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TECHNICAL REPORT

Grey-Scale Calculation for Self-Luminous Devices

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Descriptor: Perception of colour
Colour vision
Colorimetry

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This Technical Report has been prepared by CIE Technical Committee 1-93 of Division 1 "Vision and Colour" and has been approved by the Board of Administration as well as by Division 1 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

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GREY-SCALE CALCULATION FOR SELF-LUMINOUS DEVICES

Summary

Contemporary colour media, to which a self-luminous grey (or more generally, neutral) scale would apply, include light emitting diode (LED) displays and liquid crystal displays (LCD). Every colour-difference calculation has a neutral or achromatic component. In stand-alone mode, this neutral scale can be used to calculate barely-visible threshold changes in luminance, equal-appearing suprathreshold steps of grey scale, matching grey appearance or conspicuousness of grey targets during visual search. CIE lightness, L^* , as part of the CIELAB and CIELUV colour spaces, was developed to serve similar purposes for reflective materials, and it was adapted in 1983 for use with cathode-ray tube (CRT) displays. Self-luminous devices such as computer displays, wide-area luminaires (when used not for lighting but for artistic or information purposes), advertising media, signage, safety lights, scientific and medical displays, avionics and heads-up displays, often exhibit high luminance, high spatial resolution and high contrast that require a self-luminous neutral scale. A self-luminous neutral scale does not require specification of a reference white; instead it is a function of the background luminance of the visual target, thus the scale has no upper limit. Because the self-luminous neutral scale can involve high contrast over a small visual subtense, it accounts for intraocular scattering. Finally, a self-luminous neutral scale enables the calculation of colour differences (e.g. CIELAB, CIEDE2000, or OSA-UCS) between self-luminous image segments, including consideration of a neutral point. This report recommends a method to calculate a self-luminous neutral scale fulfilling these requirements. The report also refers to applications, for which the recommended calculation could be improved:

- for mesopic light levels (e.g. cinema and video);
- to calculate effects of any particular visual subtense and shape of contrasts;
- to reflect the effects of stimulus geometry (e.g. comparison of adjoining fields versus separated fields);
- to incorporate post-retinal effects (e.g. due to visual cortical computations, such as the white point), and highlights in the surround not adjoining the visual target.

CALCUL D'ECHELLE GRISE POUR DISPOSITIFS AUTO-LUMINEUX

Résumé

Les médias de couleur contemporains, auxquels une échelle grise auto-lumineuse (ou plus généralement neutre) s'appliquerait, comprennent les écrans à diodes électroluminescentes (DEL) et les écrans à cristaux liquides (LCD). Chaque calcul de différence de couleur a une composante neutre ou achromatique. En mode autonome, cette échelle neutre peut être utilisée pour calculer des changements de valeur de seuil en luminance à peine visibles, des échelons supra-seuils d'échelles de gris à l'apparence égale, l'apparence grise correspondante ou la visibilité de cibles grises pendant la recherche visuelle. La luminosité CIE, L^* , qui fait partie des espaces colorimétriques CIELAB et CIELUV, a été développée pour servir des objectifs similaires en ce qui concerne les matériaux réfléchissants, et a été adaptée en 1983 pour être appliquée sur des écrans à tube cathodique (CRT). Les dispositifs auto-lumineux tels que les écrans d'ordinateur, les luminaires à grande surface (utilisés pour des raisons artistiques ou informatives, au lieu de raison d'éclairage), les panneaux publicitaires, les enseignes, l'éclairage de sécurité, les écrans scientifiques et médicaux, l'avionique et les affichages tête haute, présentent souvent une luminance élevée, de haute résolution spatiale et de contraste élevé, qui nécessite une échelle neutre auto-lumineuse. Une échelle neutre auto-lumineuse ne nécessite pas de spécification de blanc de référence; au contraire, elle est fonction de la luminance de fond de la cible visuelle, donc l'échelle n'a pas de limite supérieure. Comme l'échelle neutre auto-lumineuse peut impliquer un contraste élevé sur un angle apparent limité, elle prend en compte la diffusion intraoculaire. Enfin, une échelle neutre auto-lumineuse permet de calculer de différences de couleur (par exemple CIELAB, CIEDE2000 ou OSA-UCS) entre des segments d'image auto-lumineux, y compris la prise en compte d'un point neutre. Ce rapport recommande une méthode de calcul d'une échelle neutre auto-lumineuse répondant à

ces exigences. Le rapport fait également référence à des applications pour lesquelles le calcul recommandé pourrait être amélioré:

- pour les niveaux de lumière mésopique (par exemple cinéma et vidéo);
- pour calculer l'effet de tout angle visuel particulier, et de la forme des contrastes;
- pour refléter les effets de la géométrie du stimulus (par exemple, comparaison de champs adjacents par rapport aux champs séparés);
- pour incorporer des effets post-rétiniens (par exemple en raison de calculs corticaux visuels, tels que le point blanc), et des surbrillances dans le champ périphérique qui ne sont pas adjacentes à la cible visuelle.

GRAUSKALABERECHNUNG FÜR SELBSTLEUCHTENDE GERÄTE

Zusammenfassung

Zu aktuellen Farbmedien, auf die eine Grau- (oder genereller, Neutral-) Skala für Selbstleuchter angewendet würde, gehören Leuchtdioden- (LED) Bildschirme und Flüssigkristall- (LCD-) Bildschirme. Jede Farbdifferenzberechnung hat eine neutrale oder achromatische Komponente. Im eigenständigen Modus kann diese Neutralskala benutzt werden zur Berechnung kaum erkennbarer Leuchtdichte-Schwellenänderungen, gleich erscheinender, überschwelliger Graustufenschritte, welche mit der Grauerscheinung oder Sichtbarkeit grauer Objekte bei visueller Suche übereinstimmen. CIE Helligkeit, L^* , als Komponente der CIELAB- und CIELUV-Farbräume, wurde entwickelt, um ähnliche Zwecke für reflektierende Materialien zu erfüllen, und wurde 1983 für die Nutzung im Zusammenhang mit Röhrenbildschirmen übernommen. Selbstleuchtende Geräte wie Computer-Bildschirme, großflächige Leuchten (nicht für Beleuchtungs- sondern für künstlerische oder Informationszwecke), Werbemedien, Beschilderung, Sicherheitsleuchten, wissenschaftliche und medizinische Bildschirme, Avionik- und Warnbildschirme haben häufig eine hohe Leuchtdichte, eine hohe räumliche Auflösung und hohen Kontrast, was eine Neutralskala für Selbstleuchter erforderlich macht. Eine Neutralskala für Selbstleuchter erfordert nicht die Spezifikation einer (Weiß-) Referenz-Leuchtdichte; stattdessen ist es eine Funktion der Hintergrundleuchtdichte des Sehobjekts, somit hat die Skala keine obere Grenze. Da die Neutralskala für Selbstleuchter einen hohen Kontrast über einen kleinen Sehbereich beinhalten kann, bedingt sie intraokulare Streuung. Schließlich ermöglicht eine Neutralskala für Selbstleuchter die Berechnung von Farbdifferenzen (z.B. CIELAB, CIEDE2000 oder OSA-UCS) zwischen selbstleuchtenden Bildsegmenten, inklusive Berücksichtigung eines Neutralpunktes. Dieser Bericht empfiehlt eine Methode zur Berechnung einer Neutralskala für Selbstleuchter, die diese Anforderungen erfüllt. Der Bericht weist auch auf Anwendungen hin, für die die empfohlene Berechnung verbessert werden könnte:

- mesopische Lichtniveaus (z.B. Kino und Video);
- die Berechnung von Effekten jeglichen Sehbereichs und jeglicher Kontrastform;
- die Wiedergabe von Effekten der Geometrie des Sehreizes (z.B. Vergleich angrenzender Felder mit getrennten Feldern);
- die Einbindung post-retinaler Effekte (z.B. aufgrund visueller kortikaler Berechnungen, wie etwa der Weißpunkt), und Highlights im Umfeld, die nicht an das Sehobjekt angrenzen.

1 Introduction

This report presents the calculation of a self-luminous neutral scale as a complement to the original use of CIE lightness, L^* , as defined in the CIELAB and CIELUV colour spaces (ISO/CIE, 2008; ISO/CIE, 2016), for reflective surfaces.

The CIE colour-matching function $\bar{y}(\lambda)$ was defined to be the same as the spectral luminous efficiency for photopic vision, $V(\lambda)$, (Wyszecki and Stiles, 1982). $V(\lambda)$ was defined based on self-luminous flicker photometry. According to Wyszecki and Stiles (p. 157), in photometry “the Y -tristimulus value in the CIE 1931 system becomes the luminance”. In applications to object-colour stimuli, in “most practical situations, only relative spectral radiant power distributions of the given light sources are required”. Hence, the “ Y -tristimulus value of the object-color stimulus, ..., defines the *luminance-factor* of the object color stimulus”. For Wyszecki and Stiles most practical situations involved reflective objects of colorimetry and isolated coloured lights, not self-luminous electronic displays with high luminance, high resolution and high contrast. The luminance of light reflected from an object depends upon the reflectance of the object and the luminous intensity of the light from the radiant source that illuminates the object. The luminous intensity of the source was measured as the Y tristimulus value of magnesium oxide or barium sulphate illuminated by that source. These highly-reflective materials were later idealized as a perfect diffuse reflector such that all of the energy incident upon the material will be reflected back into the hemisphere above the perfect diffuse reflector. When the CIELAB and CIELUV colour differences were developed (Robertson, 1977), Semmelroth suggested a pseudo-adaptation transform dividing the luminance of an object, Y , by the luminance of the perfect diffuse reflector (at first designated Y_0 and later designated Y_n as it is today). A perfect diffuse reflector would have a reflectance of $Y/Y_n = 100\%$ and thus a maximum L^* magnitude of 100. Other tristimulus values, X and Z , are normalized to $Y/Y_n = 100$. Wyszecki and Stiles (1982) state (pp. 167, 168): “The tristimulus values X_n , Y_n and Z_n are those of the nominally white stimulus. ... Under these conditions, X_n , Y_n and Z_n are the tristimulus values of the standard illuminant with Y_n equal to 100.” The point is that, depending upon whether your application requires only relative information or the actual luminance of the visual target, Y_n can be thought of as unitless, defined as 100, or alternatively as a maximum luminance of a particular radiant source or reflective object (Pointer, 2017; Fairman, 2017). The self-luminous neutral scale recommended in this report is in the latter category (requiring actual luminances measured in $\text{cd}\cdot\text{m}^{-2}$), whereas standard current practice (media-relative colorimetry) is in the former.

The use of CIE lightness, L^* , in colour-difference calculations for self-luminous electronic displays is based on a recommendation by Carter and Carter (1983), in which the tristimulus value of the white point, Y_n , is set equal to the numerical value of luminance obtained with maximum intensity on all display primaries, and the medium white point is completed by setting the other tristimulus values X_n and Z_n to CIE standard illuminant D65, relative to Y_n . This is different from the case of reflective media or isolated coloured lights, where Y_n is proportional to the luminance of a perfect diffuse reflector illuminated by a radiant source. Since the tristimulus values X_n , Y_n and Z_n represent the medium white point, the calculation of L^* is said to be “media relative” (for the definition of “media-relative colorimetry” see Annex A). In media-relative colorimetry, L^* represents the lightness relative to the range of luminances available from a specific self-luminous medium; this has become common practice (Oleari, 2016; Tooms, 2016).

1.1 Problem statement

Problems with the expedient extension of L^* into the self-luminous domain have been apparent for a long time. Contemporaneous with the recommendation, the Boeing Company was developing self-luminous electronic displays for use on the flight deck of aircraft (Silverstein and Merrifield, 1985). Of the Carter and Carter recommendation (Carter and Carter, 1983), Silverstein and Merrifield commented: “While this solution is not entirely satisfactory, it does preserve ΔE^* scale invariance with respect to the choice of luminance units and provides an acceptable interim recommendation. The choice of appropriate neutral reference values for color difference formulations to be used with self-luminous color displays will be a priority topic for a newly formed CIE committee on revised standards for self-luminous displays.” The “priority

topic” was attributed to Justin J. Rennilson in a personal communication with Silverstein and Merrifield. Rennilson confirmed (in communication with the chairman of TC 1-93) recently that this topic was not resolved by CIE TC 1-10, which had been formed to study colorimetric measurements and their correlations with colour appearance, for self-luminous displays, and published CIE 087-1990 *Colorimetry of Self-Luminous Displays, A Bibliography* (CIE, 1990).

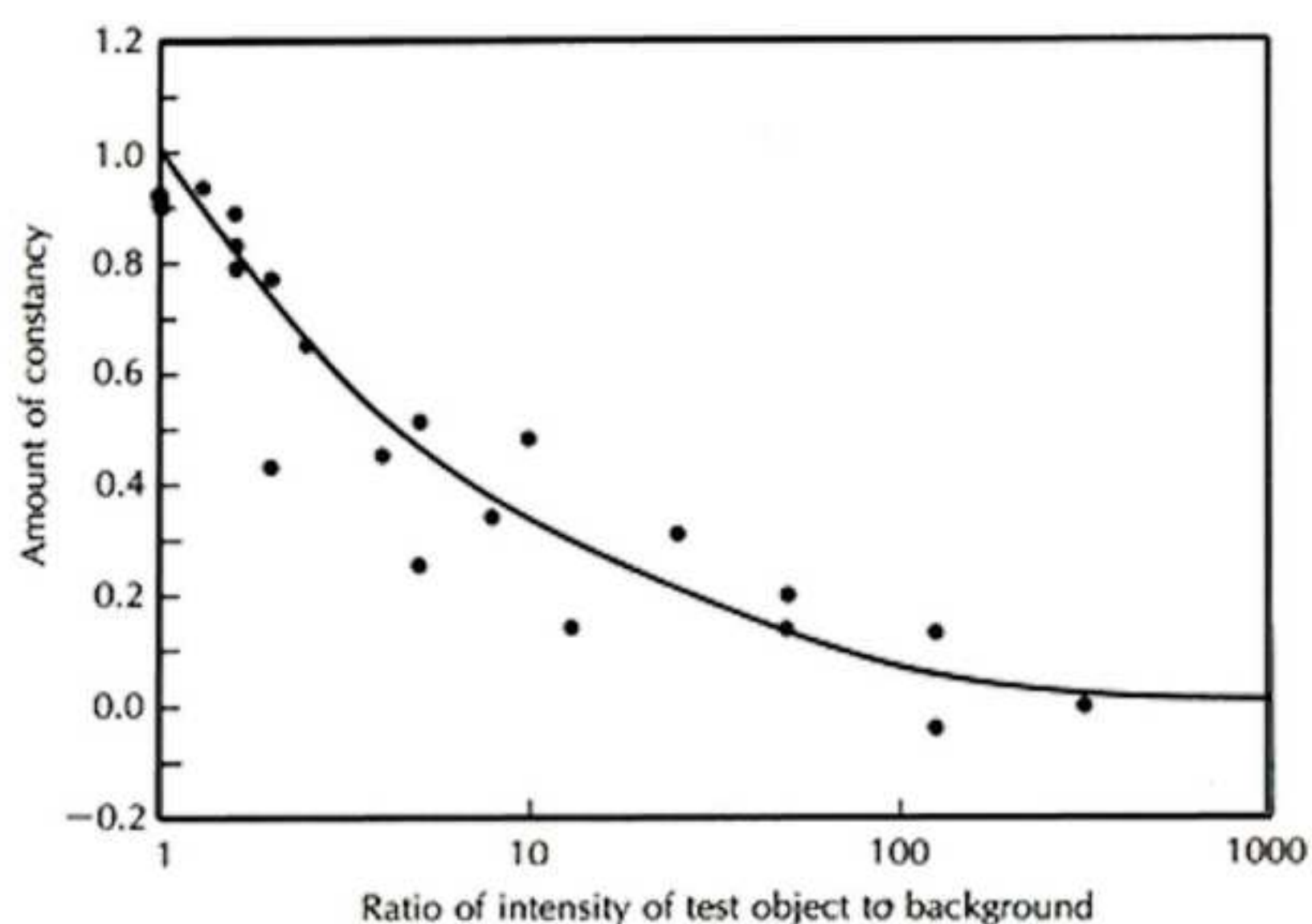
Two long-standing objectives remain:

- the choice of appropriate neutral reference values for self-luminous colour-difference formulations;
- improvement upon the “not-entirely satisfactory” nature of using maximum image or device luminance as the normalizing factor in L^* .

What is unsatisfactory about using maximum luminance (of a medium or an image) as the self-luminous normalizing factor of L^* ? Recent reviews (Gilchrist et al., 1999; Kingdom, 2011) warn against anchoring a grey scale to the maximum luminance and against thinking of the maximum luminance as white. The Gelb Effect illustrates the instability of normalizing a grey scale to Y_n ; the entire grey scale is altered by a new maximum luminance. A consequence of Y_n representing the maximum luminance of the medium is that L^* is undefined for a target luminance greater than Y_n , which is a problem familiar to experienced practitioners (Pointer, 2015). Examples include fluorescence, hyper-additivity of display primaries, changes of a power source or display device, changes of ambient light transmitted (e.g. in a heads-up display) or reflected, or a different image than the one used to establish Y_n . It would be more satisfactory to have a self-luminous lightness calculation that is not sensitive to assumptions about Y_n , and that does not have an upper limit. Furthermore, the parameters of L^* were fit to Munsell Value (Robertson, 1977), a scale of *reflective* lightness. The same L^* parameters and assumptions apply when L^* is extended into the self-luminous domain. For instance, the full scale of L^* assumes a Munsell Value N/5 reflective background. Perceptual phenomena accentuated by self-luminous stimuli, such as crispening and the black point, may not be adequately represented by assumptions retained in a self-luminous lightness calculation imported from the reflective domain.

Lightness constancy is the cornerstone of L^* as originally applied to reflective surfaces. Constancy refers to a neutral scale appearing unaltered when the intensity of the illuminant changes. For reflective samples, the ratio Y/Y_n is unaltered when the illuminant intensity changes. Indeed, the target luminance (represented by the numerical value Y) and the perfect diffuse reflector luminance (represented by the numerical value Y_n) are each proportional to the intensity of the light source illuminating the surfaces. As a result, Munsell Value and L^* for reflective lightness are constant despite changes of source intensity. However, is constancy a reliable cornerstone for a self-luminous lightness calculation? For low contrasts (e.g. less than a 10:1 luminance ratio of a visual target luminance to a background luminance), constancy is preserved at least approximately. For higher contrast ratios (beyond those achievable with ordinary reflective samples), lightness constancy is increasingly doubtful (see Figure 1 and (Heinemann, 1989)). It would be more satisfactory to avoid assuming lightness constancy for high-contrast, self-luminous applications.

Hunt (1997) explains why the neutral-scale component of a self-luminous colour image is so important: it establishes a neutral point for colour-difference (see Clauses 3 and 4), it adjusts contrasts for the luminance of the background (see Clause 2), and it efficiently transmits and displays a sharp image (see Clause 2).



NOTE Constancy decreases with increasing contrast of visual targets and their backgrounds. Lightness constancy is nearly perfect (1,0 on the ordinate) for low contrasts (near unity on the abscissa). Constancy is increasingly lost for higher contrast ratios.

Figure 1 – Lightness constancy as a function of the target/background luminance contrast ratio (Cornsweet, 1970; Figure 13.4, reprinted with permission)

1.2 Examples of self-luminous neutral-scale formulae

Whittle (1992) published a logarithmic grey-scale function of the background luminance and the target luminance to describe psychophysical results using self-luminous media. The formula is described in detail in 2.1.

Whittle's formula is not media relative. It has been commended as one of the most noteworthy developments of the previous 25 years (Kingdom, 2011). Whittle was explicitly unifying results from three perspectives: perceptual scaling (i.e. grey-scale shade B appears midway between shades A and C), matching (i.e. A looks like B), and visual discrimination (e.g. Just Noticeable Difference between A and B). His objective was to extend the reflective "neutral value" scale work of Munsell et al. (1933) to a self-luminous neutral scale.

The video industry standard grey scale PQ10K was developed by the Society of Motion Picture and Television Engineers (SMPTE, 2003; 2014) – see also Annex B. The performance of the PQ10K formula is compared with perceptual data, the Whittle formula and L^* in Annex B, dealing with digital video.

Digital Imaging and Communications in Medicine (DICOM) (NEMA, 2011; DICOM, 2006; DICOM, 2016) also defines a self-luminous neutral-scale calculation called the Grayscale Standard Display Function (GSDF) that is not media relative and does not use the ratio principle. See Annex C for an empirical comparison of the DICOM GSDF with Whittle's formula.

Seim and Valberg developed a self-luminous neutral-scale calculation, based on the physiological Naka-Rushton formula (Seim and Valberg, 2016). Their calculation is media-relative, and hence will not be considered further because it is dependent on the ratio principle and it would have a maximum scale value limited by Y_n . Similarly, IEC 61966-2-1 (IEC, 1999) recommends a media-relative formula that will not be considered further for the same reasons. Comparison of media-relative formulae (in general) with the type of formula recommended

herein (i.e. those based on absolute luminance) could be a subject for future research made possible by new high-luminance and high-contrast media.

Table 1 compares four self-luminous neutral scales. The left column lists some points of comparison among the formulae. Normalization is the process of determining the unit and/or endpoint of the scale. Independent variables are the quantities that one may vary to affect the value of the grey scale. The top of scale is the maximum grey scale value. Crispening is increased observer sensitivity to changes of luminance near the background luminance (e.g. Whittle, 1992). Most formulae are functions only of target luminance; Whittle's formula has separate branches expressing the dependence of appearance upon background luminance (see Annex D and particularly Figure D.2, Carter 1993). When the target luminance is greater than the background luminance, the contrast is called positive contrast; conversely, when the target luminance is less than the background luminance, the contrast is called negative contrast (see also Annex A). Spatial scale refers to the visual subtense of image segments. Spatial scale affects colour and grey appearance (Carter and Silverstein, 2012, Carter and Carter, 1988). For example a painted wall (large spatial scale) looks lighter than a sample paint chip (small spatial scale). A continuous curve may positively accelerate upward (concave) or negatively accelerate downward (convex). The point where the acceleration changes sign (i.e. passes through zero) is called point of inflection. Whittle's formula (Whittle, 1992) has points of inflection at the background luminance and at about half the background luminance, reflecting the effect of the background on appearance.

Table 1 – Comparison of self-luminous neutral scales

	Media-relative L^*	Whittle's formula	DICOM GSDF	SMPTE PQ10K
Normalization	Peak luminance, Y_n	Minimum of luminance (background, target)	N/A	N/A
Independent variables	Target luminance divided by Y_n	Target luminance and background luminance	Target luminance	Target luminance
Top of scale	Corresponds to Y_n	Unlimited	Corresponds to 4 000 cd·m ⁻²	Corresponds to 10 000 cd·m ⁻²
Expression of crispening	No; in CIEDE2000, L^* crispening for $L^* = 50$	Yes	No	No
Multiple branches, one for each background luminance	No	Yes	No	No
Recognizes positive contrasts versus negative contrasts	No	Yes	No	No
Accounts for spatial scale	No	Yes, parameter k	No	No
Points of inflection	1	2	0	0