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Final report

Considering the benefits of lighting by the development of efficiency requirements for lighting products

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Considering the benefits of lighting by the development of efficiency requirements for lighting products

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Kurzbeschreibung: Berücksichtigung der Lichtdienstleistung bei der Festlegung von Effizienzanforderungen an Produkte der Beleuchtungstechnik

In diesem Dokument werden die Grundlagen für einen neuen Bewertungsansatz für die Festlegung von Effizienzanforderungen an Produkte der Beleuchtungstechnik dargestellt. Diese Methode kann verwendet werden, um die Effizienz der Beleuchtungsprodukte auf eine neue, allumfassende Weise zu beschreiben. Die Schwächen der V(λ)-Funktion (als Grundlage für die heutige Berechnung der Lichtausbeute) und die Notwendigkeit für den neuen Bewertungsansatz werden erläutert. Im nächsten Schritt werden die Helligkeitswahrnehmung und deren Metriken beschrieben, sowohl im photopischen Bereich (für die Bewertung der Innenraumbeleuchtung) als auch im mesopischen Bereich (für die Bewertung der Außenbeleuchtung). Die visuellen Eigenschaften der Farbqualität und deren Metriken (der allgemeine Farbwiedergabeindex und weitere Indizes), die visuelle Qualität der Weißtöne und der Weg der circadianen Bewertung der Lichtquellenspektren werden zusammengefasst. Nach der Darstellung der Metriken für die Bewertung der Einzelnutzen der Bewertungsprodukte wird die mathematische Definition des neuen Bewertungsansatzes beschrieben. Ein Datensatz von 304 Beleuchtungsprodukten wurde mit dem neuen Bewertungsansatz bewertet. Die Anzahl der Beleuchtungsprodukte unterschiedlichen Typs in den Kategorien A-G im neuen Bewertungssystem wurde bestimmt und dargestellt. Die Vorteile und mögliche Alternativen des neuen Bewertungsansatzes wurden erläutert.

Abstract: Considering the benefits of lighting by the development of efficiency requirements for lighting products

In this document, the fundamentals of a new evaluation method of the efficiency of lighting products are described. This method can be used to determine the efficiency of lighting products in a new, comprehensive way. The deficiencies of the V(λ) function (as the method underlying the computation of luminous efficacy) and the necessity of the new evaluation method are explained. Brightness perception and its metrics are described, both in the photopic range (to evaluate interior lighting) and in the mesopic range (to evaluate exterior lighting). The visual properties of colour quality and its metrics (general colour rendering index and further indices) were summarized together with the issue of the visual quality of white tones as well as the way of the circadian evaluation of light source spectral power distributions. After introducing the metrics of these individual benefits of lighting, the mathematical definition of the new evaluation method was described. A sample dataset of 304 lighting products was evaluated by the aid of the new method. The number of lighting products of different type in the categories A-G of the new evaluation system was computed and presented. The advantages and possible alternatives of the new method were described.

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List of abbreviations

Abbreviation	Explanation
a_{mel}	Melanopic factor
BAM	Federal Institute for Materials Research and Testing
BMWi	Federal Ministry of Economics and Technology
CCT	Correlated Colour Temperature
cd	Candela
CIE	Commission Internationale de l'Ėclairage: International Commission on Illumination
CL	Circadian Light
CQS	Colour Quality Scale
CRI	Colour Rendering Index
CS	Circadian Stimulus
D65	Standard illuminant D65: Daylight spectrum with a colour temperature of 6504 K
EEI	Energie Efficiency Index
EU	European Union
H7-Lamp	Tungsten Halogen Lamp for Automotive Headlamps
HCL	Human Centric Lighting
HID	High Intensity Discharge lamp
HQL-Lamp	Halogen Metal Vapour lamp
Hz	Hertz
IES	Illuminating Engineering Society
ipRGC	Intrinsically photosensitive retinal ganglion cell
L, L_v	Luminance
$L_{äq}$	Equivalent Luminance
LED	Light Emitting Diode
lm	Lumen
L_{mes}	Mesopic Luminance
LQ	Light Quality measure
lx	Lux
MH-Lampe	Metal Halide lamp
NAV-Lampe	Sodium Vapour lamp
P	Power
PWM	Puls Width Modulation
$R_{1,14}$	Mean value of the 14 special colour rendering indices
R_a	General colour rendering index
RCRI	Rating Scale Index for Colour Rendering
R_f	Colour Fidelity Index

Abbreviation	Explanation
R_g	Colour Gamut Index
R_i	Special Colour Rendering Index
SBI	Subjective Assesment Index
SEK	Electric Efficiency Measure
TCS	Test Colour Sample
UBA	Federal Environmental Agency
UCS	Uniform Colour Space
UGR	Unified Glare Rating
USP	Unified System of Photometry
$V(\lambda)$-Funktion	Spectral luminous efficiency function
W	Watt
Xe lamp	Xenon lamp
ZVEI	Central Association of the Electrical Engineering and Electronics Industry

Zusammenfassung

Die Energieeffizienz von Beleuchtungsprodukten wird z. Z. mit Hilfe der Größe *Lichtausbeute* (lm/W) bewertet. Diese Größe wird aus der Größe Lichtstrom (lm) errechnet. Die Größe *Lichtstrom* kann die Wirkung des Lichtes (elektromagnetische Strahlung im Wellenlängenbereich von 360 nm bis 830 nm) auf die Menschen nicht vollständig beschreiben: der Lichtstrom ist keine geeignete Größe, um alle *Nutzen des Lichtes für die Menschen*, die aus allen Spektralbereichen resultieren, zu beschreiben.

Beleuchtungsprodukte und Beleuchtungssysteme ermöglichen verschiedene Sehaufgaben. Um diese Aufgaben durchzuführen, wird mehr als nur eine gewisse Menge an *Lichtstrom* benötigt: das Licht soll mit der korrekten *Helligkeit*, korrekten *Farbigkeit* und zur korrekten Zeit geliefert werden. Der Bedarf an elektrischer Leistung wird mit einem höheren *Nutzen des Lichtes* erhöht. Wird aber die *Stromeffizienz* nur mit Hilfe der Größe *Lichtausbeute* (lm/W) bewertet, dann könnte der reale Nutzen eines Beleuchtungsproduktes in einer realen Anwendung sehr niedrig sein.

Wenn die *Lichtausbeute* als einziges Kriterium für die Bewertung von *Beleuchtungsprodukten* verwendet wird, dann könnten bestimmte Beleuchtungsprodukte mit hohem, mehrfachem *Nutzen* aber niedriger *Lichtausbeute* die Anforderungen für eine ausgezeichnete Stromeffizienzbewertung nicht erfüllen und aus dem Markt verschwinden, weil sie die gesetzlichen Vorgaben nicht erfüllen, obwohl sie für die Benutzer sehr vorteilhaft wären. Darum soll der *Nutzen* der Beleuchtungsprodukte in Zusammenhang mit ihrer *Stromeffizienz* in der Zukunft besser formuliert und berücksichtigt werden.

Dementsprechend besteht das Ziel dieses Dokuments darin, neue Kenngrößen zu definieren, um die realen *Nutzen der Beleuchtung für die Menschen* zu bewerten, und die numerischen Kenngrößen der *Einzelnutzen des Lichts* zu kombinieren, um einen neuen, allumfassenden *Bewertungsansatz* zu bekommen. Dieser neue Bewertungsansatz und die entsprechende mathematische Methode werden in diesem Dokument beschrieben. Der neue Bewertungsansatz und die neue Methode wurden für einen Datensatz von *Lichtquellen* angewendet und dieser Datensatz wurde mit der neuen Methode als Beispiel ausgewertet.

Der Entwurf der *spektralen Eigenschaften der Beleuchtung* d.h. der *räumlichen Leuchtdichteverteilungen* und der *räumlichen Beleuchtungsstärkeverteilungen (*z. B. “wall washing”, diffuse Beleuchtung oder Spotbeleuchtung, Highlights und Schatten) und der *zeitlichen Eigenschaften des Lichts* (z.B. dynamische Beleuchtung d.h. Änderung der *ähnlichsten Farbtemperatur* CCT im Lauf eines Arbeitstages) ist Gegenstand der Forschung der *Lichtqualität* in der Architektur. Der vorhandene neue Bewertungsansatz beschäftigt sich nur mit den *spektralen Eigenschaften der Beleuchtung* d.h. mit solchen Eigenschaften, die aus der *spektralen Strahlungsflussverteilung* des Beleuchtungssystems, oder, spezifischer, der *Lichtquelle*, die im System benutzt wird, abgeleitet werden.

Präziser formuliert, das Konzept des neuen Bewertungsansatzes wurde so entwickelt, dass wir eine geeignete *numerische Kenngröße* suchten, die die wichtigsten Nutzen für den menschlichen Benutzer des Beleuchtungsproduktes darstellt, die aus dem Spektrum resultieren. Das Ziel bestand darin, alle Nutzen zusammenzufassen, und die *Nützlichkeit der Lichtquelle* praxisrelevant auszudrücken. Definitionsgemäß wurde eine Lichtquelle dann als *nützlich* angeschaut, wenn sie *viel Nutzen* (z.B. Helligkeit, Sehleistung, biologisch aktivierende Wirkung, Farbqualität) mit *wenig elektrischer Energie* darstellte.

Das Ziel des vorhandenen Dokuments ist, die *mathematische Definition* von zwei numerischen Kenngrößen zu beschreiben, die ein neues, einheitliches, zweidimensionales Bewertungskonzept darstellen. Dieses Konzept fasst die wichtigsten Nutzen des Lichts für den Menschen zusammen. Die numerischen Messzahlen sollen vom *spektralen Strahlungsfluss* und der *eingehenden elektrischen Leistung* (in W) der Lichtquelle errechnet werden. Wie oben bereits erwähnt, ist die *Lichtausbeute* in *lumen per watt* Einheiten keine geeignete Messzahl, obwohl sie heute weltweit benutzt wird.

Grund dafür ist, dass die *V(λ)-Funktion* (die Basis der herkömmlichen *Photometrie*) nur die Linearkombination der *im längeren Wellenlängenbereich empfindlichen Zapfen-Photorezeptoren (sog. L-Zapfen)* und der *im mittleren Wellenlängenbereich empfindlichen Zapfen-Photorezeptoren (sog. M-Zapfen)* enthält. Sie lässt die wichtigen Signale der *im kürzeren Wellenlängenbereich empfindlichen Zapfen-Photorezeptoren (sog. S-Zapfen)*, der Stäbchen-Photorezeptoren (diese sind für das sog. *skotopische Sehen* oder Nachtsehen und in Zusammenarbeit mit den Zapfen-Rezeptoren auch für das mesopische Sehen oder Dämmerungssehen verantwortlich) und der intrinsisch lichtempfindlichen retinalen Ganglienzellen (ipRGCs; diese sind für die biologisch aktivierende Wirkung des Lichts oder die sog. *circadiane Wirkung* zuständig).

Das Konzept des vorhandenen Dokuments ist, dass statt der Lichtausbeute eine Kombination von für alle Nutzen relevanten Kenngrößen verwendet wird. De Kombination enthält Messzahlen der Farbqualität, der Helligkeit und der Sehleistung sowie der *circadianen Wirkung*. Mathematisch gesehen gibt es natürlich sehr viele Möglichkeiten, um diese Messzahlen der einzelnen Nutzen, die aus dem Spektrum und der elektrischen Leistung resultieren, zu kombinieren. Im vorhandenen Dokument wird die Berechnungsmethode eines möglichen, plausiblen Vorschlages beschrieben, der für eine allgemeine Akzeptanz geeignet ist. Der Vorschlag enthält ein neues Bewertungssystem mit neuen Messzahlen für die Nutzen des Lichts für den Menschen.

Bei der Entwicklung der Methode, um eine praxisrelevante und in breitem Kreis annehmbare Lösung für die Kennzeichnung der Beleuchtungsprodukte zu bekommen, wurden nur die wichtigsten Nutzen der Beleuchtung für den Menschen für die allgemeine Innenraum- und Außenbeleuchtung betrachtet. Es wurde hervorgehoben, dass die neue Methode in einem Dialog mit den Vertretern der Industrie und der Regierung entwickelt werden soll.

Es wurde ebenfalls betont, dass die Metriken, die zur Beschreibung der ausgewählten (d.h. wichtigsten) Nutzen des Lichts herangezogen werden, auf gut etablierten und bekannten Arbeiten oder internationalen Normen basieren sollen. Ziel war dabei, die neue Methode für weltweite industrielle Anwendungen bereit zu stellen. Es wurde ebenfalls vorgenommen, das neue Bewertungssystem mit Hilfe eines Satzes von mindestens 300 repräsentativen Lichtquellendaten zu testen. Diese Daten schlossen die absoluten spektroradiometrischen Daten und die Lichtausbeute in lm/W-Einheiten von heute oft verwendeten Lichtquellen ein. Im Laufe des Projektes wurde dieser Satz (Daten von typischen kommerziellen Beleuchtungsprodukten) von METAS (Schweiz) erhalten.

Eine weitere Überlegung bestand darin, dass der Wert der neuen Kenngröße von der jeweiligen Anwendung abhängen soll. Wenn das Ziel z.B. konzentriertes Arbeiten in einem Büro ist, dann soll der Wert der neuen Kenngröße für eine warmweiße Lichtquelle sehr niedrig sein. Grund dafür ist, dass, obwohl viel elektrische Energie eingefüttert wird, die Benutzer (die arbeiten möchten) nicht zufrieden sind, weil sie für das konzentrierte Arbeiten kaltweißes Licht bevorzugen. Die gleiche warmweiße Lichtquelle soll aber einen hohen neuen Wert, wenn sie für die Beleuchtung eines Wohnzimmers am Abend benutzt wird, weil sich die Benutzer eher eine entspannende Atmosphäre wünschen. Es wurde gefordert, dass der Typ der Anwendung

(Innenraumbeleuchtung, Außenbeleuchtung), das *Leuchtdichteniveau* in der Außenbeleuchtung (Straßentyp) und die Möglichkeit der *dynamischen Beleuchtung* ebenfalls in Betracht gezogen wird.

Dementsprechend wurden die folgenden Nutzen des Lichts für den Menschen mit den folgenden Lichtqualitätsmetriken (den numerischen Messzahlen der einzelnen Nutzen) für das neue Bewertungssystem ausgewählt:

1. *Helligkeit* und *Sehleistung*: um diesen Nutzen zu beschreiben, wurden die sog. *äquivalente Leuchtdichte* $L_{äq}$ (nach Fotios und Levermore [1]) für die *Innenraumbeleuchtung* und die sog. *mesopische Leuchtdichte* L_{mes} (CIE 191:2010 [2]) für die *Außenbeleuchtung* herangezogen.

2. Farbqualität: um diesen Nutzen zu beschreiben, der *allgemeine Farbwiedergabeindex,* CIE CRI R_a[3] wurde ausgewählt.

3. Circadiane Wirkung (die biologisch aktivierende Wirkung des Lichts): um diesen Nutzen zu beschreiben, wird die Größe a_{mel}[4] benutzt.

Es wurden also drei Nutzen des Lichts, Helligkeit, Farbqualität und die circadiane Wirkung für die neue Bewertungsmethode ausgewählt. Es wurde entschieden, dass die Helligkeit für die Innenraumbeleuchtung mit der Messzahl $L_{äq} = L_v\ (S/V)^{0.24}$ nach Fotios und Levermore [1] beschrieben werden soll ($L_{äq}$ ist die sog. *äquivalente Leuchtdichte* und L_v ist *Leuchtdichte* in cd/m^2-Einheiten). Das Symbol *S* stellt das Signal der oben bereits erwähnten *S-Zapfen* dar. Dieses Signal wird berechnet, indem der *relative spektrale Strahlungsfluss* der Lichtquelle mit der *spektralen Empfindlichkeit* der S-Zapfen (mit den sog. Smith und Pokorny-Rezeptor-empfindlichkeitsdaten [5]) gewichtet und dann im sichtbaren Wellenlängenbereich integriert wird. Die Größe *V* (sog. *V*-Signal) wird so berechnet, dass der *relative spektrale Strahlungsfluss* der Lichtquelle mit der *V(λ)-Funktion* gewichtet und dann im sichtbaren Wellenlängenbereich integriert wird.

Wenn das Beleuchtungsprodukt für die Außenbeleuchtung eingesetzt werden soll, dann wird die Messzahl L_{mes} (d.h. die *mesopische Leuchtdichte* der CIE Publ. 191:2010 [2]) herangezogen anstatt mit $L_v\ (S/V)^{0.24}$ zu arbeiten. Wenn die Größe der mesopischen Leuchtdichte L_{mes} berechnet wird, soll entweder L_v=3,0 cd/m^2 (für die Straßen in der *M-Klasse* [6]) oder L_v=0,3 cd/m^2 (für die Straßen der *P-Klasse* [6] mit 5 lx und dem Leuchtdichtekoeffizient der Straße von 0,06 cd/(m^2 lx)) als Leuchtdichteniveau der Berechnungsmethode der CIE Publ. 191 [2] verwendet werden.

Der Grund, warum L_{mes}[2] für die Beschreibung der Helligkeit für die Außenbeleuchtung gewählt wurde besteht darin, dass, obwohl L_{mes} auf der Basis von Sehleistungsversuchen entstand, diese Größe (d.h. L_{mes}[2]) mit der Helligkeit gut korreliert [7] (r^2=0,86 nach der Abb. 4 in [7]). Die mesopische Messzahl L_{mes} gewichtet das Stäbchensignal und das Zapfensignal auf den charakteristisch niedrigeren (mesopischen) *Leuchtdichteniveaus* der *Außenbeleuchtung*, während die $L_{äq}$ –Metrik nach Fotios und Levermore [1] die *S-Zapfen* in Betracht zieht, die bei höheren (photopischen) Niveaus, die in der Innenraumbeleuchtung wichtiger sind, ein stärkeres Signal als die Stäbchen liefern.

Die *circadiane Wirkung* wird mit Hilfe des sog. *melanopischen Wirkungsfaktors* a_{mel} charakterisiert, die aus dem *relativen Strahlungsfluss* der Lichtquelle nach DIN SPEC 5031-100 [4] wie folgt errechnet wird: der relative Strahlungsfluss wird mit der sog. $s_{mel}(\lambda)$-Funktion [4] (nach Lucas et al. [8]) gewichtet und dann im sichtbaren Wellenlängenbereich integriert. Das Ergebnis wird noch durch das oben definierte *V*-Signal des relativen Spektrums dividiert.

Den obigen Betrachtungen entsprechend wurde das neue Bewertungssystem wie folgt definiert. Als Eingabe des Berechnungsverfahrens dienen der *spektrale Strahlungsfluss* des Beleuchtungsproduktes sowie dessen Lichtstrom (lm) und elektrische Leistung (W). Das neue Bewertungssystem wurde zweidimensional definiert: das System besteht aus zwei Werten, die graphisch in einem Diagramm mit zwei orthogonalen Achsen als Datenpunkt dargestellt werden können. Eine Messzahl der Farbqualität befindert sich auf der Abszisse. Diese Messzahl ist der allgemeine Farbwiedergabeindex (CIE CRI R_a [3]). Dieser Wert wird heute global allgemein verwendet. In den Diskussionen der Zukunft können andere Messzahlen wie CIE R_f [9] oder CQS Q_p [10] betrachtet werden.

Eine neue, kombinierte Messzahl der Helligkeit und der circadianen Wirkung wird auf der Ordinate des Diagrammes dargestellt. Diese neue, kombinierte Metrik wird *Stromeffizienzkennwert* (SEK) und das neue Diagramm R_a-SEK-Diagramm genannt. Die Größe SEK ist in der Gl. (1) definiert.

$$SEK = \left(\frac{\Phi_v}{P_{el}}\right)\cdot\left[\frac{\alpha \cdot L_{äq}}{L_v} + \beta \cdot BioNote\right] \qquad (1)$$

In Gl. (1), Φ_v stellt den Lichtstrom (lm) des Beleuchtungsproduktes und P_{el} dessen elektrische Leistung (W) dar. Es ist ersichtlich, dass die *Energieeffizienz* in dieser Komponente (SEK, Gl. 1) enthalten ist: die herkömmliche Größe *Lichtausbeute* (Φ_v/P_{el}) wird mit dem modifizierenden Ausdruck in den eckigen Klammern der Gl. (1) multipliziert. Dieser Ausdruck wird wie folgt erläutert. Wenn das Produkt für Innenraumbeleuchtung verwendet werden soll, dass verkörpert die Größe $L_{äq}$ die Messzahl der Helligkeit mit $L_{äq} = L_v\ (S/V)^{0.24}$ nach Fotios und Levermore [1]. Wenn das Produkt für Außenbeleuchtung verwendet werden soll, dann bedeutet $L_{äq} = L_{mes}$ [2], wie es oben bereits erwähnt wurde.

Um die Möglichkeit der *dynamischen Beleuchtung* zu favorisieren, ist der Wert von α in Gl. (1) gleich 1.00 wenn keine dynamische Beleuchtung in der vorhandenen Anwendung des Produktes gegeben ist und der Wert von α ist gleich 1.15 wenn dynamische Beleuchtung verwendet wird, aber nur dann, wenn die Dynamik im Bereich CCT=5500 K – 6500 K erfolgt. Die Daten (relatives Spektrum, Lichtstrom und elektrische Leistung) der höchsten Farbtemperatur-Einstellung sollen in diesem Fall für die Berechnung verwendet werden. Der Faktor α =1.15 ist vorläufig. Er wurde aus den Daten einer Studie abgeschätzt, in der die dynamische Beleuchtung eine signifikant positive Wirkung auf dauerhafte Frühschichtarbeiterinnen ausübte [11].

Die Absolutbeträge der Unterschiede der logarithmischen Werte der mittleren charakteristischen Werte aus der Studie [11] von Schlaf-Latenz, subjektiven Stimmungsurteilen von Angst/-Depression, Erregung und Herzfrequenz-Variabilität zwischen der dynamischen und der statischen Situation wurden errechnet. Im Mittel, der Wert 15% wurde als charakteristischer Nutzen der dynamischen Beleuchtung herausgefunden. Darum verwendet das neue Bewertungssystem den (vorläufigen) Wert 1.15.

Die *circadiane Wirkung* des Produktes (die durch die Größe *BioNote* in Gl. 1 dargestellt wird) wird nicht in Betracht gezogen, wenn das Produkt in der Außenbeleuchtung verwendet wird. In diesem Fall ist der Wert des sog. *Entscheidungsfaktors* β gleich 0. Für die Innenraumbeleuchtung, β ist gleich 1. Für die Innenraumbeleuchtung wird die Messzahl der circadianen Wirkung (*BioNote*) als aktivierend betrachtet, wenn die ähnlichste Farbtemperatur CCT≥3800 K ist. Sie wird als *entspannend* betrachtet, wenn die ähnlichste Farbtemperatur CCT≤3200 K ist. Dazwischen, d.h. bei 3200 K<CCT<3800 K, wird das Produkt als *weder aktivierend noch* *entspannend* aufgefasst. Für ein aktivierendes Beleuchtungsprodukt (CCT≥3800 K) errechnet sich der Wert *BioNote* nach Gl. (2).

$$BioNote(\text{aktivierend}) = 0{,}1\ [(a_{\text{mel}} / a_{\text{mel},0}) - 1] \quad (2)$$

Die Gl. (2) bedeutet, dass *stärker aktivierende* Lichtquellen (CCT≥3800 K d.h. neutralweiße – kaltweiße Lichtquellen) einen *höheren* Wert von *BioNote* bekommen. Die Größe a_{mel} in Gl. (2) wird aus der *relativen spektralen Strahlungsflussverteilung* der Lichtquelle berechnet. Das Symbol $a_{\text{mel},0}$ bedeutet den *melanopischen Wirkungsfaktor* der *Referenzlichtart*. Die Referenzlichtart wird als eine *Tageslichtphase*, ein *Schwarzkörperstrahler* oder eine Mischung der beiden definiert. Die Referenzlichtart wird (für jede CCT) aus der *relativen spektralen Strahlungsflussverteilung* der Lichtquelle (als Testlichtquelle) nach der Methode der CIE Publ. 224:2017 [9] errechnet. Diese Methode [9] beinhaltet einen kontinuierlichen, linearen Übergang von einer *Schwarzkörperstrahler-Referenz* nach einer *Tageslichtreferenz*, so dass die zu verwendende Referenzlichtart bei 4000 K und darunter ein reiner *Schwarzkörperstrahler*, bei 4500 K eine 50:50 Mischung, und bei 5000 K und darüber eine reine Tageslichtphase ist [9].

Im Bereich CCT≤3200 K (warmweiß oder entspannend) wird der Wert *BioNote* nach Gl. (3) definiert.

$$BioNote(\text{entspannend}) = 0{,}1\ [(a_{\text{mel},0} / a_{\text{mel}}) - 1] \quad (3)$$

Es soll betont werden, dass die Größe $a_{\text{mel},0}$ (der *melanopische Wirkungsfaktor* der *Referenzlichtart*) in Gl. (3) im Zähler erscheint, und nicht im Nenner, wie in der Gl. (2). So erhalten *entspannende* Lichtquellen (d.h. wärmere Weißtöne) einen höheren Wert von *BioNote* im Bereich CCT≤3200 K. Für *weder aktivierende noch entspannende* Lichtquellen (3200 K<CCT<3800 K) zeigt Gl. (4) die Berechnung von *BioNote*. Dabei werden die Gl. (2) und die Gl. (3) gemischt.

$$\text{BioNote} = 0.1\ [(a_{\text{mel},0} / a_{\text{mel}}) - 1]\ [(3800\text{K} - \text{CCT}) / 600\text{K}] + 0.1\ [(a_{\text{mel}} / a_{\text{mel},0}) - 1]\ [(\text{CCT} - 3200\text{ K}) / 600\text{ K}] \quad (4)$$

Im letzen Schritt des Berechnungsverfahrens des neuen Bewertungssystems wird ein Vorschlag dargestellt. Ziel diess Vorschlages ist eine neue Einteilung der Energieverbrauchsklassen (A bis G) bei der Energieverbrauchskennzeichnung. Die Zuordnung der genannten Beleuchtungsprodukte zu diesen Klassen wird gezeigt. Jede Kategorie (A: am besten; G: am schlechtesten) wird aus zwei Werten, R_a und SEK der Lichtquelle bestimmt. Dabei werden zwei Grenzwerte für jede Kategorie benutzt. Die in diesem Bericht veröffentlichten Grenzwerte werden als vorläufig betrachtet. Es ist vorgesehen, dass diese Werte während der zukünftigen Diskussionen geändert werden. Ein Beleuchtungsprodukt gehört zur Kategorie „A“ dann, wenn sowohl R_a und SEK größer sind, als die Grenzwerte der Kategorie “A”. Also, um das Kriterium “A” zu erfüllen, müssen sowohl R_a >R_a(Grenzwert,A) als auch SEK>SEK(Grenzwert,A) erfüllt sein.

Die Grenzen R_a(Grenzwert,A) und SEK(Grenzwert,A) stellen im neuen (zweidimensionalen) Bewertungssystem die Grenzwerte für die Kategorie “A” dar, d.h. die “beste Nützlichkeit” oder den “bester Nutzen” des Spektrums für den Benutzer in der vorhandenen Anwendung im Vergleich zur elektrischen Leistung. Der Bereich der Kategorie “A” auf der R_a-SEK-Ebene entspricht einem *rechteckigen Bereich* (Bereich“A”) in der rechten, oberen Ecke im R_a-SEK-Diagramm. Die weiteren Bereiche (B-G) sind *L-förmige Flächen* nach links und nach unten vom Bereich “A”. Um z.B. zur Kategorie “B” zu gehören, müssen sowohl R_a>R_a(Grenzwert,B) und SEK> SEK(Grenzwert,B) erfüllt sein; die Lichtquelle darf aber nicht zur Kategorie “A” gehören, usw.

Es ist sehr wichtig zu betonen, dass das neue Bewertungssystem zweidimensional ist: jedes Beleuchtungsprodukt erhält zwei Werte, R_a *und* SEK. Die Kategorien A-G werden jedem Produkt auf der Basis dieser zweidimensionalen Darstellung zugeordnet. Mathematisch gesehen wäre es grundsätzlich falsch, eine eindimensionale Größe als Basis der Bewertung auszuwählen und die Kategorien so zu bestimmen.

Es wurde eine Beispiel-Kalkulation durchgeführt, wobei die Werte R_a und SEK für einen Satz von 304 Lichtquellen (aus der Datenbank von METAS, Schweiz) mit α=1 (keine dynamische Beleuchtung) und β=1 (Innenraumbeleuchtung) berechnet wurden. Herkömmliche Glühlampen des Satzes erhielten die Kategorie G, Kompaktleuchtstofflampen die Kategorien F und G, und die anderen Leuchtstofflampen (semi-kompakte und rohrförmige) verschiedene Kategorien zwischen B und G. Nur einer rohrförmigen Leuchtstofflampe wurde die Kategorie B zugeordnet. Die 14 LED-Lichtquellen mit hoher Qualität erreichten eine Bewertung mit der Kategorie A.

Die vorläufigen R_a- und SEK-Grenzwerte der Kategorien wurden rechnerisch mit dem Kriterium bestimmt, dass sich in jeder Kategorie eine bestimmte, vordefinierte Anzahl an Produkten aus dem oben erwähnten Satz von 304 Produktdaten befindet. Dieses Kriterium stellt nur *eine* der möglichen Entscheidungsstrategien dar. Diese Strategie bzw. die Anzahl der Produkte in jeder Kategorie soll in der Zukunft diskutiert und angepasst werden.

Im Folgenden werden die allgemeinen Vorteile der neuen Methode zusammengefasst. Zuerst muss man einsehen, dass die Steigerung der Energieeffizienz der Beleuchtung heute eine sehr wichtige Angelegenheit ist. Um die Energieeffizienz zu beschreiben, wird heute weltweit die *Lichtausbeute* (lm/W) benutzt, eine Messzahl, die aus der Gewichtung des spektralen Strahlungsflusses der Lichtquelle mit der *$V(\lambda)$-Funktion* und der darauf folgenden Integration resultiert. Die $V(\lambda)$-Funktion gewichtet allerdings den spektralen Strahlungsfluss in der Nähe von 555 nm zu stark im Vergleich zum realen Nutzen [12] für den Menschen.

Im neuen Bewertungssystem werden aber alle Wellenlängen der wahren Bedeutung entsprechend in Betracht gezogen. Eine Messzahl der Farbqualität (der *allgemeine Farbwiedergabeindex* CIE CRI R_a) wird ebenfalls aufgegriffen. Diese Messzahl favorisiert ein *ausgeglichenes* Spektrum mit vielen gelben, orangenen und roten Inhalten. Die ebenfalls verwendeten Messzahlen der Helligkeit, der Sehleistung und des circadianen Effektes unterstützen kürzere (bläuliche) Wellenlängen. Wenn also das Spektrum des Beleuchtungsproduktes mit Hilfe der neuen Methode analysiert und dessen Nutzen mit Hilfe der neuen Methode dargestellt werden, dann wird die Energieeffizienz der Konversion der elektrischen Energie in sichtbare elektromagnetische Strahlung auf eine allumfassende Art und Weise quantifiziert, wesentlich besser, als mit Hilfe der herkömmlichen Lichtausbeute. Die Nutzen des Lichtes, die mit der Größe Lichtstrom (in lm) beschrieben werden können (z. B. *Sehschärfe*) bleiben in Gl. (1) durch den Ausdruck Φ_v erhalten.

Weitere Vorteile des neuen Konzeptes sind die Abhängigkeit von der Anwendung (Innenraum- oder Außenbeleuchtung) und die Berücksichtigung der Möglichkeit der *dynamischen Beleuchtung*. So bevorzugt die circadiane Komponente des neuen Bewertungsansatzes z.B. für den Abend zu Hause *warmweiße* Töne, was die Entspannung fördert und die Schlaf-Latenz (d.h. die Zeit bis zum Einschlafen) reduziert. Die *Kennzeichnung eines Beleuchtungsproduktes* mit den neuen Kategorien fördert die Produktivität der Arbeitsstunden sowie das Wohlbefinden und Lebensqualität der Benutzer. Eine verbleibende Frage besteht darin, wie die neue Methode für Nichtexperten kommuniziert wird. Das anschließende Gesetzgebungsverfahren ist schwierig. Das in diesem Dokument vorgeschlagene R_a-SEK-Diagramm ist zu diesem Zweck wahrscheinlich nicht geeignet. Viel zusätzliche Arbeit ist benötigt in der Zukunft, um neue Wege für die Darstellung zu entwickeln.

Wie oben beschrieben, wurden die Messzahlen der folgenden Nutzen der Beleuchtung in der neuen Methode aufgegriffen und kombiniert: Helligkeit und Sehleistung, der circadiane Effekt und die Farbqualität. Durch die Größe Φ_v in Gl. (1) wurde die Sehschärfe ebenfalls mitgenommen. Wie schon erwähnt, wurden nur die wichtigsten Aspekte ausgewählt, die aus dem *spektralen* Strahlungsfluss des Beleuchtungsproduktes resultieren.

So wurde z.B. die Eigenschaft der An- oder Abwesenheit von störenden Bunttönen im Weißton der Lichtquelle (z.B. grünliche oder lilafarbene Töne) [13] nicht berücksichtigt, weil die Hersteller in den meisten Fällen sehr sorgfältig auf diese sog. Weißtonqualität achten und mit schmalen visuellen Weißton-Toleranzbereichen arbeiten (in der heutigen LED-Technologie werden diese Toleranzbereiche “Bins” genannt).

Im Bericht werden statt der verwendeten Messzahlen der Einzelnutzen (z.B. CIE CRI R_a oder a_{mel}) auch weitere mögliche Metriken als *alternative Metriken* erwähnt und analysiert. So wurde z.B. Berman’s Helligkeitsmetrik [14] d.h. $L_{äq} = L_v\ (R/V)^{0.5}$ (R ist dabei das Stäbchensignal) nicht benutzt, weil (im Gegensatz zu L_{mes} der CIE 191:2010 [2]) diese Metrik (als Vorläufer der CIE-L_{mes}-Metrik) die Beiträge der Stäbchen- und Zapfensignale (bei verschiedenen Adaptationsleuchtdichten) nicht (unterschiedlich) gewichtet.

Um die wahrgenommene Helligkeit im photopischen Bereich zu beschreiben, wurde die Metrik von Fotios und Levermore [1] gewählt, weil diese experimentell sehr gut nachgewiesen wurde. Neue Experimente zeigten, dass das *S-Zapfen-Signal* ebenfalls geeignet ist, einen weiteren, wichtigen Nutzen, die sog. *Sehklarheit* [15] im photopischen Bereich zu beschreiben. Die CIE-Helligkeitsmetrik der äquivalenten Leuchtdichte [16] wurde nicht verwendet, weil sich ihre Genauigkeit bei der Deutung neuer Versuchsergebnisse als problematisch erwies.

Um die *circadiane Wirkung* zu charakterisieren, wurde der sog. *melanopische Wirkungsfaktor* a_{mel} [4] verwendet. In der Zukunft könnte dafür der sog. *circadiane Reiz* (CS) [17, 18, 19, 20] als alternative Metrik aufgegriffen werden. Die CS-Skala wurde in neuen Feldstudien verifiziert [20]. Die Größe CS beschreibt die Wechselwirkungen der Stäbchen- und Zapfen-Rezeptoren mit den Signalen der ipRGCs und die daraus resultierenden *spektralen Nichtadditivitäten.*

Der *melanopische Wirkungsfaktor* a_{mel} berücksichtigt die Neurophysiologie und Neuroanatomie der Netzhaut und die Funktionalität des *circadianen Systems* nicht [20]. Trotz dieser bekannten Schwäche wurde für die neue Methode die Größe a_{mel} gewählt, weil deren Berechnung einfach ist, im Gegensatz zum komplizierten Arbeitsablauf von CS. Die Einfachheit der Berechnung ist für praktische Lichtdesigner wichtig. Die zwei Messzahlen (a_{mel} und CS) wurden an Hand des oben erwähnten Satzes der 304 Spektraldaten verglichen. Es wurde festgestellt, dass die Größen CS und $\log_{10}(a_{mel}\ E_v)$ zwischen 10 lx und 1000 lx miteinander linear mit r^2=0.95 korrelieren.

Was die *Farbqualität* anbelangt, wurde der *allgemeine Farbwiedergabeindex* CIE CRI R_a [3] benutzt, weil dieser heute weltweit verwendet und in Messgeräten implementiert wird. In der Zukunft könnte stattdessen der sog. CIE-2017-Farbtreueindex (colour fidelity index; CIE R_f) [9] verwendet werden. Letzterer Index wurde für “wissenschaftliche Zwecke” vorgeschlagen. Darum wurde er für den neuen Bewertungsansatz des vorhandenen Berichtes nicht eingesetzt. Um die sog. Farbpräferenz-Eigenschaft (die für die Allgemeinbeleuchtung wichtiger ist, als die

Farbtreue-Eigenschaft) zu beachten (die Eigenschaften der Farbpräferenz weichen von den Eigenschaften der Farbtreue oft stark ab [8, 19]), könnte statt R_a in der Zukunft die sog. Farbqualitätsskala Q_p (*colour quality scale;* CQS Q_p [10]) verwendet werden. Die CQS Q_p-Metrik wies eine gute Leistung bei der numerischen Deutung von visuellen Farbpräferenzdaten auf [21].

Die CQS Q_p-Metrik ist leider nicht so bekannt (und wird in internationalen Arbeiten selten erwähnt), wie die andere, international bekanntere Messzahl der CQS-Methode, CQS Q_a, die eine schlechtere Korrelation mit visuellen Farbpräferenzdaten aufweist. Die Messzahlen des *Farbgamut* (wie viele Farben eine Lichtquelle wiedergibt; z.B. die sog. IES R_g[22] und CQS Q_g [10]) korrelieren schlecht mit den anderen, oben erwähnten Farbqualitätsmetriken. Dies wurde in einer weiteren Berechnung für die 304 Daten bestätigt. So könnte eine Farbgamutmetrik eine mögliche dritte Dimension der Bewertung der Lichtquellen darstellen. Eine Farbgamutmetrik wird in der neuen Methode allerdings nicht verwendet, weil sie die Übersättigung der Objektfarben unterstützen, was von den Beobachtern in der Allgemeinbeleuchtung visuell nicht bevorzugt wird [21].

Zusammenfassend kann festgestellt werden, dass der vorhandene Bericht ein neues Bewertungssystem für Beleuchtungsprodukte beschreibt. Mit Hilfe dieser neuen Methode können die wichtigsten Nutzen des Lichts für den Menschen quantifiziert werden [23]. Das neue Bewertungssystem ist zweidimensional mit zwei orthogonalen Komponenten: 1. der *allgemeine Farbwiedergabeindex* (CIE CRI R_a; Abszisse), die die Farbqualität beschreibt und 2. SEK, eine neue Messzahl, der sog. Stromeffizienzkennwert (Ordinate).

Die erste Komponente, d.h. die Größe CIE CRI *R*a hängt (bei fixem relativen Spektrum eines Beleuchtungsproduktes) vom Leuchtdichteniveau und dadurch von der elektrischen Leistung (P_{el}) per Definition nicht ab. Die zweite Komponente, d.h. der Stromeffizienzkennwert SEK (die die Messzahlen der Helligkeit, der Sehleistung, der circadianen Wirkung und die konventionelle Lichtausbeute kombiniert) beinhaltet die Abhängigkeit von der elektrischen Leistung des Beleuchtungsproduktes.

Die Abhängigkeit von der Anwendung bedeutet, dass die neue Messzahl SEK für *entspannende* Anwendungen *warmweiße* Lichtquellenspektren, für *aktivierende* Anwendungen aber *neutralweiße* oder *kaltweiße* Lichtquellenspektren favorisiert. Es gibt ebenfalls eine Abhängigkeit davon, ob das Beleuchtungsprodukt in der Innenraum- oder der Außenbeleuchtung eingesetzt wird, bzw. davon, ob dynamisches Licht vorhanden ist. Die Definition der Kategorien (A-G) des Beleuchtungsprodukts im neuen Bewertungssystem ist zweidimensional. Die Grenzen der Kategorien in einem eindimensionalen System würden ein falsches Ergebnis liefern, weil der Bewertung der Nutzen des Lichts für den Menschen (min.) zwei Dimensionen zugrunde liegen. Diese neuen Kategorien (A-G) charakterisieren den allgemeinen Nutzen eines Beleuchtungsproduktes für den menschlichen Benutzer im Vergleich zu dessen elektrischer Leistung.

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Summary

The energy efficiency of lighting products is currently evaluated by the quantity *luminous efficacy* (lm/W). This quantity is calculated from *luminous flux* (lm). But the quantity of *luminous flux* does not provide a full description of the effect of light (electromagnetic radiation in the wavelength range of 360 nm to 830 nm) on humans: luminous flux is not a suitable quantity to describe all *benefits of lighting* for humans resulting from every *spectral range*.

Lighting products and lighting systems enable different visual tasks. To carry out these tasks, much more than a certain amount of luminous flux alone is needed: light should be delivered with the correct brightness, correct chromaticity and at the correct time. *Electric power* demand usually increases with increasing *lighting benefit* requirements. But if we evaluate electric efficiency only by the aid of the quantity *luminous efficacy* (lm/W) then the real benefit of a lighting product can be very low in a real application.

If *luminous efficacy* is used as the only evaluation criterion of *lighting products* then the lighting products with high, multiple benefits but with lower luminous efficacy might not fulfil the requirements to obtain excellent energy efficiency assessment. Consequently, they might disappear from the market because they do not fulfil legal requirements although they would be very beneficial for their users. This is why the benefit of lighting products in terms of energy efficiency shall be better formulated and better taken into account in the future.

Accordingly, the aim of the present document is to derive new quantities to evaluate the real benefits of lighting for human users and to combine the numeric descriptors of the single benefits of lighting as a new, comprehensive numeric *evaluation concept*. This new evaluation concept and the corresponding mathematical method are presented in this document. The new concept and the new method were applied to a sample set of *light source* data and this set was evaluated by the new method as an example.

The design of the *spatial properties of light* e.g. *spatial radiance distributions* and *spatial irradiance distributions* e.g. "wall washing", diffuse lighting or spot lighting, highlights and shadows and the *temporal properties of light* e.g. dynamic lighting (i.e. changing the *correlated colour temperature* abbreviated by CCT during a working day) constitute the subject of *lighting quality* considerations in architectural design. The present evaluation concept deals only with the *spectral properties of lighting* i.e. with those properties that result from the *spectral power distribution* of the lighting system, or, more specifically, the *light source* used in it.

More precisely, the present evaluation concept was developed by searching for an appropriate *numeric quantity* to represent the most important benefits resulting from the spectrum of the light source for a human user. The aim was to summarize all these benefits and to express the *usefulness of the light source* in a practicable way. By definition, we considered a light source or a lighting system *useful* if it exhibits as many benefits of lighting (e.g. brightness, visual performance, biological activating effect, *colour quality*) as possible by the use of *as less electric energy as possible*.

Thus, the aim of the present document is to describe the *mathematical definition* of a set of two numeric quantities that constitute a unique two-dimensional evaluation concept. This evaluation concept summarizes the most important benefits of a light source for a human. The numeric quantities are to be computed from the *spectral power distribution* and the *input electric power* (in W) of the light source. As mentioned above, the *luminous efficacy of a source* in *lumens per watt* units (which is still widely used today to this aim) is *not* an appropriate quantity.

More specifically, the reason is that the *V(λ) function* (the basis of conventional *photometry*) represents only the linear combination of the *long-wavelength sensitive* and the *medium-wavelength sensitive* cone photoreceptors. It disregards the important signals of the *short-wavelength sensitive* cone photoreceptors, the rod photoreceptors (that are responsible for *scotopic vision* and co-working with the cone photoreceptors in mesopic vision) and the *intrinsically photosensitive retinal ganglion cells* (ipRGCs; these are responsible for the biologically activating effect or *circadian effect of light*).

The concept of the present document is that, instead of the concept of the *luminous efficacy of a source*, a combination of benefit-relevant descriptor quantities should be used to characterize the light source including a *colour rendition index*, a measure of brightness and *visual performance*; and a measure of the *circadian effect*. Of course, mathematically, there are many possibilities to combine such *descriptor quantities* that result from the spectral power distribution of the light source and the electric power. In the present document, the computational method of one possible, plausible proposal (suitable for general industrial acceptance) is described. This proposal contains a new evaluation system with a new usefulness measure.

During the development of the new evaluation method, for the sake of a practicable and widely acceptable solution for the characterization of the light source, only the most essential *benefits of lighting for humans* for general *interior lighting* and *exterior lighting* were considered. It was accentuated that the new method should be discussed in a dialogue with lighting industry and governmental representatives during the development phase.

It was also emphasized that the metrics to describe the selected (i.e. most important) *benefits of lighting* should be based on well-established and well-known work e.g. widely-known publications or international standards. By doing so, the aim was to be ready for world-wide industrial applications. We also proposed that the new evaluation system should be tested for a representative set of at least 300 absolute spectra (i.e. absolute spectro-radiometric data including the luminous efficacy of a source in lm/W units) of today's widely used light sources. During the development of the project, this set (typical commercial lighting products) was obtained with the cordial help of METAS, Switzerland.

Another consideration was that the value of the new usefulness measure should be *application dependent*. For example, if the aim is *concentrated work* in an office then the new value should be very low in case of a *warm white* light source. The reason is that, although we input electric energy, the users (who would like to work) will not be satisfied as they rather need a *cool white* light source for concentrated working. But the same *warm white* light source should obtain a higher new value if it is being used to illuminate a living room in the evening for relaxing. Additionally, we demanded that the type of application (interior lighting, exterior lighting) and the *luminance level* in exterior lighting (type of street) as well as the possibility of *dynamic lighting* should also be considered.

According to the above, the following *benefits of lighting* and *lighting quality metrics* (the numeric descriptors of the benefits of lighting) were selected to be represented in the new evaluation system:

1. *Brightness* and *visual performance*: to describe this benefit, the so-called *equivalent luminance* $L_{äq}$ (Fotios and Levermore [1] was selected for *interior lighting* applications and the so-called *mesopic luminance* L_{mes}(CIE 191:2010 [2]) was selected for *exterior lighting* applications.

2. Colour Quality: to describe this benefit, the *general colour rendering index,* CIE CRI R_a[3] was selected.

3. Circadian Effect (the biological activating effect of light): to describe this benefit, the quantity a_{mel}[4] was selected.

Summarizing the above, three benefits of lighting, brightness, colour quality and the circadian effect were selected to be included in the new evaluation method. It was decided that the concept of brightness should be described by the quantity Läq = Lv (S/V)0.24 according to Fotios and Levermore [1] if the light source should be used for interior lighting ($L_{äq}$ means equivalent luminance and L_v means luminance in cd/m2). Here, the symbol S represents the signal of the short-wavelength sensitive human photoreceptors (the so-called S-cones) computed by weighting the relative spectral power distribution of the light source with the spectral sensitivity of the S-cones (with the so-called Smith and Pokorny cone photoreceptor sensitivity data [5]) and integrating in the visible wavelength range. The quantity V (so-called V-signal) is obtained by weighting the relative spectral power distribution of the light source with the V(λ) function and integrating in the visible wavelength range.

If the light source should be used for exterior lighting then the quantity L_{mes} (the mesopic luminance of CIE Publ. 191:2010 [2]) comes into play instead of Lv (S/V)0.24. When computing the value of the mesopic luminance L_{mes}, either L_v=3.0 cd/m2 (that represents M-class streets [6]) or L_v=0.3 cd/m2 (that represents P-class streets [6] with 5 lx and with a luminance coefficient of the road of 0.06 cd/(m^2 lx)) is used as the luminance level in the computational method of CIE Publ. 191 [2].

The reason of choosing L_{mes}[2] to describe brightness for exterior lighting is that although it was developed from visual performance data, this measure (i.e. L_{mes}[2]) correlates well with brightness [7] (r2=0.86 according to Fig. 4 in [7]). The mesopic metric L_{mes} weights the rod photoreceptor signal and the cone photoreceptor signals at the characteristic lower (mesopic) luminance levels of exterior lighting while the $L_{äq}$ metric according to Fotios and Levermore [1] considers the S-cone photoreceptors that have a more accentuated response at the characteristically higher (photopic) luminance levels of interior lighting than the rod photoreceptors.

The circadian effect is characterized by the so-called melanopic factor a_{mel} computed from the relative spectral power distribution of the light source according to DIN SPEC 5031-100 [4] in the following way: the relative spectral power distribution is weighted by the so-called $s_{mel}(\lambda)$ function [4] (based on Lucas et al. [8]) and integrated in the visible wavelength range; and the result is divided by the above defined V-signal of the relative spectrum.

According to the above considerations, the new evaluation system was defined as follows. Input quantities of the computational method are the spectral power distribution of the light source, the luminous flux (lm) and the electric power (W) of the light source. The new usefulness measure was defined as a two-dimensional quantity (i.e. consisting of a set of two values) to be represented as a point in a diagram with two orthogonal axes. A measure of colour quality (Ra) is on the abscissa. Due to its widespread use today, this measure is the conventional CIE general colour rendering index CIE CRI Ra [3], as mentioned above. In future discussions, the quantities CIE Rf [9] or CQS Qp [10] can also be considered.

A new combined measure of the brightness and the circadian effect of the light source appears on the ordinate of the above mentioned diagram. This new combined measure is called new energy efficiency measure (abbreviated by SEK). This the new diagram is called Ra-SEK diagram. The new quantity SEK is defined by Eq. (1).

$$SEK = \left(\frac{\Phi_v}{P_{el}}\right) \cdot \left[\frac{\alpha \cdot L_{äq}}{L_v} + \beta \cdot BioNote\right] \quad (1)$$

In Eq. (1), Φ_v is the luminous flux (lm) of the light source and P_{el} is the electric power (W). As can be seen, *energy efficiency* is incorporated in this second component (SEK, Eq. 1) by multiplying the *luminous efficacy of a source* (Φ_v/P_{el}) by the compound modification term in the square brackets in Eq. (1). This modification term is explained as follows. If the light source should be used for *interior lighting* then the quantity $L_{äq}$ represents the measure of scene brightness with $L_{äq} = L_v\ (S/V)^{0.24}$ according to Fotios and Levermore [1], and, if the light source should be used for exterior lighting then $L_{äq} = L_{mes}$ [2], as already mentioned above.

To be in favour of *dynamic lighting*, the value of α in Eq. (1) equals 1.00 if there is no dynamic lighting in the given application of the light source. The value of equals 1.15 if there is dynamic lighting with correlated colour temperatures in the range CCT=5500 K – 6500 K. Data (relative spectrum, luminous flux and electric power) of the highest available CCT shall be used to carry out the computation in this case. The factor α =1.15 is a preliminary value estimated from a previous experiment in which significant positive effect of dynamic lighting on female permanent morning shift workers was found [11].

The absolute values of the differences of the logarithms of the mean characteristic values of sleep latency, subjective mood rating of anxiety/depression, arousal and heart rate variability between the dynamic and the static conditions were calculated from the above mentioned data [11]. In average, the value of 15% was found as a characteristic benefit percentage of dynamic lighting hence the multiplicative factor of α =1.15 is used.

The *circadian effect* of the light source (represented by the value of *BioNote* in Eq. 1) is not taken into consideration if the light source is used for *exterior lighting* and this is expressed by setting the so-called *decision factor* β to *zero* in case of *exterior lighting* applications. For i*nterior lighting*, β equals 1. For interior lighting, the descriptor of the circadian effect (*BioNote*) is considered *activating* in case of CCT≥3800 K, *relaxing* for CCT≤3200 K and *neither activating nor relaxing* for 3200 K<CCT<3800 K. For an activating light source (CCT≥3800 K), Eq. (2) shows how to compute the value of the descriptor of the circadian effect, the so-called *BioNote*.

$$BioNote(\text{activating}) = 0.1\ [(a_{mel} / a_{mel,0}) - 1] \quad (2)$$

Equation (2) means that more activating light sources get a higher *BioNote* value in the range of CCT≥3800 K (i.e. the neutral white – cool white light sources). In Eq. (2), the quantity a_{mel} is computed from the *relative spectral power distribution* of the light source while the symbol $a_{mel,0}$ means the *melanopic factor* of the *reference light source* which is defined as a *phase of daylight*, a *blackbody radiator* or a mixture of the two. This reference light source is determined (for any CCT) according to the method of CIE Publ. 224:2017 [9] from the *relative spectral power distribution* of the light source to be evaluated (as a test light source). This method includes "a smooth, linear transition from a *Planckian reference light source* to a *daylight reference light* *source* such that at 4000 K and below it is purely *Planckian*, at 4500 K it is a 50:50 mix of the two, and at 5000 K and above it is purely a *daylight reference light source*."[9]

In the range of CCT≤3200 K (warm white or relaxing), the value of *BioNote* in Eq. (1) is defined according to Eq. (3).

$$BioNote(\text{relaxing}) = 0.1\ [(a_{mel,0} / a_{mel}) - 1] \qquad (3)$$

Note that the quantity $a_{mel,0}$ (the *melanopic factor* of the *reference light source*) is in the numerator in Eq. (3) unlike Eq. (2). In Eq.(2), $a_{mel,0}$ appears in the denominator. Thus, *more relaxing* light sources (i.e. warmer *white tones*) obtain a higher value of *BioNote* in the range of CCT≤3200 K. Finally, in case of *neither activating nor relaxing* light sources (3200 K<CCT<3800 K), Eq. (4) shows the way of computing the value of *BioNote* by mixing Eq. (2) and Eq. (3).

$$\text{BioNote} = 0.1\ [(a_{mel,0} / a_{mel}) - 1]\ [(3800\text{K} - \text{CCT}) / 600\text{K}] + 0.1\ [(a_{mel} / a_{mel,0}) - 1]\ [(\text{CCT} - 3200\ \text{K}) / 600\ \text{K}] \qquad (4)$$

As a last step of the computations in the new evaluation system, a *usefulness category* (A: best; down to G: worst) is determined from the values of R_a and SEK of the *light source* in the *R_a-SEK plane* by the use of a set of *category limit* values. These *category limit* values are considered as preliminary (subject to subsequent discussions). A light source belongs to the category „A" if both R_a and SEK are greater than the limiting value of the category "A". This means that, in order to satisfy the "A" criterion, both R_a >R_a(limit,A) and SEK>SEK(limit,A) shall be satisfied.

The quantities R_a(limit,A) and SEK(limit,A) represent the limits for the category "A" (i.e. "best usefulness" or "best benefit" of the spectrum for the user in the given application) in the new (two-dimensional) evaluation system. This corresponds to a *rectangular domain* (domain "A") in the top right corner of the R_a – SEK diagram. The following domains (B-G) are *L-shaped areas* to the left of and below domain "A" in the R_a-SEK diagram of the new evaluation system. To belong to the category "B", both R_a>R_a(limit,B) and SEK> SEK(limit,B) shall be true but the light source should not belong to domain "A", etc.

At this point, it is very important to point out that the new evaluation system is *two-dimensional*: every light source obtains two values (R_a and SEK). The categories A-G are determined based on this two-dimensional representation. Mathematically, it would be false to use a one-dimensional quantity as a basis of the new evaluation system and the determination of the categories in the framework of the new concept.

In a sample computation, the values R_a and SEK were calculated for a *sample set* of 304 light sources (thankfully obtained from METAS, Switzerland) with α=1 (no dynamic lighting) and β=1 (interior lighting) in this example. Conventional incandescent lamps in this *sample set* obtained the category G, compact fluorescent lamps obtained the categories F and G while the other fluorescent light sources (semi-compact and tube-shaped) obtained a broad range of category assignments between B and G with one tube-shaped fluorescent lamp in the category B. Finally, 14 high-quality LED light sources reached the "category A" evaluation.

The preliminary category limit values were determined computationally to get a predefined percentage value in each category. The use of predefined percentage values represents just one possible decision strategy. This strategy and the percentage values themselves should be discussed in the future.

Concerning the general advantages of the new usefulness evaluation method, it should be noted that the increase of *electric energy efficiency* of lighting is a very important issue today. To quantify energy efficiency, today's accepted metric is *luminous efficacy of a source* (lm/W), a quantity which is the result of weighting the *spectral radiant flux* of the light source by the *$V(\lambda)$ function*. But, as mentioned in the Introduction, the $V(\lambda)$ function over-weights the *spectral power distribution* of the light source in the range around 555 nm compared to its benefit [12] for human users.

In the new evaluation system, however, all useful wavelengths are equally considered because a *colour quality measure* (the CIE CRI R_a *general colour rendering index* in the present version) is also included. Latter measure is in favour of a *balanced* spectrum with ample yellow, orange and red content. At the same time, the measures of brightness and the circadian effect support shorter (bluish) wavelengths. Therefore, if the spectrum of the light source is characterized and then categorized by the aid of the new method then the efficiency of converting electric energy into electromagnetic radiation is represented in a more comprehensive way than provided by the conventional concept of *luminous efficacy of a source*. The *benefits of lighting* described by the luminous flux (in lm) of the light source (e.g. *visual acuity*) remain included via the term Φ_v in Eq. (1).

Also, the new concept includes a dependence on the type of *lighting application* (*interior lighting* or *exterior lighting*) and a possible way of considering the availability of *dynamic lighting*. E.g. for "relaxing" applications, the *circadian* component is in favour of *warm white tones* and this fosters relaxation and reduces sleep latency in the evening. The *labelling of a light source* by the new categories fosters the productivity of working hours and the satisfaction and life quality of the light source user. A remaining issue is how to communicate the new method for the labelling of lighting products for non-experts. The succeeding legislative procedure is a difficult task. The proposed R_a-SEK diagram is possibly not appropriate to this purpose and much additional work is required in the future.

As seen above, the descriptor quantities of the following *benefits of lighting* were combined in the new concept: brightness, the circadian effect and colour quality; and, implicitly, via the term Φ_v in Eq. (1), also a further aspect, *visual acuity*. As already mentioned, only some *selected* aspects were considered in the present version and only those aspects that can be described based on the *spectral* power distribution of the light source.

The presence or absence of *disturbing tints* (e.g. greenish or purplish shades) in the perceived *white tone* of the light source [13] was not included in the new method because manufacturers tend to avoid such *white tones* by the use of appropriately tight LED chromaticity regions (so-called "bins") in recent times.

Concerning the use of *alternative metrics* to quantify the individual *benefits of lighting*, Berman's metric [14] i.e. $L_{äq} = L_v (R/V)^{0.5}$ (R is the *rod photoreceptor signal* to be computed by weighting the *relative spectral power distribution* of the light source by the *scotopic luminous efficiency function*) was not used because (unlike L_{mes} of CIE 191:2010 [2]) this metric (a forerunner of L_{mes}) does not *weight* rod photoreceptor and cone photoreceptor contributions at different mesopic levels *differently*.

To compute *brightness* in the photopic range, the Fotios and Levermore [1] metric was chosen because it is experimentally well-established. Also, recent experimental evidence showed the appropriateness of the *S-cone photoreceptor signal* to describe another important attribute, *visual clarity* [15] in the *photopic range of vision*. The *equivalent luminance metric* of the CIE [16] was not used because its accuracy was problematic when predicting some recent experimental results.

To characterize the *circadian effect*, the *melanopic factor* a_{mel} [4] was used. In future possible modifications of the present version of the new evaluation method, the so-called *circadian stimulus* (CS) [17, 18, 19, 20] is an alternative. The CS scale was tested and verified in recent field studies [20]. The quantity CS accounts for the interactions of the rod photoreceptor and cone photoreceptor signals with the signals of the *intrinsically photosensitive retinal ganglion cells* (ipRGCs) and also for *spectral non-additivities*.

The *melanopic factor* a_{mel} does not take the neurophysiology and neuroanatomy of the retina nor the operating characteristics of the *circadian system* into account [20]. Despite this known deficiency, a_{mel} was chosen in the present version of the new evaluation method due to its simplicity. Simplicity is important for practical *lighting design*. Comparing the two measures (a_{mel} and CS) in case of the sample set of 304 light source data, it was found that the quantities CS and $\log_{10}(a_{mel}\,E_v)$ correlate linearly with r^2=0.95 between 10 lx and 1000 lx.

Concerning *colour quality*, the *general colour rendering index* CIE CRI R_a [3] is used in the present version of the new evaluation method due to its worldwide acceptance and universal implementation today. In the future, the CIE 2017 colour fidelity index (CIE R_f) [9] can also be considered instead. Latter index is intended only for "scientific use" at the moment, therefore it was not included in the present (application oriented) new evaluation method. To incorporate *colour preference* characteristics which are more relevant for *general lighting* than *colour fidelity* (*colour preference* characteristics deviate from the colour fidelity framework, see e.g. [8, 19]), the *colour quality scale metric* CQS Q_p [10] can be applied as an alternative metric in the future to replace R_a. Latter metric (CQS Q_p) performed reasonably well in recent visual *colour preference* experiments [21].

The metric CQS Q_p (which correlates better with visual *colour preference* characteristics than the other metric of the CQS method, CQS Q_a) is not so well known and it is not incorporated in international standards. The measures of *colour gamut* (IES R_g[22] and CQS Q_g [10]) do not correlate well with the other considered *colour quality* metrics. This was shown in an additional computation in case of the 304 light sources. Thus the measures of *colour gamut* represent a possible third dimension in a future version of the new evaluation method. A *colour gamut measure* was not included in the new evaluation method because a (standalone) *colour gamut metric* is in favour of oversaturating the coloured objects of an illuminated scene and this is *not preferred* by the users in *general lighting* applications [21].

In summary, it can be concluded that the present document contains a new evaluation system with a new measure to describe the most important benefits of a light source for human users [23]. The new evaluation system is two-dimensional with two orthogonal components, 1. the *general colour rendering index* (R_a; abscissa) and 2. SEK, a new *energy efficiency measure* (ordinate). The first component, the conventional general colour rendering index (CIE CRI R_a) is intended to describe the *colour quality* of the light source.

As it is assumed that (above a certain *illuminance level*) *colour quality* does not depend on the amount of *electric energy* consumed, this quantity (R_a) was used because it intrinsically does not depend on input electric power (P_{el}). The second component (SEK) is an *application dependent* combination of a descriptor of *brightness* and a descriptor of the *circadian effect*. The dependence on *luminous flux* was preserved in the definition of the new quantity SEK (see Eq. 1) in order to retain a descriptor of *visual acuity*.

The dependence of lighting application (or *application dependence*) means that the value of SEK supports *warm white* light source spectra for *more relaxing* applications while it supports *neutral white* and *cool white* spectra for *activating* applications. The definition of the categories (A-G) of the *lighting product* in the *new evaluation system* is two-dimensional. Mathematically, a one-dimensional quantity to determine the category limits would be meaningless because there are (at least) two underlying dimensions. The categories (A-G) characterize the overall benefit of the lighting product for the human user (i.e. its usefulness) related to its electric energy consumption.

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1 Objective

The energy efficiency of lighting products is currently evaluated by the quantity luminous efficacy (lm/W). This quantity is calculated from luminous flux (lm). But the quantity of luminous flux does not provide a full description of the effect of light (electromagnetic radiation in the wavelength range of 360 nm to 830 nm) on humans: luminous flux is not a suitable quantity to describe all benefits of lighting for humans resulting from every spectral range. Lighting products and lighting systems enable different visual tasks. To carry out these tasks, much more than a certain amount of luminous flux alone is needed: light should be delivered with the correct brightness, correct chromaticity and at the correct time. Electric power demand usually increases with increasing lighting benefit requirements. But if we evaluate electric efficiency only by the aid of the quantity luminous efficacy (lm/W) then the real benefit of a lighting product can be very low in a real application.

Lighting products and lighting systems enable different visual tasks. To carry out these tasks, much more than a certain amount of luminous flux alone is needed: light should be delivered with the correct brightness, correct chromaticity and at the correct time. Electric power demand usually increases with increasing lighting benefit requirements. But if we evaluate electric efficiency only by the aid of the quantity luminous efficacy (lm/W) then the real benefit of a lighting product can be very low in a real application.

If luminous efficacy is used as the only evaluation criterion of lighting products then the lighting products with high, multiple benefits but with lower luminous efficacy might not fulfil the requirements to obtain excellent energy efficiency assessment. Consequently, they might disappear from the market because they do not fulfil legal requirements although they would be very beneficial for their users. This is why the benefit of lighting products in terms of energy efficiency shall be better formulated and better taken into account in the future. Accordingly, the aim of the present document is to derive new quantities to evaluate the real benefits of lighting from the current state of the art of our knowledge. These new quantities that describe the single, standalone benefits of lighting will be combined to arrive at a new, comprehensive numeric evaluation concept.

2 The $V(\lambda)$-function as a basis for the computation of luminous efficacy

2.1 Introduction

In the year 1924, the CIE defined the function which is known today as $V(\lambda)$, the spectral luminous efficiency function for daylight (photopic) vision [1]. Thus, the basis for the perceptual characterisation of light sources and illumination situations was established from those days' point of view. Based on this function (which was considered as provisional already at the beginning) and the quantities derived for lighting engineering application, numerous studies and research and development work have been carried out up to now. Their results are to be found in references and standards of interior and exterior lighting, automotive lighting and display lighting. The CIE defined in 1931 the colorimetric system with spectral colour matching functions which is officially endorsed today. In this system, one of the basic functions, the so-called $y(\lambda)$ function is identical with the $V(\lambda)$ function thus there is a very tight relationship between colorimetry and photometry and the two domains cannot be separated.

From 1924 up to now, there have been several development steps of lighting engineering and colorimetry. At the beginning of the 20th Century, blackbody radiators (incandescent lamps) were introduced. At the middle of 20th Century, discharge lamps like mercury and sodium vapour discharge lamps, Xenon lamps and fluorescent lamps were developed with different spectra, colours and luminous efficacies. Since the 1960's, generations of well-established technologies have appeared on the market: tungsten halogen, compact fluorescent and halogen metal vapour lamps. A couple of years ago, the era of solid state light sources began. This era shall influence the history of lighting engineering to a huge extent never seen before: a plethora of different LED lamp spectra shall appear and the application areas of illumination technology shall be increased by several orders of magnitude.

Parallel to this technological development, according to the increasing demand for good illumination, a fundamental scientific discussion took place about the effect of optical radiation on humans. Especially, the following aspects were discussed: colour rendering, its deficits and amendment concepts in the framework of today's colorimetry, the effect of light on health (this issue has been intensively elaborated in the last years) as well as the perceptual and visual performance related aspects of light and lighting both in daylight and in twilight vision.

It is easy to note that we need deep scientific thoughts and knowledge to solve the problems of correct lighting in every application related to the above described tasks. The following fundamental questions have to be answered:

1. What are the underlying physiological and psychophysical processes to establish the spectral sensitivity functions of vision? What perceptual processes constitute the basis of the $V(\lambda)$ function?
2. Can the processes of the visual tasks brightness, contrast and visual acuity detected physiologically? What are their most important parameters of their spectral and integrative behaviour?
3. What are the limits of application of today's spectral sensitivity functions?
4. What kind of modern perceptual models are at our disposal today? How large and relevant are the differences between recent models and the classical models of lighting engineering that are still in used today?

5. Can we describe glare by the aid of V(λ) based quantities like luminance or illuminance? Alternatively, shall the spectral evaluation of glare be based on another physiological process which cannot be described by the V(λ) function?
6. What process is responsible for the state of adaptation of the human visual system under photopic and mesopic viewing conditions? How does the visual system express a certain state of adaptation in a certain illumination situation?

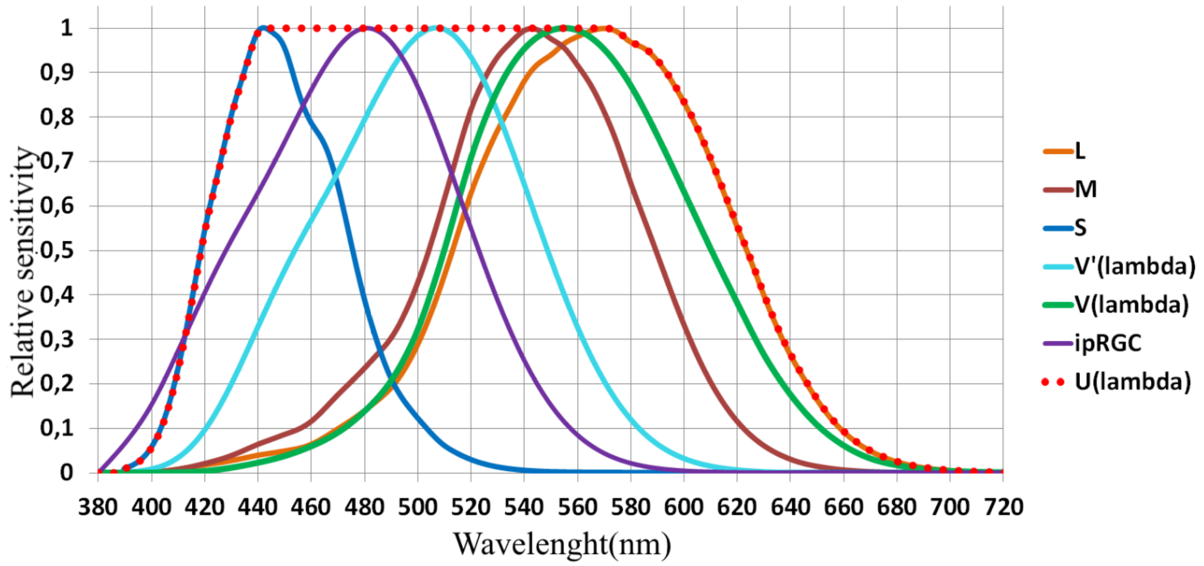
2.2 Retinal mechanisms and *V(λ)* function

The most important components of the human eye are, from the direction of incident light, the cornea, the pupil, the lens and the retina. According to current, generally accepted practice, the diameter of the pupil depends solely on photopic object luminance. This means that the chromaticity of the object has no effect on pupil size according to today's possibly most widely used formula [2] in Eq. (2.1).

$$d = 5 - 3 \cdot \tanh\left(0{,}4 \cdot \mathrm{Log}\left(L_p\right)\right) \tag{2.1}$$

In Eq. (2.1), d represents pupil diameter and L_p is photopic luminance calculated by the $V(\lambda)$ function. If luminance is high (>150.000 cd/m^2) then pupil diameter comes close to 2 mm. If luminance is low (about 0.001 cd/m^2) then the value equals about 8 mm. The formulae is valid for a viewing field of 50° or more. There are 4 type of photoreceptor on the retina. They receive optical information and transform them into nerve signals. The three types of cone photo-receptors (so-called L, M and S) are active in case of daylight and also in twilight. Their spectral sensitivity functions peak in the long- (L), medium (M) and short (S) wavelength range of the visible spectrum. The spectral sensitivity of the rods, $V'(\lambda)$, has ist maximum at 507 nm, see Figure 1. Rods are active by twilight and during the dark viewing conditions i.e. at night.

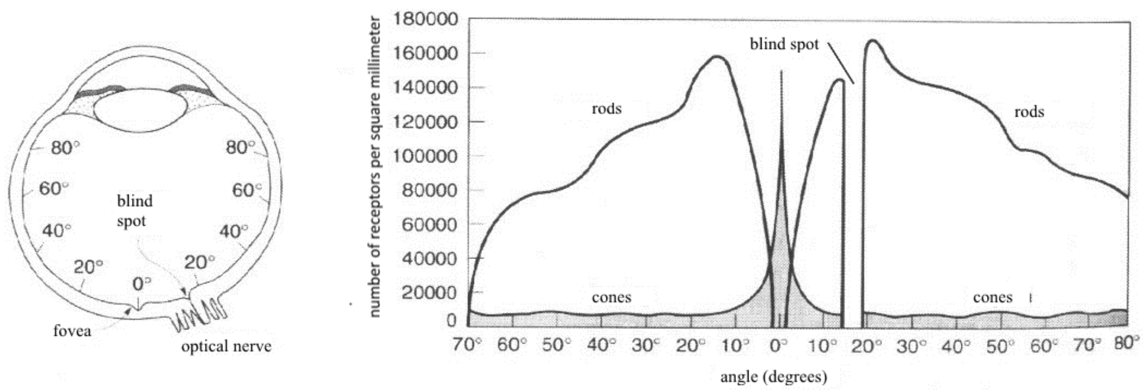
Figure 1: Spectral sensitivity functions of the L-, M-, and S-cones, the ipRGCs, the *V*(λ) function, the *V'*(λ) function (rods) and the so-called *U*(λ) function



The local spatial distribution of the cones and the rods on the retina is shown in Figure 2. It can be seen that the foveal area at about 2 ° contains only cone receptors. Going outwards, the density of cones is reduced and rod density increases.

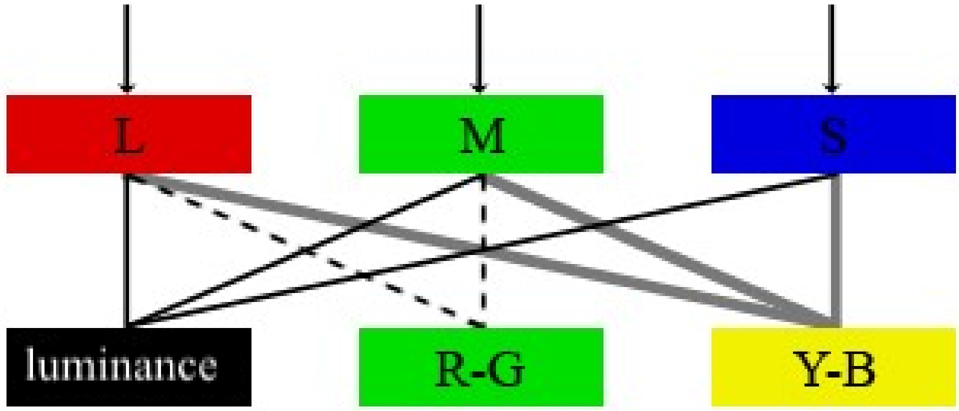
A scientific explanation about the occurrence of brightness perception in the human visual system and the modelling of brightness were described in literature in detail /5,6/. As a reaction to the light incident to the retina, three different retinal signals are generated in the three different types of cone in a photo-chemical reaction. According to today's standard model (supported by psychophysical and physiological evidence), an achromatic signal appears in the so-called luminance channel and two chromatic signals appear in the two different so-called chromatic difference channels, R-G and Y-B, see Figure 3.

Figure 2: Local angle dependent distribution of the rods and the cones on the retina [4]



The spectral sensitivity functions of the human visual system depend on the method used to obtain them and on the viewing conditions under which they were obtained. Applying the so-called procedure of minimum flicker, subjects are stimulated by a coloured test light signal under 2° viewing angle in quick comparison with a reference light signal at a certain frequency (at about 25 Hz, depending on the subject). Subjects have to adjust the radiance of the coloured light signal in such a way that the perception of flicker is at minimum. This frequency is above the mixing frequency of colours (the chromatic channels are inactive) but below the mixing frequency of the luminance channel (the achromatic channel is active). Depicting the reciprocal value of this radiance as a function of the wavelength of the coloured test signal, we get the luminous efficiency function $V(\lambda)$.

Figure 3: Retinal mechanisms of processing the visual signal in the brain[6]



Using another brightness matching procedure, the so-called direct heterochromatic matching, subjects have to adjust the perceived brightness of a quasi-monochromatic test stimulus to match the perceived brightness of a reference stimulus (e.g. Planckian radiator with 2045 K, or a quasi-monochromatic stimulus at 555 nm or the daylight illuminant D65) in a visual photometer device. As this is a process at low frequencies, all signals components (achromatic and chromatic) influence the matching result. An example of this matching method is the so-called method of small-step changes.

Wyszecki und Stiles [2] formulated the basic principles of photometry (also called Abney-principles) as follows:

Symmetry: If a visual stimulus A equals stimulus B in brightness, the stimulus B is equally bright as stimulus A.

Transitivity: If the stimuli A is matched to B and B is matched to C then A is also matched to C.

Proportionality: If a stimulus with intensity A matches the other stimulus with intensity B then the stimulus with intensity ($k \cdot$ A) is also matched to the stimulus with intensity ($k \cdot$ B). Here, k is an arbitrary positive factor with which the intensity of both stimuli are increased ot decreased without changing the relative shape of the spectra.

Symmetry and transitivity were corroborated many times in visual experiments [2] but the validity of the proportionality relation is not so evident. E.g. two stimuli with different relative spectra were matched for equal perceived brightness under foveal viewing conditions (2°) in the medium photopic range (about 100 cd/m^2). Then , the radiance of both test fields was increased to a much higher adaptation luminance level (20.000 cd/m^2). The perceived brightness of the two fields became different because the relative weighting of the mechanisms changed in a spectrally selective way [2]. Proportionality requires that spectral sensitivity should remain constant in a large range of different radiance levels. This is especially not true in the mesopic (twilight) range in which also the so-called Purkinje effect comes into play.

To build a photometric system and to derive the quantities frequently used in lighting engineering, we often apply Eq. (2.2).

$$L_v = 683\ \mathrm{lm/W} \cdot \int V(\lambda) \cdot L_e(\lambda)\mathrm{d}\lambda \qquad (2.2)$$

with $V(\lambda)$: the spectral luminous efficiency function for daytime vision

$L_e(\lambda)$: spectral radiance of the object being observed or the light source

At every wavelength, the spectral radiance of the light source, $L_e(\lambda)$, is evaluated with the spectral sensitivity function of the visual system, $V(\lambda)$ and a signal $S(\lambda)$ is built in the brain. Then, all such signals $S(\lambda)$ are summed up in the visible wavelength range to arrive at an entire signal which corresponds to perceived brightness. A linear summation takes place only in that case if the individual signals $S(\lambda)$ do not influence each other. Latter condition is the so-called additivity condition, the basis of today's photometry. From today's scientific viewpoint, additivity hold only if the visual signals of incident radiation have a high spatial and temporal frequency. A high temporal modulation frequency (greater than about 25 Hz) stops the functionality of the chromatic channels (R-G) and (Y-B). A high spatial frequency occurs e.g. when spatially complex letters or other figures with sharp edges are viewed under about 2° viewing angle. This is a visual task which requires a lot of visual acuity.

2.3 History of the *V(λ)* function

At the beginning of the 20th Century, several visual experiments took place in the USA to determine „spectral relative visibility" or the so-called „relative visibility function". These studies had different methods, wavelength ranges, viewing angles and adaptation luminance ranges. Figure 4 shows the spectral sensitivity functions of the different studies. Table 1 lists the parameters used in these studies /7, 8, 9, 10,11/. It can be seen that:

1. Most procedures were flicker photometric. The procedures of Hyde & Co (1918) and Gibson & Tyndall (1923) applied the method of small-step changes.
2. The visual field size equalled either 1.5 ° (So, 1920), 2 ° (Ives, Nutting, Coblentz & Emerson), 3 ° (Gibson & Tyndall) or 7 ° (Hyde & Co).
3. All studies were carried out in the adaptation luminance ranges of 0.135 cd/m² up to 3.65 cd/m² and were thus conducted in the mesopic (twilight) range. The hypothesis that the resulting $V(\lambda)$ function is appropriate for daytime vision is thus incorrect.
4. Most subject were young although demographic developments in most countries show a contradicting tendency with more elderly people in the 21th Century.

Figure 4: Spectral sensitivity functions in the studies before 1923 [7]

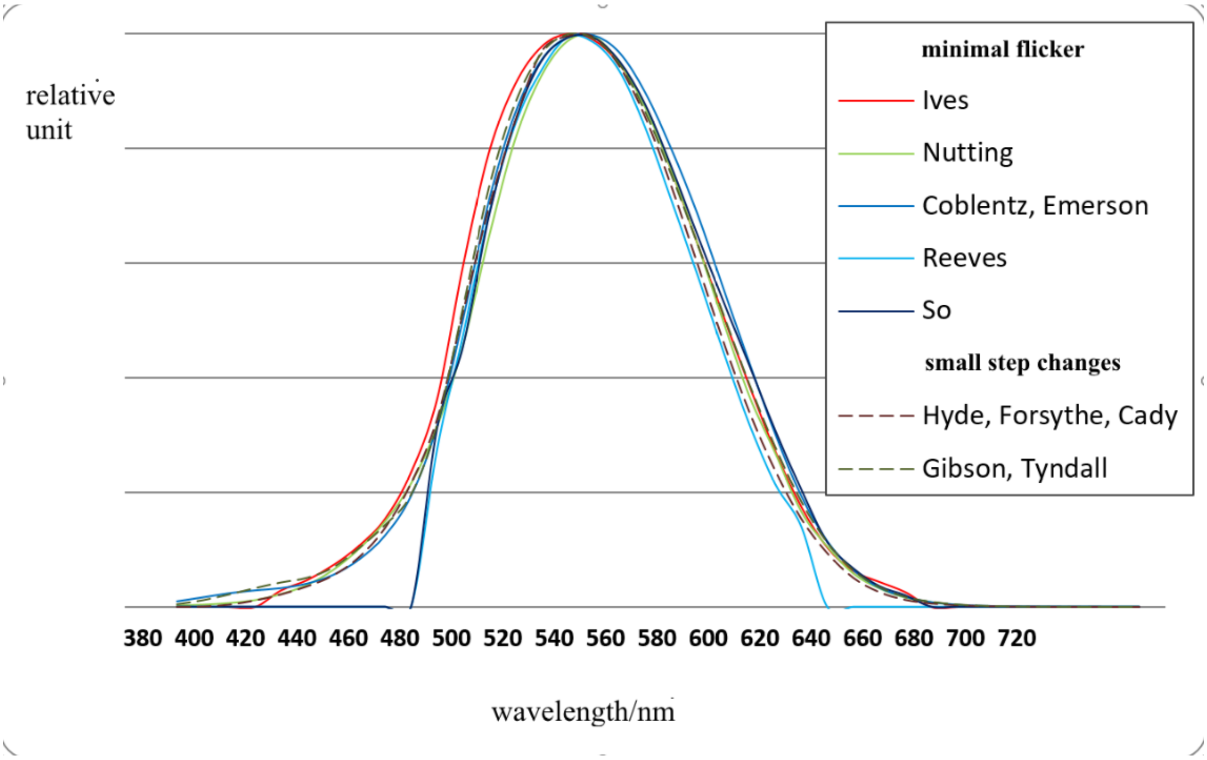


Table 1: Parameters of the studies to obtain the spectral sensitivity function [7]. *n*: number of subjects

Author	Method	Ocular Shutter	Anlge	Luminance *L* (cd/m²)	Retinal illuminance/Troland	λ ranges (nm)	*n*	Age
Ives (1912e)	Flicker	0.5 mm* 2 mm	2 °	2.095	95	481-655	18	18-40
Nutting (1914)	Flicker	0.57 mm* 2.57 mm	2 °	3.66	163	490-640: 400-700:	21 5	
Coblentz & Emerson (1918)	Flicker	0.52 mm* 2.63 mm	2 °	490-690 nm: 0.47 435-490 nm: 0.14 690-750 nm: 0.14	490-690 nm: 22 435-490 nm: 7 690-750 nm: 7	490-690: 435-750:	125 20	19-59 Mean: 29
Hyde, Forsythe & Cady (1918)	Small step changes	0.6 mm²	7 °	560 nm: 0.705 500 nm: 0.135 650 nm: 0.401	560 nm: 29 500 nm: 6 650 nm: 17	500-660	29	
Reeves(1918)	Flicker					490-640	13	
So (1920)	Flicker		1.5 °	ca. 3.58	ca. 168	500-680	20	16-48
Gibson &	Small step	0.2 to 0.8	3 °	580 nm: 0.97	560 nm: 43	490-680:	52	

Author	Method	Ocular Shutter	Anlge	Luminance L (cd/m²)	Retinal illuminance/Troland	λ ranges (nm)	n	Age
Tyndall (1923)	changes	mm * 1.25 mm (λ-dependent)		490 nm: 0.24 680 nm: 0.195	500 nm: 11 650 nm: 9	430-740:	38	

In 1923, in the framework of the CIE committee of the USA, Gibson and Tyndall determined spectral visibility by the use of the method of small step changes, see Table 1. They published a detailed work comparing previous results with their own ones and presented a hybrid function to the CIE. This function was introduces in 1924 as the CIE's well-known and widely used „spectral luminous efficiency function $V(\lambda)$" (see e.g. von Vikari [7] describing some of the development steps). In principle, the $V(\lambda)$ function consists of the following components (according to Sharpe und Stockman [14]):

1. from 400 nm to 490 nm: according to the results of Hyde & al. (1918) with the method of small step changes;
2. from 490 nm to 540 nm: according to the results of Coblentz & Emerson (1918) with the procedure of minimum flicker;
3. from 540 nm to 650 nm: according to the results of Gibson & Tyndall (1923) with the method of small step changes
4. over 650 nm: according to the results of Coblentz & Emerson (1918) with the procedure of minimum flicker.

The mixed function $V(\lambda)$ is therefore an artificial product from different results with different methods obeying different mechanisms of the human visual system. This function does not represent any real perceptual effect or task.

According to the implementation of the results of Hyde et al. (1918) in the wavelength range less than 460 nm, the $V(\lambda)$ function is significantly different from other results of Nutting (1914), Coblentz & Emerson (1918) and Gibson & Tyndall (1923). It was amended by Judd in 1951 and then also by Vos (1978) [12]. Finally, the CIE published the so-called $V_m(\lambda)$ function in 1988 [13] as a further amendment.

Latter function is not used in today's lighting engineering, anyway. In 1964, the CIE defined a colorimetric system for viewing angles of 10 ° [2] with a $y_{10°}(\lambda)$ function as brightness axis but not a corresponding luminous efficiency function $V_{10°}(\lambda)$. Because most applications of lighting engineering are confronted with a viewing angle greater than 2°, the $y_{10°}(\lambda)$ function was provisionally suggested to be used as $V_{10°}(\lambda)$ by Schanda, Morren, Rea, Ronchi and Walraven [3]. Since 2000 until today, there have been a series of scientifically deeply founded investigations by Stockman and Sharpe to re-determine the $V(\lambda)$ function [14], under the following experimental conditions.

The procedure of minimum flicker was applied at the photopic adaptation luminance level of about 3.0 log photopic trolands corresponding to about 246 cd/m² and at a flicker frequency of 25 Hz. Thus they avoided the deficiency of $V(\lambda)$ caused by the low adaptation levels in the mesopic range.

The adaptation stimulus was equivalent to daylight D65. The viewing field equalled 2 ° thus the additivity condition was ensured. Forty subjects were tested with the mean age of 33 years.

The new so-called $V^*(\lambda)$ function is discussed within the CIE today. Due to the correct experimental conditions, it is supposed that this function describes the functions of the human visual system correctly, at least in the used photopic range, high frequency and visual field size of 2°. According to Sharpe and Stockman [14], the new $V^*(\lambda)$ function is formulated in Eq. (2.3).

$$V^*(\lambda) = |1.62434 \cdot l(\lambda) + m(\lambda)| / 2.525598 \qquad (2.3)$$

According to Eq. (2.3), only the signals of the L and M channels are considered while S-cones are not represented. Figure 5 shows the four functions $V(\lambda)$, $V_m(\lambda)$, $V_{10°}(\lambda)$ and $V^*(\lambda)$.

Table 2 lists the ratios of the $V_m(\lambda)$-, $V^*(\lambda)$- and $V_{10°}(\lambda)$-luminance values and today's conventional luminance with the $V(\lambda)$ function for a series of representative light source spectra.

Figure 5: The spectral functions $V(\lambda)$, $V_m(\lambda)$, $V_{10°}(\lambda)$ and $V^*(\lambda)$

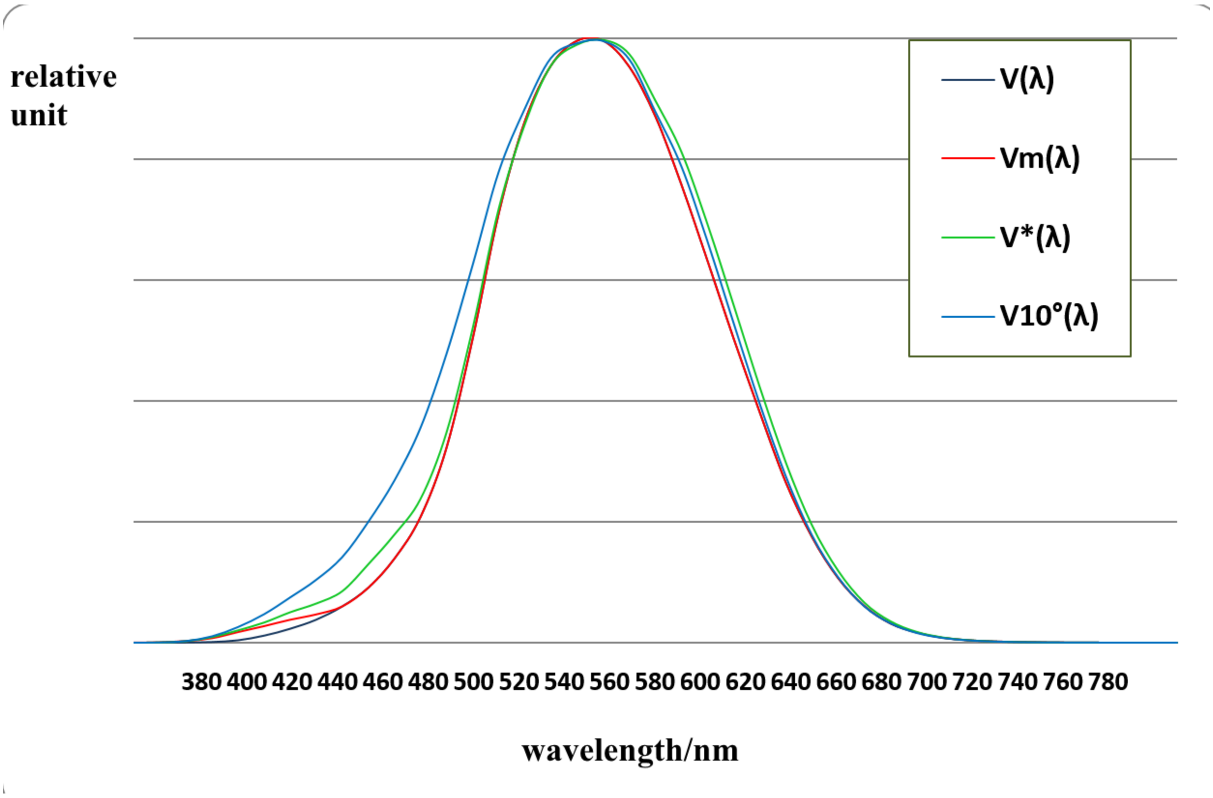


Table 2: Ratios of the $V_m(\lambda)$, $V^*(\lambda)$ and $V_{10°}(\lambda)$ luminances and today's conventional $V(\lambda)$ luminance

No.	Light source	L(Vm)/ L(V)	L(V*)/ L(V)	L(V10°)/ L(V)
1	LED Rebel warm white 3300 K, Ra 92	1.003	1.06	1.08
2	LED Rebel cool white 6000 K, Ra 68	1.009	1.048	1.07
3	LED Ledon warm white 2950 K, CRI 86	1.0014	1.051	1.06
4	Xenon HID 4285 K	1.004	1.05	1.08
5	Standard illuminant D65	1.002	1.05	1.08
6	Standard illuminant A	1.00	1.05	1.06
7	Fluorescent 58 W-840	1.00	1.05	1.06
8	HQL 80 W deluxe	1.00	1.05	1.06
9	HQI TS 70 W-WDL	1.00	1.055	1.06
10	NAV-T 70 W Super	1.00	1.06	1.04
11	LED Luxeon K2 Amber	1.00	1.08	1.04
12	Luxeon K2 Red	1.00	1.11	1.02
13	Platinum Dragon Deep Blue	1.036	1.35	2.05

Looking at Table 2, we can conclude the following:

1. The difference between today's $V(\lambda)$-luminance and $V_m(\lambda)$-luminance according to Judd and Vos is (in case of most light sources except the blue LED No. 13) very low.
2. The $V^*(\lambda)$ luminance after Stockman & Sharpe has (in case of the most polychromatic light sources, 4th column, No. 1-10) a 5 % to 6 % higher value than $V(\lambda)$ luminance. In case of the red and blue LEDs in the 4th column (No. 12-13), the difference is much higher, about 11 % to 35 %.
3. The 10 ° luminance calculated by the aid of the $V_{10°}(\lambda)$ function of CIE 1964 is (in case of most polychromatic light sources, 5th column, No. 1-10) about 4%-8 % higher than the $V(\lambda)$ luminance. In case of the blue LEDs (5th column, No. 13), the difference is much higher, about 105 % (i.e. about 2.05 times).

In addition, both the $V(\lambda)$ and the $V^*(\lambda)$ function are valid only for 2° viewing field and in the photopic luminance range (L > 5 cd/m^2) as well as for applications with high spatial and temporal (f > 25 Hz) frequencies, when the chromatic channels, the rods and the blue cones do not work any more. Most lighting engineering applications are chromatic, static and take place under a higher viewing angle. Almost all street lighting and vehicle lighting applications occur in the mesopic (twilight) range. It should be mentioned here that these problems of the $V(\lambda)$ function have already been known since 1938 (Jainski's work [31]).

The subject of brightness has been studied since decades with success. As already mentioned above, psychophysical evidence (beginning in the years 1955-1960 by Hurvich und Jameson [6]) showed that the underlying mechanisms of our perception of optical radiation can be differentiated into an achromatic range and two chromatic ranges. In optical physiology and biophysics, attempts have been taken to identify brain cells responsible for the achromatic and chromatic channels. Finally, in 1988, by the use of microprobes, it became possible to record the behaviour of the magnocellular layer (the so-called MC pathway). Its spectral response corresponded to the CIE photopic luminous efficiency function for 10° (CIE 1964) [16]. In the parvocellular layer (so-called PC pathway), there are „red-green" cell groups receiving signals from the L- and M-cones, and there are also „yellow-blue" cell groups receiving S-cone signals from the centre and L- and M-cone signals from the periphery or vice versa [17].

2.4 Further aspects: visual tasks, adaptation fields

In general, the human visual system has three adaptation luminance ranges: scotopic (night vision), mesopic (twilight vision) and photopic (daylight vision). The CIE defines these ranges according to the characteristic values of luminance. Luminances up to 0.001 cd/m² are in the scotopic range. Luminances between 0.001 cd/m² and about 5 cd/m² are in the mesopic range while higher luminances are in the photopic range.

With changing luminance, the relevance of the visual tasks to be carried out by the visual system also change. In the photopic range (e.g. in modern office lighting or factory lighting complying with EN-DIN-criteria like establishing 300 lx to 2000 lx), the prerequisites of good contrast vision and good visual acuity are usually given e.g. to read documents or mails on the monitor or for milling, shaping and mounting in industry. Under these circumstances, it is more important to concentrate on the brightness impression of the whole lit scene (e.g. whether it is being assessed as „dim" or „bright").

If we decrease luminance down to mesopic values then the perception of brightness has less importance in the following sense. The luminance of the street in front of a car (until 20 m distance) equals during night time driving 2 cd/m² to 10 cd/m². At a distance of 60 m to 70 m, which is the characteristic area domain of the drivers' gaze points, the luminance of the road surface equals only 0.1 cd/m² to 0.2 cd/m². In European countries, DIN EN 13201 is valid for street lighting design. According to this standard, main streets with medium to high traffic should be designed to have a mean luminance value in the range of 0.5-2.0 cd/m². According to the knowledge of classic lighting engineering, human brightness perception mechanisms operate at this mean luminance at which a certain minimum amount of contrast (so-called thresholds contrast) shall be present at (dangerous) objects or hazards for their safe detection. If the object has more contrast compared to its background then the threshold contrast then the driver will be able to safely detect it and avoid the accident.

But this is, unfortunately, not always the case and this is why it is more important, especially in the mesopic range, to model contrast perception. If the luminance in the whole field of view generally low (i.e. if the adaptation luminance is low) then objects of similar luminance i.e. with low contrasts cannot easily be detected. Therefore, the visual system activated all photoreceptors on the retina to strengthen the detection signal: all succeeding processing channels including the chromatic channels and the rod channel will have a contribution in order to be able to evaluate the weak detection signal of the object (i.e. the obstacle). This situation is what a traffic participant experiences if the street is only illuminated by a low-beam headlamp and a low level of street lighting illuminance although obstacles and unknown objects may appear at any time.

2.5 Summary

Summarising the above, it can be stated that the V(λ) function is a mixed function which does not represent any real visual effect. The new $V^*(\lambda)$ function is physiologically better founded. But latter function is also only valid for achromatic vision in case of high frequencies, in the photopic range, and only for 2° stimuli, similar to the V(λ) function. To describe brightness and contrast perception in the photopic and mesopic ranges, new models were developed in the CIE. These models are not perfect but significantly better than V(λ)-based way of modelling. Also, glare research has the important task (after its 100 year old history in the CIE), to describe the perception of glare with a more comprehensive model in which the V(λ) function is only a single component.

2.6 Literature for Section 2

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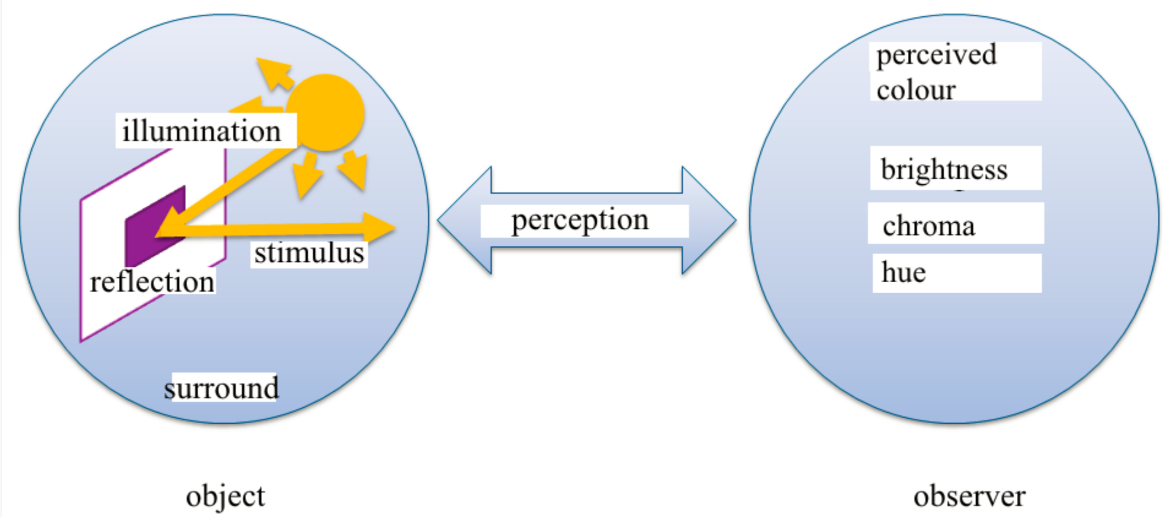
3 Brightness

3.1 Brightness in the photopic range (interior lighting)

3.1.1 Introduction

It is well-known from the visual experience of lighting engineers, designers and users that white light with a higher correlated colour temperature (CCT) evokes a higher level of perceived brightness and a better three dimensional, spatial room perception in a building or in a hall. Generally, the path of optical radiation transfer consists of the absolute spectral power of the light source, the spectral reflection factor of the objects seen by the observer and the optical system of the human eye (cornea, eye lens, pupil, vitreous body and retina), see. Figure 6.

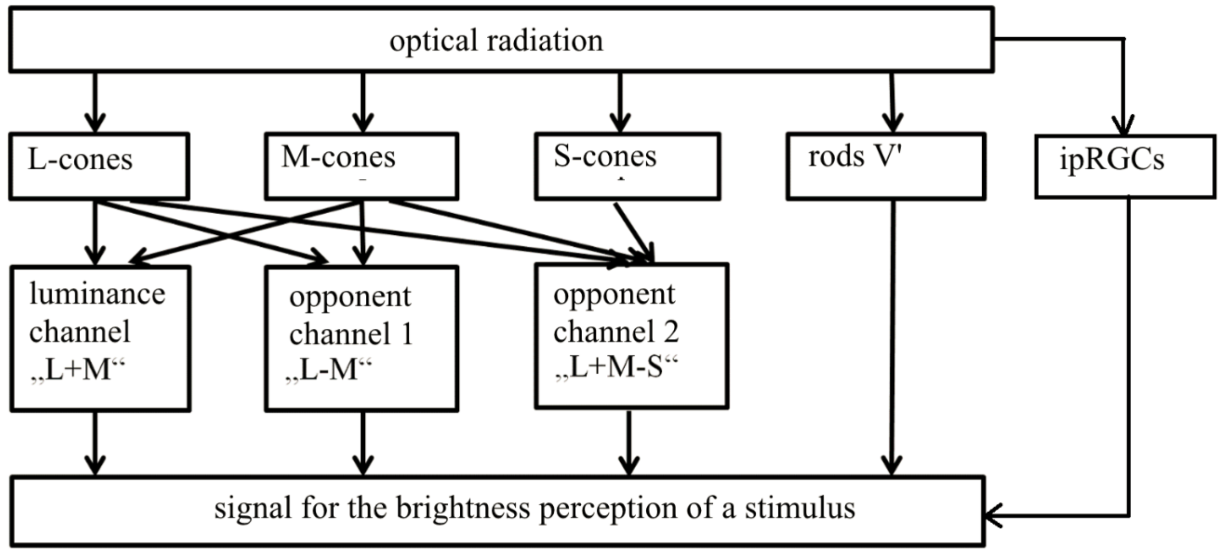
Figure 6: Representation of the interaction between the emission spectra (illumination), reflection spectra of the objects and the perceptual behaviour of the human visual information processing system



There are cones (L-, M- and S-cones), rods and the so-called intrinsically photosensitive retinal ganglion cells (ipRGCs) on the retina. After absorbing the photons, electric impulses come to existence and these impulses are transferred to the different phases of brain processing. At these phases, the signals of the individual receptors or receptor groups are cross-linked. The workflow within this network depends on the position of the object in the field of view, state of adaptation, and the structure of the surround.

The processes of brightness and colour perception can be summarised according to the scheme of Figure 7.

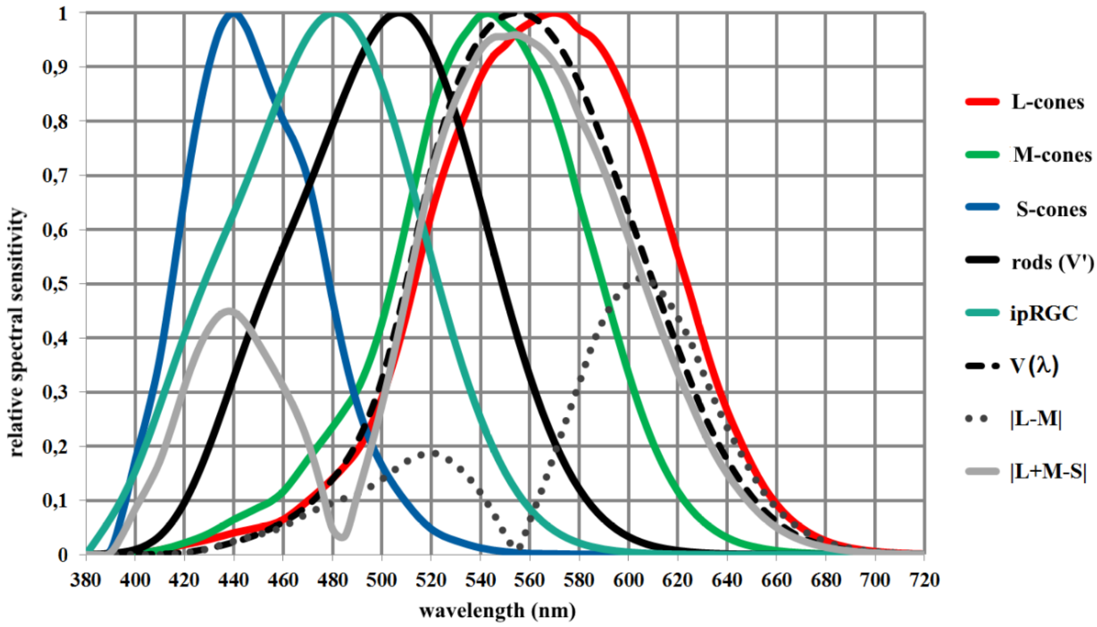
Figure 7: Scheme of the human visual mechanisms that contribute to the brightness perception of a colour stimulus. The signal of the intrinsically photosensitive retinal ganglion cells (ipRGCs; right) also contributes



According to the scheme of Figure 7, the so-called luminance channel is being built from the signals of the L- and M-cone signals. The difference of the L- and M-cone signals constitute the so-called opponent channel 1. The difference of the (L+M)- and S-signals constitute the so-called opponent channel 2. In the mesopic range (e.g. in a private flat in the evening, in night-time street lighting, in a 3D-cinema with absorbing 3D-glasses), there is also a contribution of the rods (V´) to the perception of light and the colours. From the point of view of colour perception, colour attributes like saturation and hue are also mesopically biased until about 30 cd/m^2 [12]. In the higher photopic range from about 60 cd/m^2 on, rods are become inactive. Brain processing units generate from the signals (L+M), (L-M), (L+M-S), V´ and ipRGCs the perceptual colour attributes brightness, hue and saturation, see. Figure 6.

Figure 8 shows the relative spectral sensitivity functions of the three types of cone, the rods, the ipRGCs, the opponent (chromatic) channels (L-M) and (L+M-S) as well as the $V(\lambda)$ function.

Figure 8: Relative spectral sensitivity functions of the three types of cone, the rods, the ipRGCs, the opponent (chromatic) channels (L-M) and (L+M-S) as well as the V(λ) function

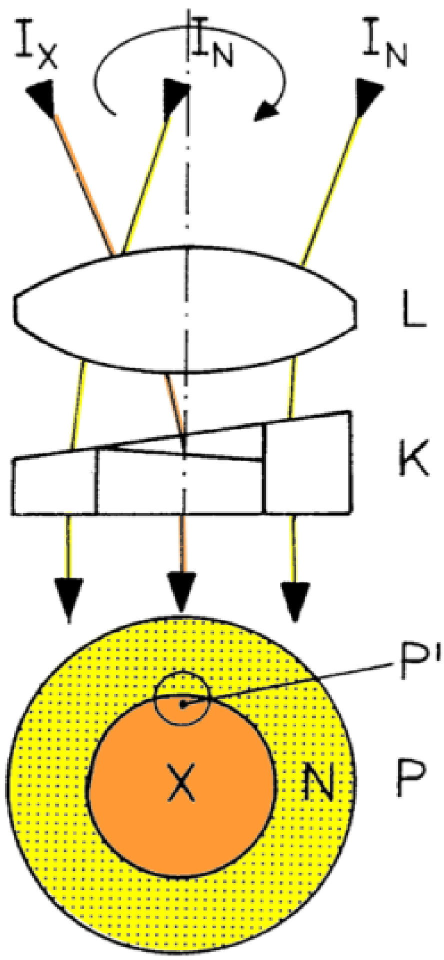


In the context of colour perception and daytime dependent dynamic lighting (see also Chapter 6), the following insights arise from Figure 8:

1. Besides the *V*(*λ*) function, there are some other spectral sensitivities of important mechanisms on the shorter-wavelength side (cyan, blue) of the visible spectrum, in the wavelength range of about 440 nm (S-cones), 480 nm (ipRGCs) and 507 nm (rods). If we combine the effect of ipRGCs with the rod signal then the sensitivity in the range between 470 nm and 525 nm will become very important. At about 470 nm, all three channels are highly sensitive.
2. L-cones and the opponent channel (L-M) have high sensitivity in the range between 620 nm and 680 nm.
3. In the evening (in case of a relatively small illumination level), the wavelengths below about 580 nm can be important for the suppression of producing the melatonin hormone. Every spectral variation above about 580 nm (e.g. in order to amend the colour perception of yellow or red objects or to increase visual performance or visual acuity) does not influence the degree of melatonin suppression and cannot physiologically change the state of alertness.
4. If we continuously shift the blue spectral content of light sources e.g. the maximum wavelength of a blue LED towards shorter and shorter wavelength ranges between 470 nm down to 435 nm then the ipRGCs cells will be continuously less stimulated and circadian rhythms have less potential to be well-synchronised. This shifting toward shorter wavelengths, however, increases S-cone signals and the colours of bluish object might appear more beautifully (in other words: colour rendering in the bluish range increases) and this is an advantageous effect.

As explained earlier, the *V*(*λ*) function represents only the relative spectral sensitivity of the luminance channel (L+M) because it was obtained under the viewing conditions of flicker photometry. Flicker photometry is further explained here as follows. Two light signals of different colour (I_X and I_N in Figure 9) are matched by a subject while they are presented after each other modulated by a frequency of about 24 Hz in a 2° field of view. The matching occurs after the flicker of both light signals had been visually minimised. At these relatively high temporal frequency, the chromatic channels (L-M) and (L+M-S) are not operating in contrast to the luminance channel (L+M) which is still active.

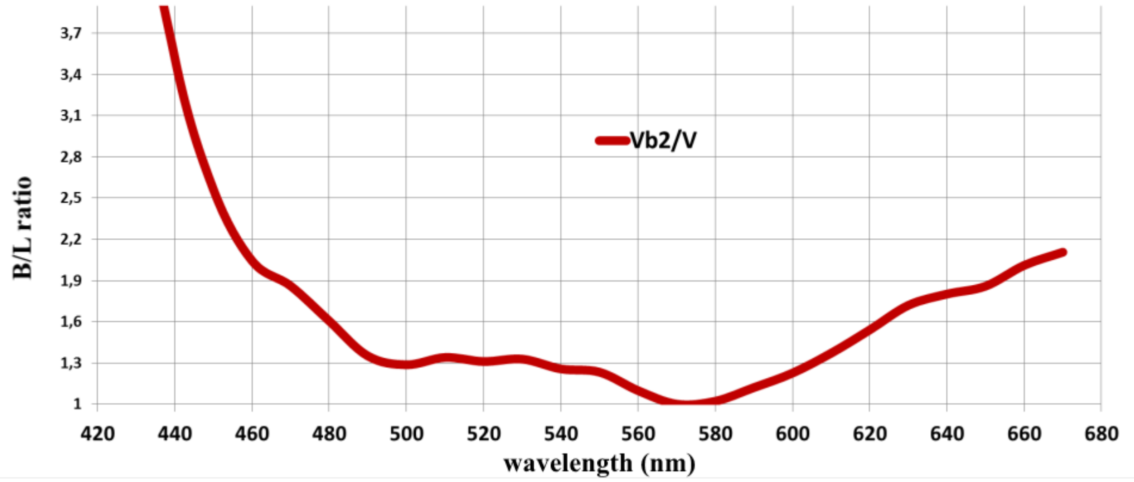
Figure 9: Flicker photometry according to Bechstein [13]



If we carry out everyday visual tasks (e.g. looking at objects like paintings, textiles, building façades or cooking etc.) then the objects are usually static so that the chromatic channels are operating (see Figure 7). In 1988, CIE defined the spectral brightness function $V_{b,2}(\lambda)$ for 2° viewing angle and the static observation of monochromatic colour stimuli. If we divide this function by the $V(\lambda)$ function and depict this ration as a function of wavelength from 430 nm to 670 nm (see Figure 10) then it becomes obvious that brightness (i.e. luminance signal plus chromatic signal contributions) equals luminance only at 570 nm (then the ratio equals 1.000).

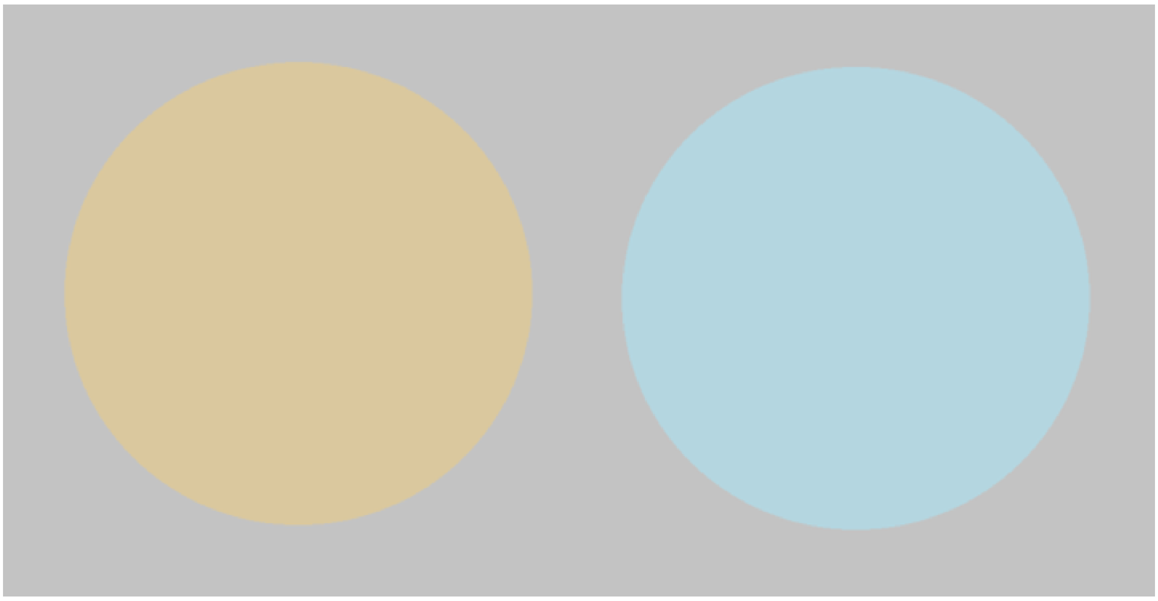
For other wavelengths, brightness is significantly higher than the luminance signal. E.g. in case of 460 nm (blue) and 660 nm (deep red), brightness is about twice as high as the luminance signal. The chromatic contributions ignored by the $V(\lambda)$ function are very significant at theses wavelengths: chromatic brain signals (hue) increase if a subject observes monochromatic radiation with a wavelength which is greater than 570 nm. At 460 nm and 660 nm, although the chromatic signals are significant, they are completely ignored in today's everyday photometric practice and lighting design. It should be noted that the above brightness considerations are only valid in case of monochromatic self-luminous stimuli.

Figure 10: Brightness/Luminance ratios for monochromatic light stimuli on a 2° viewing field



In the real world, the radiation from light sources or from objects are polychromatic. They consist of numerous different wavelengths. Such reflecting objects or self-luminous objects are e.g. the colourful images of a computer monitor or a TV set (self-luminous images) or real object surface colours e.g. a pair of blue trousers, fruits or flowers. The perceived brightness of a coloured surface or a certain white tone of a light source (warm white, neutral white or cool white) depends not only on luminance but also on chromaticity (i.e. hue and saturation). Latter effect is the so-called Helmholtz-Kohlrausch effect or, in other words, brightness-luminance discrepancy. This is demonstrated in Figure 11.

Figure 11: Example for a so-called heterochromatic brightness matching experiment [14]



The luminance of the bluish colour stimulus in Figure 11 (right) is being changed until the perceived brightness of the two stimuli are matching visually. The left stimulus (yellowish) remains constant. After arriving at the matching point of visual brightness, there is still a remaining luminance difference: the bluish stimulus should have less luminance than the yellowish one. One of the quantities that describe perceived brightness is the so-called *equivalent luminance* denoted by $L_{äq}$.

3.1.2 Equivalent luminance $L_{äq}$ according to Ware and Cowan

The equivalent luminance $L_{äq}$ according to Ware and Cowan (see [15] in Section 2.6) is defined as follows. First, the ratio (B/L) of the brightness B to the luminance L of the test light source with the chromaticity coordinates x, y are computed, see Eq. 3.1. In the second step, the (B/L) ratio is multiplied with the conventional (photopic) luminance L_P of the test light source (in cd/m^2), see Eq. 3.2.

$$\log_{10} (B/L) = 0{,}256 - 0{,}184\, y - 2{,}527\, xy + 4{,}656\, x^3y + 4{,}657\, xy^4 \tag{3.1}$$

$$L_{äq} = (B/L)\, L_P \tag{3.2}$$

3.1.3 A lightness measure according to Fairchild and Pirrotta

For coloured objects (i.e. reflecting surfaces and not self-luminous stimuli) that are positioned in an illuminated surround (so-called „related colours", see Figure 12) e.g. fruits or vegetables in a grocery shop or paintings in a museum or coloured books or journals on the table of a book-store, we can apply the concept of „lightness" instead of „brightness". Lightness is a relative concept, it corresponds to the brightness of the object related to the brightness of an ideal white surface material under the same illumination.

Figure 12: Different coloured oil paintings with different lightness

To describe lightness by considering the Helmholtz-Kohlrausch effect visually correctly, Fairchild and Pirrotta (see [15] in Section 3.4) developed the formula defined by Eqs. (3.3)-(3.5).

$$L^{**} = L^{*} + \mathrm{f}(L^{*})\,\mathrm{g}(h^{\circ})\,C^{*} \tag{3.3}$$

with

$$g(h/^{\circ}) = 0{,}116\,|\sin((h/^{\circ} - 90^{\circ}) / 2)| + 0{,}085 \tag{3.4}$$

and

$$f(L^{*}) = 2{,}5 - 0{,}025\,L^{*} \tag{3.5}$$

The symbols in Eqs. (3.3)-(3.5) mean:

- L^{**}: Quantity to predict perceived lightness by taking the Helmholtz-Kohlrausch effect into account
- L^{*}: Quantity to predict perceived lightness in the CIELAB 1976 system
- $f(L^{*})$: L^{*} based correction function
- $g(h^{\circ})$: Correction function dependeing on the hue angle h
- C^{*}: Chroma according to CIELAB 1976

Therefore, the chromatic lightness defined by Eqs. (3.3)-(3.5) depends on the chroma and hue (e.g. green, red, blue or cyan) of the surfaces. This quantity is not used in today's practice of lighting design and assessment.

3.1.4 Brightness measure according to Fotios und Levermore

The brightness metric of Fotios and Levermore [17] ($L_{äq}$; this is used in the new evaluation system proposed in the present document) divides the signal of the blue-sensitive S-cones (S) by the signal V of the $V(\lambda)$ function and calculates with the 0.24 exponent: $L_{äq}$(Fotios)=$(S/V)^{0,24}$. In order to compute the signal S, the relative spectral power of the lighting product shall be multiplied with the spectral sensitivity of the S-cones and this value shall be integrated in the visible wavelength range.

3.2 Brightness in the mesopic range (exterior lighting)

3.2.1 Introduction

In street lighting, the visual tasks of traffic participants are carried out in the mesopic (twilight) range, typically between 0,05 cd/m^2 and about 5-10 cd/m^2. Important visual tasks include

1. Visual assessment of (mesopic) brightness perception,
2. Visual search,
3. Detection of (often dangerous) objects (detection targets),
4. Quick reaction to these objects
5. Identification of these objects.

The visual task of detection (without identification) is the basis for a quick reaction and this is especially relevant for traffic safety. In the following, these (mesopic) visual tasks will be explained in detail.

The assessment of the (spatial) brightness perception of the entire street scene is a longer procedure taking typically more than 3 seconds. The total amount of perceived light reflected from all objects is being integratively assessed. Subsequently, the subject is experiencing a certain feeling of safety and an aesthetic impression about the street scene being viewed.

Visual search means the visual exploration of the scene. The subject is searching for certain visual objects she or he is interested in whereby the conspicuity of the object and the number of distractors (other objects in the scene that reduce attention) play an important role.

The visual task of detection means that the subject is able to discern a visual object (so-called detection target) and react to it without recognising the object. It is not necessary to see the fine spatial details of the object, therefore for detection, a high visual acuity is not necessary. In order to initiate a quick reaction, it is not necessary to identify the object. E.g. to avoid an accident by night-time driving, it is not relevant to know what kind of object it is. It is only important to avoid the collision with it.

The identification (recognition) of a visual object is based on the analysis of its spatial structure. This structure shall be fine-resolved on the retina of the subject. During the process of recognition, the shape and structure of the object is compared with previously known patterns stored in the long-term visual memory of the subject, e.g. a red STOP traffic sign. The features „octogonal", „red colour" and the string „STOP" are being matched with the properties of the STOP sign stored in memory. If this matching has a positive result then the subject (e.g. the car driver) will know how to behave after having seen this traffic sign.

Within the mesopic range, there is a huge amount of different possible viewing conditions and the characteristics of the workflows of the human visual system change very strongly depending on the actual type of mesopic viewing condition. The deciding influencing parameters are:

1. The type of visual task, e.g. brightness perception or detection,
2. The luminance level, e. g. 0.05 cd/m² or 0.5 cd/m²,
3. The white tone or light chromaticity of (street) lighting e.g. a yellowish high-pressure sodium lamp or a cool white street lamp with phosphor-converted LEDs, and
4. The position of the visual target, e. g. central appearance of the visual target in the middle of the viewing field or appearance in the periphery under a certain viewing angle from 5 ° to 30 ° [1].

The significant dependence of the perceptual processes on these parameters are caused by the complex interactions of all photoreceptor types (L-, M- and S-cones and rods) in the retina. These interactions determine the processing of the above mentioned visual tasks in the mesopic range. The different photoreceptor signals are combined in different ways in the course of processing depending on the above influencing parameters.

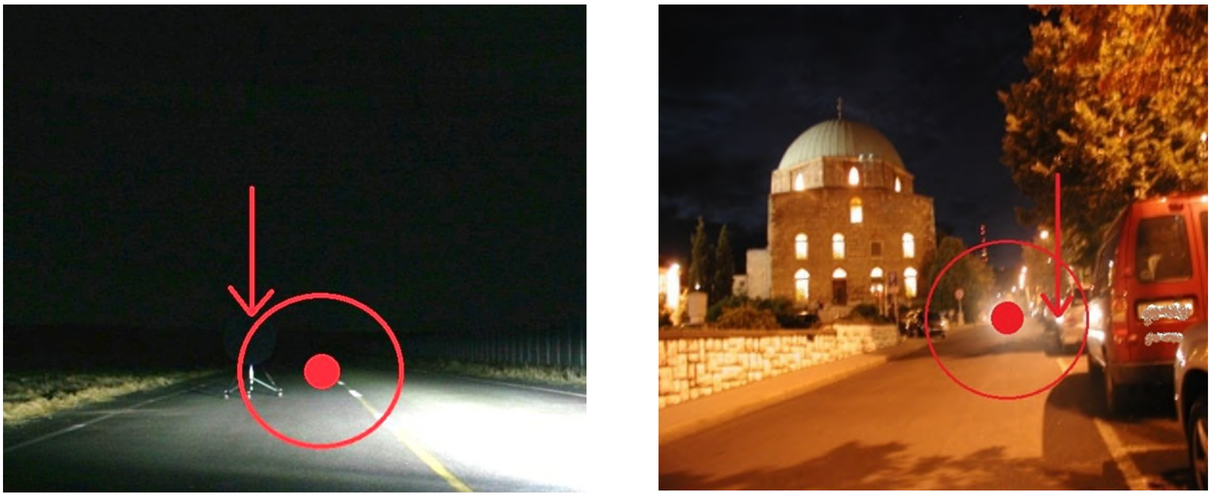
Conventional photometry with ist quantities derived from the $V(\lambda)$ function (luminance and illuminance) describe only one visual task: the recognition of smaller objects in the centre of the viewing field enabled by the L- and M-cones only. We can apply the quantity of (conventional photopic) luminance and luminance contrast to describe the recognition of small (2°) foveal objects only. This task plays only a minor role in everyday's traffic events and for traffic safety. In order to describe traffic-relevant mesopic visual tasks, mesopic models of visual performance shall be applied. This will be explained in the following.

3.2.2 Mesopic models of visual performance and brightness

From the 1950's until the beginning of the 21st Century, several brightness models were proposed [1]. The International Commission on Illumination (CIE) is currently working on a comprehensive model of mesopic and photopic brightness perception. In 2004, the so-called X-model or USP (Unified System of Photometry [2]) was defined using the reaction time criterion. Another model was established in the framework of a EU research project, this was the so-called MOVE model with the criteria reaction time, visual acuity and detection ability. Latter model has a similar form to USP [3].

Mesopic brightness models are based on the observation procedure of heterochromatic brightness matching [1]. In this procedure, the perceived brightness of a test field is matched to that of a reference field. This viewing task is very far from the tasks in real night-time traffic. More relevant models for traffic safety and street lighting design are the so-called mesopic visual performance models describing the detection probability of dangerous objects (hazards) and the related reaction times to objects of low contrast at the detection threshold, see Figure 13. Compared to brightness models, these models have a different mathematical form.

Figure 13: Comparison of the mesopic visual tasks detection and brightness assessment. Filled red circle: the central viewing field at the fixation point of the observer with a diameter of 2°. Red circle: a viewing field with a diameter of 10°. Left: detection of a typical mesopic object, here: an artificial grey object in a field experiment at 5 ° in the periphery, at the red arrow. Right: mesopic brightness perception: long-term viewing of the entire street scene. The red arrow shows a possible point of appearance of an object to be detected (e.g. pedestrian) between the two parking cars



In the example of Figure 13 (left), the artificial grey object appears in the periphery under 5 ° with a certain radiance difference (contrast) compared with its background. The contrast of this typical mesopic object (detection target) is at the detection threshold. The detection threshold can be defined as follows: the contrast at which the target can be detected at a probability of 75 %. The visual task of mesopic detection is a so-called threshold observation in the periphery typically between 5 ° and 30 °. To carry out this visual task, the spatial differences at low spatial frequencies of the photoreceptor signals between the object and its background are evaluated at later processing stages of the human visual system.

In the examples of Figure 13 (right), the subject observes and assesses the brightness of the whole scene; the central viewing field at the fixation point (2 °) and one part of the viewing field with a diameter of 10° are marked in the Figure. A typical point of appearance (5 °) of a detection target (e.g. a pedestrian) between the two parking cars is also marked. Opposed to detection, the visual system is working with supra-threshold receptor signals in case of brightness assessment. These signals are integrated over spatially extended parts of the field of view. According to the above, the retinal and post-retinal processing mechanisms of the human visual system differ between detection and brightness evaluation.

In order to recognise a visual object (e.g. letters), the central 2° viewing field of the subject is first moving via eye movements to the object to be recognised. The central 2° field (see the red filled circles in Figure 13) are the areas of highest visual acuity in the retina in which the spatial details of the letters are being scanned step by step. The efficiency of object recognition in the central field of view can be described by the quantity *photopic* luminance contrast both in the mesopic and in the photopic range. For the other mesopic visual tasks, *mesopic* visual performance models shall be applied.

3.2.3 Mesopic brightness models

In order to describe mesopic perceived brightness, the quantity equivalent luminance $L_{äq}$ can be used. This quantity is defined by the CIE as follows: the equivalent luminance of a test stimulus equals the luminance of a quasi-monochromatic reference stimulus of 555 nm which has the same perceived brightness as the test stimulus [4]. Equivalent luminance predicts if two brightness perceptions are the same or if one brightness perception is greater or less than the other. Equivalent luminance, however, is not an absolute brightness scale and it cannot predict the absolute visual magnitude of brightness perception.

So called two-component brightness models calculate the value of $L_{äq}$ from the values of the (photopic) luminance L and the scotopic luminance L'. Hence they take the so-called Purkinje effect into account (the shifting of spectral sensitivity into the bluish spectral range in case of lower mesopic levels). We should also take the Helmholtz-Kohlrausch effect into account (more saturated colours evoke more perceived brightness than de-saturated or greyish colours of the same luminance). To do so, so-called four-component brightness models also contain a chromatic component. They use four values (L', X, Y, and Z) as input quantities.

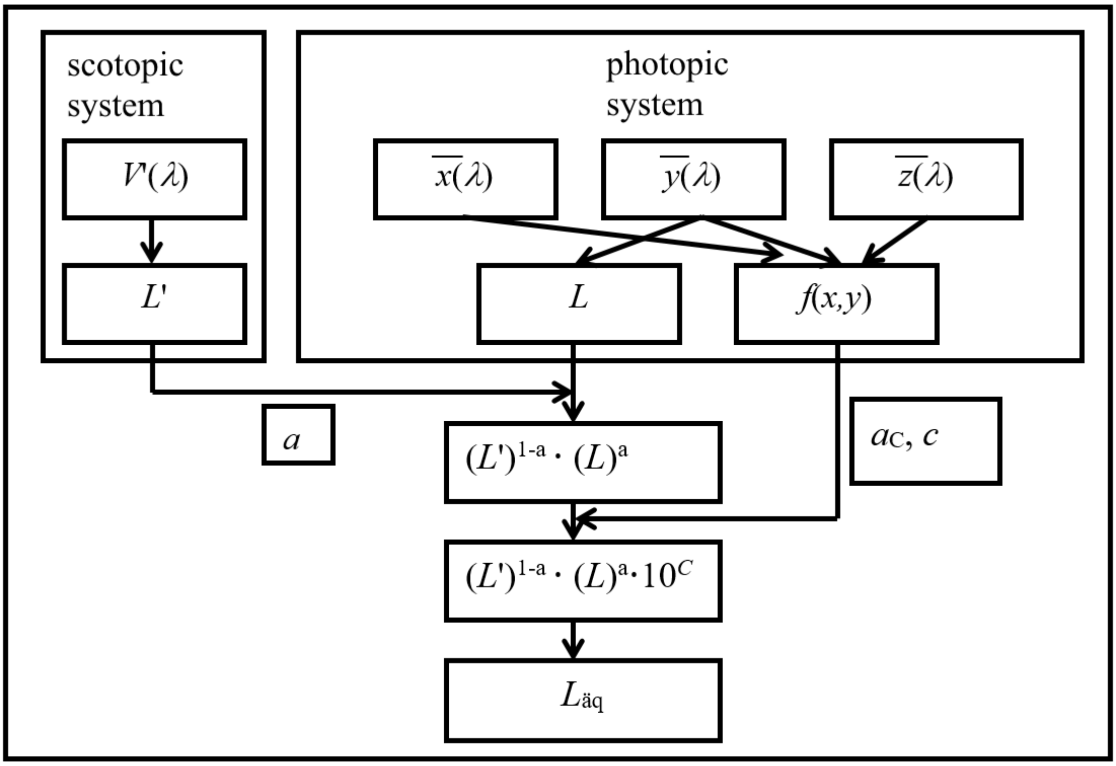
The CIE model (or Sagawa model) [5] uses the sum of the adapted photopic and scotopic luminance signals (achromatic signals) and the adapted chromatic signal (signal of the opponent channels). Figure 14 shows the processing steps of the photoreceptor signals in this model that computes equivalent luminance. The quantity $f(x, y)$ represents the chromatic signal of the equivalent luminance. This is computed by Eq. (3.6) [5]. In the underlying publication [5] appeared the false value of -0.054. This is already corrected in Eq. (3.6).

$$f(x,y)=(1/2)\log_{10}\{-0.0054-0.21x+0.77y+1.44x^2-2.97xy+1.59x^2-2.11[(1-x-y)y^2]\}-\log_{10}(y) \quad (3.6)$$

The numeric values of the parameters α, β and k equal: α=0.05 cd/m²; β=2.24 cd/m²; k=1.3 [5]. In the last step, we compute the quantity *equivalent luminance* according to Eq. (3.7).

$$L_{äq}=L'^{(1-a)}\, L^{a}\, 10^{c} \quad (3.7)$$

Figure 14: Signal flow diagram of the CIE brightness model (also called Sagawa model)[5]. a=L/(L+α): adaptation coefficient for the combination of the achromatic signals L' (scotopic luminance) and L (photopic luminance); c=a_C·f(x,y): chromatic signal; $a_C=kL^{1/2}/(L^{1/2}+\beta)$: adaptation coefficient for the chromatic signal f(x,y), see Eq. (3.6), $L_{äq}$: equivalent luminance, see text



In comparison to the tendencies of visual brightness results (according to the computations of the authors of the present report), the CIE brightness model [5] (also called Sagawa model) does poorly, even after correcting the above mentioned erroneous value (-0.054).

In the brightness model of Berman designated by $L_{äq}$(Berman) rod signals are represented by $(\text{Rods}/V)^{0,5}$. In order to compute the rod signal „Rods", the relative spectral power of the light source or lighting product shall be multiplied by the V'(λ) function (representing the spectral sensitivity of the rods) and then integrated in the visible spectral range.

As a further, alternative quantity to describe all visual and non-visual effects of light on humans, (incl. brightness), the so-called $U(\lambda)$ function [16] was introduced (see the red dot curve in Figure 1). This function covers the entire spectral range of the spectral sensitivity functions of the S-cones, M-cones, L-cones, rods and ipRGCs. This is a much broader range than the one of the $V(\lambda)$ function. In order to obtain a possible rough approximation of perceived brightness, the spectral radiance of the lighting product shall be multiplied with the $U(\lambda)$ function and integrated in the visible wavelength range. The resulting quantity represents only a first approximation for a general description of all visual and non-visual effects. For a more accurate brightness model, the individual processes shall be combined and weighted in a more precise manner.

3.2.4 Mesopic contrast perception

The concept of *contrast perception* includes two different visual tasks:

1. Detection;
2. Object recognition based on visual acuity.

When detecting, subjects have to notice an object (detection target) but she or he does not necessarily have to recognise it. It should only be decided whether an object was noticed or not. By doing so, spatial structures of the object with higher spatial frequencies are not important. Only the processed receptor signals of lower spatial frequencies are relevant. To avoid accidents, all dangerous objects (detection targets or hazards) shall be detected. The mesopic detection in the non-central viewing field between 5° and 20° (i.e. beyond the foveal region) is especially important for the design of street, traffic and vehicle lighting.

In order to *recognise* an object, subjects shall identify the spatial details of the object, e.g. the number plate of the preceding vehicle. The question is what kind of object was seen. Higher spatial frequencies of the object play an important role. The analysis of this higher spatial frequency content of the object (e.g. the visual task of a visual acuity test) results in the recognition of the object.

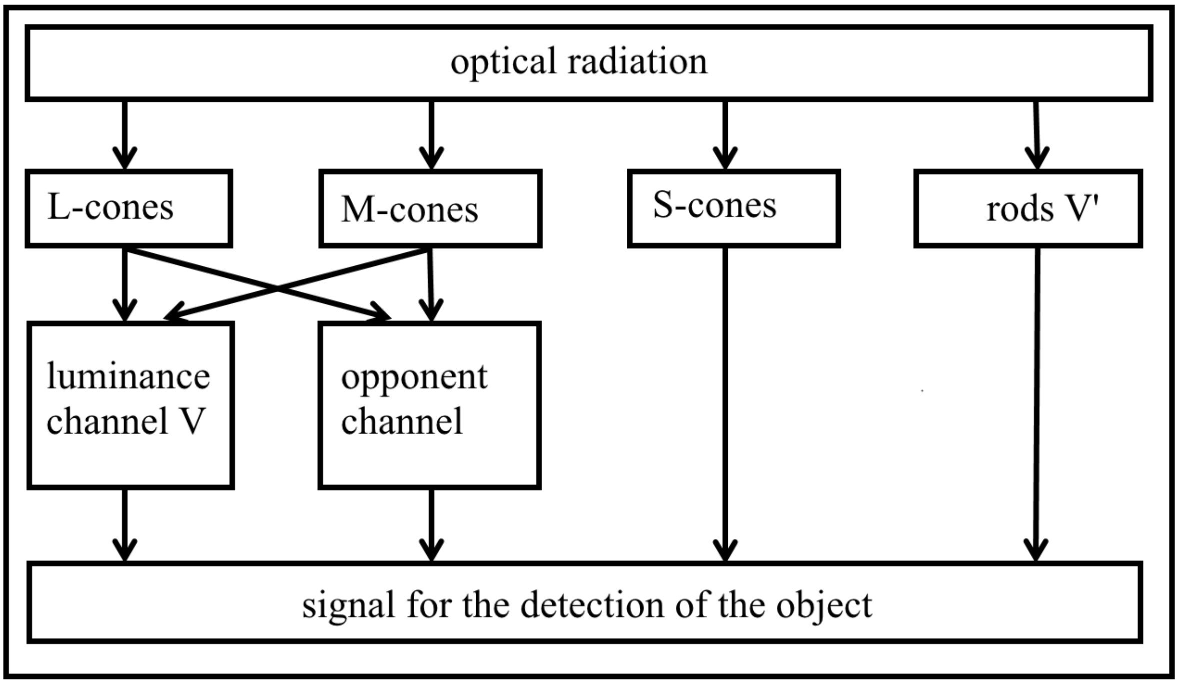
In order to describe contrast perception in the mesopic range, CIE recommends the so-called mesopic visual performance model [10]. Chromatic visual mechanisms contribute to mesopic detection except for the lowest mesopic range (below about 0.01 cd/m^2) [11]. In order to account for these chromatic mechanisms, more mesopic research is needed.

The contribution of the chromatic visual mechanisms is obvious from the shape of the psychophysically obtained mesopic spectral detection sensitivity functions ($V_{mes,det}$). These functions reveal more local maxima in the visible wavelength range than a combination of $V(\lambda)$ and $V'(\lambda)$ [12, 13, 14]. The wavelengths of these local maxima depend on the mesopic adaptation level and the point of appearance (retinal position) of the detection target [11]. Empirical sensitivity function was modelled by a linear combination ($V_{mes,lin}(\lambda)$) of the following visual mechanisms [11]:

1. The spectral sensitivity functions of the L-, M-, and S-cones: $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$,
2. The spectral sensitivity functions of the rods: $V'(\lambda)$,
3. A chromatic mechanism: the opponent channel $|L(\lambda) - M(\lambda)|$ and
4. The sum of the L- and M-cone signals, the so-called luminance channel V.

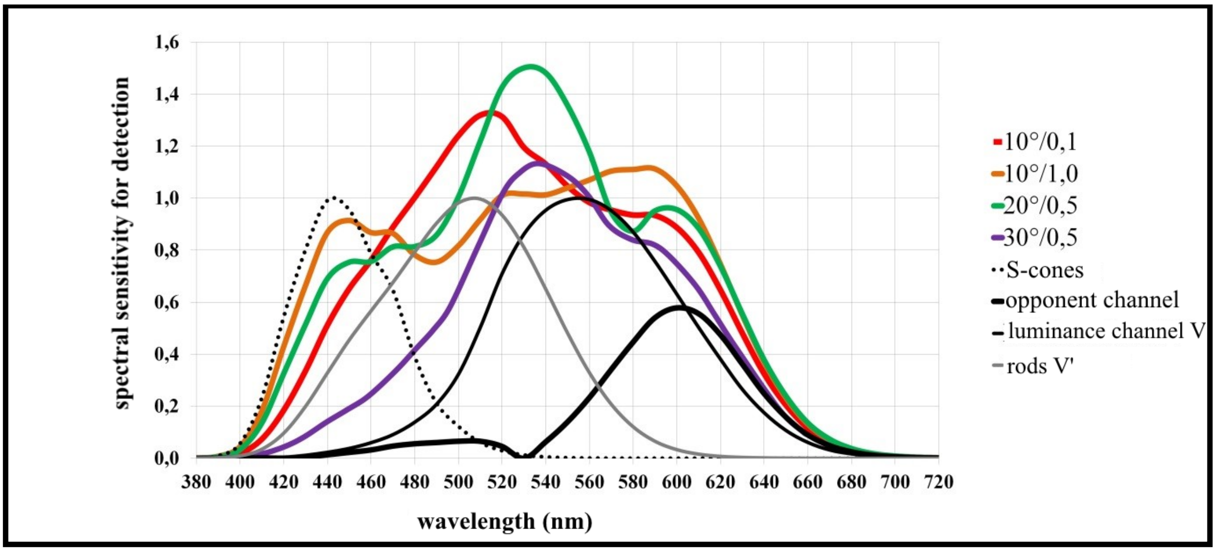
The signal flow diagram of Figure 15 illustrates the scheme of these visual mechanisms.

Figure 15: Scheme of the visual mechanism contributing to the detection of an object in the mesopic range. The sum of the L- and M-cone signals constitute the luminance channel V. The difference of the L- and M-cone signals constitute the opponent channel. S-cones and rods (V') also contribute to the detection signal



The relative contributions of the mechanisms depend on the mesopic adaptation level and the point of appearance of the object on the retina [11]. Figure 16 shows the fitted $V_{mes,lin}(\lambda)$ functions from Figure 15 in case of the different adaptation levels and retinal positions of the object.

Figure 16: Coloured curves: modelled mesopic spectral sensitivity functions $V_{mes,lin}(\lambda)$ for detection as a function of viewing angle (in degrees) for different adaptation levels. 10 °/1.0 means e. g. the retinal position of 10 ° and the adaptation with a background luminance of 1.0 cd/m². Grey curves: spectral sensitivities of the individual mechanisms to interpret the coloured $V_{mes,lin}(\lambda)$-curves. Compare with Figure 15



The different courses of the spectral sensitivity functions as a function of the different mesopic viewing conditions can be explained by the different contributions of the individual mechanisms. E.g. S-cones and the opponent channel do have an important contribution under 10°/1.0 cd/m² as opposed to 30°/0,5 cd/m².

3.2.5 The mesopic visual performance model of the CIE

The mesopic visual performance model of the CIE [10] is an intermediate model. Its numeric predictions are situated between two other mesopic visual performance models, the X-model [2] and the MOVE model [3]. Lighting systems and components for safe traffic management shall ensure excellent mesopic visual performance always and everywhere. This is why the most important application of this model is street lighting and vehicle lighting. In latter applications, mesopic visual conditions usually correspond a luminance level between 0.05 and 1.5 cd/m². The model [10] describes all three above mentioned aspects of mesopic visual performance i.e. detection, reaction times and object recocgntion.

The visual task of detection is very important in order to avoid accidents (as already mentioned earlier). In order to increase traffic safety, the detection probability of typical objects shall be increased by designing lighting *mesopically*. To do so, the mesopic visual performance model of the CIE offers a good design tool.

Applying conventional (photopic) photometry causes substantial errors because typical objects are detected as a result of mesopic processes. A typical object appears vertically oriented, at 5 °-30 ° i.e. outside the foveal area where both the rods and the cones are active. The object usually exhibits only a small contrast i.e. a small radiance difference between the object itself and its background.

In order to safely detect such an object, we need a certain minimum amount of contrast, the so-called threshold contrast. If the threshold contrast is low then objects of low contrast appear above the threshold hence they can be detected.

In the mesopic range, the value of the threshold contrast decreases with an increasing value of the *mesopic* surround luminance. It should be emphasised that a *mesopic* luminance value shall be used and not photopic or scotopic luminance. Otherwise, one shall obtain a false prediction [10]. Therefore, the purpose of street and vehicle lighting design is to increase the *mesopic* luminance level of the scene (e.g. the traffic scene of a road by night-time driving) in order to increase the detection probability of typical hazards (objects to be detected to avoid an accident).

Maintenance values in today's standard are given in terms of photopic luminance or illuminance values and the design shall comply with this standard. But the designer is free to choose different lamp spectra with different chromaticities (i.e. colours of the light). Different light sources of different chromaticity exhibit different mesopic luminance values at the same fixed photopic luminance. Thus they also represent different levels of mesopic visual performance, especially of mesopic detection performance.

In the mesopic visual performance model of the CIE [10], the value of mesopic luminance is computed from the values of the photopic luminance L (sum of L- and M-cone signals) and the scotopic luminance L' (rod signal). To carry out the computation, first let us define the so-called S/P ratio: this parameter equals the ratio of scotopic luminance to photopic luminance. The spectral radiance distribution of the light source ($X_e(\lambda)$) can be multiplied either by the $V'(\lambda)$ function (see Figure 15 ; for night vision or scotopic vision where rods are active) or with the $V(\lambda)$ function (see Figure 15; for daytime vision or photopic vision where the cones are active). The product shall be integrated spectrally in order to obtain the quantities scotopic luminance (L_S) or photopic luminance (L_P). In the next step, the *S/P ratio* can be computed, see Eq. (3.8).

$$L_S = 1699\ (\mathrm{lm/W}) \int_{380nm}^{780nm} X_e(\lambda) V'(\lambda)\, d\lambda$$

$$L_P = 683\ (\mathrm{lm/W}) \int_{380nm}^{780nm} X_e(\lambda) V(\lambda)\, d\lambda \tag{3.8}$$

$$(S/P) = L_S / L_P$$

The relative contribution of both receptor types depends on the actual luminance level, the chromaticity and the (S/P) ratio of the stimulus. The stimulus is usually the background of the object to be detected e.g. in a night-time road scene. A scene illuminated by a *cool white* street lamp has a higher *mesopic* luminance (hence better visual performance) than the same scene illuminated by a *yellowish* street lamp *at the same photopic* luminance level. So we can increase detection performance by the use of a cool white light source at mesopic levels.

The computational steps of the CIE mesopic visual performance model [10] can be summarised as follows [10]:

1. Input: photopic luminance L in cd/m^2 and S/P ratio of the light source
2. Computation of the scotopic luminance L'
3. m_0:=0.5 (initial value for the adaptation coefficient m for the combination of the achromatic signals L' and L)
4. Computation of an initial value for the mesopic luminance: $L_{mes,1}$

5. Computation of m_1 (first approximation for m) from the value of $L_{mes,1}$
6. Computation of the next value of the mesopic luminance ($L_{mes,2}$) from L, L' and m_1
7. Computation of the next value of the adaptation coefficient (m_2) from the value of $L_{mes,2}$

The steps No. 6 and No. 7 shall be iterated as long as the value of mesopic luminance (L_{mes}) remains constant with a required accuracy. According to experience, 4 to 7 iterations deliver a usable result. Over 5.0 cd/m², the model outputs photopic luminance. Eqs. (3.9)-(3.11) show the mathematical formulae of the above description.

$$L' = (S/P)\,L \qquad (3.9)$$

$$L_{mes,n} = \frac{m_{n-1}L + (1-m_{n-1})\,L'\,(683/1699)}{m_{n-1} + (1-m_{n-1})(683/1699)} \qquad (3.10)$$

$$m_n = 0.767 + 0.3334\,\log_{10}(L_{mes,n}),\ 0 \le m_n \le 1 \qquad (3.11)$$

Table 3 visualizes the dependence of the mesopic luminance L_{mes} on the photopic luminance L (in the first row of Table 3) and on the (S/P) ratio (in the first column of Table 3) in the mesopic visual performance model of the CIE [10].

Table 3: Dependence of the mesopic luminance L_{mes} on photopic luminance L (in the first row) and on (S/P) ratio (in the first column). All L_{mes} values were computed by Eq. (3.9)-(3.11). Over 5.0 cd/m², the model works photopically

	Photopic luminance *L* (cd/m²)						
S/P	0.01	0.03	0.10	0.30	1.00	3.00	4.50
0.25	0.0025	0.0145	0.0705	0.2467	0.9130	2.9265	4.4782
0.35	0.0035	0.0174	0.0750	0.2545	0.9253	2.9367	4.4812
0.45	0.0045	0.0198	0.0793	0.2620	0.9373	2.9468	4.4842
0.55	0.0057	0.0220	0.0834	0.2693	0.9492	2.9568	4.4872
0.65	0.0069	0.0239	0.0873	0.2764	0.9608	2.9666	4.4901
0.75	0.0079	0.0258	0.0911	0.2833	0.9722	2.9763	4.4929
0.85	0.0088	0.0275	0.0947	0.2901	0.9835	2.9859	4.4958
0.95	0.0096	0.0292	0.0983	0.2967	0.9945	2.9953	4.4986
1.05	0.0104	0.0308	0.1017	0.3032	1.0054	3.0046	4.5014
1.15	0.0111	0.0323	0.1051	0.3096	1.0161	3.0139	4.5041
1.25	0.0118	0.0338	0.1083	0.3158	1.0267	3.0230	4.5068
1.35	0.0125	0.0353	0.1115	0.3220	1.0371	3.0319	4.5095
1.45	0.0132	0.0367	0.1147	0.3280	1.0473	3.0408	4.5122
1.55	0.0138	0.0381	0.1178	0.3339	1.0575	3.0496	4.5148
1.65	0.0145	0.0395	0.1208	0.3398	1.0674	3.0582	4.5174
1.75	0.0151	0.0408	0.1238	0.3455	1.0773	3.0668	4.5200
1.85	0.0157	0.0421	0.1267	0.3512	1.0870	3.0753	4.5225
1.95	0.0163	0.0434	0.1295	0.3568	1.0966	3.0836	4.5250
2.05	0.0169	0.0446	0.1324	0.3623	1.1060	3.0919	4.5275
2.15	0.0174	0.0459	0.1352	0.3677	1.1154	3.1001	4.5299
2.25	0.0180	0.0471	0.1379	0.3731	1.1246	3.1082	4.5323
2.35	0.0185	0.0483	0.1406	0.3784	1.1338	3.1162	4.5347
2.45	0.0191	0.0495	0.1433	0.3836	1.1428	3.1241	4.5371
2.55	0.0196	0.0506	0.1459	0.3888	1.1517	3.1319	4.5395

	Photopic luminance *L* (cd/m²)						
S/P	**0.01**	**0.03**	**0.10**	**0.30**	**1.00**	**3.00**	**4.50**
2.65	0.0201	0.0518	0.1485	0.3939	1.1605	3.1396	4.5418
2.75	0.0207	0.0529	0.1511	0.3989	1.1693	3.1473	4.5441

As can be seen from Table 3, a higher (S/P) ratio results in a higher mesopic luminance L_{mes} – at the same photopic luminance L. The importance of the mesopic visual performance model of the CIE [10] is that the value of L_{mes} does not only depend on the photopic luminance L but also on the (S/P) ratio. A yellowish high-pressure sodium lamp (NAV) exhibits the lower (S/P) value (i.e. a lower blue part in its spectral radiance distribution) of only 0.422. This causes lower mesopic luminance values according to Table 3, between the (S/P) rows 0.35 and 0.45. In contrast, a white LED light source with the high (S/P) value (i.e. a high blue content its spectral radiance distribution) of 2.240, between the (S/P) rows 2.15 and 2.25 in Table 3, and this causes higher mesopic luminance values (compare with the photopic luminance values in the first row of Table 3).

As a further example to apply the mesopic visual performance model of the CIE [10], mesopic luminance values L_{mes} were computed for seven typical street lamps and car headlamp light sources by using Eqs. (3.9)-(3.11) supposing that the (grey) road surface reflects the light of the street lamps approximately neutrally, see Table 4. In this example, the photopic luminance requirements of the ME illumination classes for dry road surfaces of the standard DIN EN 13201 were applied. These are intended for roads with medium to high velocities and are so-called maintenance values. Table 4 also shows the results of the computation of the mesopic luminance values, corresponding to the photopic maintenance values of DIN EN 13201. In Table 5, the gain of visual performance is expressed as a percentage compared to photopic luminance if street lighting is designed with a light source selected according to Table 4. Negative values in Table 5 represent a loss of visual performance.

Table 4: Comparison of the mesopic luminance values corresponding to the photopic maintenance values according to the CIE model [10] in case of usual street and automotive light sources acording to Table 3 in the ME classes of DIN EN 13201

ME class	Photopic maintenance value (cd/m²)	HQL	CPO	MH	NAV	H7	Xe	LED
1	2.000	2.012	2.001	2.029	1.930	2.059	2.071	2.133
2	1.500	1.512	1.501	1.530	1.429	1.560	1.572	1.634
3	1.000	1.011	1.001	1.028	0.934	1.055	1.067	1.124
4	0.750	0.760	0.751	0.775	0.690	0.800	0.811	0.862
5	0.500	0.508	0.501	0.521	0.449	0.542	0.551	0.594
6	0.300	0.306	0.301	0.316	0.260	0.333	0.339	0.373
	S/P	**1.101**	**1.008**	**1.259**	**0.422**	**1.526**	**1.644**	**2.240**

Table 5: Gain (positive numbers) or loss (negative numbers) of visual performance in % if the photopic luminances (maintenance values) are retained according to DIN EN 13201. The computation is based on Table 4

ME class	Maintenance value (cd/m²)	HQL	CPO	MH	NAV	H7	Xe	LED
1	2.000	0.58	0.04	1.47	-3.49	2.94	3.57	6.64
2	1.500	0.78	0.06	1.99	-4.73	3.97	4.82	8.93
3	1.000	1.09	0.08	2.76	-6.61	5.51	6.68	12.37
4	0.750	1.32	0.10	3.35	-8.05	6.67	8.09	14.96
5	0.500	1.67	0.13	4.23	-10.26	8.43	10.21	18.84
6	0.300	2.16	0.17	5.46	-13.38	10.85	13.14	24.17
	S/P	**1.101**	**1.008**	**1.259**	**0.422**	**1.526**	**1.644**	**2.240**

As can be seen from Table 4 and Table 5, light sources with higher S/P ratios (see the last rows of Table 4 and Table 5) enable higher visual performance if we retain ME maintenance values but compute mesopically. Therefore, light sources with a higher blue content in their spectrum enable better mesopic detection performance. The highest performance gain in comparison with the photopic prediction (24 %) is exhibited by the white LED in the ME6 class. If we apply instead a yellowish high-pressure sodium lamp with a lower S/P ratio then we will lose 13.38 %. Critical traffic situations might occur under latter light source because hazards cannot be safely detected.

3.3 Summary

Brightness is important for the three-dimensional impression of interior and exterior space in architecture, to ensure good visual performance and feeling of safety. Brightness perception cannot be fully described by the quantities luminance and illuminance because photometric quantities (e.g. luminous flux) do not describe all human visual system mechanisms that contribute to brightness. This is a significant deficiency of all photometric quantities including luminous flux (lm). Therefore, the brightness and visual performance models introduced in this Section apply further quantities derived from the spectrum and define appropriate measures to characterise brightness and visual performance. The equivalent luminance of Ware and Cowan (3.1.2) and the lightness metric of Fairchild and Pirrotta (3.1.3) are not related to real, spatially extended scenes and therefore, they are less relevant from the point of view of *general* lighting engineering. In this respect, the brightness metric of Fotios et al. (3.1.4) is more relevant and this will be applied in the new evaluation concept of the present report in the photopic range. In the mesopic range, the mesopic visual performance model of the CIE will be applied (3.2.5). Latter model is based on a large set of experimental data.

3.4 Literature for Section 3

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4 Colour quality, Colour Quality Metrics

4.1 Introduction

At the beginning of the era of electric lighting, the most important factor of lighting system design was lighting quality based on the parameters luminance level, illuminance level, glare metrics and contrast metrics. Later, at the beginning of the 1960's, the general colour rendering index (CIE CRI R_a) was introduced in order to define a colour quality parameter during lighting design and characterise colour quality in terms of a numeric quantity for different lighting situations, e.g. offices, retail or hotels). The definition of the colour rendering index made it possible to choose an appropriate light source from the (those days i.e. until 2010-2012) quite limited set of light sources (thermic radiators like incandescent, tungsten halogen and discharge lamps, e.g. fluorescent lamps T8 and T5, HMI or HTI lamps) for the interior colour design of higher demand.

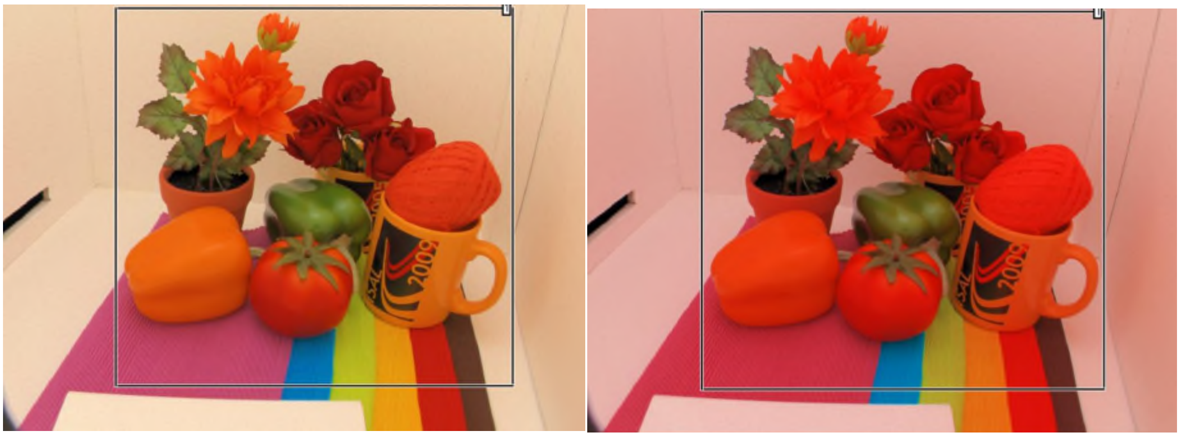
The colour rendering property of a certain (so-called „test") light source can be defined as the effect of the test light source on the colour perception of objects illuminated by this test light source compared with the colour perception of the same objects under a reference light source in a conscious or unconscious manner. This definition is based on the assumption that the colour impression of the objects shall be similar to the reference situation. As reference emission spectra are defined as Planckian radiators (similar to tungsten light) or daylight phases and these spectra are quite continuous in the sense that radiation is represented at every wavelength between 380 nm and 780 nm, illuminating the coloured objects' surfaces by these reference spectra, we obtain full and unbiased colour information for the human visual system. Processing this information, the visual system should concentrate on the „relationship between the rendered colour under the test light source and the original colour under the reference light source" and this should already involve context related judgements about „colour naturalness", „identification of coloured objects" and „colour originality".

In the time between 1945 and about 2008-2010, only light sources of fixed spectra (except halogen metal vapour lamps) without the possibility of spectral variations were available for lighting design. The aim of technological development was the optimisation of the luminous efficiency (in lm/W) of the light source. However, those days, colour scientists already carried out some studies about the visual aspects of colour quality and these results were very welcome in the academic field. In recent years, these research activities about the different aspects of colour lighting design have been intensified and quickly implemented into real lamp concepts and illuminating guides for lighting industry.

This increase of the speed of research and its industrial implementations can be traced back to the previously unknown flexibility of emerging LED lighting technology. Today, a world-wide competition of LED lighting ideas and industrial re-orientation is taking place. Coloured products can not only be rendered in their original colour in retail but the way of their presentation under LED illumination can stimulate customers to purchase them if LED lighting renders the products in their preferred colour. Thus, beside the above defined *colour rendering* aspect, a new aspect of colour quality, *colour preference* was arising and became the subject of discussions and research.

An important task of modern lighting design is to select a light source with a suitable spectrum and a luminaire with a suitable spatial light distribution to fulfil the actual visual task for the long-term acceptance of the lighting system [1]. One important component of acceptance is good colour rendering and this happens on the basis of the colour memory of the subject when comparing the illuminated objects und daylight or tungsten light with their colour perception under the actual artificial emission spectrum, see Figure 17. Colour rendering properties play a very important role in today's lighting practice when selecting the appropriate light source.

Figure 17: In order to judge the colour rendering property of a test light source, the colour perception of the coloured objects under the test light source (right) are compared by the subject with the colour perception under the reference light (left). In most real situations, the reference (left) is not present and the judgement is based on the subject's colour memory



Today, several artificial light sources featuring a white tone similar to natural daylight at a certain time of the day or to the white tone of a tungsten halogen lamp can be found. This means that the light source does not „disturb" the „white" perception of a neutral white surface as long as the white tone of the light source is perceived as „white". Problems with the perceived object surface colours occur if some spectral range are missing or too low in the spectral power distribution of the light source. A fully satisfactory numeric assessment of the effect of spectral power distribution on the perceived colour rendering property of a light source is not available today. This is why the subject of colour rendering and colour rendering indices are so important in today's lighting engineering research within or outside the International Commission on Illumination (CIE) [2].

The colour rendering of a test light source is acceptable if the colour appearance of reflecting colour object surfaces under the test light source matches their colour appearance under the reference light source. This matching is being judged by the user visually in a conscious or unconscious comparison between the test and reference situations [3]. The colour rendering property is characterised internationally by the CIE general colour rendering index R_a [2] today. Visual experiments showed, however, that this colour rendering index cannot precisely describe the visual colour rendering property of modern light sources, especially of white LED light sources. This was also corroborated by the CIE [4] in 2007.

In the following, the deficits of the mathematical colour rendering index definitions will be elucidated and possible solutions will be shown. The number of mathematical colour rendering models is very high. The criterion of accepting one model is its agreement with visual colour rendering results. Thus, important colour rendering experiments will be described. The amendment and the validation of the different versions of the colour rendering indices is based on these experiments. The interpersonal scatter of perceived colour differences will also be discussed. The reason is that different observers perceive colours and their differences differently and this influences their colour rendering judgments.

Besides colour rendering, other aspects of colour quality like colour harmony, colour preference and colour gamut might also come into play. These aspects cannot be described by the colour rendering index. They need their own indices, the harmony rendering index, the preference index and the gamut index. Especially, the difference between the two aspects colour rendering and colour preference is important. Colour preference means that a certain observer likes or does not like a certain appearance (e.g. a more or less saturated appearance) of a coloured object. In contrast, colour rendering means that the coloured object has the same colour appearance under the test and reference light sources and this concept is by definition independent of the preference of a certain colour appearance.

The CIE first characterised the colour rendering property of a light source by a spectral band method with 8 spectral bands [5] with the following limits: 380-420 nm, 420-440 nm, 440-460 nm, 460-510 nm, 510-560 nm, 560-610 nm, 610-660 nm and 660-760 nm. Radiance values in these 8 bands were compared with those of a reference light source [6, 7, 8]. The weighting of the individual spectral bands and the optimum choice of the band limits had problems when the method was applied to fluorescent lamps (when it was tried to evaluate a spectrum with sharp spectral lines). Bad results in comparison to visual assessments could not be amended, despite changing of the number of bands, the wavelengths of the band limits and introducing a weighting function [9].

Therefore, the CIE suggested alternative numeric assessment methods of colour rendering, valid for all types of light source [10, 11]. As a usable alternative method, the method of colour shifts of different test objects (i.e. reflecting coloured surfaces) seemed to be appropriate. This method evaluates changes of colour appearance between the reference and the test source numerically. This principle has been used to evaluate colour rendering in all methods until today. These methods and their problems, especially the way how chromatic adaptation and visually uniform colour spaces can be described, were taken into consideration by numerous authors [12, 13, 14].

Based on these studies, the method of colour shifts was endorsed by the CIE and not the spectral band method. It was shown (at least in case of the light sources that were available those days) that a relatively small number (8 to 15) of test colour samples was enough to describe the colour rendering property of the test light source and that a visually uniform colour space was important [9, 15, 16, 17]. The first version of the method was presented [18]. It was described later in a CIE publication (first edition) [19]. The most important result of this method is a real number computed from the spectral power distribution of the light source. This number characterises the colour rendering property of the light source. It is called the CIE general colour rendering index (CIE CRI R_a).

Open questions of the first edition concerned the possibilities of simplifying the method, a better description of chromatic adaptation and the use of fluorescent colours. The second edition of the CIE publication about the method [20] changed only the chromatic adaptation formula [21, 22]. This amendment is only valid for small colour differences between the chromaticity coordinates of the test and reference light sources. This small colour difference is guaranteed by the choice of a small tolerance limit when choosing the reference light source [20]. For the third, current edition [2] only printing errors were corrected and the recommendations of the second edition remained unchanged.

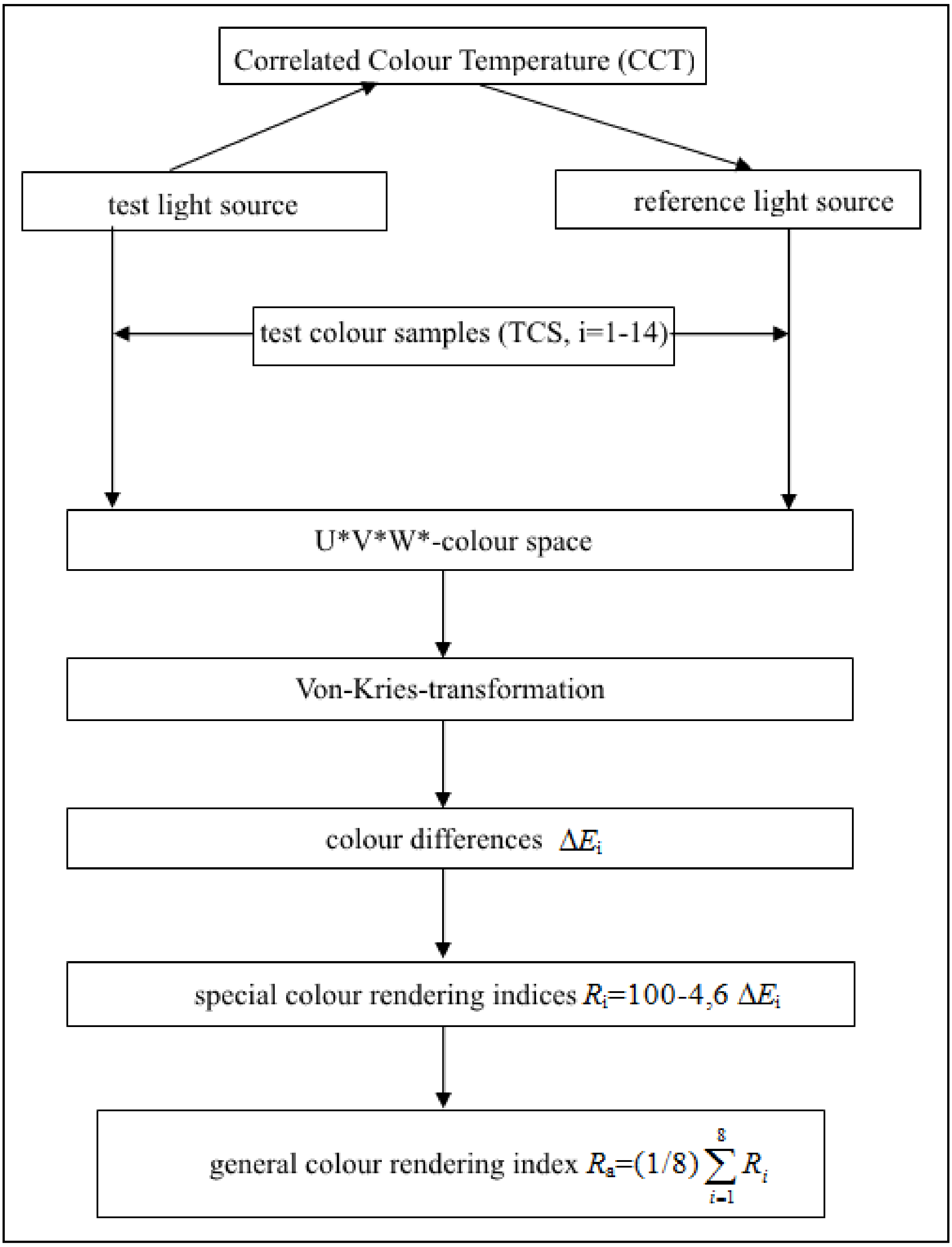
4.2 Definition of the current CIE method to calculate the colour rendering index, CIE CRI R_a

The detailed description and sample numeric values can be found in the publication of the current CIE colour rendering method [2]. In the present document, only a summary of the method will be described with the most important steps of calculation (1 to 7), see also Figure 18.

1. A reference light source is selected with the same correlated colour temperature (CCT) as the test light source. If CCT is less than 5000 K then a Planckian radiator (similar to tungsten light) of the same colour temperature is used as reference. If the CCT of the test light source is equal or higher than 5000 K then a phase of daylight of the same CCT is used as reference. The chromaticity difference ΔC in the u, v colour diagram shall be less or equal $5{,}4\cdot10^{-3}$.

2. Fourteen colour samples are selected from the Munsell colour atlas as test colour samples (TCS). From the first eight TCS, so-called special colour rendering indices are computed from which the general colour rendering index is computed as an average value (R_a). From the last six TCS, special colour rendering indices for further, supplementary purposes are computed.
3. The CIE 1931 tristimulus values X, Y, Z are computed for the 14 TCS under the test and reference light sources and they are transformed into CIE 1960 UCS coordinates (u, v) and also into the CIE 1964 U^*-V^*-W^* colour space.
4. The chromaticity of the test light source is transformed into the chromaticity of the reference light source by a von Kries transformation [21].
5. The fourteen CIE 1964 colour differences are computed for the 14 TCS (ΔE_i, i=1…14) between the U*, V* and W* values under the test light source and the reference light source.
6. For every TCS, the equation $R_i=(100-4.6\ \Delta E_i)$ is used to compute a special colour rendering index (i=1…14).
7. The general colour rendering index (R_a) is defined as the arithmetic mean value of the first 8 special colour rendering indices.

Figure 18: Workflow diagram of the computational steps of the CIE colour rendering index [2]



4.3 Properties of the general colour rendering index CIE CRI R_a

Visual colour rendering experiments showed that the value of the general colour rendering index (R_a) cannot accurately describe visual colour rendering results, it has a false prediction of the rank order of light sources according to their visual colour rendering property. This deficit is especially conspicuous if RGB LED light sources or sometimes also phosphor converted LEDs are involved. Causes of these deficits of applying the value of R_a (especially to LED spectra) were identified [23]. These causes can be summarised as follows.

Choice of the test colour samples (TCS): The first 8 TCS are unsaturated and the interaction of the LED spectra with saturated object colours (e.g. with saturated red) results in such a colour appearance that cannot be predicted by the aid of the first 8 (desaturated) TCS, see Figure 19.

Figure 19: Choice of the test colour samples (TCS) in the CIE colour rendering index method [2]. Top (Source: NIST, USA): the unsaturated test colour samples TCS01-TCS08, the basis to compute the general colour rendering index R_a; middle (source: NIST, USA): the saturated test colour samples TCS09-TCS14; bottom: interaction of a RGB LED emission spectrum with the spectral reflection of TCS09 (see also the text)

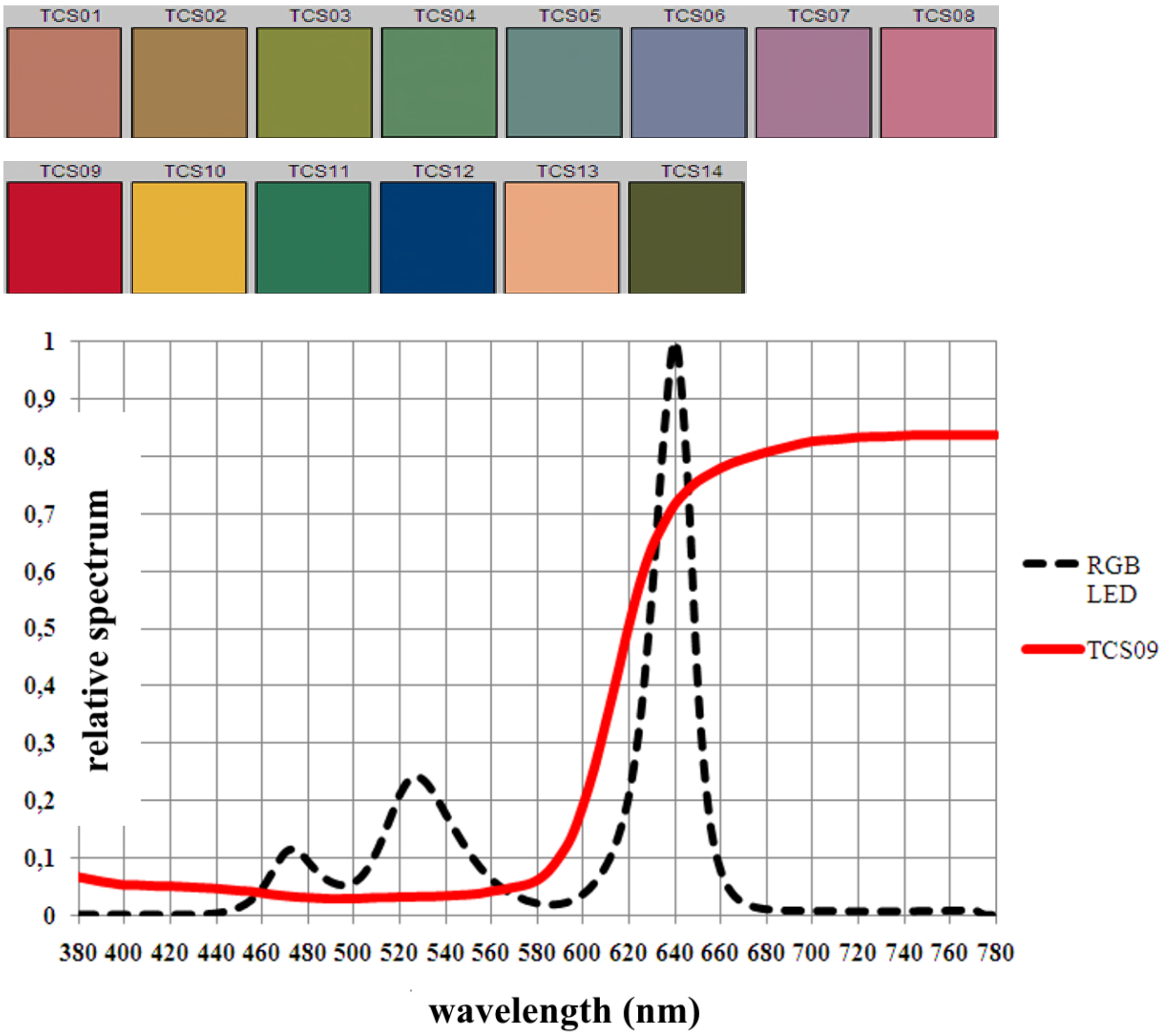


Figure 19 shows that the spectral power distribution of the LED light source (CCT=2690K) has a peak at 640 nm. Consequently, TCS09 (saturated red) enhances the red colour strongly. Due to this change, the corresponding special colour rendering index R_9 equals in this example -180. This effect cannot be described by the value of the colour rendering index (R_a=17 in this example) because latter value is only based on the desaturated TCS (TCS01-TCS08).

Reference light source: Subjects are rather a categorical and not a continuous characterisation of the perceived white tone [24]. Also, the choice of the reference white is discontinuous in the present CIE colour rendering index method: there is an interruption at the transition point between the Planckian radiator and the phase of daylight at 5000 K [2]. This causes a problematic computational workflow. Furthermore, the colour appearance of the objects under low colour temperatures is rather yellowish (e.g. under a Planckian radiator with 2000 K) due to the not perfect colour constancy of the human visual system, see Figure 20.

Figure 20: Illustration of not perfect colour constancy: colour appearance of a still life with coloured objects under low colour temperature illumination

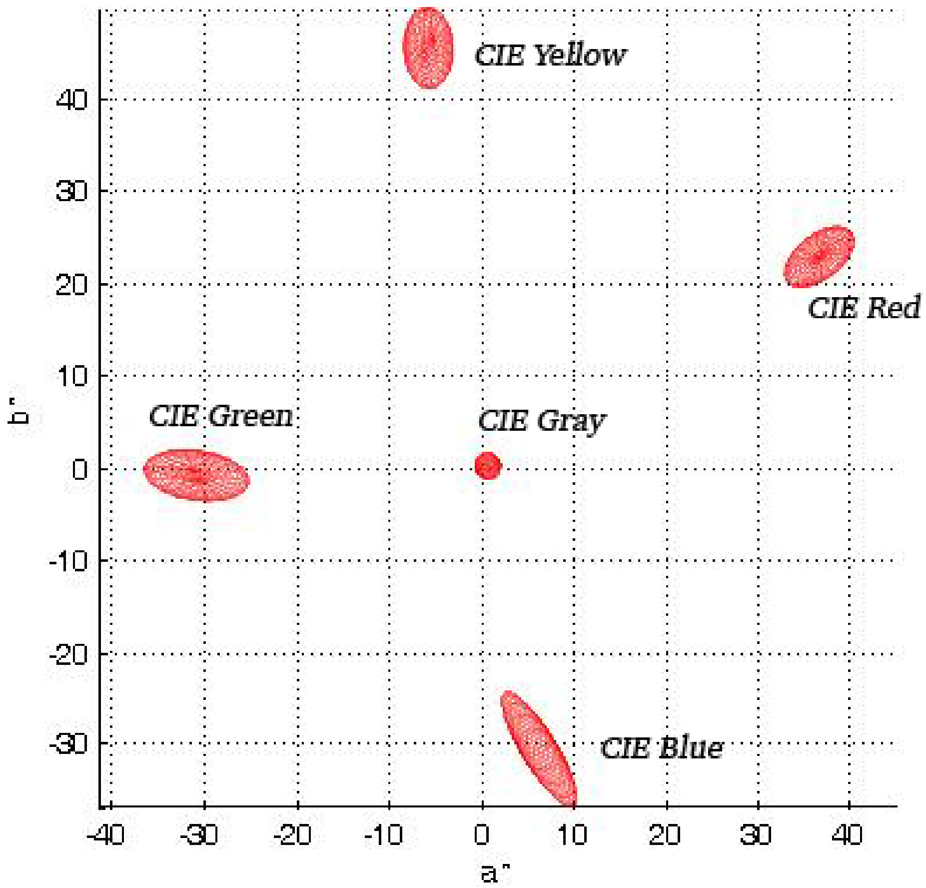
Chromatic adaptation formulae: For bigger chromatic adaptation differences which often occur when trying to predict colour rendering properties, the performance of the von Kries transformation is very poor.

Colour space and colour difference formulae: The correlation between the colour difference computed in the U*-V*-W* colour space (ΔE_{calc}) and perceived colour differences (ΔE_{vis}) is small. Such a poor colour space is called „visually not uniform". In a uniform colour space, all test colours T with a constant perceived colour difference (ΔE_{vis}) between T and a fixed reference colour R should be situated on a spherical surface with the reference colour R as a centre. Also, the diameter of the spheres shall be the constant for all reference colours.

Instead of these uniform spheres, there are ellipsoids of changing axis length in U*-V*-W* colour space. To visualise a non-uniform colour space, such a tolerance ellipsoid is shown in Figure 21. This is projected onto the CIELAB-a^*-b^* plane. The colours on this ellipsoidal surface represent a colour difference from the centre which is tolerable for 50 % of all subjects [25].

It can be seen from Figure 21 that visually obtained tolerance ellipsoids depend on the colour of the centre very strongly. Therefore, CIELAB colour space is visually non-uniform.

Figure 21: Tolerance ellipsoids projected onto the CIELAB-a*-b* plane (Source: [25])



Arithmetic mean value: A single number (i. e. a linear transformation of the mean value of the colour differences of the eight desaturated test colour samples between the test and the reference light source) cannot predict all possible colour shifts of all possible colours (including saturated colours) in modern interior lighting. This effect is especially significant in case of new, very saturated pigments combined with new spectra (e.g. LEDs), see Figure 19.

Interpretation of the R_a scale: It is not easy to interpret the values on the R_a scale (e. g. R_a=83) as a visual criterion of colour appearance, similar to the interpretation of the *differences* on the R_a scale (e.g. ΔR_a=3).

Colour quality: Perceived colour quality has further aspects (as already mentioned) in addition to colour rendering like colour gamut, colour harmony and colour preference. Visually scaled values of these aspects do not correlate with R_a in visual experiments [26, 27].

4.4 Alternative colour rendering indices and colour quality indices

By the aid of the average of all 14 special colour rendering indices ($R_{1\text{-}14}$) we can better describe the interaction between the emission spectrum of the light source and the spectral reflectance of the lighting product (Figure 19 shows an example for this interaction). Using the expansion of R_9 to R_{14}, we can also consider saturated colours missing from the computation with R_a. Further amendment possibilities were already considered by the CIE in 1991 when the technical committee TC 1-33 was founded and in 1999 a new calculation method ($R96_a$) was proposed

[28]. In this method which was finally not endorsed, the following amendment concepts of the CIE CRI colour rendering method were suggested:

1. The new test colour samples (TCS) were taken from the MacBeth-ColorChecker® chart. This contains both saturated and desaturated colours and important memory colours.
2. Instead of the continuous set of reference light sources (Planckian radiators and daylight phases), only 6 fixed reference light source were allowed (D65, D50, P4200, P3450, P2950 and P2700; here, P is a Planckian radiator with the CCT indicated) [24].
3. Instead of the von Kries transformation, the CIE adaptation formula [29] is used as adaptation transformation.
4. Tristimulus values of the test colour samples are transformed into D65 both under the test and the reference light source. To compute colour differences, CIELAB colour space is used because CIELAB was experimentally verified under D65.

In addition to this $R96_a$ method, other colour rendering indices were also suggested. In the following some interesting candidates are described.

4.4.1 The CQS method to describe colour preference: CQS Q_f, Q_a, Q_p and Q_g

While observing coloured objects (e.g. in a museum, a furniture store or in a food supermarket), observers compare the actual colours with their visual imagery containing the ideal appearance of these coloured objects. Subject require that these coloured objects should look attractively and this can be achieved by targeted illumination spectra. This so-called colour preference property is often associated with the concept of colour *vividness*. This has been especially relevant in the history of film, TV and cosmetics industry.

Colour preference is often related to a certain amount of hue shift and saturation enhancement compared to the reference situation (e.g. enhancing the chroma of skin colours in the red hue range by using a cream or a facial mask). Chroma enhancement by the light source is often applied in arts and also in cosmetics industry. In food retail (e.g. in the butcher‘s), chroma enhancement could cause product adulteration but this can be avoided by using products of high-end manufacturers who are aware of this problem during their spectral design.

Some important colour quality indices are defined in the NIST (**N**ational **I**nstitute for **S**tandards and **T**echnology) *CQS-method*. In version 9 (2011), the following three indices are defined:

1. *CQS* Q_a – preference index in which a moderate chroma enhancement has a better score than CIE CRI R_a;
2. *CQS* Q_f – fidelity index, this has a similar numeric assessment of test light sources to R_a i.e. chroma enhancement is penalised;
3. *CQS* Q_g – gamut index, this is strongly in favour of chroma enhancement by quantifying the volume of all rendered colours under a given test light sources compared to the reference.

When developing *CQS*, some principles of R_a were retained: *CQS* is also based on test colour samples and a reference light source. The reference is chosen in a similar manner as for *CIE* R_a. The most important differences compared to CIE R_a are as follows.

1. Test colour samples are 15 highly saturated colours (see Figure 22) because saturated colour samples are important to avoid false spectral optimisation with only desaturated samples (such falsely optimised spectra cannot render saturated colour samples correctly). Optimising with these 15 saturated samples, generally also the desaturated samples are rendered correctly.

2. Instead of the *von Kries* chromatic adaptation transformation, the so-called *CMCCAT2000* system is used to better describe the human visual system's properties.
3. The colour difference between the test and the reference is calculated in the *CIE 1976* L^*-a^*-b^*-colour space instead of the W^*-U^*-V^**(1964)* colour space because CIELAB is visually more uniform.
4. In order to compute the general index, the quadratic mean of the 15 colour differences is computed and not the arithmetic mean:

$$\Delta E^*_{rms} = \sqrt{\frac{1}{15}\sum_{i=1}^{15}\left(\Delta E^*_{ab,i}\right)^2}$$

   Using te above square root formula, test colour samples with higher deviations from the mean value get a higher weight than in case of the arithmetic mean. Higher deviations influence the value of the general index more strongly.
5. Also, *CQS* has a lower limit of zero hence there are no negative index values unlike in case of R_a.

Figure 22: Test colour samples of the CQS method (NIST, USA, Version 7.1), VS1-VS15 [30]

In order to numerically assess a light source according to the attractive appearance of the illuminated colours (to do so, ΔC^*_{ab} should be max. 10), the following so-called *chroma enhancement* factor is introduced in the computational workflow of CQS Q_a:

$$\Delta E^*_{ab,i,sat} = \Delta E^*_{ab,i} \qquad \text{for} \qquad \Delta C^*_{ab,i} \leq 0$$

$$\Delta E^*_{ab,i,sat} = \sqrt{\left(\Delta E^*_{ab,i}\right)^2 - \left(\Delta C^*_{ab,i}\right)^2} \qquad \text{for} \qquad \Delta C^*_{ab,i} > 0$$

And with this,

$$\mathbf{Q_a = 100 - 3{,}2 \cdot \Delta E_{rms}\left(E^*_{ab,i,sat}\right)}$$

To compute the colour *fidelity* metric CQS Q_f, the chroma enhancement factor is not used:

$$\mathbf{Q_f = 100 - 3{,}0305 \cdot \Delta E_{rms}\left(E^*_{ab,i}\right)}$$

The gamut based index CQS Q_g is the only index of the CQS method that can have greater than 100 values i.e. greater than the value of the reference. This feature is similar to other colour gamut indices. CQS Q_g always uses standard illuminant D65 as a reference with $Q_g(D65)=100$.

The fourth index (which, unfortunately, appeared only in previous versions of the CQS method) CQS Q_p weights the oversaturation of the objects more strongly than Q_a [48]. Otherwise, Q_p is computed similar to CQS Q_a but, in the last step, we use the following equation*:*

$$Q_{p,rms} = 100 - 3.780\left[\sqrt{\frac{1}{15}\sum_{i=1}^{15}\left(\Delta E^*_{ab,sat,i}\right)^2 - \frac{1}{15}\sum_{i=1}^{15}\Delta C^*_{ab,i}\,K(i)}\right]$$

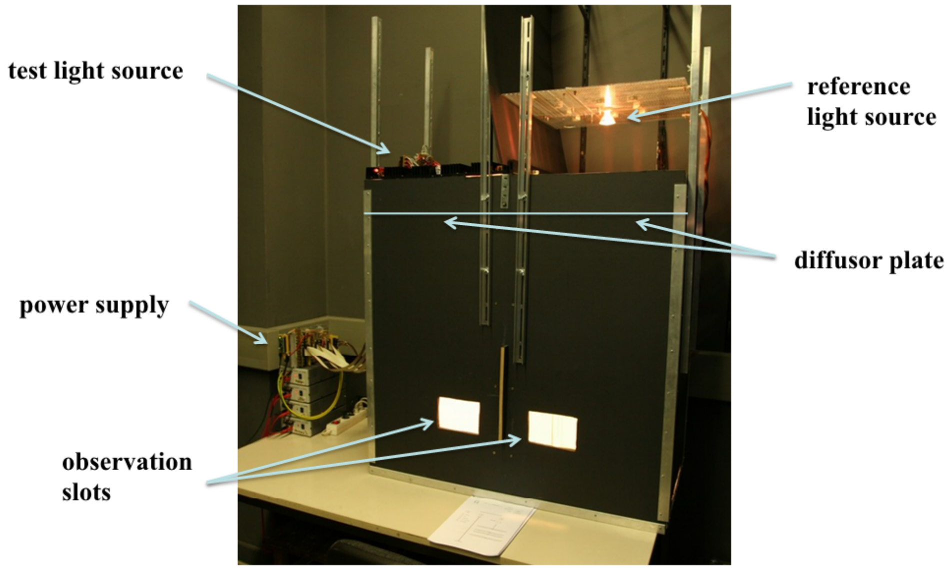
In the above equation, if $C^*_{ab,i,test} \geq C^*_{ab,i,ref}$ then K(i)=1 and if $C^*_{ab,i,test} \leq C^*_{ab,i,ref}$ then K(i)=0. This means that the value of Q_p is in favour of a stronger oversaturation in comparison with Q_a. Among all colour quality indices, the index f CQS Q_p has the best (very good) correlation with visual colour preference assessments as it was pointed out in recent visual experiments on colour preference.

4.4.2 CRI-CAM02UCS

This new colour rendering index developed at the University of Leeds (Great Britain) [33] applies a new, perceptually uniform colour space (the so-called CAM02-UCS) [34]. Colour differences of the test colour samples between the test and reference conditions are computed in this colour space. The reference light source is the same as in the CIE method [2] and the first 8 CIE test colour samples [2] are used. As the change of the adaptation viewing conditions is intrinsically included in the CIECAM02 colour appearance model [35], CIECAM02 based colour difference formulae or uniform colour spaces are suitable to describe the colour rendering property of a light source under different adaptation luminance and chromaticity conditions.

The supremacy of the CAM02-UCS colour space compared to previous colour spaces was corroborated in an own study at the Laboratory of the authors of the present report independent of the underlying studies at the University of Leeds. The own study was carried out in a double-chamber viewing booth (Figure 23) at the Technische Universität Darmstadt [36].

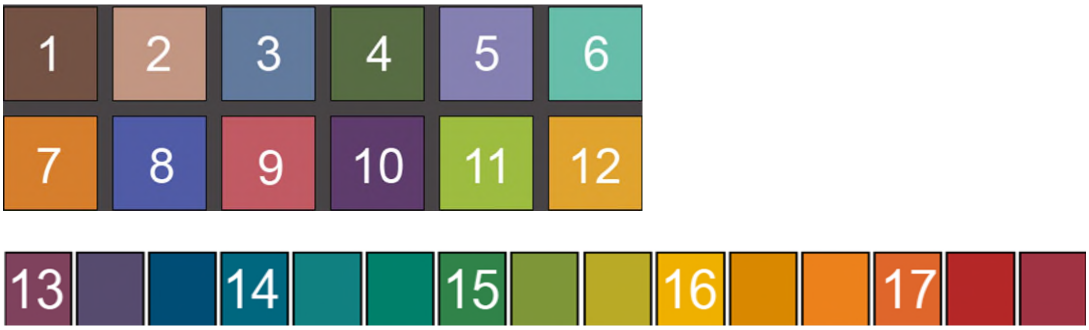
Figure 23: **Double-chamber viewing booth to scale perceived colour differences (ΔE_{vis}) visually. The same two colour samples were placed under the test (left chamber) and the reference light sources (right chamber).**



4.4.3 RCRI (Rating Scale Index for Colour Rendering)

This is why the new colour rendering index of the Technische Universität Darmstadt (RCRI) [36] was based on CAM02-UCS metric colour differences. In the RCRI method, colour differences are computationally assigned to categories (so-called ordinal ratings) with the degree of similarity of colour appearance of a test colour sample between the test and reference conditions. If the computed value of the CAM02-UCS colour difference of a test colour sample has a very low (very high) value then this sample will obtain a „very good" („very bad") rating. Similar to this, every one of the 17 RCRI test colour samples can also have a rating in between i.e. „good", „tolerable", or „not acceptable". The 17 RCRI test colour samples were partially taken from the MacBeth-ColorChecker® chart and partially from the set of CQS test colours [30], see Figure 24.

Figure 24: **The 17 RCRI test colour samples [36] taken from the MacBeth ColorChecker® chart (top) and the set of CQS test colours (bottom)**



The RCRI method works with the same reference light source as the CIE method [2]. The value of RCRI is computed from a transformation of the number of „very good" and „good" ratings of the 17 test colour samples. By doing so, the user obtains an easy interpretation of the index about how many test colour samples are rendered „well“ or „very well“ by the test light sources compared to the reference light source.

4.4.4 Colour quality index according to memory colours (S_a)

This index is *not a colour rendering scale*. It is a metric that describes the similarity of colour appearance of ten coloured objects often seen in real life under a test light source to their *long-term memory colours* as stored in the human subject's memory [37]. The method works without a reference light source. The maximum value of the index S_a (=1.000) means that the test light source renders the colour appearance of the objects in such a way that is expected by the subject when the colours of the objects are recalled from long-term colour memory. The general index S_a is computed as a geometric mean of the special indices of the ten objects.

4.4.5 Summary of the new concepts to correct the deficits of the CIE colour rendering index

Table 6 summarises the new concepts to correct the deficits of the CIE colour rendering index.

Table 6: Colour quality indices compared to the CIE colour rendering index. Advantages, Disadvantages

Method	Description	Advantages	Disadvantages
$R_{1\text{-}14}$	Average of the 14 special colour rendering indices (R_1-R_{14})	The interaction of the emission spectrum with the spectral reflectance of the objects can be better described. More colours are considered including saturated colours	
CQS Q_a	Combined colour rendering and preference index	Takes colour preference into account	Falsifies colour rendering
CQS Q_f	Colour rendering index	Visually uniform colour space (CIELAB)	There are more uniform colour spaces than CIELAB, e.g. CAM02UCS
CQS Q_p	Combined colour rendering and preference index	Correlates with visual colour preference results better than Q_a	The set of 15 test colours constitute a limited representation of real object colours

Method	Description	Advantages	Disadvantages
CQS Q_g	Colour gamut index	Describes vividness	
CRI-CAM02UCS	A colour rendering index	Based on a validated, uniform colour space (CAM02-UCS) with built-in chromatic adaptation	
RCRI	Ordinal scale based index	Visually uniform CAM02-UCS colour space. Semantic ratings for easy interpretation for non-experts	Validation in independent visual experiments has not been carried out.
S_a	Memory colour rendering index	Correlates well with visual colour preference results	Not a real colour rendering index
IES TM30-15 R_f, R_g	Modern colour quality metrics according to IES (2015, TM30-15) and CIE 2017, see 4.4.6	Modern colour space, a representative set of test colour samples	These indices are not yet in the standards and they should be validated experimentally
SBI	Index based on subjective assessments	A number of subjective assessments are considered: Brightness (H), Saturation (S), Temperature (T), Perception (E) and Colour Shift (FV)	Not a numeric method, no calculation. It is always based on subjective answers

The colour quality indices in Table 6 are new concepts to correct the deficits of the CIE colour rendering index. These concepts should be validated in visual experiments. There are two promising metrics (R_f und R_g) that also need experimental validation at the time of writing. These two metrics are described in Section 4.4.6. In the future, these metrics (R_f and R_g) can possibly used to describe colour quality, possibly in a combined manner. The combined colour rendering and preference index CQS Q_p is an alternative, promising metric. Latter metric correlates very well with visual results.

4.4.6 Modern colour quality metrics according to IES (2015, TM30-15) and CIE 2017

In 2015, an IES (Illuminating Engineering Society of North America) working group defined two new colour quality metrics, R_f (for colour rendering which is recently called *colour fidelity*) and R_g (for colour gamut). The aim of the new definitions (so-called TM-30-15 method) were:

1. Apply the best available colour space (CAM02-UCS) with the most uniform colour difference metric both for small and for large colour differences.
2. Determine a manageable set of test colour samples (99 colours of different lightness) from a database with 105000 available colours (see Figure 27). The proposed colour rendering and colour gamut metrics shall be computed on the basis of the same set of test colour samples and the numeric values R_g and R_f should well represent the large set for any arbitrary light source (including conventional and LED/OLED light sources).

The IES R_f and IES R_g metrics use a reference light source of the same correlated colour temperature as the test light source. Until 4500 K, a Planckian radiator, from 5500 K on, a phase of daylight, and between 4500 K and 5500 K, a linear combination of both is applied. The attributes *J'* (lightness) as well as *a'* and *b'* (red-green and yellow-blue components of the colour) are computed for every test colour sample both under the test and the reference light sources in CAM02-UCS colour space and the CIE 1964 10° colour matching functions. Then, the colour difference (ΔE), the colour rendering index R_f and the colour gamut index R_g are computed:

$$R_f = 100 - 7.54 \cdot \Delta E$$

$$R_g = 100 \cdot A(\text{test}) \,/\, \text{A(reference)}$$

Here, ΔE represents the average colour difference of all 99 colours in CAM02-UCS colour space between the test and reference situations. A(test) is the area of the polygon of all 99 colours in the *a'* - *b'* plane under the test light source. A(reference) is this area under the reference light source. The computational workflows of the indices R_a (CIE 1965, CIE 1995) and R_f (IES, 2015) have similar underlying concepts and structures. The values of R_f is also less than or equal 100. The new colour rendering index R_f with the 99 colours in the uniform colour space is a good candidate to replace today's CIE colour rendering index R_a. The colour gamut index R_g was defined by the IES to describe the object saturation effect of a test light source compared to a reference light source of the same correlated colour temperature. At first sight, R_g would be very appropriate to this aim because it can be greater than 100 sein because the polygon areas of the test colour samples under the test light source can be greater than under the reference. It is possible to get R_g values until 140-150 i.e. these light sources might exhibit a gamut which has 50 % more colour gamut than the reference.

Looking at Figure 25(right), the polygon areas under the test and reference light sources are seemingly different and obtain different numeric colour gamut index values. If the user of the test light source would like to illuminate reddish objects (e.g. in the butcher's) or greenish objects (e.g. plants) then a smaller colour gamut is experienced in case of these specific colours and this is not desirable in most cases. But a more extended area appears in case of yellow and violet objects (e.g. yellow banana or violet plum), see the example of Figure 25.

Therefore, the value of R_g does not yield any information about the shape of the colour gamut or the polygon area hence it cannot predict object saturation in a given hue group (e.g. red, yellow or green). The colour gamut index R_g has not been able to predict visual the important *colour preference* and *colour naturalness* assessments in recent experiments until 2015. This is why currently intensive research is being carried out to find an appropriate parameter to describe the visual assessment results of latter two attributes.

In Figure 26 (left), the spectral reflectance curves of the eight test colour samples of the CIE general colour rendering index R_a (1995) can be seen. The course of these curves is continuous between 380 nm and 780 nm, the test colours are desaturated and they cannot reveal the colour rendering deficiencies of discontinuous lamp emission spectra (spectra with high local maxima or spectral lines). The lightness *J*‘ of these 8 colours are in the range *J*‘=62-68 and represent only the colours in the medium lightness range.

Figure 25: Colour gamut and arrangement of 99 IES colours for a given phase of daylight and a cool white LED

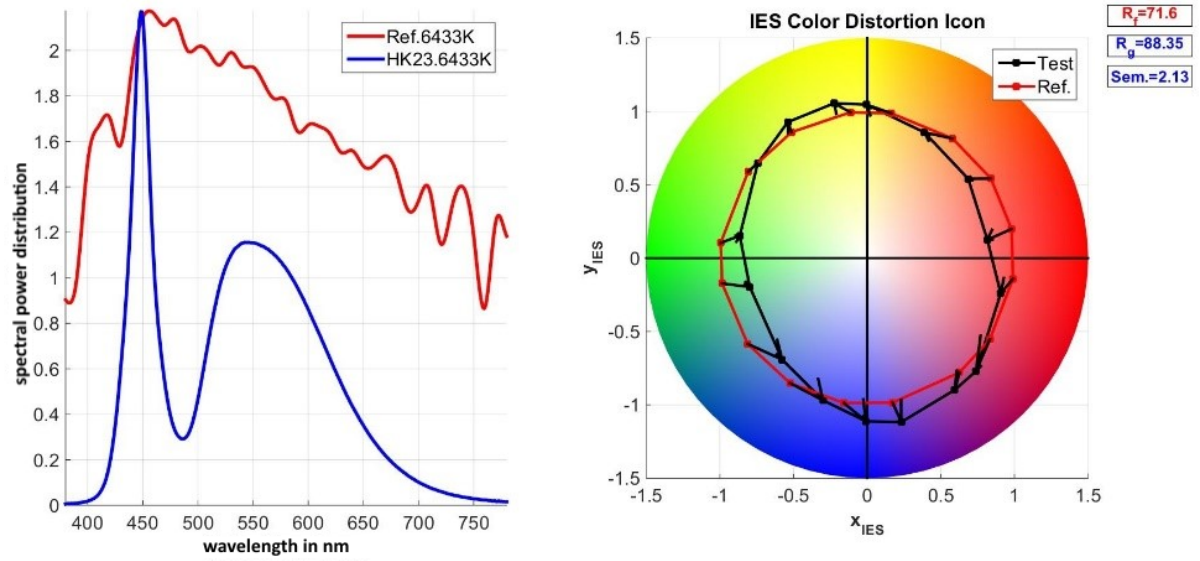


Figure 26: Spectral reflectance and chromaticity distribution of the 8 CIE test colour samples (CIE CRI, 1995) when illuminating with a blackbody radiator with 3200 K. Lines in the right 3D diagram visualise an area fitted to the 8 points of the 8 CIE test colour samples

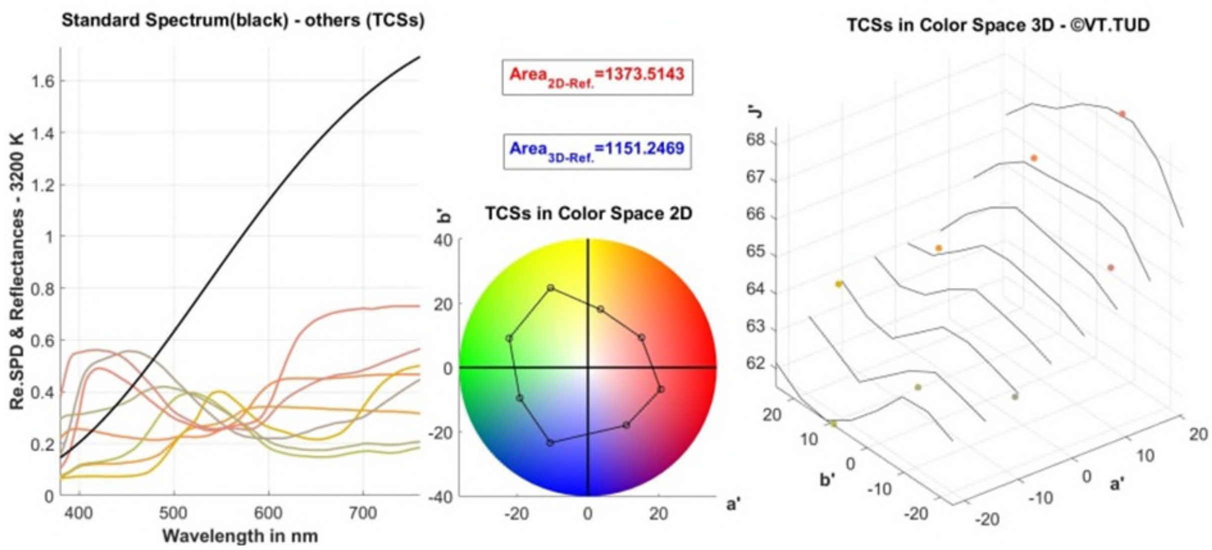


Figure 27 shows the spectral reflectance curves of the 99 IES test colour samples. There are numerous types of spectral reflectance curves with more or less reflectance below 550 nm and above 550 nm with saturated yellow, orange and red. There are also many colours with a high reflectance in the range between 500 nm and 570 nm (cyan, green and green-yellow object colours). All these colours are distributed uniformly around the hue axis (see the middle diagram of Figure 28) and along the lightness axis *J*‘ between 20 and 85 (see the right diagram of

Figure 28). Dark and light colours are equivalently represented. A sample colour rendering computation yielded a reliable prediction of the distortion of colour rendering in case of discontinuous lamp spectra (e.g. in case of RGB LED mixtures).

Figure 27: Spectral reflectance curves of the 99 IES test colour samples (IES, TM30-15, 2015)

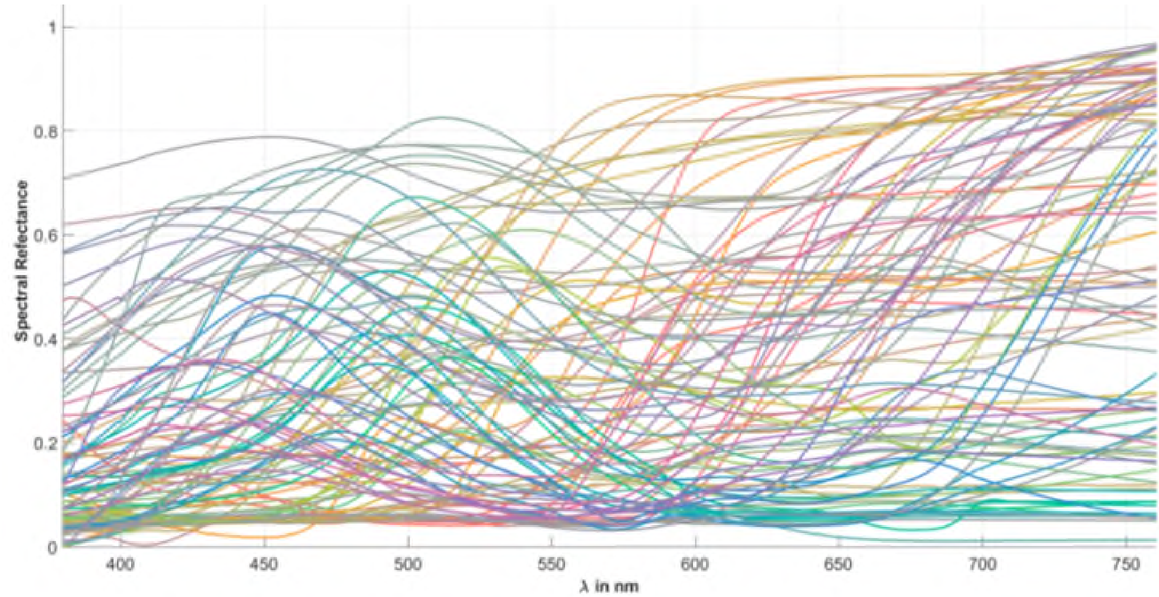
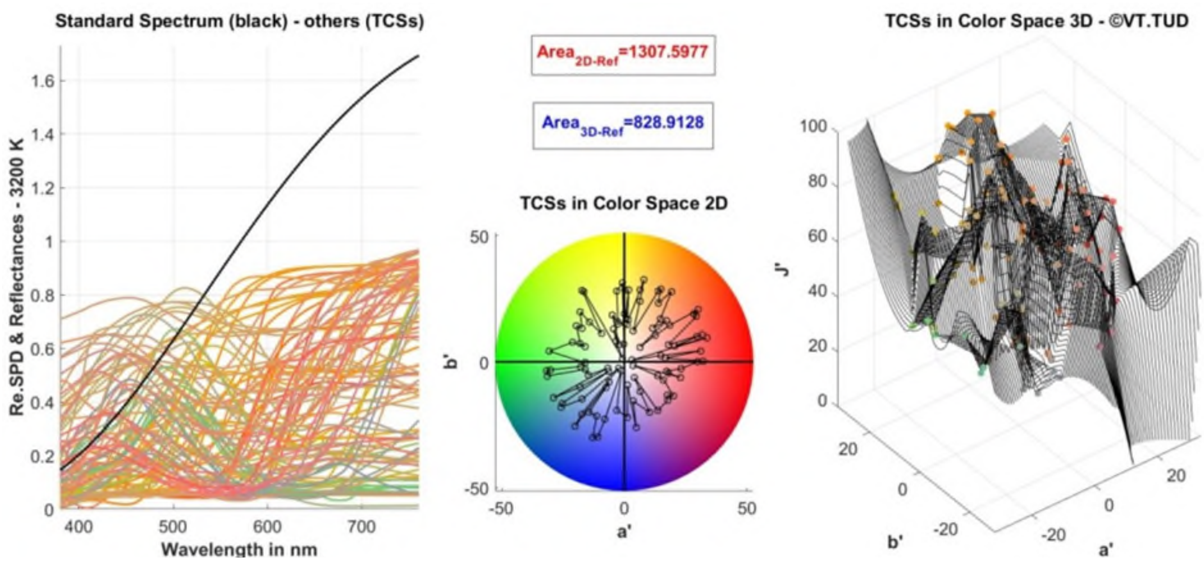


Figure 28: Spectral reflectance curves and chromaticity distribution of the 99 IES test colour samples illuminated by a blackbody radiator with 3200 K. The colours of the 99 IES test colour samples under this light source are in a two-dimensional (middle)and in a three-dimensional diagram (right)



4.4.7 SBI

The SBI index (Jungnitsch et al. [49]) is based in the subjective assessment of a simultaneous visual comparison of the colour appearance of test objects under a test light source and a reference light source. The index is based on subjective assessments of observers. The index cannot predict any colour quality descriptor from the physical parameters of the lighting product. Subjective assessment attributes include brightness (H), saturation (S), temperature (T), perception (E) and colour shift (FV). The index SBI is defined from these parameters as follows:

$$SBI = \frac{1}{n_c} \sum_{c} A$$

Here, n_c is the number of coloured objects being assessed. Computational steps include:

$$A = 100 \times \frac{1}{5} \sum x_i \qquad i = H, S, T, E, FV$$

$$x_i = 1 - \frac{|s_0 - s|}{|s_0 - s_{max}|} \qquad \text{for } i = \text{brightness(H), saturation(S), temperature (T), perception (E)}$$

$$x_i = 1 - \frac{|\vec{s}|}{|\vec{s}_{max}|} \qquad \text{for } i = \text{colour shift vector (FV)}$$

The maximum value of *SBI* equals 100. In this case there are no perceived colour differences between the test and the reference scenes. The lower the value of *SBI*, the larger these differences will become.

4.5 Literature for Section 4

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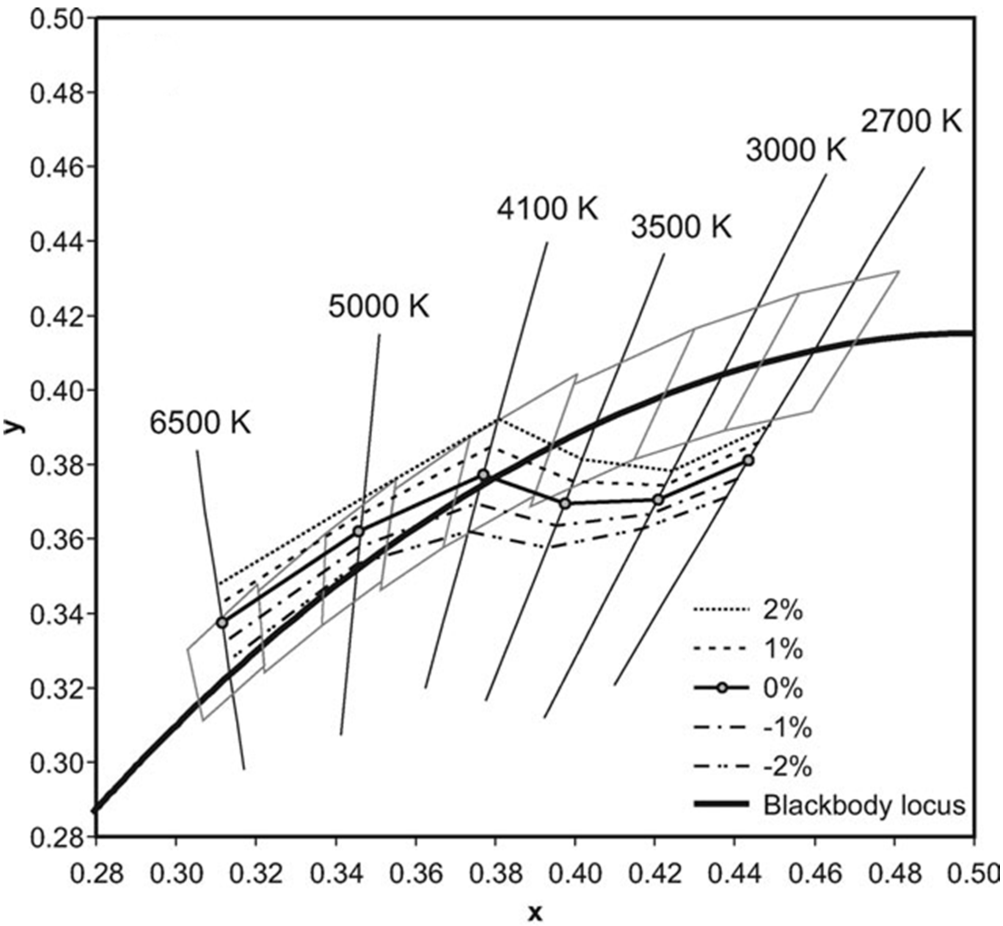
5 White tone quality of lighting products

Highly qualitative white tones (in other words: white points) enable the observers to achieve and maintain full colour constancy and chromatic adaptation when a scene with grey and white surfaces and coloured objects is viewed. According to the recent investigation of M. Rea et al. (the reference is cited in Figure 29), these highly qualitative white tones (that are *perceived* really *white*) are situated below the Planckian curve until about 4000 K, see Figure 29). Scenes with coloured objects and a white tone below the Planckian curve (until Δ*u*'*v*'= 0.0054) are usually judged by subjects as attractive. White points in this range also enable a better chroma increase of reddish objects. Although this research is not finished today, this result is often implemented in real *retail lighting* products nowadays.

Figure 29: Chromaticity coordinates in the experiment of M. Rea et al. for the perception of white points. Source: M. S. Rea, J. P. Freyssinier, White Lighting, Color Res. Appl. 38/2, pp. 82–92, 2013; reproduced with permission from Color Res. Appl.



The rendering of the white tone of the lighting product is not included in the new evaluation system of the present report (this will be described in Secion 9) because manufacturers are strongly aware of its importance and usually implement only high-quality white tones in the domain of perceptually acceptability. It will be shown in Section 7.4 that the fine-tuning of white tones has no significant effect on electric energy efficiency.

6 Circadian effect of lighting products

6.1 Introduction

To evaluate lighting products (luminaires, lamps, light sources), both the mechanisms of light and colour perception and the mechanisms of „non-visual" signal processing in the brain are relevant [1]. These two aspects shall be considered simultaneously. The so-called circadian effect characterises the effect of electromagnetic radiation reaching the human eye on the so-called „circadian clock" of the human organism. The circadian clock organises the temporal coordination of human biological functions during the day (so-called circadian rhythms) [2]. The functioning of the human organs follows these circadian rhythms. The performance of humans during the day depends on the maxima and minima of the individual biochemically controlled functions [3]. If the production of melatonin is suppressed by light within a certain time interval during a day then the performance of human beings increases.

Now, the question is how the performance of a human user can be increased by consciously changing the spatial and spectral power distribution of the lighting product. During the daytime, there is always strong melatonin suppression by predominating daylight and it is virtually impossible to influence the level of melatonin suppression by artificial light. Thus, in this respect, only illuminating concepts without daylight come into play in which the circadian rhythm shall be supported by artificial lighting. During the day, lighting concepts supporting colour quality, visual performance and further biological, emotional or psychological aspects are more relevant.

In the evening or during the night, artificial lighting has a more significant effect and the question is how the circadian rhythm can be supported by lighting and how the emission spectrum of e.g. an intelligent, multi-channel LED light engine can be optimised according to the circadian effect.

According to the concept of daytime-dependent dynamic lighting, the final aim of lighting optimisation is not simply to increase colour quality or to support human circadian rhythm. Instead, within a more comprehensive framework, the general user acceptance of the lighting system shall be optimised for a given group of users and for a certain type of lighting application. This is only possible by intelligently combining both aspects, visual and non-visual. Only one single human brain exists and the complex stages of visual and non-visual signal processing are intrinsically intertwined [4] when the subject reacts to the light of a light source or assesses a certain scene consciously.

In order to quantify the circadian effect of a light stimulus, the computational procedure of the so-called Circadian Stimulus (CS) of the Rea et al. model [2] will be described in this report. The quantity CS describes the efficacy of a light stimulus for melatonin suppression depending on its intensity and spectral composition. The quantity CS can be used e.g. to evaluate the emission spectra of a multi-channel LED lighting system according to the circadian effect. At the same time, colour quality aspects can also be optimised.

Figure 30 [2] illustrates experimental data from literature [5, 6, 7]: the effect of spectral radiance of a light source on night-time melatonin suppression is shown.

Figure 30: Experimental data from literature [5, 6, 7] on the effect of the spectral radiance of a light source on night-time melatonin suppression. Subjects were stimulated during the night with narrowband ([5], [6]) and broadband [7] light (its characteristic wavelength is shown on the abscissa). The Ordinate shows the reaction of the subjects (melatonin suppression). Reproduced with permission of the Journal of Circadian Rhythms [2]

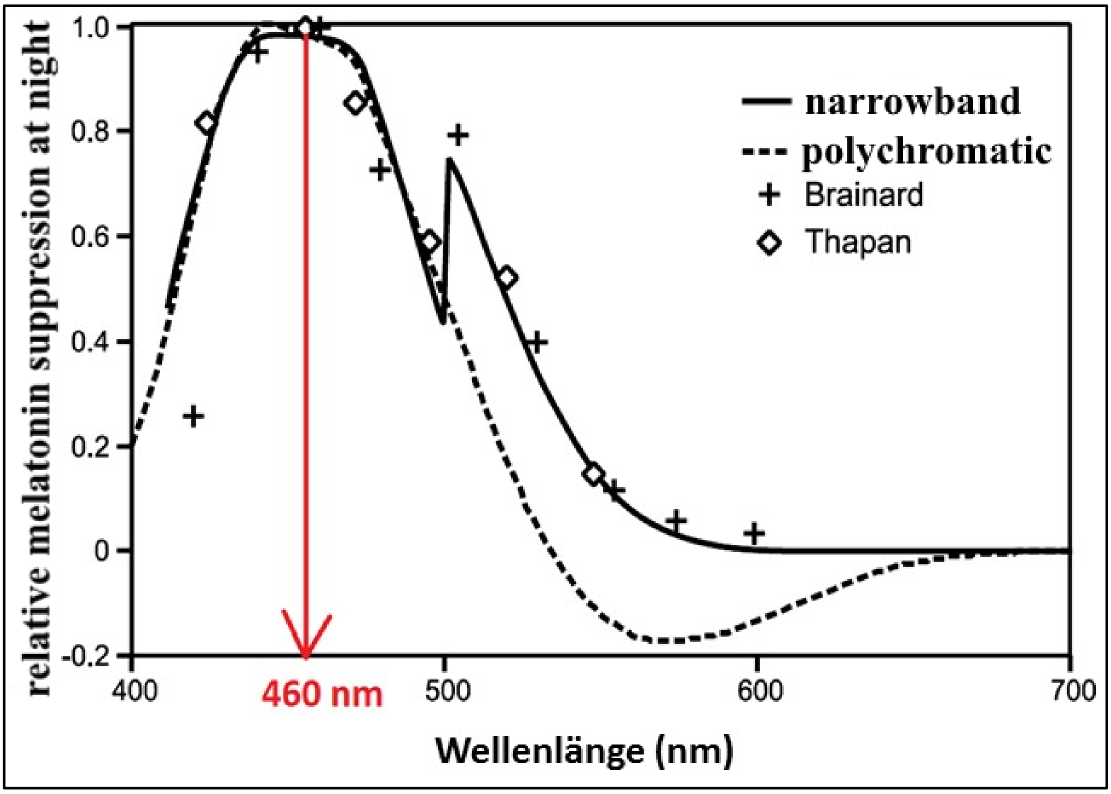


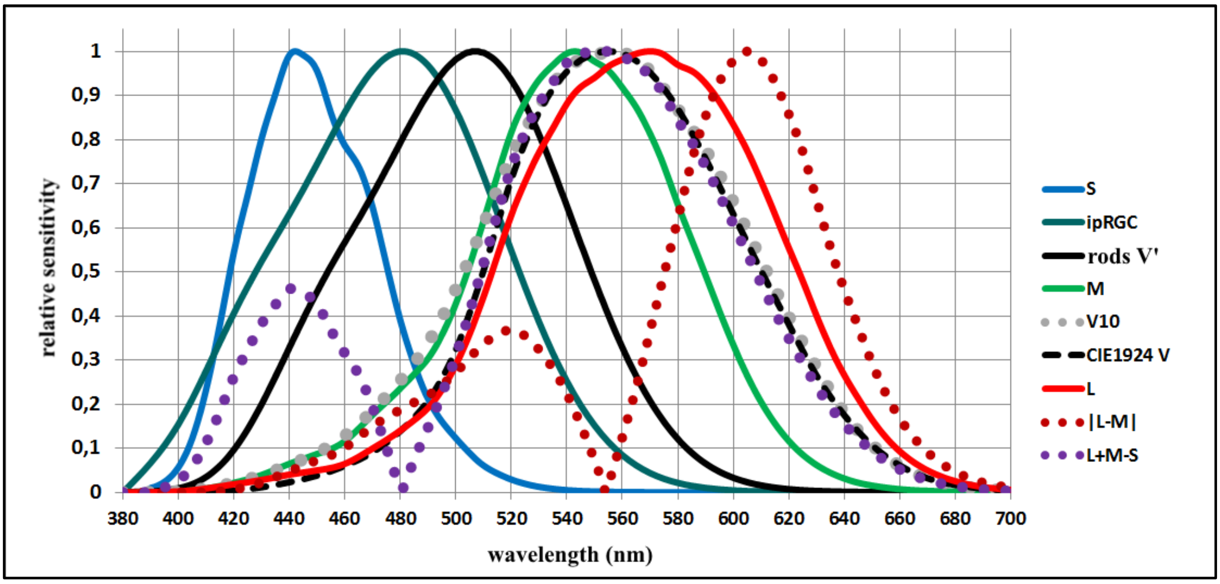
Figure 30 shows that in case of narrowband light [5, 6], at least two retinal mechanisms are active because two spectral maxima appear [2]. A local maximum at about 505 nm is conspicuous in case of narrowband stimuli. This maximum disappears when stimulating by broadband light due to a spectrally opponent mechanism [1], see the dash curve in Figure 30. The absolute maximum of melatonin suppression is located at 460 nm in case of these studies (see the red arrow in Figure 30) and not at 480 nm (480 nm would be the maximum of the spectral sensitivity of melanopsin).

Melanopsin is the photopigment of the so-called intrinsically photosensitive retinal ganglion cells (ipRGCs). These cells are themselves photosensitive and contribute to the regulation of the circadian clock [8].

6.2 The Rea et al. model to compute the Circadian Stimulus (CS)

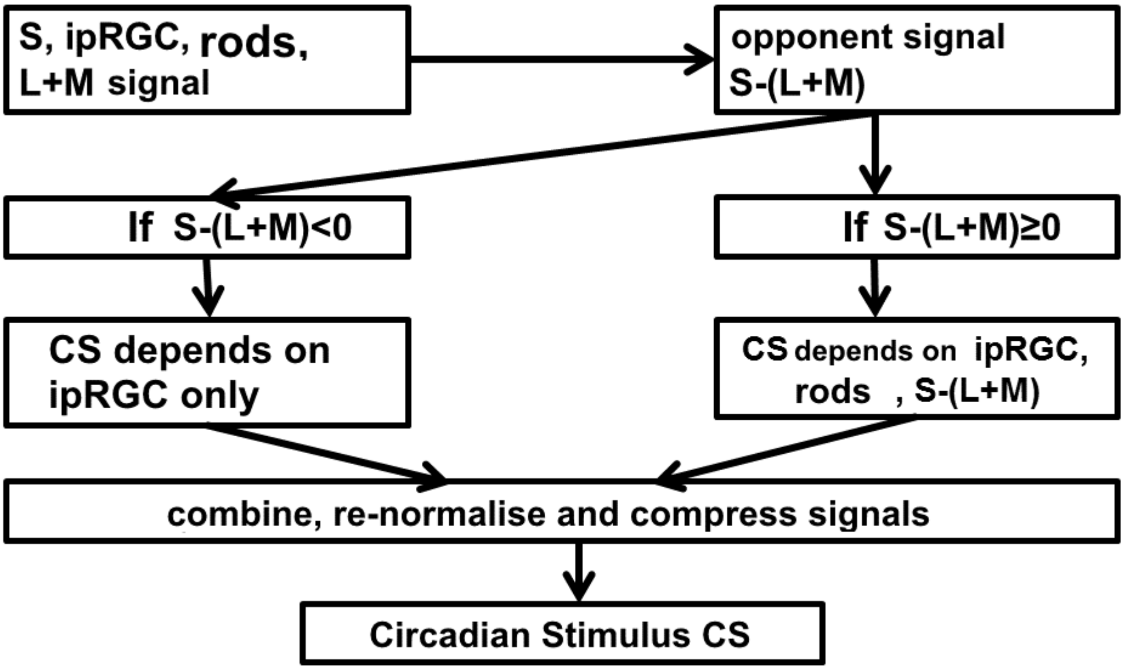
Figure 31 shows the spectral sensitivity of those receptors and retinal mechanisms that contribute to the non-visual effect of melatonin suppression via the Circadian Stimulus CS in the Rea et al. model [2].

Figure 31: Spectral sensitivity of those receptors and retinal mechanisms that contribute to the non-visual effect of melatonin suppression via the Circadian Stimulus CS in the Rea et al. model [2]



The following mechanisms can be seen from Figure 31: 1. S-cones; 2. Intrinsically photosensitive retinal ganglion cells (ipRGCs); 3. Rods modelled by the $V'(\lambda)$ function; 4. The luminance channel L+M; this is modelled by the $V_{10}(\lambda)$ function due to the large spatial subtense of a stimulus which exhibits significant circadian activity[9]; this was modelled by the so-called 10° observer; and 5. the opponent channels 1-2 (|L-M| and |L+M-S|). The mechanism |L-M| is shown only for the sake of completeness; this is not used in the Rea et al. model. Figure 32 demonstrates the computational procedure of the Circadian Stimulus (CS) in the Rea et al. model.

Figure 32: Computational procedure of the Rea et al model [2]. Input: vertical illuminance at the eye and relative spectral radiance of a stimulus. Its S-cone, rod, ipRGC, and L+M signals are also computed; Output: Circadian Stimulus (CS) modelling the non-visual effect of melatonin suppression evoked by the stimulus



The computational steps of Figure 32 are explained in the following.

1. The S-cone, ipRGC, rod (V´) and (L+M) signals are computed from the relative spectral radiance $L_{e,rel}(\lambda)$ of the stimulus considered responsible for the circadian effect (e. g. a big wall surface in an office) according to Eq. (6.1)-(6.4) with an absolute liaison to the illuminance at the eye represented by Eq. (6.5).

$$S = k \int_{380\,nm}^{780\,nm} L_{e,rel}(\lambda)\, S(\lambda)\, d\lambda \tag{6.1}$$

$$ipRGC = k \int_{380\,nm}^{780\,nm} L_{e,rel}(\lambda)\; ipRGC(\lambda)\, d\lambda \tag{6.2}$$

$$V' = k \int_{380\,nm}^{780\,nm} L_{e,rel}(\lambda)\; V'(\lambda)\, d\lambda \tag{6.3}$$

$$(L+M) = 0.31\, k \int_{380\,nm}^{780\,nm} L_{e,rel}(\lambda)\; V_{10}(\lambda)\, d\lambda \tag{6.4}$$

$$\text{with } k = \frac{E_v}{\int_{380\,nm}^{780\,nm} L_{e,rel}(\lambda)\; V(\lambda)\, d\lambda} \tag{6.5}$$

In the integrals of Eqs. (6.1)- (6.5), the following spectral weighting functions are used: sensitivity of the S-cones ($S(\lambda)$), sensitivity of the intrinsically photosensitive retinal ganglion cells (ipRGC(λ)), the V′(λ) function as well as the $V_{10}(\lambda)$ function (see Figure 31). The symbol E_v in Eq. (6.5) means the illuminance at the eye of the observer (lx).

2. The signal of the 2nd opponent channel, S – (L+M), is computed by the aid of Eq. (6.1), (6.4) and (6.5).

3. If the signal of the 2nd opponent channel is negative i.e. if S-(L+M)<0 then the quantity of the so-called „circadian light" CL (an intermediate quantity in the computational procedure of the circadian stimulus CS) will be computed according to Eq. (6.6). In this case, CS depends only on the ipRGC signal.

   $$CL = 0.285\ ipRGC - 0.01\ lx \quad (6.6)$$

4. If the signal of the 2nd opponent channel is non-negative i.e. if S-(L+M)≥0 then CL depends on the interaction of the ipRGC, rod and S-(L+M) signals according to Eq. 6.8. To do so, the so-called saturation effect of the rod signal at higher illuminance levels shall be taken into account by Eq. (6.7).

   $$R_{saturated} = 1 - e^{-(V'/6.5\ lx)} \quad (lx) \quad (6.7)$$

   $$CL = [(0.285\ ipRGC - 0.01) + (0.2\ \{S-(L+M)\} - 0.001)] - 0.72\ R_{saturated} \quad (6.8)$$

5. The value of CL in Eq. (6.6) or in Eq. (6.8) is re-normalised according to Eq. (6.9).

   $$CL_A = 5831\ CL \quad (6.9)$$

   The re-normalisation factor in Eq. (6.9) corresponds to the criterion that a stimulus with a chromaticity of CIE standard illuminant A and an illuminance of 1000 lx at the eye should exhibit a CL_A value of 1000 lx.

6. The quantity CL_A is re-scaled by Eq. (6.10) (so-called signal compression) in order to obtain the output quantity CS (the circadian stimulus).

$$CS = 0.75 - \frac{0.75}{1+\left(\frac{CL_A}{215.75\ lx}\right)^{0.864}} \quad (6.10)$$

6.3 The melanopic factor a_{mel} (of visible radiation)

The melanopic factor a_{mel} (of visible radiation) is defined according to DIN SPEC 5031-100 [15] as the „ratio of melanopically effective radiation to photometrically effective radiation, latter obtained by the use of the sensitivity of daylight vision" according to Eq. (6.11). In latter equation, the relative spectral power distribution is weighted by the so-called $s_{mel}(\lambda)$ function [15] (based on Lucas et al. [16]) and integrated in the visible wavelength range; and the result is divided by the so-called V-signal of the relative spectrum which can be seen in the denominator.

$$a_{\mathrm{mel,\,v}} = \frac{\int_{\lambda_u}^{\lambda_o} X_\lambda(\lambda)\cdot s_{\mathrm{mel}}(\lambda)\cdot d\lambda}{\int_{\lambda_u}^{\lambda_o} X_\lambda(\lambda)\cdot V(\lambda)\cdot d\lambda} \tag{6.11}$$

6.4 Summary

The considering of the circadian effect of lighting products is very important in order to model their activating or relaxing effect. If the circadian effect is considered then the well-being, satisfaction and work performance of the user can be increased by appropriately optimised lighting. In order to describe the circadian effect numerically, two descriptor quantities were defined, the so-called Circadian Stimulus (CS) and the so-called melanopic factor a_{mel}. The circadian stimulus (CS) has the advantage that it includes all relevant contributing mechanisms while the melanopic factor a_{mel} considers only the ipRGC mechanism. In the luminance range which is relevant for lighting engineering, (a simply transformed) value of a_{mel} correlates well with the value of CS. Due to its simple and standardised computational method, a_{mel} is used in the present report. The disadvantage of CS is its mathematically complex computational method.

6.5 Literature for Section 6

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7 The new evaluation concept: develoment steps and advantages

7.1 General advantages of the new evaluation concept

Increasing electric efficiency is very important today because energy shall be saved in households, traffic and industry. Today's evaluation concept of electric energy efficiency (luminous efficacy, lm/W) weights the spectral range at about 555 nm via the $V(\lambda)$ function too strongly compared to its benefit for human users of lighting products. Thus, electric energy is wasted around the peak wavelength range of the $V(\lambda)$ function. The reason is that manufacturers tend to optimise light sources with the aim of increasing luminous flux to the disadvantage of the equally important wavelengths further away from the $V(\lambda)$ function's maximum.

According to the new evaluation concept, however, spectral ranges outside $V(\lambda)$'s peak wavelength range are also included in the evaluation method of electric energy efficiency. This happens after analysing the state of the art of recent literature. Thus, electric energy can be converted into electromagnetic radiation in a correct manner i.e. in those spectral ranges and with those relative weightings of the individual wavelengths that yield an optimum benefit of lighting for the human user of the lighting product.

As spectral ranges outside the $V(\lambda)$ function are included in the new evaluation concept, lighting products optimised according to the new evaluation method convert electric power into electromagnetic radiation at all relevant and beneficial wavelengths. This optimum conversion does *not* occur by the use of a new spectral efficiency curve replacing the $V(\lambda)$ function but by a step-by-step method to be described in Section 8. The new method includes e.g. bluish spectral components of radiation in order to enhance brightness and visual performance and it is hoped that the number of road accidents can be reduced and the costs of hospital treatments decrease. Also, manual work in industry halls will be carried out with less error.

Non-visual effects and the possibility of daytime-dependent dynamic lighting are also considered in the new evaluation method with the hope of being able to increase concentration and creativity in a workplace and amend the ability to relax after work, in a home lighting environment. This can increase the productivity of invested work hours and lead to higher work performance in all EU countries. The satisfaction and life quality of all citizens (employers and employees) can be enhanced.

The individual benefits of lighting described in the preceding sections (e.g. brightness, visual performance, circadian effect, colour quality) are combined in the new evaluation concept and this combination results in a new categorisation of every lighting product in a new labelling system (A-G). A major advantage of the new evaluation concept is that it includes all individual benefits of lighting (see Table 7) considered by the authors of this report relevant. These benefits also enter the new labelling system automatically by the aid of an algorithm that assigns every lighting product a category (A-G) computed from the physical characteristics of the lighting product (spectral power distribution, electric power and luminous flux).

The new evaluation method contributes not only to energy saving but also to the enhancement of the benefits of lighting for humans by the aid of the new labelling system (see Sections 8 and 9) which is based on recent state of the art of scientific knowledge about the benefits of lighting.

7.2 Advantages of taking the selected benefits of lighting into consideration in the new evaluation system and description of the metrics used

Table 7 contains the list of the selected benefits of lighting and their numeric descriptor quantities (metrics) used in the new evaluation system and also some possible alternative metrics.

Table 7: List of the selected benefits of lighting and their numeric descriptor quantities (metrics) used in the new evaluation system and also some possible alternative metrics.

Benefit of lighting	Metric	Alternative (not used) metrics
Brightness	$L_{äq}$ (Fotios)*; L_{mes} (CIE)**	$L_{äq}$ (Berman); Luminous flux
Colour quality	CIE CRI R_a	CIE CRI R_{1-14}; R_f, CQS Q_a, Q_p
Circadian effect	a_{mel}	CS
Visual performance	same as for brightness	same as for brightness

*for interior lighting; **for exterior lighting

The properties of lighting products associated with the benefits in Table 7 will be described below.

Brightness (visual performance): The demand of electric power increases in case of light sources of the same technology with increasing brightness and increasing visual performance. Brightness and visual performance depend not only on the entire radiant power of the lighting product but also on the blue content of its spectrum. Latter property can be described by correlated colour temperature (CCT). It depends on the technology of light generation strongly.

Colour quality: This benefit remains constant if the radiant power of the lighting product increases provided that the relative spectral radiance of the lighting product does not change.

Circadian effect: The circadian effect (as measured by a_{mel}) remains constant if the radiant power of the lighting product increases provided that the relative spectral radiance of the lighting product does not change. It depends on the blue content of the spectrum: a higher blue content (high CCT) implies a higher circadian effect.

Table 7 shows that four benefits of lighting were identified for the sake of the new evaluation concept, brightness, visual performance, colour quality and circadian effect. The new concept only those physical and technological properties of a lighting product are evaluated that result from relative spectral radiance, electric power and luminous flux. The rendering of white tones by the lighting product was not considered because white tones are in most cases correctly managed by manufacturers and its changes have no significant effect on electric efficiency.

It will be explained below why the benefits selected to be included in the new evaluation method were identified as relevant. Brightness is important for the perception of the interior (room perception or perception of three-dimensionality), visual performance and feeling of safety. High colour quality evokes positive emotions while low colour quality diminishes the acceptability of lit interior space significantly. The circadian effect is related to the sleep quality and long-term well-being of lighting product users. The choice of these benefits results from a deep study of underlying literature and the own know-how and experience of the authors of the present report.

Other properties like luminous flux reduction, changing spatial light distributions, focusing, shielding, light guiding, the avoidance of glare and flicker, partial matting, full matting, satin finishing shall not be included in the new evaluation system. The reason is that latter properties are not related to the technology of the light source built in the lighting product. They characterise the structure and arrangement of individual luminaires and complete lighting systems. Latter properties shall be labelled and regulated supplementary. It should be noted that the properties focusing (e.g. in case of reflector lamps), flicker and matting are closely related to the technology of the individual light sources built in the lighting product. Advantages of including the most important benefit metrics in Table 7 will be explained below.

A higher amount of perceived brightness results in a higher level of visual performance: visual performance is automatically considered by including brightness. Visual performance means the ability of identifying small visual details (like letters) or quickly detect dangerous objects (e.g. hazards of road traffic). According to the literature presented in previous sections, visual performance increases with the increasing brightness (e. g. in an office or night-time traffic space).

The quantity *luminous flux* (lm) in the conventional evaluation concept ignores the dependence of brightness impression on the type of white tone of the lighting product (e. g. warm white, neutral white, cool white) although cool white (with high blue content) results in a much higher brightness impression (and higher visual performance) in case of the same luminous flux than warm white.

The benefit *colour quality* is especially relevant due to the enhancement of the emotional effect of lighting and the identification of colours. This benefit is well considered in the new evaluation system in order to label lighting products correctly. The present evaluation system by luminous efficacy (lm/W) ignores the benefit of colour quality. Also, the new evaluation concept does not work with a standalone „surcharge" quantity to include colour quality, this would not be correct from the mathematical point of view. In the new evaluation system, the desciptor quantity of colour quality is integrated with the metrics of brightness, visual performance and circadian effect in a new, mathematically sound framework (see Sections 8 and 9).

The benefit *circadian effect* means the activating or relaxing effect of light. According to the recent results from literature, the descriptor of this benefit is included in the new evaluation concept.

7.3 Advantages and disadvantages of the metrics considered for the new evaluation system in comparison to other metrics (from Table 7)

Relevant evaluation concepts will be shown and assessed below. It will be explained why the specific metrics were selected to be used in the new evaluation method.

The metric $L_{äq}$(Fotios et al.) used in the new evaluation method describes the benefit brightness for interior lighting. This metric divides the signal of the S-cones by the signal of the $V(\lambda)$ function: $(S/V)^{0,24}$. The advantage is that thus the blue content of the spectrum is taken into consideration according to the results of literature. In today's evaluation with luminous efficacy of a source (lm/W), blue content is strongly underestimated because in the quantity luminous flux the spectrum is weighted by the aid of the $V(\lambda)$ function.

The disadvantage of the $V(\lambda)$ function is (as already mentioned before) that important spectral content (especially the blue content) is ignored. In Berman's alternative formula $L_{äq}$(Berman), however, rods are also considered by the quantity (rod signal / V)^{0,5}. But rods are no more active in the typical luminance range of interior lighting. In case of the mesopic range in which rods are active, the mesopic luminance of the CIE, L_{mes} (CIE), is applied in the new evaluation method. Latter quantity was described in the CIE publication No. 191. It is based (in contrast to the Berman formula) on the results of several international research projects on mesopic visual performance. An alternative mesopic model, the brightness model $L_{äq}$(Sagawa) had controversial assessments in literature hence it was decided not to use this model in the new evaluation method.

In order to include the benefit colour quality, the general colour rendering index CIE CRI R_a is used. The new colour rendering index of the CIE (R_f) was developed and recommended only for scientific purposes hence it was not taken up.

The best current model of colour quality is the CQS Q_p metric from a scientific point of view. This metric is in favour of a moderate oversaturation of object colours evoking the best colour preference impression in the human user of the lighting product. Unfortunately, the Q_p metric is not well known, even among lighting experts. Lighting experts rather work with the CQS Q_a metric allowing for a too small amount of the oversaturation of coloured object by the light source spectrum. Unfortunately, the entire CQS model (NIST-USA) is not well enough known among lighting engineers and designers.

In order to describe the benefit *circadian effect*, the new evaluation concept uses the quantity a_{mel} defined in DIN SPEC 5031-100 and characterising the activating or relaxing biological effect of light. This effect was completely ignored by earlier metrics of lighting quality and electric energy efficiency. Compared to the alternative so-called CS metric (Rea et al., see above), a_{mel} has the advantage that it is linearly scaled and more suitable for the new evaluation concept.

The computational method of the CS metric has a discontinuity and this could cause mathematical difficulties for general practice. Introducing the quantity a_{mel} in the new evaluation method, we will have the possibility to take the circadian effect of light (for the first time in the history of lighting engineering) into consideration integrated with the descriptors of the other benefits of lighting in the framework of the new mathematical concept and new labelling system (A-G) to be introduced in Sections 8 and 9.

7.4 Relationship between the identified benefits and the reduction of electric efficiency. Description of benefits associated with the lower electric efficiency of lighting products. Description of development steps: decisions about including different benefits in the new concept

In the following, it will be described which benefits are or can be associated with a lower value of the numeric assessment of luminous efficacy of a lighting product. In this section, the development steps of the new evaluation method will be emphasised. The new evaluation concept and method will be defined in Sections 8 and 9. It will be pointed out how it was decided which benefits and metrics shall be included. Relevant evaluation concepts will be shown and analysed.

The benefits brightness and visual performance depend on luminous flux hence they can cause a lower electric efficiency of lighting products if luminous flux decreases from a technological reason e.g. inefficient LED phosphor conversion. These benefits also depend on correlated colour temperature (CCT). Lighting products with a lower CCT usually exhibit a lower electric efficiency. Hence these benefits were considered in the new evaluation concept. The reason is that both benefits have a positive correlation with CCT: lighting products with cool white light evoke a higher brightness impression and visual performance than lighting products with warm white radiation. This property is associated with the following relevant numeric assesement metrics:

1. In the brightness metric of Fotios et al. [1], the value of the brightness metric increases with the increasing signal of the S-cones monotonically. This signal correlates, in turn, with the CCT of the lighting product positively. The same is true for the CIE brightness metrics[2]
2. In the brightness metric of Berman [3], the value of the brightness metric increases with the increasing signal of the rods monotonically (according to the $V'(\lambda)$ function). This signal correlates with the CCT of the lighting product positively again.
3. In the mesopic visual performance metrics of the CIE [4], the value of mesopic luminance increases with the increasing signal value of the rods (depending on the luminance level of the actual exterior lighting situation) monotonically. This signal correlates with the CCT of the lighting product positively again.

White tone quality is related to the fine-tuning of the spectrum at a predefined white point in order to avoid disturbing small but disturbing hues perceived in the white tone. This is not related to electric efficiency. By considering this benefit (white tone quality), absolute spectral power distributions of lighting products are varied only slightly. In order to describe white tone quality, the quantity $\Delta u'v'$ can be used. In case of CCT< 5000 K, this quantity represents the distance of the white point of the lighting product from the Planckian locus in the u'-v' diagram. In case of CCT≥ 5000 K, this quantity represents the distance of the white point of the lighting product from the locus of daylight phases in the u'-v' diagram. The quantity $\Delta u'v'$ is located in case of most lighting products of general interior lighting (in which white tone quality is important) in the range 0.0001 – 0.006. The fine-tuning the value of $\Delta u'v'$ in this range has no significant effect on electric efficiency thus $\Delta u'v'$ is not included in the new evaluation concept.

But if we want to change the level of colour quality as an individual benefit of lighting then the spectrum and the luminous flux of the lighting product might change significantly. E.g. a further LED maximum might appear in the red spectral range in order to increase colour quality and this can be associated with less electric efficiency because the red LED is less efficient. Thus, this benefit of lighting is included in the new evaluation system. In order to account for colour quality, the following numeric assessment concepts were analysed:

1. The first concept was the general colour rendering index of the CIE, CRI R_a [5]. If the relative spectrum of the lighting product has a higher value of CRI R_a then the value of luminous efficacy will generally decrease. With target oriented spectral design of LED lighting products, however, this decrease can be avoided and colour rendering and luminous efficacy can be increased at the same time.
2. The arithmetic mean values of the 14 special colour rendering indices of the CIE CRI method and the new colour fidelity index of the CIE [5]were also considered as alternatives of CIE CRI R_a. These parameters behave in a similar way: a decrease of electric efficiency can be avoided by conscious LED spectral design.
3. The indices of the CQS method [6] exhibit the same behaviours described above.

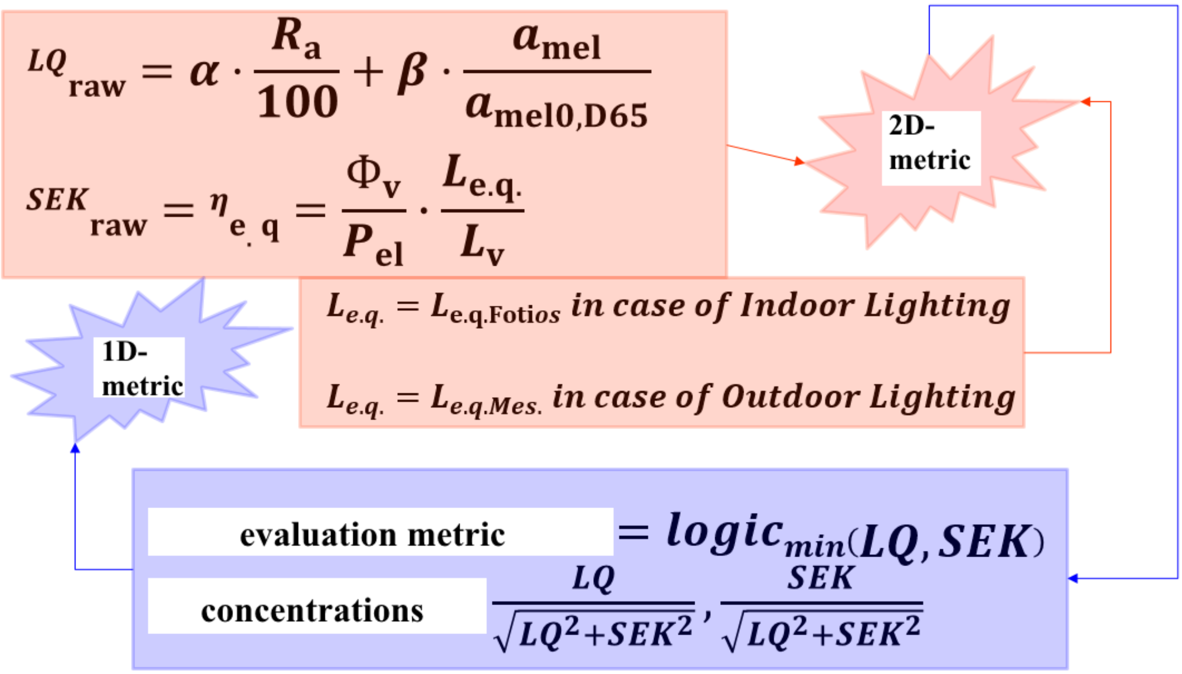
The benefit *circadian effect* (and the related concept of daytime-dependent dynamic lighting) requires a systematic change of correlated colour temperature (CCT) between warm white and cool white in a wide CCT range. Consequently, electric efficiency can decrease (depending on technology) as already explained above. Thus, this benefit of lighting is included in the new evaluation system. In order to describe the circadian effect, the quantities a_{mel} [7] and CS [8] were used. Both metrics include a spectral weighting function characterising melatonin suppression to weight the spectral power distribution of the lighting product. This function has a maximum in the bluish spectral range, 490 nm in case of a_{mel}; and 480 nm in case of CS. Thus there is positive correlation with the CCT of the lighting product.

The new evaluation method deals with the labelling of lighting *products*. Their current spatial light distributions depend on their current application in a certain lighting system of a certain (unknown) geometry. Thus, this benefit of lighting (spatial light distribution) is not included in the new evaluation system. This is also true in case of the product property *dimming luminous flux*. The product property *spatial light distribution* is associated with a higher brigthness of certain areas and also with the avoidance of glare which has three aspects, *entire matting*, *partial matting* and the achievement of a *lower UGR value*. Changing light spatial distributions (e.g. by the aid of focusing) causes in general, depending on the structure of the lighting product, more or less losses of electric power e.g. because lenses and reflectors absorb a certain amount of input luminous flux.

The benefits of flicker free lighting and lighting without the perception of stroboskopic effect are associated with the physical parameters modulation depth (difference between the maximum and minimum luminance divided by their sum) and the PWM frequency applied (in case of LED lighting products with PWM dimming) [9]. The smaller the value of modulation depth and the higher the PWM frequency is, the less flicker perception can be expected visually. The ranges of PWM frequencies and modulation depths used in current lighting products do not cause any change of electric efficiency. Electric efficiency rather depends on maximum current but latter value remains constant when PWM dimming (which could cause flicker or stroboscopic artefacts) is applied. Thus the benefits of *flicker free lighting* and *lighting without the perception of stroboscopic effect* are not associated with electric efficiency (in LED driver and power supply technology). Thus, these benefits of lighting are not included in the new evaluation system.

The most relevant development steps of the new evaluation concept are summarised below. In the first concept, two evaluation dimensions (so-called SEK_{raw} and LQ_{raw}) were proposed. On 16 June 2017, this concept with two components were discussed during a meeting. In this meeting, it was proposed to change the concept in order to include only one dimension as an output quantity. Therefore, this so-called 1D metric was elaborated and presented on 3 July 2017. Figure 33 shows the transition from the two-component concept (or 2D metric) to the 1D metric. As can be seen from Figure 33, the two dimensions of the 2D metric were summarised as one single dimension, the so-called evaluation metric.

Figure 33: Development of the new evaluation concept: Transition from the two-component concept (or 2D metric) to the 1D metric (presented on 3 July 2017)



In this so-called 1D metric, the evaluation of the lighting products were differentiated according to their field of application (12 such applications were identified): streets (S class, M class), office, education, nursing, retail, industry, hotel, museum, hospital, sports centre, household. After this meeting on 3 July 2017, the final new evaluation concept (see Sections 8 and 9) was evaluated according to the following points of view resulting from the discussions:

1. The conventional quantity of luminous flux includes neither colour quality, nor brightness, nor the circadian effect. This is false because of the known deficiencies of the $V(\lambda)$ function.
2. All these new aspects of lighting science from the last 50 years were integrated in the above 1D and 2D metrics, see Figure 33.
3. The above two metrics were used to define the category limits for product labelling.
4. The so-called 1D metric seemed to be scientifically disadvantageous (see also Section 8) because there are two independent components of the system of benefits of lighting and this intrinsic two-dimensionality shall be included in the new evaluation concept.
5. It will be advantageous to define only two applications in the photopic range (interior lighting), „relaxation" (at home but also for working)and „activity-functionality" (both for a working environment and at home for e.g. home-office) with different a_{mel} levels. There should also be only two applications in the mesopic range (exterior lighting or street lighting): S class streets and ME-class streets.

7.5 Literature for Section 7

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[8] Circadian Stimulus; M. S. Rea, M. G. Figueiro, A. Bierman, J. D. Bullough, Circadian light, Journal of Circadian Rhythms 8:2, 2010.

[9] D. Polin, T. Q. Khanh, Flimmern und Stroboskopische Effekte von PWM-gesteuerten Autoscheinwerfern, 48 Seiten, 2017, ISBN 978-3-927787-59-9.

8 The new evaluation concept: Mathematical Definition

In this Section, the new evaluation concept [1] is defined mathematically. In Section 9, the method of the evaluation concept is applied to a representative sample set of 304 lighting products, see Table 9. Section 9 also contains a proposal for a new labelling system with the energy classes A to G. Every lighting product in the above mentioned sample set will be assigned a category (A to G).

8.1 Input parameters and result of the new evaluation method

Input: Relative spectrum (a resolution of min. 1 nm is required); luminous flux (lm) and electric power (W) of the lighting product to be evaluated. The electric power of the *light source* of the lighting product shall be considered.

Result: the so-called *new energy efficiency measure* (abbreviated by SEK) and a category between A and G in the new evaluation system.

8.2 Mathematical definition of the computational method

The new usefulness measure was defined as a two-dimensional quantity (i.e. consisting of a set of two values) to be represented as a point in a diagram with two orthogonal axes. A measure of *colour quality* (R_a) is on the abscissa. Due to its widespread use today, this measure is the conventional CIE *general colour rendering index* CIE CRI R_a. A new combined measure of the brightness and the circadian effect of the light source appears on the ordinate of the above mentioned diagram.

This new combined measure is called *new energy efficiency measure* (abbreviated by SEK). This the new diagram is called R_a-SEK diagram. The new quantity SEK was defined as follows:

$$SEK = \left(\frac{\Phi_v}{P_{el}}\right) \cdot \left[\frac{\alpha \cdot L_{äq}}{L_v} + \beta \cdot BioNote\right]$$

Here, Φ_v is the luminous flux (lm) of the light source and P_{el} is the electric power (W). As can be seen, *energy efficiency* is incorporated in the second component (SEK) by multiplying the *luminous efficacy of a source* (Φ_v/P_{el}) by the compound modification term in the square brackets. This modification term is explained as follows. If the light source should be used for *interior lighting* then the quantity $L_{äq}$ represents the measure of scene brightness with $L_{äq} = L_v\ (S/V)^{0.24}$ according to Fotios and Levermore, and, if the light source should be used for exterior lighting then $L_{äq} = L_{mes}$.

To be in favour of *dynamic lighting*, the value of α equals 1.00 if there is no dynamic lighting in the given application of the light source. The value of α equals 1.15 if there is dynamic lighting with correlated colour temperatures in the range CCT=5500 K – 6500 K. Data (relative spectrum, luminous flux and electric power) of the highest available CCT shall be used to carry out the computation in this case.

The *circadian effect* of the light source (represented by the value of *BioNote* in Eq. 1) is not taken into consideration if the light source is used for *exterior lighting* and this is expressed by setting the so-called *decision factor* β to *zero* in case of *exterior lighting* applications. For i*nterior lighting*, β equals 1. For interior lighting, the descriptor of the circadian effect (*BioNote*) is considered *activating* in case of CCT≥3800 K, *relaxing* for CCT≤3200 K and *neither activating nor relaxing* for 3200 K<CCT<3800 K. For an activating light source (CCT≥3800 K), the following equation shows how to compute the value of the descriptor of the circadian effect, the so-called *BioNote*:

$$BioNote(\text{activating}) = 0.1\,[(a_{\text{mel}} / a_{\text{mel,0}}) - 1]$$

This means that *more activating* light sources get a higher *BioNote* value in the range of CCT≥3800 K (i.e. the neutral white – cool white light sources). The quantity a_{mel} is computed from the *relative spectral power distribution* of the light source while the symbol $a_{\text{mel,0}}$ means the *melanopic factor* of the *reference light source* which is defined as a *phase of daylight*, a *blackbody radiator* or a mixture of the two.

This reference light source is determined (for any CCT) according to the method of CIE Publ. 224:2017 from the *relative spectral power distribution* of the light source to be evaluated (as a test light source). This method includes "a smooth, linear transition from a *Planckian reference light source* to a *daylight reference light source* such that at 4000 K and below it is purely *Planckian*, at 4500 K it is a 50:50 mix of the two, and at 5000 K and above it is purely a *daylight reference light source*."

In the range of CCT≤3200 K (warm white or relaxing), the value of *BioNote* in Eq. (1) is defined according to the following equation.

$$BioNote(\text{relaxing}) = 0.1\,[(a_{\text{mel,0}} / a_{\text{mel}}) - 1]$$

Note that the quantity $a_{\text{mel,0}}$ (the *melanopic factor* of the *reference light source*) is in the numerator in the "relaxing" equation unlike the "activating" equation. In "activating" equation, $a_{\text{mel,0}}$ appears in the denominator. Thus, *more relaxing* light sources (i.e. warmer *white tones*) obtain a higher value of *BioNote* in the range of CCT≤3200 K. Finally, in case of *neither activating nor relaxing* light sources (3200 K<CCT<3800 K), the following (so-called "mixed") equation shows the way of computing the value of *BioNote* by mixing the "relaxing" and "activating" equations.

$$\begin{aligned}\text{BioNote(mixed)} &= 0.1\,[(a_{\text{mel,0}} / a_{\text{mel}}) - 1]\,[(3800\text{K} - \text{CCT}) / 600\text{K}] \\ &+ 0.1\,[(a_{\text{mel}} / a_{\text{mel,0}}) - 1]\,[(\text{CCT} - 3200\text{ K}) / 600\text{ K}]\end{aligned}$$

In order to characterise the circadian effect, the melanopic factor a_{mel} was used. As already mentioned, the circadian stimulus CS is an alternative because a_{mel} does not consider the neurophysiology and neuroanatomy of the retina nor the interconnections of the circadian system. From the reasons mentioned in Section 7, especially the simple definition and application of the quantity a_{mel}, latter quantity was selected to be included in the new evaluation system. This quantity (a_{mel}) is very important for lighting practice and lighting design. In the relevant luminance range for interior lighting, there is a linear relationship between the transformed value of a_{mel} and CS, see Figure 34.

Figure 34: Comparison of the two numeric descriptors of the circadian effect a_{mel} and CS for the sample dataset of 304 lighting products. Reproduced with permission from Optics Express [1]

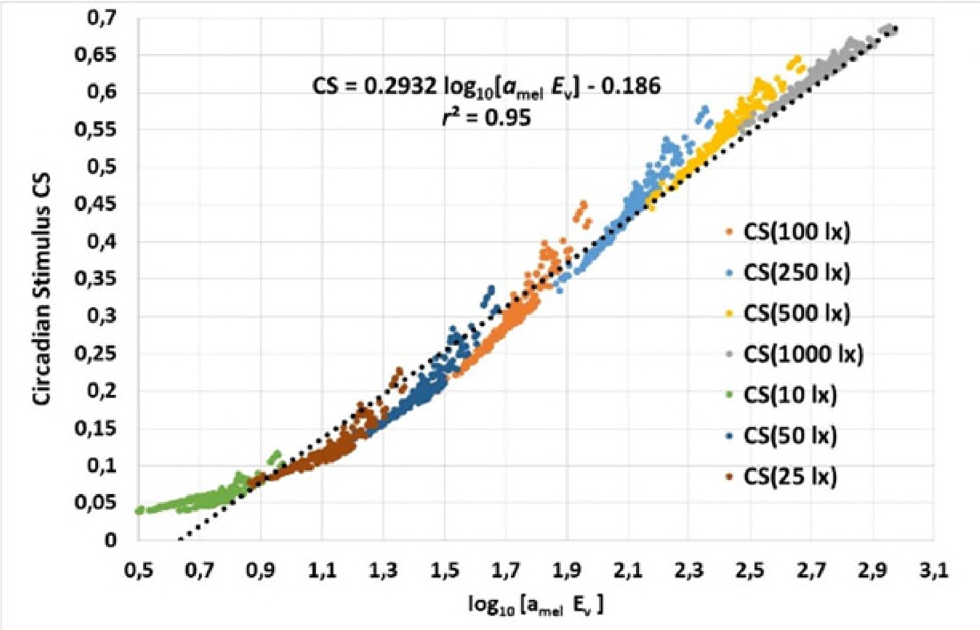


Figure 34 shows that the quantity $\log_{10}(a_{mel}\ E_v)$ correlates well with the quantity CS linear (r^2=0.95). There are also some deviations from this linear trend, max. ΔCS=0.08. In order to explain the quantity BioNote, Figure 35 shows this quantity as a function of CCT in case of the 304 lighting products of the sample set.

Figure 35: The quantity BioNote in case of the sample set of 304 lighting products as a function of CCT. Reproduced with permission from Optics Express [1]

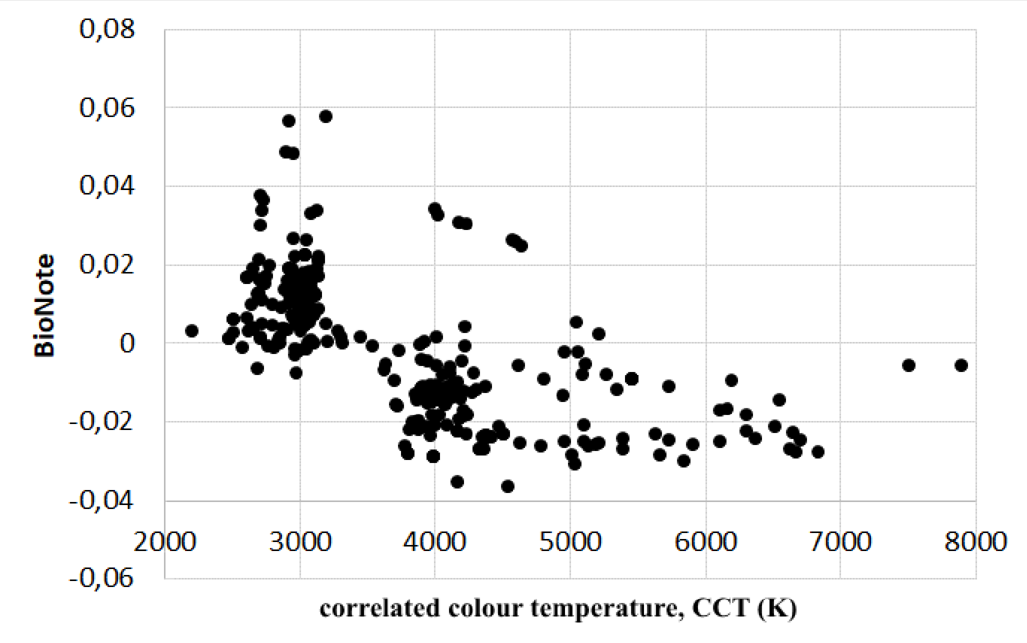
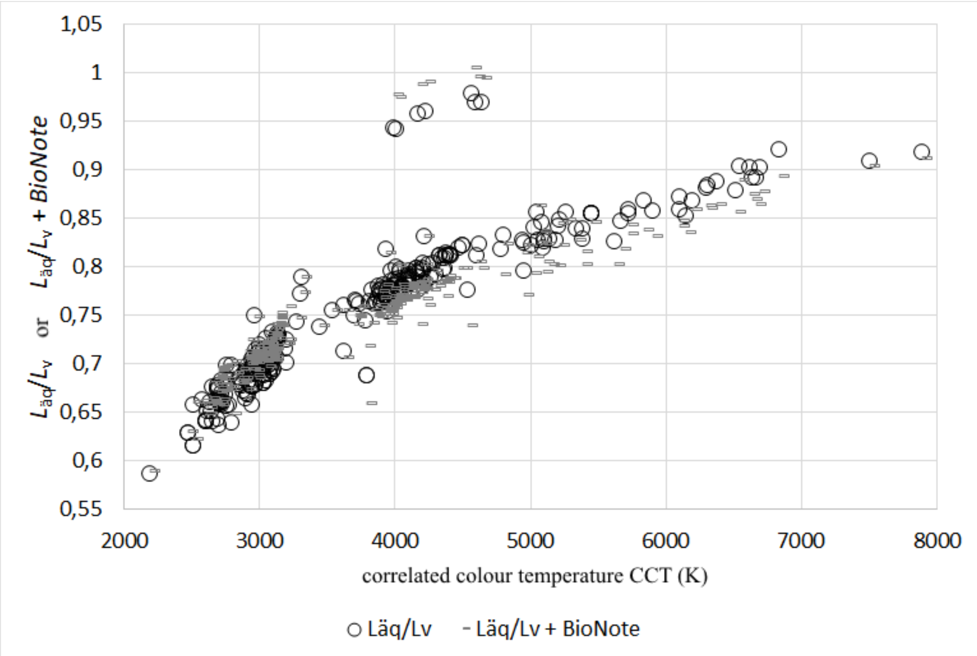


Figure 35 shows that warm white light sources obtain (in tendency) a greater (and positive) BioNote value than neutral or cool white light sources (which tend to have negative BioNote values). The reason is that, for „relaxing" light sources, the quantity $a_{mel,0}$ (the melanopic factor of the reference light source which is in tendency greater than a_{mel}) is in the numerator unlike neutral and cool white („activating") for which $a_{mel,0}$ appears in the denominator. A negative BioNote value indicates that the circadian effect of the light source is less than the circadian effect of its reference illuminant thus the light source should obtain a negative circadian evaluation.

As a further explanation, it is also interesting to represent the value of ($L_{äq}/L_v$) and also the value [($L_{äq}/L_v$) + BioNote] as a function of CCT for the same sample set of lighting products, see Figure 36. In the sample computation of Figure 36, interior lighting without dynamic lighting was considered (α=β=1).

Figure 36: The values ($L_{äq}/L_v$) and [($L_{äq}/L_v$) + BioNote] as a function of CCT for the sample set of 304 lighting products (in this sample set, interior lighting is considered without dynamic lighting; α=β=1). Reproduced with permission from Optics Express [1]



As can be seen from Figure 36, the value of the term [($L_{äq}/L_v$) + *BioNote*] increases in tendency with increasing CCT. It can also be seen that, in the present version of the method, the brightness term (L_{eq}/L_v) prevails but the value of this brightness term is modified (increased for warm white and decreased for neutral and cool white) by the quantity *BioNote* that represents the circadian effect in comparison with the reference illuminant. The value of *BioNote* tends to be positive for warm white sources because a_{mel}<$a_{mel,0}$ usually holds in case of the present set of 304 light sources. Therefore, according to the "relaxing" equation (i.e. for warm white), *BioNote*>0 (see Fig. 36). Thus, by adding the value of *BioNote*, we get a better score than with the ($L_{äq}$ / L_v) term alone. The reason is that it is advantageous if a warm white light source has less a_{mel} than its reference source as the aim is to provide a relaxing environment. But the value of *BioNote* tends to be negative for neutral and cool white spectra because a_{mel}<$a_{mel,0}$ generally holds in case of the present set of 304 light sources and, according to the "activating" equation, *BioNote* <0. This means that we obtain less circadian effect for the sample set of 304 light sources (as none of them was circadian-optimized) than it would be possible by conscious circadian optimization. Hence, by adding *BioNote* (small grey rectangles in Fig. 36), we obtain a worse score in case of CCT>3800 K than with the ($L_{äq}$ / L_v) term alone (see the open circles in Fig. 36).

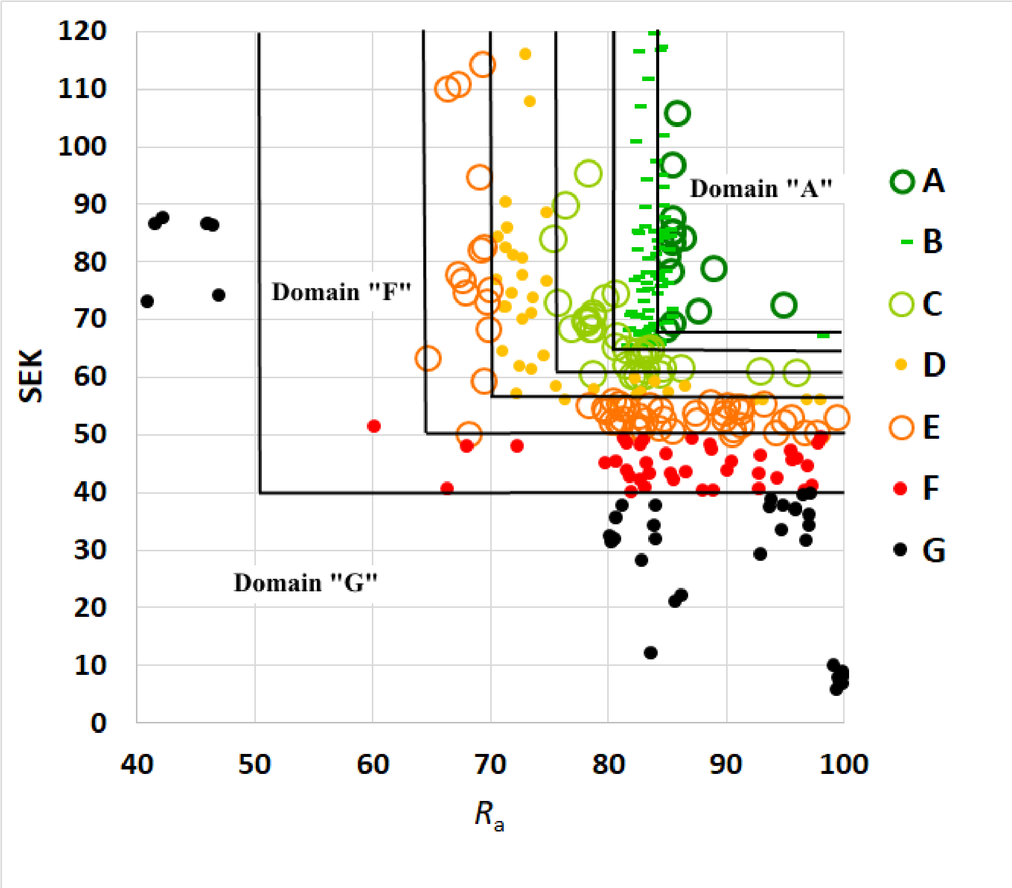
8.3 Literature for Section 8

[1] Q. T. Vinh, P. Bodrogi, T. Q. Khanh, Preliminary measure for the characterization of the usefulness of light sources, Optics Express 26, 14538-14551 (2018); https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-26-11-14538&id=389907

9 The new evaluation concept: Proposal for a new definition of energy labels with categories A to G. Assignment of the 304 sample lighting products to these new categories

In this section, a proposal is described for the new definition of energy labels with categories A to G. Every one of the 304 lighting products of the sample set will be assigned a category and this assignment will be shown as an example. The so called *usefulness category* (or *new energy label*; A: best; down to G: worst) is determined from the values of SEK and CIE CRI R_a in the new evaluation system (in the R_a-SEK diagram) by the use of a set of new category limit values. These category limit values are considered as preliminary (i.e. subject to subsequent discussions). A light source belongs to the category „A“ if both R_a and SEK are greater than the limiting value of the category "A". This means that, in order to satisfy the "A" criterion, both $R_a > R_a$(limit,A) and SEK>SEK(limit,A) shall be satisfied. This is a domain in the R_a-SEK plane, see Figure 37. In Figure 37, there are 304 lighting products with different symbols for the different *usefulness categories*. Table 8 contains the preliminary limit values SEK(A), Ra(A), SEK(B), Ra(B), etc. in order to assign a usefulness category (or energy label) to every lighting product in the new evaluation system. These category limits correspond to the separating lines of the usefulness category domains in Figure 37 in which the values α=1 (no dynamic lighting) and β=1 (interior lighting) were taken as an example.

Figure 37: **The R_a-SEK plane of the new evaluation system with the sample set of 304 lighting products. The limits of the different domains are preliminary (they are shown here as a starting point for future discussions). Reproduced with permission from Optics Express [1] (see Section 8.3). The values α=1 (no dynamic lighting) and β=1 (interior lighting) were taken as an example**



It can be seen from Figure 37 that the new evaluation system has two dimensions: every lighting product obtains two continuous values, 1. the colour quality measure (R_a value; abscissa) and the SEK value (ordinate). The reason of two-dimensionality is that the two quantities (R_a and SEK) do not correlate with each other thus representing two independent dimensions.

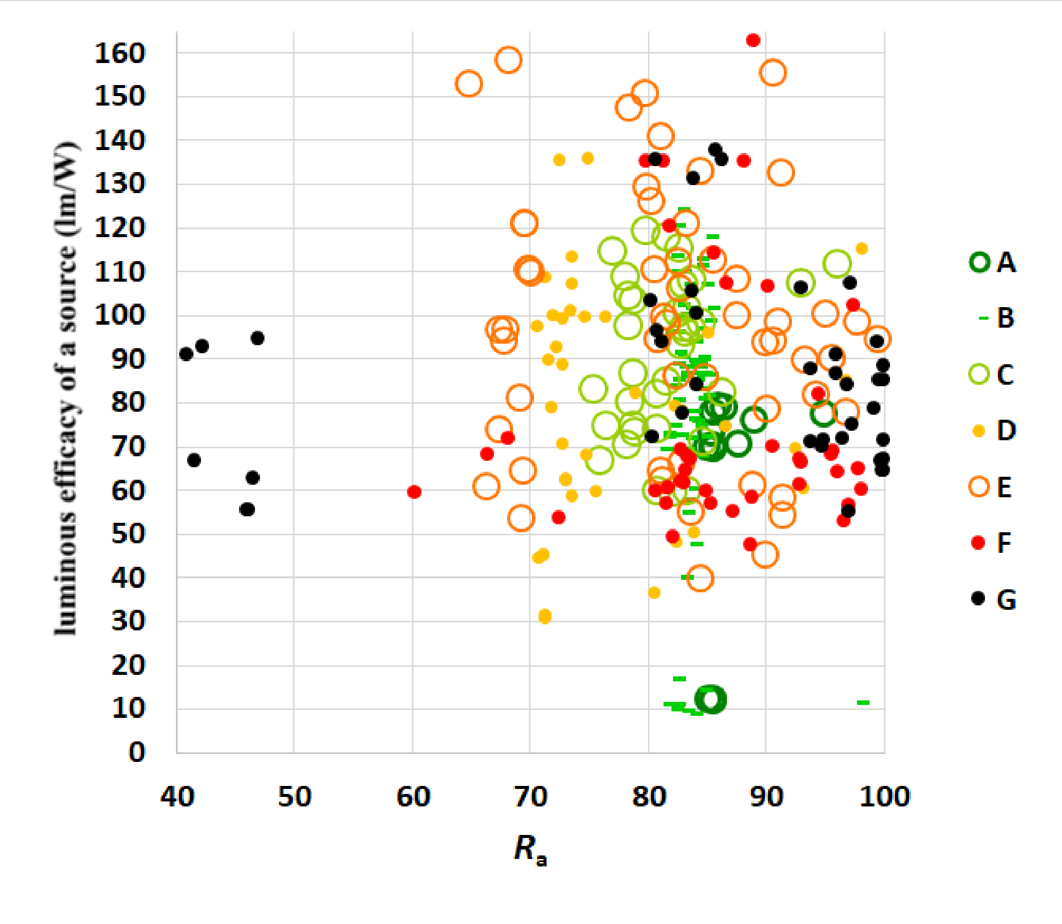
Mathematically, it is meaningless to summarise a two-dimensional quantity by the aid of one single dimension. In mathematics, physics and in technology, vectorial quantities (e.g. velocity, electric field, etc.) often occur and cannot be projected into a scalar without a loss of their original meaning. Analogiously, the assignment of categories (energy labels A-G) to a lighting product happens on the basis of the two-dimensional quantity {R_a; SEK}, see Figure 37. The limits of the domains in Figure 37 are preliminary. They are presented as a starting point of future discussions here. These preliminary category limit values, R_a(A), SEK(A), etc. are listed in Table 8.

Table 8: Preliminary category limit values SEK(A), R_a(A), etc. to assign a category (energy label A-G) to a lighting product, see the limiting black lines in Figure 37).

Quantity	Category (label)	Limit value	Symbol in Fig. 37
SEK	A	67.725	Dark green circle
SEK	B	64.800	Light green dot
SEK	C	60.563	Yellow-green circle
SEK	D	55.900	Yellow dot
SEK	E	51.200	Orange circle
SEK	F	40.400	Red dot
R_a	A	84.656	Dark green circle
R_a	B	81.000	Light green dot
R_a	C	75.703	Yellow-green circle
R_a	D	69.875	Yellow dot
R_a	E	64.000	Orange circle
R_a	F	50.500	Red dot

Table 9 shows the distribution of the 304 lighting products of the sample set according to light source and category. This distribution was calculated by the aid of the preliminary limit valued of Table 8. Limit value van be changed later on during the future discussions of the new evaluation method. Then, Table 9 can be re-calculated immediately by the software that implements the method. It is also very interesting to represent the same set of 304 lighting products in another diagram with conventional luminous efficacy (in lm/W) on the ordinate (instead of SEK), see Figure 38.

Figure 38: **The same lighting products as in Figure 37 but in a different representation in which conventional luminous efficacy (in lm/W) is on the ordinate (instead of SEK). Reproduced with permission from Optics Express [1] (see Section 8.3)**



As can be seen from Figure 38, the order of the lighting products in Figure 37 is disrupted and a huge scatter of the categories arises. The reason is that the quantity of *luminous efficacy* is based on the $V(\lambda)$ function that ignores the bluish-sensitive mechanisms of vision (in this example of interior lighting: ipRGCs and S-cones) although these mechanisms yield a significant contribution to brightness perception, visual performance and the circadian effect.

Table 9: Distribution of the sample dateset of 304 lighting products in the new evaluation system (A-G) according to the type of light source

Type	Description	Number of lighting products in every category							
		A	B	C	D	E	F	G	All
Incandescent	conventional	0	0	0	0	0	0	11	11
Incandescent	halogen-	0	0	0	0	0	0	0	0
Compact fluorescent	with built-in ballast	0	0	0	0	0	2	2	4
Compact fluorescent	without built-in ballast	0	0	0	0	0	0	0	0
Other fluorescent	‚half-compact‘: U-, ring-, brezel-shaped	0	0	1	2	1	2	0	6
Other fluorescent	tube-shaped (tubes)	0	1	12	5	7	0	7	32
LED	lamp	6	37	11	22	34	36	21	167
LED	module	0	0	0	0	0	0	0	0
LED	luminaire	12	38	3	17	4	5	5	84
High-pressure discharge lamp	high-ressure sodium	0	0	0	0	0	0	0	0
High-pressure discharge lamp	mercury vapour	0	0	0	0	0	0	0	0
High-pressure discharge lamp	metal halogen	0	0	0	0	0	0	0	0
All	all	**18**	**76**	**27**	**46**	**46**	**45**	**46**	**304**

10 Summary

According to the aims of the project, a new evaluation method of the electric efficiency of lighting products was presented in this report. This new method can be used to determine the electric efficiency of lighting products in a new, comprehensive way. Deficiencies of the $V(\lambda)$ function (as the method underlying the computation of the conventional quantity of *luminous efficacy of a source*) and the necessity of the new evaluation method were explained. The characteristics of human brightness perception and its metrics were described, both in the photopic range (to evaluate interior lighting) and in the mesopic range (to evaluate exterior lighting). The visual properties of colour quality and its metrics (general colour rendering index and further indices like colour preference indices) were summarized together with the issue of the visual quality of white tones as well as the way of the circadian evaluation of light source spectral power distributions. After introducing the metrics of these individual benefits of lighting, the mathematical definition of the new evaluation method was described. A sample, representative dataset of 304 lighting products was evaluated by the aid of the new method. The number of lighting products of different type in the categories A-G of the new evaluation system was computed and presented. The advantages and possible alternatives of the new method were described.

A Annex A: Consumer Workshop on Lighting (GD1 – 1 November 2017 – Forsa)

The Consumer Workshop took place in the framework of the project. Eight participants (not familiar with the subject) discussed 135 minutes (by the aid of a moderator of Forsa which is a market and opinion research institute) about different questions on the subjects of lighting, lighting products, their package, applications and labelling. A detailed minutes document was created and is attached to this report anonymously. The gender and occupation of the 8 participants was:

1. Female, 58, administration employee;
2. Female (no age information), working in public services, administration employee;
3. Male, 37, building technician;
4. Male, 40, recycling company;
5. Male, 56, external retail services;
6. Female, 26, student;
7. Male, 65, factory economist;
8. Female, 54, nurse.

The consumer workshop took place at the Forsa premises in a room in which different questions were answered by the aid of the moderator. Sample lighting product packages were displayed on a table with today's current labelling and a luminaire with changeable colour temperature was shown. After an introduction of 5 minutes about the relevance of electric light and lighting, user requirements and demands concerning electric lighting were discussed for 20 minutes. Then, discussions of 15 minutes about the subjects „purchasing lamps“ and „purchasing light sources“ followed together with the behaviour of manufacturers presenting information about the lighting product printed on their packages and the own criteria of the participants when choosing a certain lighting product. In the next 10 minutes, the packages of light sources put onto the table as examples were assessed by the participants at the first time. After that, the group talked about the meaning and general perception of the energy labels on the packages (10 minutes). Later on, participants had to evaluate the packages of the presented light sources in detail (15 minutes). In the subsequent period of 45 minutes, the 8 invited subjects interpreted, discussed and evaluated package information details (energy label, electric power, luminous flux, colour temperature, colour rendering) together. In the next 10 minutes, participants were asked how the package of lighting products could or should be optimised. Finally, in the last 5 minutes, the results of the consumer workshop were summarised.

Questions and discussion items (always formulated using understandable everyday language) included the following aspects:

► What aspects do you consider if you are thinking about electric lighting? **Answers:**

1. Much money. Very expensive. In our factory, we had normal luminaires before in the high rack area and they consumed very much electricity. I am a stakeholder in the company and it is very interesting to see the energy saving luminaires, we can save several thousand euros in every year with them. In Frankfurt, I have a small flat with two rooms because I do not want to go to Idstein every evening. But the house in Idstein has energy saving lamps and AAA+ devices and I do notice this in my purse. In the internet, there are calculators showing that by replacing an incandescent bulb, we can save 70 euros a year if they burn 2-3 hours a day. It is really worth doing so.
2. I am thinking about the replacing of lamps which are out of order. We really notice that.
3. Yes, it is really more efficient if we replace all of them.
4. I never buy energy saving lamps. I have only LEDs. Completely. This is more environment friendly.

► What is important for you if you when you are considering lighting at home? What are the most important requirements? What lighting quality do you need for your rooms? What are your important thoughts and emotions when you are thinking about light and lighting? **Answers:**

1. First of all brightness: when I need light then I really need it and then it should be very bright. When relaxing, I sometimes miss lighting and even if I have it, it is sometimes too white or too bright or too yellowish. Yes, it is true. Sometimes I really miss light.
2. It depends on the type of room, in which room I need or use the light source. In the living room, I do not have cool, disturbing light but I do need this kind of strong lighting in the office. In the bathroom, it depends. At the ceiling, we have the spots but I can dim them well, dimming is important for me. This is very easy when we have LEDs and halogen lamps.
3. The possibility to have light where ever we need it. In bigger rooms, their are different types of circulation. There are many people who unite dining rooms with living rooms. They can „switch off“ the dining room function when they go over to the living room corner turning on another type of lighting. Thus, electric power can also be saved.

► Do you have different light sources in the individual rooms? **Answers:**

1. For sleeping, when we e.g. do not work like cutting meat, we need less light than in the kitchen in which e.g. we are often doing so.

► What kind of light source do you choose for the individual types of rooms? **Answers:**

1. I have only spotlights in the kitchen, also under the cupboards, it is important to be able to switch on the light at the place where I currently am in the flat and depending on what I would like to illuminate and this is like this in the whole house.
2. More light sources in the same room, yes. In our living room, we have not only one lamp but two ceiling lights and a standing luminaire.

- Have the light sources that you plug in or have installed different „strengths"?
  Answers:

1. Yes, we have a LED lamp but we also have some energy saving lamps.
2. Then, we should consider if we also want to dim them or not. When I am sitting in the living room and watch a film then I would like to be able to dim.
3. We have bulbs in the standing luminaire an the in kitchen area, we have two different ones: first, the plug-in system for bulbs and second, the LEDs under the cupboards.

- What is your decision criterion when you have the choice to have different light sources in a room? Do you have such situations in which there are special areas in which you can control lighting in such a manner that it is appropriate for the given situation? **Answers:**

1. Yes. And especially now when it is so dark even at earlier hours of the day, we have three light sources in the kitchen and when I am cooking something then all of them are probably on but if I just go into the kitchen for a short time to fetch something then I only need a small amount of light.

- Is there a difference between the lightings you use at the different hours of a day? (e.g. in the afternoon or in the evening?) **Answers:**

1. If it is bright then I do not need any light.

- Do you like it if it is getting darker by dimming the light source or you would like to control brightness by the number of light sources? **Answers:**

1. We have a standing luminaire in the living room and when we watch TV then I only use this and when I am reading then I use this plus the ceiling light otherwise it is too dark.

- How is your impression if you take a look at this package of a lighting product?
  Answers:

1. There is too much information on it. The ISO standard and the CE seal are OK. But what is the meaning of the triangle at the bottom? Yes, there is too much on it. 60 watts, lifetime 15000 hours, warm white and it has. This would be enough and possibly the price.
2. The ISO certificate is not needed, this is not interesting for the consumer.
3. This is a typical thing: it was decided that this and that must be on it but in reality nobody knows what the ISO standard 4001 is.
4. This is for experts only. This is a certified company authorised to produce light sources.
5. This is also a quality label. There are many areas that have to be certified and this is important. But I am not sure if this should be printed onto the package but at least the consumer knows that the manufacturer was certified.

6. Safety, because this was certified by CE, this is enough for me. I do not need the ISO standard any more. Then, I should know what the ISO standard is and what is included in it.
7. I know ISO from the university but I am no more interested in it. I would not explore it in detail, this would be simply too much. Unfortunately, it is not only ISO on the package but six squares are printed and I especially do not understand what FIECQ means but this is irrelevant for me.

- So, the value itself is not so helpful as the graphic scale, is this true? **Answers:**

1. Exactly.
2. Graphic scales are at the back and too small.
3. Although the value 2800 stands on the front side, I do not understand this value.
4. I can see four values. 9.5 watts correspond to 60 watts, I understand this. At the rear side, it is shown how many lumens these 9.5 watts are, this is also nice. But should not these pieces of information appear next to each other? Or, the best way would be to write either W or lm but not both of them. The easiest way would be to only print onto the front side that 810 lm correspond to 60 W and this would then be enough.

- We have here some other packages, too, not all of these are lettered in the same way. Could you please look at them and tell us what kind of information it is? **Answers:**

1. I think, this package is OK. Philips, warm white, save 84% energy, 60 W.
2. „Without Mercury" is a useful information.
3. The consumer is absolutely overloaded with this.
4. I think the little boxes in the picture are OK.
5. It is good to have this table here on this side. At the bottom, we have the scale and now I also know that we can dim it and I also see the Kelvin value, I think this is good. But it is too much here on the front side, I do not know what I should be looking at.

- What is your opinion about the table here that contains all values again? **Answers:**

1. This is too small again, I need my glasses again.
2. What does R_A mean here?

- Does somebody know what R_A means? **Answers:**

1. (All participants remain silent)

- Did somebody consider the value of R_a when buying a product? **Answer:**

1. Moderator: It is the so-called colour rendering. In an interior, we have values between about 80 – 100 of R_a and if we have lower R_a values then this is provided for such rooms in which we do not need a high colour rendering. (The colour rendering was not important or unknown for the participants).

- Light has an effect: if you have warm and dark illumination then you will be tired or possibly more creative but light can also evoke an activating, stimulating effect because hormones become more impulsive and you feel yourself fit then, if e.g. you receive cool, strong light. Would an information on this aspect on the package be helpful for you? It would actually show if the lighting product has an activating effect. With the arrow to the right means that this light has a more activating effect.
  Answers:

1. No.
2. Not at all.
3. Especially certain age group would be completely embarrassed.
4. I miss something additional: is this light for chilling or rather for more sportive activities??
5. Yes, I would like to see this in this way, me too, as a supplement to the colour scale but not in such a way that it makes me more active or it helps me be more quiet.
6. This is just an additional useless value. Even now, it is already too complex with Kelvin, Lumen and Watt and this would be simply too much. So instead of becoming simple, we are getting more and more complex.
7. Although they would like to make it simple, we are getting more complex.

- Have you ever been thinking about the activating or relaxing effect of a light source when you were buying one? How would you represent this information in order to better understand that? Because you were not sure about what it means. What kind of symbol would you choose to depict the activating or relaxing effect then?
  Answers:

1. This is simply too much with those tiny boxes.
2. Who is able to say whether activating light should be bright or dark? Because, seemingly, everybody has a different feeling of well-being, somebody might also say that she or he feels active even with yellowish light.
3. I think the colour scale with yellow and white light already provides this information. This is why I would not show another scale. Yellow is rather relaxing, everybody knows this and also that white is bright and activating, and this would be enough.

- At the beginning, we have been talking about switching capacity. Is this important for you? This symbol looks like a light switch and it is printed here how often you can switch it on and off. **Answers:**

1. This is important.
2. Yes.
3. And this means 1 million times?
4. But this is 100000 only.
5. Yes, this would be 900000 times less off and on and this would be significant.

- We have also been talking about warm-up time, how long it takes for a lamp to be completely switched on. Did you find this on the packages? **Answers:**

1. On and off. Immediately on but off means that we need a longer time. This is printed here.

- If you have LEDs at home, have you already noticed that certain LEDs flicker? Does this disturb you? **Answers:**

1. Yes.
2. No.
3. Yes, sure.
4. Yes, this is irritating me because I am thinking that it is out of order, this is an immediate association.
5. I noticed this but only during the initial period of switching it on.
6. I cannot tell this surely whether this happens only when I switch it on, I will be more aware of this now.
7. I have never noticed that before.

- We have already seen many different packages. How can we optimise the package: what should be printed on it for an optimum look for you? **Answers:**

1. The colour scale showing the warmth of the light.
2. That it is an LED and also the wattage.
3. The energy label
4. I can't interpret lumen values. A comparison of watts between „before“ and „now“.
5. How often we can switch it on and off.
6. The information on +40 °C until -30°C is not important, we do not understand what to do with this. Another opinion: I would not omit this information because it is actually imoprtant at least for those who are electrically or technically a little bit more experienced and for those such information should be displayed rather with smaller letters. Non-experts can only use the information on colour scale, power difference, brightness and watt values and these items should be written on the package conspicuously.
7. Lumen values could be omitted. It should be printed on the rear side how many hours it lasts. The information 2800 Kelvin (warm light) should be rather displayed on the front side. E.g. 2800 K is not so useful for many people as the graphic scale.
8. We should not forget that manufacturers do not produce for only one country but for many countries in our modern, globalised world in which there are surely different user requirements.

B Annex B: Questions of the surway in the internet

We also carried out a survey in the internet about the new labelling of lighting quality and electric efficiency of lighting products (light sources, lamps, luminaires). This survey was not a part of our initial project proposal, it was carried out to prepare for the consumer workshop (Annex A) and it was carried out before it. These results will be evaluated later. Here we present only the result and the questions of the survey.

Introduction:

If you buy a light source (e.g. a „LED lamp“) then it is often not so easy to choose the most appropriate one that best corresponds to your demand among the plethora of different products. We would like to elaborate at labelling for it on the package. To do so, we would like to ask you to tell us your opinion by the aid of this short survey that will take 5 minutes only. All answers will be recorded anonymously.

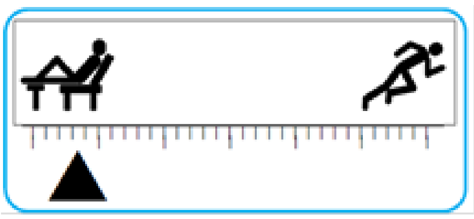
Questions:

1. How often do you consider the information printed on lighting product packages?
2. Do you know the information on „Electric power“ (e.g. 12 W)?
3. Do you know the information on „Luminous flux“ (e.g. 1055 lm)?
4. Do you know the information on „Colour temperature“ (e.g. CCT=2700 K)?
5. Do you know the information on „Colour rendering“ (e.g. R_a>80)?

Figure 39: Sample graphic representation of CCT

6. Can you recognise the meaning of the above labelling? (see Figure 39)
7. Free input field: Please describe the meaning of the above picture (labelling of a light source).

Figure 40: Alternative labelling for light sources according to the relaxing and activating effect of light



8. How would you interpret the above labelling on a light source package? (free input field)
9. Would a labelling of a light source according to its relaxing or activating effect helpful?
10. What kind of information do you use when you are buying a light source? (free input field)

11. Would you like to rather have a bright or a dim environment in the evening (e.g. in the winter at 19 o'clock)? Choice: 1. Very bright 2. Rather bright 3. Moderate 4. Rather dim 5. Dark or just a faint light level
12. Would you like to use for your living room in the evening in the family domain (e.g. cooking, eating, talking, playing together) warm white, neutral white or cool white? Warm white has a more yellowish i.e. warmer tone. Cool white exhibits a rather more bluish i.e. colder tone. Neutral white is in between. Choice: 1. Warm white, 2. Cool white, 3. Neutral white
13. Would you like to use for your living room in the evening in order to work (e.g. working in the kitchen, do-it-yourself, enter data, read a book or a newspaper) warm white, neutral white or cool white? Warm white has a more yellowish i.e. warmer tone. Cool white exhibits a rather more bluish i.e. colder tone. Neutral white is in between. Choice: 1. Warm white, 2. Cool white, 3. Neutral white
14. How important is the price of the light source when you are buying a light source?
    Very important, important, moderate, not at all (Choice)
    How important is the white tone (warm white, neutral white or cool white) when you are buying a light source? Very important, important, moderate, not at all (Choice)
15. How important is lighting quality (e.g. the beautiful appearance of the coloured objects illuminated) when you are buying a light source? Very important, important, moderate, not at all (Choice)
16. How important is the presence of matting (in order to produce uniformly distributed light) when you are buying a light source? Very important, important, moderate, not at all (Choice)
17. How important is the presence of a directed, focused light distribution (e.g. the targeted, strong illumination of a visual task) when you are buying a light source? Very important, important, moderate, not at all (Choice)
18. When you are buying a light source, are you rather considering a lower electric energy consumption first of all (i.e. efficient lighting products) and the aspects of lighting quality like white tones or brightness (the highest possible amount of light) only at the second place? Yes, No
19. When you are buying a light source, are you rather considering the aspects of lighting quality like white tones or brightness (the highest possible amount of light) first of all and a lower electric energy consumption (i.e. efficient lighting products) only at the second place? Yes, No

C Annex C: Information exchange with experts

C.1 Meeting of the co-workers of industry representatives of ZVEI, UBA and the co-workers of the Laboratory of Lighting Technology of the TU Darmstadt on 3 July 2017 and the conference of the LED leading market initiative and Federal Ministry of Economics and Technology (BMWi) (Presentation of Prof. Khanh about the project) on 14 July 2017. Meeting of the TU Darmstadt and DENA

The results of the discussions of the Federal Environmental Agency (UBA), the Ministries, the Association of the Electrical Engineering and Electronics Industry (ZVEI) Ministries and the representatives of the individual companies will be summarised below. Until 14 July 2017, two concepts were elaborated. One version was already presented at the TU Darmstadt on 3 July 2017 about the new evaluation of lighting products (lamps, modules and luminaires but no complete illumination systems).

The new evaluation method proposed had two relevant differences compared to the current one:

1. partially different numeric assessment parameters are used; and
2. lighting products are no more evaluated on the basis of only one criterion. Also, there is a dependence on application, e.g. office, hospital, museum etc. that give rise to different requirements concerning the lighting product's physical properties (e.g. its spectrum).

This new product assessment method can be used to formulate both minimum efficiency requirements and to elaborate a new energy label system. The above mentioned presentation tackled especially the latter issue.

The new concept uses the following numeric assessment parameters:

For brightness, not only luminous flux Φ_v (in lm) but also the equivalent luminance ($L_{äq}$) are used. Latter should be calculated in a different way for different applications. For exterior applications (S4 and ME streets), mesopic luminance is used as equivalent luminance ($L_{äq}$). For interiors, the Fotios et al. concept shall be used as equivalent luminance ($L_{äq}$). Thus, relative spectral influence on brightness perception can be considered (according to CIE 191:2010) that were ignored by the exclusive use of luminous flux.

The general colour rendering index Ra (CIE 13.3:1995) is used to evaluate colour quality.

The biological (circadian) effect of light on alertness is taken into account by a_{mel} (DIN SPEC 5031-100).

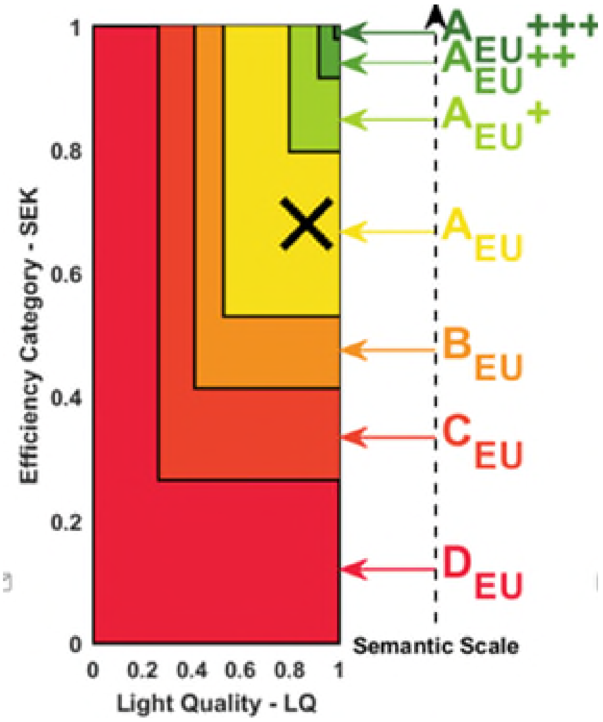
The difference of user demands will be considered as follows: there will be 12 applications. For every application, a numeric assessment parameter of lighting quality (LQ) will be computed with the following input parameters: R_a and a_{mel} computed from the spectrum and weighted by the factors α for R_a and β for a_{mel}. Latter factors should be different in case of different lighting applications. E.g. for museums, the weighing factor α will be higher than for an office. The β value in an industrial hall is less than in a hospital. Thus, a raw value of lighting quality is computed (LQ_{raw}). For better understanding, this raw value is transformed into the 0 to 1 range.

For the computation of the new energy efficiency measure in this intermediate stage of project development, the so-called brightness efficiency was proposed as a product of the luminous efficacy of a source and $L_{äq}/L_v$. This raw value (SEK_{raw}) was then transformed into the 0 to 1 range.

The quantities LQ and SEK can be assigned a category similar to the current labelling system (A++ down to E or possibly in the future A down to G.

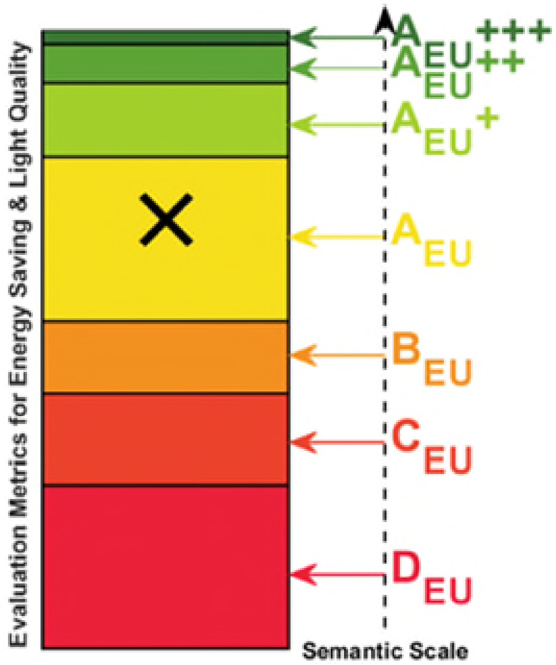
These results were represented in two dimensions i.e. the SEK value and the LQ value, see Figure 41.

Figure 41: Assessment of lighting products by the values SEK and LQ



In the next project development step, a one-dimensional representation was achieved, see Figure 42.

Figure 42: One-dimensional representation of Figure 41 in a further development step



The following was stated:

Conventional luminous flux contains neither colour quality nor the circadian effect. This is false because of the incorrect use of the V(λ) function in the parameters illuminance and luminance.

All new aspects were integrated in the new concepts in Figures 41-42 which can be used both to define category limits and for labelling. At this development stage, the 1 dimensional concept seemed to be more appropriate those days although scientific concerns about the necessity of two dimensions arose. The reason is that all relevant lighting engineering concepts were integrated according to the most important requirement of the project proposal.

It was suggested to define only two applications, relaxation (both for the office and for homes) and activity-functionality (both at the workplace and for homes or for home-office) with different a_{mel} weightings or, optionally, also a third application for high colour quality (museum, shop, medical investigations) with R_a>90. There should not exist more than three applications in the photopic range and 2 applications for exterior lighting (S and ME street classes).

The 1-dimensional concept was suggested those days to be used to compute the category limits and the labelling of lighting products. It was also proposed that two products could be depicted on the package: a product for home lighting and another one for professional applications.

As a summary, 5 applications were proposed those days, 2 for exterior lighting (S and ME street classes) and maximum 3 applications for interior lighting (relaxing, activity, and special applications for high colour quality) and also 2 additional product groups for living rooms and the professional lighting domain.

The new evaluation concept was further discussed with expert groups, see Annex C2.

C.2 Meeting of Lighting Europe, WG (Working Group) HCL (Human Centric Lighting) on 7 September 2017 in Brussels

During this meeting, the proposal (see Annex C1) was presented for Lighting Europe asking for an opinion to support the German delegation to present the concept to the EU Commission.