



International Commission on Illumination
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TECHNICAL REPORT

CIE 2017 Colour Fidelity Index for accurate scientific use

CIE 224:2017

UDC: 159.937.51
535.67
612.843.31
535.66

Descriptor: Perception of colour
Colour of objects
Colour vision
Colorimetry

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5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

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This Technical Report has been prepared by CIE Technical Committee 1-90 of Division 1 "Vision and Colour" and has been approved by the Board of Administration as well as by Division 1 of the Commission Internationale de l'Eclairage. 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.

Ce rapport technique a été élaboré par le Comité Technique CIE 1-90 de la Division 1 "Vision et Couleur" et a été approuvé par le Bureau et Division 1 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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CIE 2017 COLOUR FIDELITY INDEX FOR ACCURATE SCIENTIFIC USE

Summary

The CIE Colour Rendering Index (CRI), defined in CIE 13.3-1995, in particular the general colour rendering index, R_a , is widely adopted and used by the lighting industry, in regulatory documents and in international and regional standards and specifications. However, limitations of the CRI have been recently addressed, especially for solid-state light sources, whereby the R_a values do not always correlate well with visual evaluation by general users. This mismatch arises, first, from inaccuracies of the CRI in its intended role as a colour fidelity index; and second, from perception-related colour quality effects beyond colour fidelity. It was determined by the CIE that, for both aspects, better colour quality characterization methods are needed to measure and specify white-light sources, and the work was divided into two corresponding tasks: (1) to develop a scientifically accurate colour fidelity index, assigned to TC 1-90, and (2) to develop one or more perception-related colour quality measures beyond fidelity, assigned to TC 1-91 for initial work.

This Technical Report, developed by TC 1-90, is a research report describing a general colour fidelity index, R_f , as a scientifically accurate measure of colour fidelity with respect to a reference illuminant, although there still remain some technical issues for further research. This colour fidelity index, based on the fidelity index of the Illuminating Engineering Society of North America, defined in TM-30-15, addresses aspects for only the first part of the limitations of the CRI – it does not address the need for perception-related colour quality measure(s) beyond fidelity. However, it does correct several previously reported inaccuracies of the CRI as a colour fidelity measure. The important improvements of this measure, relative to the CRI, are the update of the colour difference calculation, in particular the object colour space, and the incorporation of 99 test-colour samples which provide a more uniform distribution of slope and curvature values as a function of wavelength and which have colour appearance values that are more widely and uniformly distributed in the three dimensions of a uniform colour space.

The general colour fidelity index, R_f , represents how closely the colour appearances of the entire sample set are reproduced (rendered) on average by a test light as compared to those under a reference illuminant. Thus, similar to the general colour rendering index, R_a , the general colour fidelity index, R_f , combines the computed colour differences for all test-colour samples in one single average index value, and is only one aspect of colour quality not considering perception/preference effects. Therefore, it is considered that such unintended uses of CRI as an overall colour quality measure for end users is not better fulfilled by the more scientifically accurate general colour fidelity index, R_f . This is because the users' evaluation is influenced by factors beyond colour fidelity such as chroma effects, and the detailed nature of specific illumination tasks. The general colour fidelity index, R_f , is therefore not a replacement of the general colour rendering index, R_a , neither for the purpose of rating and specification of products nor for regulatory or other minimum performance requirements. Replacement of the CRI will be a matter of future study and discussion that will include the evaluation of the general colour fidelity index, R_f , along with development of a harmonized set of new colour quality measures for assessing perception-related effects beyond colour fidelity and practical aspects for manufacturers and end-users.

INDICE DE FIDELITE DES COULEURS CIE 2017 POUR UN USAGE SCIENTIFIQUE PRECIS

Résumé

L'indice de rendu des couleurs de la CIE (IRC), défini dans la publication CIE 13.3-1995, et en particulier l'indice général de rendu des couleurs (R_a), est largement adopté et utilisé par l'industrie de l'éclairage, dans les réglementations et dans les normes nationales et internationales. Cependant, certaines limites de l'IRC ont été récemment soulignées. En particulier, les valeurs de R_a ne correspondent pas toujours à l'évaluation visuelle des observateurs pour les sources à base de semi-conducteurs. Ce décalage provient,

premièrement des imperfections de l'IRC dans son rôle attendu d'indice de fidélité des couleurs et deuxièmement, d'effets liés à la perception de la qualité des couleurs qui ne sont pas pris en compte et qui sont plus vastes que la seule notion de fidélité des couleurs.

Sur ces deux aspects, la CIE a suggéré de développer, de meilleures méthodes de caractérisation de la qualité des couleurs pour mesurer et spécifier les sources de lumière blanche. Pour ce faire, le travail a été divisé en deux tâches : (1) développer un indice de fidélité des couleurs scientifiquement précis (attribué au comité technique TC 1-90), et (2) développer une ou plusieurs mesures de la perception de la qualité des couleurs au-delà de la fidélité (attribué au comité technique TC 1-91).

Ce Rapport Technique, développé par le comité technique TC 1-90, est un rapport de recherche décrivant un indice général de fidélité des couleurs (R_f) par rapport à un illuminant de référence. Bien que certains problèmes techniques requièrent encore de plus amples recherches, cette mesure de la fidélité des couleurs est scientifiquement précise. Cet indice, basé sur l'indice de fidélité TM-30-15 développé par Illuminating Engineering Society of North America, répond à la première partie des limites de l'IRC (il ne couvre pas le besoin de mesure de la qualité des couleurs autre que la fidélité) et corrige plusieurs imprécisions de l'IRC (R_a) en tant que mesure de la fidélité des couleurs. Les améliorations les plus importantes par rapport à l'IRC sont la mise à jour de la méthode de calcul des différences de couleur, en utilisant en particulier un espace de couleur uniforme, et l'introduction de 99 échantillons colorés ayant une répartition plus uniforme des pentes et des courbures en fonction de la longueur d'onde et étant plus largement et uniformément répartis dans les trois dimensions de cet espace de couleur uniforme.

L'indice général (R_f) représente à quel point les apparences des couleurs de l'ensemble de la collection sont en moyenne reproduites (rendues) sous une source test par rapport à leurs apparences sous un illuminant de référence. Ainsi R_f , comme R_a , combine les différences de couleurs calculées pour chaque échantillon de couleur en une valeur moyenne unique. Il traite seulement d'un aspect de la qualité des couleurs et ne prend pas en compte les effets liés à la perception/préférence. Par conséquent, des utilisations fortuites de l'IRC comme une mesure globale de la qualité des couleurs ne seront pas mieux remplies par l'indice de fidélité des couleurs scientifiquement précis, R_f . En effet, l'évaluation des utilisateurs est influencée par des facteurs plus vaste que la fidélité des couleurs tels que les effets de saturation des couleurs ou l'influence de la nature des tâches à effectuer. L'indice général de fidélité des couleurs R_f ne se substitue pas à l'IRC pour classer ou spécifier les produits ni pour répondre aux exigences minimales de performances réglementaires. Le remplacement de l'IRC sera matière à des études et des discussions futures qui devront évaluer R_f ainsi que l'ensemble de nouvelles mesures de la qualité des couleurs et proposer des recommandations pratiques pour les produits manufacturés et les utilisateurs finaux.

CIE 2017 FARBTREUEINDEX FÜR GENAUE WISSENSCHAFTLICHE ANWENDUNG

Zusammenfassung

Der Farbwiedergabeindex CRI (Colour Rendering Index) der CIE, definiert in CIE 13.3-1995 (CIE 1995), speziell der allgemeine Farbwiedergabeindex, R_a , ist weitestgehend angenommen und wird von der Beleuchtungsindustrie, in Vorschriften sowie in internationalen und regionalen Standards und Spezifikationen verwendet. Jedoch wurden kürzlich Grenzen des CRI dahingehend aufgezeigt, dass speziell für Halbleiter-Lichtquellen die R_a -Werte nicht immer gut mit visuellen Beurteilungen durch Benutzer im Allgemeinen korrelieren. Diese Diskrepanz entsteht erstens aus den Ungenauigkeiten des CRI in seiner definitionsgemäßen Rolle als Farbtreueindex und zweitens aus wahrnehmungsbezogenen Farbqualitätseffekten jenseits der Farbtreue. Die CIE hat sich entschieden, dass für beide Aspekte bessere Charakterisierungsmethoden für die Farbqualität nötig sind, um weiße Lichtquellen messen und spezifizieren zu können. Die Arbeit wurde in zwei zusammenhängende Aufgaben geteilt: 1) in TC 1-90 einen wissenschaftlich genauen Farbtreueindex zu entwickeln und 2) einen oder

mehrere wahrnehmungsbezogene Farbqualitätsmaßzahlen jenseits der Farbtreue zu entwickeln. Mit dieser initialisierenden Arbeit wurde TC 1-91 beauftragt.

Der vorliegende, von TC 1-90 erarbeitete Technische Report beschreibt im Sinne eines Forschungsreports einen allgemeinen Farbtreueindex, R_f , als wissenschaftlich genaues Maß der Farbtreue bezogen auf eine Referenzlichtart, auch wenn noch einige technische Aspekte verblieben sind, die weitere Untersuchungen benötigen. Dieser Farbtreueindex, der auf dem Dokument TM-30-15 der Illuminating Engineering Society of North America basiert, befasst sich nur mit dem ersten Teil der Einschränkungen des CRI – er befasst sich nicht mit dem Bedarf an wahrnehmungsbezogenen Farbqualitätsmaßzahlen jenseits der Farbtreue. Er korrigiert jedoch mehrere der kürzlich festgestellten Ungenauigkeiten des CRI als ein Maß für die Farbtreue. Die wichtigen Verbesserungen bezogen auf den CRI sind: Die Aktualisierung der Farbdifferenzberechnung, speziell der Objektfarbraum, und die Einführung von 99 Test-Farbmustern, die eine gleichmäßigere Verteilung von Steigung und Krümmung als Funktion der Wellenlänge zur Verfügung stellen, wobei deren Farberscheinungen weitgehend und gleichmäßiger im dreidimensionalen gleichförmigen Farbraum verteilt sind.

Der allgemeine Farbtreueindex, R_f , gibt an, wie genau die Farbeindrücke aller Farbmuster im Mittel unter einer Testlichtquelle im Vergleich mit den Farbeindrücken unter der Referenzlichtart wiedergegeben (gerendert) werden. Somit vereinigt der allgemeine Farbtreueindex, R_f , ähnlich dem allgemeinen Farbwiedergabeindex, R_a , die berechneten Farbdifferenzen für alle Test-Farbmuster zu einem einzigen gemittelten Indexwert. Er adressiert damit nur einen Aspekt der Farbqualität und berücksichtigt keine Wahrnehmungs- und Präferenz-Effekte. Daher ist davon auszugehen, dass die Problematik der irrtümlichen Verwendung des CRI als allgemeine Farbqualitätsmaßzahl für den Endverbraucher auch von einem wissenschaftlich genaueren allgemeinen Farbtreueindex, R_f , nicht besser gelöst wird. Die Ursache dafür ist, dass die Bewertung durch den Benutzer von Faktoren jenseits der Farbtreue, wie etwa Farbsättigungseffekte oder die detaillierte Anforderung der speziellen Beleuchtungsaufgabe, beeinflusst wird. Der allgemeine Farbtreueindex, R_f , ist daher kein Ersatz des allgemeinen Farbwiedergabeindex, R_a , weder zum Zweck der Bewertung und Spezifikation von Produkten noch für die Regulierung oder andere Anforderungen an die minimale Leistungsfähigkeit. Ein Ersatz des CRI wird Gegenstand zukünftiger Studien und Diskussionen sein. Diese werden die Beurteilung des allgemeinen Farbtreueindex, R_f , in Kombination mit der Entwicklung eines harmonisierten Satzes neuer Farbqualitätsmaßzahlen zur Bewertung wahrnehmungsbezogener Effekte jenseits der Farbtreue sowie Anwendungs-Aspekte für Hersteller und Endverbraucher umfassen.

1 Introduction

The CIE Colour Rendering Index (CRI), defined in CIE 13.3-1995 (CIE 1995), in particular the general colour rendering index, R_a , is widely adopted and used by the lighting industry, in regulatory documents and in international and regional standards and specifications. However, limitations of the CRI have been recently addressed, especially for solid-state light sources, whereby the R_a values do not always correlate well with visual evaluation by general users. This mismatch arises, first, from inaccuracies of CRI in its intended role as a colour fidelity index and second, from perception-related colour quality effects beyond colour fidelity.

It was determined by the CIE that, for both aspects, better colour quality characterization methods are needed to measure and specify white-light sources, and the work was divided into two corresponding tasks; (1) to develop a scientifically accurate colour fidelity index, assigned to TC 1-90, and (2) to develop one or more perception-related colour quality measure(s) beyond fidelity, assigned to TC 1-91 for initial work.

This Technical Report, developed by TC 1-90, is a research report describing a general colour fidelity index, R_f , as a scientifically accurate measure of colour fidelity with respect to a reference illuminant, although there still remain some technical issues for further research. This colour fidelity index, based on the fidelity index of Illuminating Engineering Society of North America, defined in TM-30-15 (IES, 2015), addresses aspects for only the first part of the limitations of the CRI – it does not address the need for perception-related colour quality measure(s) beyond fidelity. However, it does correct several previously reported inaccuracies of the CRI as a colour fidelity measure.

The important improvements of this measure, relative to the CRI, are the update of the colour difference calculation, in particular the object colour space, and the incorporation of 99 test-colour samples which provide a more uniform distribution of slope and curvature values as a function of wavelength and which have colour appearance values that are more widely and uniformly distributed in the three dimensions of a uniform colour space. The general colour fidelity index, R_f , represents how closely the colour appearances of the entire sample set are reproduced (rendered) on average by a test light compared to those under a reference illuminant. Importantly the general colour fidelity index, R_f has, by design, a key limitation in common with the general colour rendering index, R_a – it calculates the average perceptual closeness of colour sample appearances under a test light to those under a reference illuminant, a procedure that does not take into account additional perception effects beyond fidelity, such as chroma preferences and their hue dependence.

It is considered that such unintended uses of CRI as an overall colour quality measure for end users is not better fulfilled by the more scientifically accurate colour fidelity index. The general colour fidelity index, R_f , is therefore not a replacement, for the purpose of rating and specification of products nor for regulatory or other minimum performance requirements, of the CRI. Replacement of the CRI will be a matter of future study and discussion that will include the evaluation of R_f along with the development of a harmonized set of new colour quality measures for assessing perception-related effects beyond colour fidelity and practical aspects for manufacturers and end-users.

To help further introduce this report, it may be helpful to briefly review the history of the CIE Colour Rendering Index (CRI). In 1948, the CIE made a first recommendation for a colour rendering index based on an eight-band method proposed in 1937. The method divides the spectrum into eight bands and compares the spectral content of each band with that of a full spectrum radiator. Later, in 1965, the Test Sample Method was developed and adopted by the CIE. In this method the CIE general colour rendering index, R_a , is calculated from the average magnitude of the colour appearance shift of a set of standard coloured samples, comparing between a test source and a reference illuminant. The reference illuminant, set at the same Correlated Colour Temperature (CCT) as the test source, is a Planckian radiator below 5 000 K and a defined phase of daylight at or above 5 000 K. Any deviation from the colour appearance of the colour sample under this reference illuminant reduces the R_a value below its maximum value of 100.

At first, only eight Munsell samples of moderate chroma were used. But in 1974, the method was revised to include six additional samples: a sample with Caucasian skin colour, a sample with a green leaf colour, and four high Munsell chroma samples. The method was further adjusted by including a revised von Kries type chromatic adaptation transform and by a slight change in the calculation procedure. It should be noted that the six additional samples are not used to calculate the general colour rendering index, R_a , but they provided six new special colour rendering indices, R_i , values which have proven useful.

In the current CIE CRI method according to CIE13.3-1995 (CIE 1995), a reference illuminant at the same CCT as the test source is first selected (a daylight illuminant if the CCT is at or above 5 000 K or Planckian radiation if below). Then the tristimulus values for each test samples (8+6) are calculated using the spectral power distribution of the test source and the reference illuminant. A von Kries chromatic adaptation transformation is used to bridge the difference between the chromaticity values with both sources. The next step is the calculation of colour shifts between the values obtained for each sample. Then the magnitudes of differences are transformed into special colour rendering indices, R_i , and averaged into the general colour rendering index, R_a , from the values for the first eight test samples.

Despite its known imperfections, the CIE general colour rendering index, R_a , has gained international acceptance and has been included in many regulations and commercial lamp specifications. Since the last revision of the CRI in 1974, improved colorimetric formulae (such as object colour space and chromatic adaptation transform) (Fairchild 2005, CIE 2004a, CIE 2004b) became available and the CRI therefore became outdated. In the 1990s, CIE TC 1-33 attempted to update the formula and the test-colour samples, but it did not reach a consensus and was closed without any recommendation. In 1995, the CIE corrected some small descriptive errors by publishing CIE 13.3 (CIE 1995), but no changes were made to the technical contents. As solid-state lighting emerged since the early 2000s, it became clear that further improvements would be desirable. The problems were investigated by CIE TC 1-62, which published a report presenting the analyses of the problems and the need for improvement of the CRI, as also summarized in Clause 3. Following this, CIE TC 1-69 discussed proposed metrics such as Colour Quality Scale (Davis & Ohno 2010) addressing the perception effect of chroma saturation, CRI2012 (Smet et al. 2013) introducing a wavelength uniform mathematical sample set, and MCRI (Smet et al. 2010) which is a reference-illuminant-free index using the memory colours of a set of familiar objects as reference. The TC was closed without consensus. As previously mentioned, the CIE subsequently decided to separate the efforts to develop new metrics for 1) colour fidelity and 2) aspects other than colour fidelity. This Technical Report is a result of the first task.

Excel calculation tools for the CIE 2017 Colour Fidelity Index (1 nm and 5 nm step versions), including a table of the spectral data of the 99 Test Colour Samples, are downloadable at http://files.cie.co.at/933_TC1-90.zip.

2 Point of Clarification

2.1 The purpose of a colour fidelity index

The CIE definition of the term “colour rendering” is: “effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant” (CIE 2011). In recent scientific literature, the term “colour fidelity” has come into use with a very similar meaning; it has been chosen to help avoid a common error whereby some misinterpret the term “colour rendering” to have a broader meaning. Thus, the term “colour fidelity” is used in this Technical Report in a manner that is consistent with the definition of “colour rendering” as above, especially to distinguish from other aspects of colour quality beyond colour fidelity.

For example, some have incorrectly interpreted colour rendering as being intended to measure the value, or overall colour quality, of a light source. However, colour quality includes more aspects than only colour fidelity and there can be situations in which a subject may report a preference for a lamp illuminating a scene, even though it has lower colour fidelity value, e.g. when the chroma of objects is increased. This is due to some additional factors related to perception that may be desirable in that circumstance. Such additional factors are currently

being considered by TC 1-91 and may include the detailed nature of the colour shifts that various specific objects undergo in a scene illuminated by a lamp. Importantly, the impact of all of these factors on a lamp's overall quality will depend upon the type of task and its duration, and also individual preference, which may vary considerably from region to region and/or from one individual to another.

In contrast to the difficulty in defining such perception effects beyond colour fidelity, the concept of colour fidelity is simple, clear and objective: experiments have established that people with normal colour vision report their perception of the size of colour differences of various object colours in similar ways (Fairchild 2005), and therefore it is meaningful to develop quantitative summaries of perceived colour shifts of objects as a means for assessing colour fidelity. These measures are objective in the sense that they are not dependent on the opinions and tastes of certain observers and groups. For this reason, the CIE considers the assessment of colour fidelity to be amenable to international standardization, and this Technical Report is a first step in that direction.

2.2 Terminology used in this Technical Report

For the purposes of this document, the terms and definitions given in CIE S 017/E:2011 (partly repeated in this document) and the following apply.

2.2.1

colour rendition

effect of an illuminant (spectrum) on the colour appearance of objects

2.2.2

colour rendering

effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant

[SOURCE: CIE S 017/E:2011, Term 17-221]

Note 1 to entry: This definition does not specifically say that estimations of the magnitude of colour shifts would be used to assess the effect.

2.2.3

colour fidelity

degree to which a light source causes a shift in the colour appearance of a surface it illuminates, relative to that surface's colour appearance when illuminated by a defined reference illuminant, and whereby the magnitude of the colour shift is assessed by considering the shifts along all three cardinal axes of the colour appearance space

Note 1 to entry: Although this definition is quite similar to the one of "colour rendering", it provides a more complete operational definition in order to reduce possible confusion.

3 Limitations and inaccuracies in the calculation of the CIE general colour rendering index in view of the current status of science and technology

3.1 Outdated colour science

Likely, at the developing stage of the CIE CRI, it was planned that it would be possible to integrate future improvements in colour science without changing the overall test sample concept, but that has seldom been done. For years, it has been known that the colour space adopted in the calculation of the current CIE general colour rendering index, R_a , i.e. the CIE 1964 uniform colour space with coordinates U^* , V^* , W^* , lacks sufficient uniformity. In other words, in different regions of the $U^*V^*W^*$ space equally-spaced colours do not appear equally different. This means that colour shifts for some samples will be over- or under-represented in computing the R_a value, which is based on an average of the individual colour shifts. Additionally, the nature of the calculation creates a CCT dependence that adds further distortion: in $U^*V^*W^*$ the region containing the set of all possible test-colour samples undergoes significant shape changes as a function of CCT. This means that the colour non-uniformity is CCT-dependent, and therefore the inaccuracies in CRI predictions, too (Smet et al. 2015b).

Finally, it is recognized that the von Kries chromatic adaptation transform used in the calculation of the CIE general colour rendering index, R_a , is only accurate for light sources with their chromaticity coordinates close enough to the reference illuminant, i.e. with a chromaticity difference in the CIE 1960 UCS (u, v) diagram of less than 0,01. (Teunissen 2016). An improvement is desirable for evaluating sources further off the Planckian locus.

3.2 Spectrally non-uniform sensitivity of the CIE general colour rendering index

Recent studies (Smet et al. 2013, David et al. 2015, Smet et al. 2015a, Smet et al. 2015b) show that the sensitivity of the R_a value to spectral perturbation, as a function of the central wavelength of the perturbation, is quite non-uniform: some wavelengths are privileged in the sense that they contribute disproportionately to the general colour rendering index value. On a broad scale this is to be expected, due to the non-uniformity of differences between the sensitivity functions of the human visual perception system. However significant short-range sensitivity variations are also found, which arise from the arbitrary details of the spectral radiance factors of the eight CIE test-colour samples (TCS) used for the calculation of R_a . (The spectral radiance factor, for each tabulated wavelength, is the quotient of the spectral radiance of the test sample in a specified direction and the spectral radiance of a perfect reflecting diffuser when identically irradiated and viewed.) Evidence that the details of the spectral radiance factor are important can be seen in the fact that, if the eight colour samples used are replaced with other common samples that match in colour but differ in their spectral radiance factors, those short-range sensitivity variations change very significantly. These arbitrary short-range sensitivity variations are problematic, because they cause significant changes in the R_a value for some lamps, yet these changes provide limited information about the lamp's actual colour fidelity – they merely increase overall uncertainty. If, as may reasonably be expected in some cases, an optimization process is used to generate the most desirable set of performance values for a lamp, then the wavelength bias of the current CIE general colour rendering index, R_a , could cause that process to yield a spectral power distribution (SPD) that scores higher than it should according to its actual perceived level of colour fidelity.

3.3 Insufficient information about colour shifts

The CIE CRI provides information about the magnitude of the colour shift of 14 samples which are neither uniformly distributed in the three dimensions of the colour space nor necessarily representative of actual materials found in the real world. Previously, researchers have pointed out the merits of providing colour shift information for a larger number of samples (van der Burgt & van Kemenade 2010) that represent a greater diversity of real objects and also represent a wider range of the colour space. For those reasons as well as for overcoming the sensitivity non-uniformity problem mentioned in 3.2 the proposed scientifically accurate index uses a larger sample set.

4 Development of recommended improvements for the CRI calculation

As described in several publications (Smet et al. 2013, David et al. 2015, Smet et al. 2015a, Smet et al. 2015b, van der Burgt & van Kemenade 2010), it is now possible to address all of these problems in a consistent manner, as briefly outlined below, with the precise mathematical details concisely set out in Clause 6. Here the key changes are highlighted.

4.1 Implementation of CAM02UCS colour space

For computing the colour shifts the CAM02-UCS colour-appearance space (Luo et al. 2006) is used. CAM02-UCS is based on CIECAM02, but has its colour-appearance axes rescaled to better predict colour differences. The space has been shown to have good perceptual uniformity, in addition to implicitly including the most recent chromatic adaptation transform, CAT02. The CAM02-UCS adopted white point is the equi-energy white (EEW).

This built-in chromatic adaptation transform and the implicitly-adopted white point in CAM02-UCS have the advantage that fidelity calculations are largely independent of the CCT of the test light source (Smet et al. 2015b). Prior to calculating the colour differences, both the colour coordinates of the reflectance samples under the test source and under the reference source are first transformed to their corresponding colours under the EEW. In contrast, in the CIE CRI the colour coordinates of the samples under the test source are transformed to the reference

illuminant, thereby making the colour difference calculation dependent on the shape of the colour space at that CCT.

In determining the colour coordinates for each of the test-colour samples, the 1964 10° colour-matching functions (CMFs) are used. This is in contrast to the calculation procedure of the CIE general colour rendering index, R_a , where 2° CMFs are used. The main motivation for this change is that it is believed that the 2° CMFs are somewhat less accurate than the 10° CMFs (Csuti & Schanda 2008, Csuti & Schanda 2010).

The calculation requires determining the CCT of the source. This is done using the 2° CMFs, since this is the common practice. Regarding the CCT range where the present method is valid, CAM02-UCS and CAT02 were developed by respectively considering a variety of colour-difference and corresponding colour data, collected under (near) neutral illuminants ranging from D65 to A. Therefore, it is expected that the results are at least accurate within the range from 2 700 K to 6 500 K, which covers many practical lighting situations. In addition, CIECAM02 has been adopted in computer display applications requiring even higher CCTs.

It should be noted that CIECAM02, while largely accepted, is still being researched and improved. In particular, improvements have been proposed in past years to fix numerical inaccuracies which could arise in some cases (e.g. yellow-blue problem, purple problem). These modifications were found to have negligible impact on R_f calculations (much less than 1 point for most SPDs). (Li et al. 2012) Thus it is recommended to use the “standard” form of CIECAM02 (CIE 2004b) in the calculation of CAM02-UCS, both for simplicity and because it is most widespread. Another possible improvement area for CAM02-UCS has been raised and suggested for future evaluation. It has been noted that the location of the peak wavelength in a white phosphor-based LED has a greater impact on the R_f value than it has on the R_a value. A recent publication questions whether CAM02UCS may over-estimate colour differences in the blue region (Tsukitani et al. 2015), suggesting further study.

4.2 Development of an improved sample set

The 99 test-colour samples (TCS) employed in IES TM-30-15 (David et al. 2015, IES 2015), recently published by the Illuminating Engineering Society (IES), were adopted. These samples were obtained from a careful selection process, starting from a set of over 100 000 measured real spectra compiled from numerous online databases (Chou et al. 2012, David et al. 2015). All samples correspond to measurements, rather than computer-generated data. They represent a broad sampling from all major types of samples (natural and human-made), a broad uniform sampling of colours (including fairly saturated regions of the colour space), and importantly, they have been selected so as not to impart short-range non-uniformity in the spectral sensitivity of the colour fidelity calculation, which would increase its uncertainty. As mentioned before, minimizing any wavelength bias present in the sample set is essential to avoid selective spectral optimization of light sources. More information on this important topic can be found in (David et al. 2015, Smet et al. 2015a, Smet et al. 2015b). It should be noted that not all of the sample reference data was available for the range specified here from 380 nm to 780 nm. For one third of the samples the data was only available in the range from 400 nm to 700 nm. Because the extrapolation method currently used in IES TM-30-15 is not a CIE recommended procedure for extrapolating missing data, another extrapolation method, the constant-value extrapolation described in 7.2.2.1 of CIE15:2004 (CIE 2004c), was used in this Technical Report.

The resulting spectral radiance factors for all 99 test-colour samples are set out in Annex A, in 5 nm wavelength intervals. For those wishing to carry out the calculation using 1 nm intervals, Annex C should be followed to create 1 nm tables for the TCS.

Figure 1 depicts the approximate colour of these 99 samples plus white when illuminated by a D50 illuminant, which was also used for the sample selection process. It should be noted that a different set of test-colour samples may have resulted if an illuminant with another CCT had been used for the sample selection process.

01	02	03	04	05	06	07	08	09	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	W

Figure 1 – The 99 test-colour samples plus white with the samples' indexing numbers indicated

The number of samples employed in IES TM-30-15 was decided upon by carefully balancing the desire for a small sample set and the need for enough samples to maintain a high accuracy. Specifically, the choice of the test samples was determined as follows. At first, a large sample set ('Reference Set' of about 5 000 samples) was established; this set met all required properties discussed above and in (David et al. 2015) – among which:

- an even distribution across a gamut of “common colours” in CAM02-UCS;
- spectral uniformity (typically an order of magnitude better than “standard” sample sets such as the Test-Colour Samples (TCS) used for the calculation of the CIE general colour rendering index, R_a);
- samples chosen from a variety of manufactured and natural objects.

Subsequently, a smaller set was sought with the objective of reproducing the predictions of the Reference Set as well as possible. Namely, the objective was that the two sets yield colour fidelity scores that differ by less than 1 point for most SPDs. This difference limit was chosen because it is small enough compared to visually perceptible differences (~5) (CIE 1995), and therefore does not add much to the total error bar in comparing experiments and calculations.

A larger sample set size also provides the additional benefit of statistical averaging – individual independent samples differ from one another in ways that introduce random variation in the average value R_i , and according to the laws of statistics, the resultant standard deviation of the mean is reduced as the number of samples increases (Smet et al. 2015b).

As a result, a set of 99 test-colour samples was devised which met all these constraints.

It may be helpful to briefly summarize the important advantages of the new set of 99 real test-colour samples, in comparison to the eight real test-colour samples used to calculate R_a . In both cases, the samples were selected to have a reasonably uniform distribution of hue values. However, the selection algorithm for the new set of 99 samples has the following important advantages:

- 1) The samples are reasonably uniformly distributed in chroma (including strong, but not extreme chroma levels), and also in lightness (although variation in lightness values are less important);

- 2) The sample features are uniformly distributed in wavelength space (Smet et al. 2015b);
- 3) There is reduced statistical uncertainty, through the use of a larger number of samples
- 4) When the sample selection algorithm is repeated, yielding a different subset of samples that fulfill the prescribed criteria, the R_f values are essentially unchanged (Smet et al. 2015b).

4.3 Avoiding negative values for the general colour fidelity index and the special colour fidelity index

The following method, presented in (Davis & Ohno 2010), is used for avoiding negative values for the general colour fidelity index, R_f , and the special colour fidelity indices, $R_{f,i}$, using the following form of conversion formula:

$$R_{out} = 10 \ln(\exp(R_{in}) + 1) \quad (1)$$

where R_{in} is the uncorrected value that could potentially go below zero in some cases, and R_{out} is the corrected value, which is essentially unchanged except in the case of extremely low values, for which R_{out} asymptotically approaches zero instead of becoming negative. This approach is used in the calculation of $R_{f,i}$ and R_f values in Equations (15a) and (15b).

4.4 Minor change to reference illuminant between CCT of 4 000 K and 5 000 K

Although of little practical consequence, the calculation of the CIE general colour rendering index, R_a , has a minor but inelegant discontinuity at 5 000 K: for lower CCT values a Planckian reference is recommended, whereas above 5 000 K a phase of daylight is used. To avoid this, the procedure recommended here is to make a smooth, linear transition from a Planckian reference to a daylight reference such that at 4 000 K and below it is purely Planckian, at 4 500 K it is a 50:50 mix of the two, and at 5 000 K and above it is purely a daylight reference. The introduction of the transition region for the reference illuminant between 4 000 K and 5 000 K mainly affects blackbody radiator-like sources for which some will not obtain a general fidelity index value of 100. The maximum obtainable general fidelity index value for these reference sources is reduced by 1 or 2 and up to 5 for some of the special fidelity indices, $R_{f,i}$.

It is noted that this proposal is slightly different from that made in IES TM-30-15 (IES 2015), where the region of transition is in the range from 4 500 K to 5 500 K. This modification is made in order to directly employ D50, since it is a reference illuminant that is used in many other standards. The precise choice of the transition region is somewhat arbitrary, and changing the transition region only induces very small R_f value differences (typically 1 or less, always less than 2,5 and up to 6,5 for some of the special fidelity indices, $R_{f,i}$).

4.5 Rescaling of average colour shifts

The calculation of the R_f value is done as with the CIE general colour rendering index, R_a – by averaging the magnitude of the colour shifts (including differences in lightness) for all of the samples, multiplying by a selected multiplication factor and subtracting that product from 100. There are two open questions in this process:

- (i) What averaging method should be used?
- (ii) How is the multiplication factor determined?

Regarding the first point, root mean square averaging has been proposed (Davis & Ohno 2010), in part to mitigate the limitation of using only a few samples. It is expected that this issue is alleviated by the use of 99 samples. Therefore, it is recommended to use the simpler arithmetic mean, as is currently analogously used for the calculation of R_a . An advantage of this approach is that the average fidelity value is the average of the special values for each sample (except for very low-fidelity sources, due to the rescaling procedure described in 4.3).

For the second point, the following approach was first considered, presented by Davis and Ohno, which ensures that the mean R_a value for a set of CIE standard fluorescent lamps (F1–F12) remains unchanged (Davis & Ohno 2010). While this is a data set from the well-known CIE publication CIE 15 (2004), it is a set of fluorescent lamps that were available 30 years ago,