying the text according to the majority view of the TC. During these three years CIE Division 1 was able to achieve major progress in the field of colour appearance and chromatic adaptation transformation [ix]. Thus Division 1 felt at its meeting in Kyoto in 1997 that it would be more appropriate to consider a new start of the work, and close TC 1-33 with a chairman's report. This has now been accomplished.

3. SUMMARY

In summarising the conclusions the TC reached during its work – mainly between 1994 and 1997 – and to give some guidance for a subsequent TC, we would like to provide the following for consideration.

3.1 Flow chart of the new calculation method

A possible complete flow chart of a new colour rendering calculation method could be as seen in figure 3. The single steps could be the following:

- As mentioned previously first the reference illuminant has to be selected, and this is done in CIELAB space or using only the 6 reference illuminants.
- The eight ColorChecker and two complexion colours are then illuminated by the two sources. Chromaticity co-ordinates and Y values are calculated for samples illuminated by the test lamp $(x, y, Y)_{i,T}$ and by the reference illuminant $(x, y, Y)_{i,R}$.
- Chromatic adaptation (based on a new CIE recommendation) is then applied for both sets of data transforming them to D65 illuminant adaptation. All further calculations are performed in D65 adapted space, as it is thought that the CIELAB space is most equidistant under D65 conditions, and most tests of CIELAB were performed under D65 illumination.
- Accordingly for further calculations the $(x, y, Y)_{i,R}$ and $(x, y, Y)_{i,T}$ values are transformed into CIELAB space.
- Colour differences between the two sample sets of equal i values are then calculated.
- The final step is the determination of the R_i values and from the 10 R_i values to conclude on a general colour rendering index (R_a). The constant c coupling ΔE_i to R_i has to be chosen according to some non-technical decision.

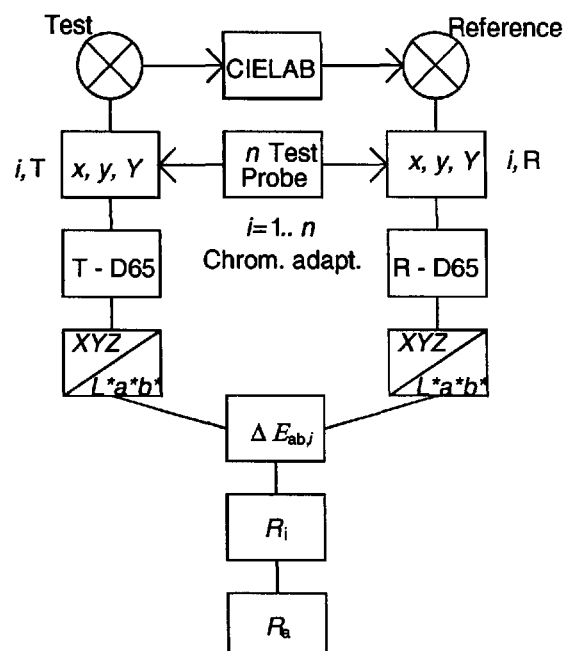


Figure 3. Flow chart of a possible colour rendering calculation.

Actually one could state that CIE TC 1-33 concluded its technical task. The method of colour rendering calculation has been modernised, all outdated colorimetric methods have been eliminated. The calculation method

- is based now on a better colour space, and thus it could also be used in selecting the reference illuminant;
- uses test samples readily available for eventual visual checking;
- could use the best recommended chromatic adaptation formula.

The two outstanding questions that produced a dead-lock in the work of the TC are more of a political nature than of technical character:

- Selection of the six IEC target chromaticities or a continuous set of daylight/black-body reference illuminants (advantage of adhering to target lamp-light chromaticities versus somewhat higher colour rendering indices if the lamp chromaticity is further away from the IEC target chromaticity). This will influence also the selection of constant c .
- Selection of those lamp spectra on which the transition from the old system to the new system should be based.

It is sincerely hoped that a follow up Technical Committee will be able to solve the above questions, perhaps including further steps of a colour appearance model. In the meantime may we recommend to experiment with the above described method and compare the calculated values with visual experiments. This is the correct way to choose among the different options colorimetry provides.

APPENDIX 1.

INTRODUCTION AND PARTIAL BIBLIOGRAPHY TO THE 1ST DRAFT OF TC 1-33, 1994.METHOD OF MEASURING AND SPECIFYING COLOUR RENDERING PROPERTIES OF
LIGHT SOURCES - NEW METHOD

CIE TC 1-33

0-1 DRAFT, 1994-08-18

I. PREFACE

The CIE recommended in 1948 an eight band method to calculate the colour rendering of light sources [1]. In 1951 the CIE requested National Committees (NCs) to further investigate the question of colour rendering of light sources [2] and established a Technical Committee (TC) for this purpose in 1955 [3].

The scope of this Committee was [4]:

"To establish methods of measuring and specifying the colour rendering and colour matching properties of light sources".

Based on the work of J. L. OUWELTJES [5], D. NICKERSON [6], W. MÜNCH and K. SCHULTZ [7] as well as of I. HENNICKE [8], the committee decided to use eight test colour samples and to evaluate colour rendering by comparing the colour of these samples when illuminated by the test source and a reference source. As a reference source, a Planckian or daylight radiator of equal correlated colour temperature was chosen. The following Munsell samples were selected.

7,5	R 6/4	5	YR 8/4
5	Y 6/4	5	GY 4/4
5	GY 6/8	5	Y 8/10
2,5	G 6/6	4,5	G 5/8
10	BG 6/4*	3	PB 3/11
5	PB 6/8	4,5	R 4/13
2,5	P 6/8	10	B 6/4
10	P 6/8	5	P 6/8

* Replacing 10 B6/4 which was originally proposed.

The first edition of the CIE recommended method of measuring and specifying colour rendering properties of light sources, based on a test colour sample method was published in 1965 [9] as CIE 13-1965.

In 1967 the Committee was entrusted [10] to prepare a second edition of publication 13, mainly to include a correction for the adaptive colour shift. This work was based on the experiments by OUWELTJES [11], and MÜNCH and SCHULTZ [12], and was done by applying a VON KRIES type transformation with a reference stimulus given by JUDD [13]. It was pointed out that even this corrected form of colour rendering calculation was applicable only when the colour difference between the test and the reference lamp was not too large.

Comments regarding the meaning of the *Colour Rendering Indices* were added, dealing with the uncertainties in the determination of R , influences of test conditions, just perceptible differences in terms of R and interchangeability of lamps with regard to their colour rendering properties.

Also a footnote regarding T_C was added. This footnote concerns the definition of T_C given in the International Lighting Vocabulary [14].

Moreover, the Committee stated that it was desirable to obtain an improved method for allowing for chromatic adaptation which could apply to illuminants having large chromaticity differences between them, but this would necessitate more knowledge about chromatic adaptation.

Some further amendments compared to CIE 13-1965 were also undertaken, bringing the document in line with CIE's fundamental publication on colour [15].

The 2nd edition of CIE 13 was published in 1974 [16]. Several reprints of this recommendation were published during the past twenty years, correcting misprints in tables and equations.

In 1994 the CIE published as a Technical Report an updated version of CIE 13.2 - 1974 as CIE 13.3 - 1994 [17] with unchanged technical content. The CIE Central Bureau provided also two application software programs on a disk.

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APPENDIX 2.

Spectral radiance factor $\beta_i(\lambda)$ of Test colour samples selected by TC 1-33.

TCS MacBeth λ/nm	TCS01 MCC15 Red	TCS02 MCC7 Orang	TCS03 MCC16 Yellow	TCS04 MCC11 Yellow Green	TCS05 MCC14 Green	TCS06 MCC18 Cyan	TCS07 MCC13 Blue	TCS08 MCC17 Magenta	TCS09 .Cauc. skin	TCS10 .Orient. skin
380	0,052	0,053	0,054	0,056	0,055	0,093	0,069	0,118	0,200	0,131
385	0,052	0,054	0,053	0,058	0,056	0,110	0,081	0,142	0,214	0,139
390	0,052	0,054	0,054	0,059	0,057	0,134	0,096	0,179	0,226	0,147
395	0,052	0,054	0,053	0,059	0,058	0,164	0,114	0,228	0,235	0,153
400	0,051	0,054	0,053	0,060	0,058	0,195	0,136	0,283	0,240	0,158
405	0,051	0,054	0,053	0,061	0,058	0,220	0,156	0,322	0,240	0,162
410	0,050	0,053	0,053	0,061	0,059	0,238	0,175	0,343	0,238	0,164
415	0,050	0,053	0,052	0,061	0,059	0,249	0,193	0,354	0,233	0,167
420	0,049	0,052	0,052	0,062	0,059	0,258	0,208	0,359	0,224	0,170
425	0,049	0,052	0,052	0,063	0,060	0,270	0,224	0,357	0,208	0,175
430	0,049	0,052	0,053	0,064	0,062	0,281	0,244	0,350	0,207	0,182
435	0,049	0,052	0,053	0,066	0,063	0,296	0,265	0,339	0,199	0,192
440	0,049	0,052	0,053	0,068	0,065	0,315	0,290	0,327	0,207	0,203
445	0,049	0,052	0,054	0,071	0,067	0,334	0,316	0,313	0,247	0,212
450	0,049	0,052	0,055	0,075	0,070	0,352	0,335	0,298	0,266	0,221
455	0,048	0,052	0,056	0,079	0,074	0,370	0,342	0,282	0,278	0,229
460	0,048	0,052	0,059	0,085	0,078	0,391	0,338	0,267	0,291	0,236
465	0,047	0,052	0,065	0,093	0,084	0,414	0,324	0,253	0,306	0,243
470	0,047	0,053	0,075	0,104	0,091	0,434	0,302	0,239	0,315	0,249
475	0,046	0,054	0,093	0,118	0,101	0,449	0,273	0,225	0,327	0,254
480	0,045	0,055	0,121	0,135	0,113	0,458	0,239	0,209	0,334	0,259
485	0,045	0,056	0,157	0,157	0,125	0,461	0,205	0,195	0,344	0,264
490	0,044	0,057	0,202	0,185	0,140	0,457	0,172	0,182	0,354	0,269
495	0,044	0,059	0,252	0,221	0,157	0,447	0,144	0,172	0,361	0,276
500	0,044	0,061	0,303	0,269	0,180	0,433	0,120	0,163	0,372	0,284
505	0,044	0,064	0,351	0,326	0,208	0,414	0,101	0,155	0,378	0,291
510	0,044	0,068	0,394	0,384	0,244	0,392	0,086	0,146	0,386	0,296
515	0,044	0,076	0,436	0,440	0,286	0,366	0,074	0,135	0,382	0,298
520	0,044	0,086	0,475	0,484	0,324	0,339	0,066	0,124	0,372	0,296
525	0,044	0,101	0,512	0,516	0,351	0,310	0,059	0,113	0,357	0,289
530	0,044	0,120	0,544	0,534	0,363	0,282	0,054	0,106	0,337	0,282
535	0,044	0,143	0,572	0,542	0,363	0,255	0,051	0,102	0,320	0,276
540	0,045	0,170	0,597	0,545	0,355	0,228	0,048	0,102	0,310	0,274
545	0,046	0,198	0,615	0,541	0,342	0,204	0,046	0,105	0,306	0,276
550	0,047	0,228	0,630	0,533	0,323	0,180	0,045	0,107	0,308	0,281
555	0,048	0,260	0,645	0,524	0,303	0,159	0,044	0,107	0,319	0,286
560	0,050	0,297	0,660	0,513	0,281	0,141	0,043	0,106	0,323	0,291
565	0,053	0,338	0,673	0,501	0,260	0,126	0,042	0,107	0,326	0,289
570	0,057	0,380	0,686	0,487	0,238	0,114	0,041	0,112	0,316	0,286
575	0,063	0,418	0,698	0,472	0,217	0,104	0,041	0,123	0,306	0,280
580	0,072	0,452	0,708	0,454	0,196	0,097	0,040	0,141	0,309	0,285
585	0,086	0,481	0,718	0,436	0,177	0,092	0,040	0,166	0,348	0,314
590	0,109	0,503	0,726	0,416	0,158	0,088	0,040	0,198	0,406	0,354
595	0,143	0,520	0,732	0,394	0,140	0,083	0,040	0,235	0,471	0,398

Appendix 2 cont.

TCS	TCS01	TCS02	TCS03	TCS04	TCS05	TCS06	TCS07	TCS08	TCS09	TCS10
MacBeth	MCC15	MCC7	MCC16	MCC11	MCC14	MCC18	MCC13	MCC17	.	.
λ/nm	Red	Orang	Yellow	Yellow Green	Green	Cyan	Blue	Magenta	Cauc. skin	Orient. skin
600	0,192	0,532	0,737	0,374	0,124	0,080	0,039	0,279	0,529	0,440
605	0,256	0,543	0,742	0,358	0,111	0,077	0,039	0,333	0,577	0,470
610	0,332	0,552	0,746	0,346	0,101	0,075	0,040	0,394	0,617	0,494
615	0,413	0,560	0,749	0,337	0,094	0,074	0,040	0,460	0,644	0,511
620	0,486	0,566	0,753	0,331	0,089	0,073	0,040	0,522	0,671	0,524
625	0,550	0,572	0,757	0,328	0,086	0,073	0,040	0,580	0,687	0,535
630	0,598	0,578	0,761	0,325	0,084	0,073	0,041	0,628	0,701	0,544
635	0,631	0,583	0,765	0,322	0,082	0,073	0,041	0,666	0,709	0,552
640	0,654	0,587	0,768	0,320	0,080	0,073	0,042	0,696	0,722	0,559
645	0,672	0,593	0,772	0,319	0,078	0,073	0,042	0,722	0,727	0,565
650	0,686	0,599	0,777	0,319	0,077	0,074	0,042	0,742	0,743	0,571
655	0,694	0,602	0,779	0,320	0,076	0,075	0,043	0,756	0,739	0,576
660	0,700	0,604	0,780	0,324	0,075	0,076	0,043	0,766	0,747	0,581
665	0,704	0,606	0,780	0,330	0,075	0,076	0,043	0,774	0,748	0,586
670	0,707	0,608	0,781	0,337	0,075	0,077	0,044	0,780	0,750	0,590
675	0,712	0,611	0,782	0,345	0,077	0,076	0,044	0,785	0,754	0,594
680	0,718	0,615	0,785	0,354	0,078	0,075	0,044	0,791	0,761	0,599
685	0,721	0,619	0,785	0,362	0,080	0,074	0,044	0,794	0,768	0,603
690	0,724	0,622	0,787	0,368	0,082	0,074	0,045	0,798	0,776	0,606
695	0,727	0,625	0,789	0,375	0,085	0,073	0,046	0,801	0,785	0,610
700	0,729	0,628	0,792	0,379	0,088	0,072	0,048	0,804	0,790	0,612
705	0,730	0,630	0,792	0,381	0,089	0,072	0,050	0,806	0,795	0,614
710	0,730	0,633	0,793	0,379	0,089	0,071	0,051	0,807	0,800	0,616
715	0,729	0,633	0,792	0,376	0,090	0,073	0,053	0,807	0,804	0,616
720	0,727	0,633	0,790	0,373	0,090	0,075	0,056	0,807	0,807	0,616
725	0,728	0,636	0,792	0,372	0,090	0,078	0,060	0,810	0,811	0,616
730	0,729	0,637	0,792	0,375	0,089	0,082	0,064	0,813	0,812	0,615
735	0,729	0,639	0,790	0,382	0,092	0,090	0,070	0,814	0,813	0,613
740	0,727	0,638	0,787	0,392	0,094	0,100	0,079	0,813	0,814	0,612
745	0,723	0,633	0,782	0,401	0,097	0,116	0,091	0,810	0,815	0,610
750	0,721	0,633	0,778	0,412	0,102	0,133	0,104	0,808	0,816	0,609
755	0,724	0,636	0,780	0,422	0,106	0,154	0,120	0,811	0,817	0,608
760	0,728	0,641	0,782	0,433	0,110	0,176	0,138	0,814	0,818	0,607
765	0,727	0,639	0,781	0,436	0,111	0,191	0,154	0,813	0,818	0,607
770	0,702	0,616	0,752	0,426	0,112	0,200	0,168	0,785	0,818	0,609
775	0,680	0,598	0,728	0,413	0,112	0,208	0,186	0,765	0,819	0,610
780	0,664	0,582	0,710	0,404	0,112	0,214	0,204	0,752	0,819	0,611

Note: All the data of spectral radiance factors are rounded to the 3rd decimal places from the original data [CS McCamy, H Marcus, JG Davidson, A Color Rendition Chart. *Jr. Photographic Engng.* 2 (1976), pp. 95-99; No. 3.] including the 4th decimal places.

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