

# A UNIFIED FRAMEWORK FOR EVALUATING NON-VISUAL SPECTRAL EFFECTIVENESS OF OCULAR LIGHT EXPOSURE: KEY CONCEPTS

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## Abstract

The first evidence for a novel type of photoreceptor in humans was published in the form of an action spectrum for melatonin suppression. This action spectrum has very different spectral sensitivities compared to rod and cone photoreceptors. This discovery led scientists to rethink how lighting needs for human health are evaluated. Existing literature provides useful information about how to evaluate and report non-visual spectral sensitivities to light but lacks a unified description. In this paper, key concepts in the existing methods are identified and categorized to formulate a unified framework to assess the non-visual potential of light that is adaptable to a wide range of lighting solutions.

**Keywords:** light, health, lighting design, non-visual, circadian, spectral effectiveness factor, equivalent illuminance, effective

## 1 Introduction

Research in the past decade has revealed that ocular light exposure stimulates not only visual functions but also a range of non-visual effects. Studies on humans have demonstrated that monochromatic short-wavelength light is more effective than light at higher wavelengths in suppressing melatonin (Brainard *et al.* 2001, Thapan *et al.* 2001), resetting the circadian clock (Gooley *et al.* 2010), enhancing alerting effects (Cajochen *et al.* 2005, Lockley *et al.* 2006), and cognitive function (Vandewalle *et al.* 2007), and constricting the pupil (Gamlin *et al.* 2007, Gooley *et al.* 2012). These non-visual effects of light are primarily mediated by recently discovered intrinsically photosensitive retinal ganglion cells (ipRGCs) (Provencio *et al.* 2000). These cells use melanopsin as a photopigment and, as a result, the ipRGCs are characterized by a spectral sensitivity curve that peaks in the short wavelength region at 480 nm, distinguished from the spectral sensitivity of rod and cone photoreceptors. The discovery of the new photoreceptors has led scientists to rethink how lighting needs for humans are evaluated. In recent years, new measures have been proposed to evaluate the spectral effectiveness of ocular light exposure, complementary to the existing photometric system developed by the International Commission on Illumination (CIE). While providing useful information about how to evaluate and report non-visual spectral sensitivity to light, these measures currently lack a unified description. Building on the existing literature, we have identified key components and categorized them to provide a unified framework to assess the non-visual potential of light.

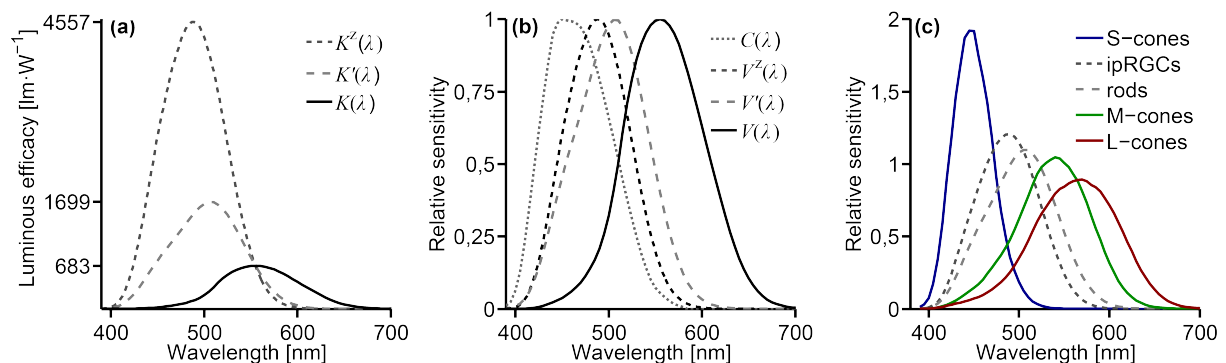
Spectral properties of light sources are commonly evaluated in absolute or relative terms. Absolute terms refer to physical quantities such as irradiance or illuminance and relative terms refer to unit-less quantities obtained as ratios of absolute terms. The choice of using absolute or relative terms depends on the research objective or the lighting application. Absolute quantities are usually reported in biological studies (Enezi *et al.* 2011, Lucas *et al.* 2014) where relative quantities are more commonly used in applied physics and optics (Kozakov *et al.* 2008, Aubé *et al.* 2013). The uses of the two are combined in real-world applications of lighting research and design (Gall and Bieske 2004, Pechacek *et al.* 2008, Bellia and Bisegna 2013). The majority of existing absolute and relative measures, for evaluating non-visual spectral sensitivity to light, are scaled in relation to the photopic luminous efficiency function,  $V(\lambda)$ . Due to differences in uses by research disciplines, existing literature is composed of different terminology and units that overlap in terms of their usability. In order to avoid confusion and misunderstanding across disciplines, it is important to provide a well-formulated description of non-visual spectral effectiveness of light.

In this paper we explain the key concepts that drove the development of a unified framework. The relationships between measures of light standardized by the CIE and more recent measures to quantify the non-visual spectral sensitivity to light are briefly explained to provide an adequate basis for explaining the structure of the unified framework. The framework consists of both relative and absolute measures. Equal-area normalization of spectral sensitivity curves is applied to define a new unit-less quantity, called the relative spectral effectiveness (RSE) factor. The RSE factor shows the relative relationship between weighted irradiance and radiometric or photometric quantities. It can be used to compare the non-visual spectral effectiveness of different light sources and to derive absolute measures relevant to the existing radiometric and photometric systems. The overlaps and relations to other existing methods are explained using examples of electric light sources.

## 2 Background

### 2.1 The CIE system

The fundamental method for quantifying light is in terms of radiant flux,  $\Phi_e$ , in units of power [W] or in irradiance,  $E_e$ , in units of power per area [ $\text{W}\cdot\text{m}^{-2}$ ]. These quantities are purely physical and are called radiometric quantities. Photometric quantities are derived from the radiometric quantities based on the definition of luminous efficacy. The SI unit of luminous efficacy is lumens per watt [ $\text{lm}\cdot\text{W}^{-1}$ ]. Photopic luminous efficacy,  $K(\lambda)$ , has a maximum value of  $K_m = 683 \text{ lm}\cdot\text{W}^{-1}$  for monochromatic light of wavelength 555 nm (green), where scotopic luminous efficacy,  $K'(\lambda)$ , reaches a maximum of  $K'_m = 1699 \text{ lm}\cdot\text{W}^{-1}$  for monochromatic light of wavelength 507 nm, see Figure 1(a). The luminous flux,  $\Phi_v$ , [ $\text{lm}$ ] falling on a unit area at a point on a surface is called illuminance,  $E_v$ , and is measured in lux [lx]. Illuminance is widely used in lighting practice to quantify the brightness of a space and the stimulus to the visual system.



**Figure 1 – (a) The luminous efficacy for melanopic  $K^w(\lambda)$ , scotopic  $K'(\lambda)$ , and photopic  $K(\lambda)$  vision. (b) The relative spectral sensitivity of the circadian  $C(\lambda)$ , melanopic  $V^w(\lambda)$ , scotopic  $V'(\lambda)$ , and photopic  $V(\lambda)$  luminous efficiency functions normalized to peak value of unity. (c) The spectral sensitivity of the five human photoreceptors normalized to the area of the  $V(\lambda)$  function. The cone spectral sensitivity curves are the  $10^\circ$  cone fundamentals (Stockman and Sharpe 2000) and the rod spectral sensitivity curve is the scotopic  $V'(\lambda)$  function. The ipRGC spectral sensitivity curve is constructed by assuming  $\lambda_{\max}$  480 nm using an opsin template (Govardovskii *et al.* 2000) and a lens transmittance of a 32 year old observer (van de Kraats and van Norren 2007).**

### 2.2 Towards non-visual (biological) quantities of light

Since the discovery of the ipRGCs, new terminology and new units have been proposed to complement the existing radiometric and photometric measurement systems (Rea *et al.* 2002, Gall and Bieske 2004, Enezi *et al.* 2011, Bellia and Bisegna 2013, Lucas *et al.* 2014). In the following sections, we have selected three different methods for review that have been proposed to evaluate the spectral sensitivity of the non-visual system.

### 2.2.1 Melanopic illuminance

Enezi *et al.* (2011) proposed a melanopic spectral efficiency function,  $V^z(\lambda)$ , peaking close to 490 nm, based upon the spectral efficiency of melanopsin to measure the light stimulus to the ipRGCs for a 30 year old observer. The melanopic illuminance can be written as

$$E_{v,z} = K_m^z \int E_{e,\lambda} V^z(\lambda) d\lambda, \quad (1)$$

where the melanopic luminous efficacy constant  $K_m^z = 4557 \text{ lm}\cdot\text{W}^{-1}$  ensures that, for illuminance at 555 nm, melanopic illuminance is equal to photopic illuminance.

This method is the only way to be consistent with the conventional quantities used in photometry but may not be practical for comparing responses of different photoreceptors types (Lang 2011, Lucas *et al.* 2014). Since the spectral luminous efficacy functions are normalized to  $683 \text{ lm}\cdot\text{W}^{-1}$  at wavelength 555 nm, the melanopic system,  $K^z(\lambda)$ , has a much higher weight compared to the scotopic and photopic systems, see Figure 1(a).

### 2.2.2 Circadian action factor and effective irradiance

A spectral sensitivity function for circadian non-visual responses, the circadian efficiency function,  $C(\lambda)$ , was proposed by Gall and Lapuente (Gall and Lapuente 2002) using the effects on melatonin suppression as the indicator of spectral sensitivity based on measured data from Brainard *et al.* (2001) and Thapan *et al.* (2001). The circadian efficiency function,  $C(\lambda)$  in Figure 1(b), has a peak sensitivity at 450 nm and was implemented in the German pre-standard DIN V 5031-100:2009 (DIN 2009). The standard recommends a circadian (biological) effective value to be derived by weighting a radiometric quantity,  $X_e$ , with  $C(\lambda)$

$$X_{e,c} = \int X_{e,\lambda} C(\lambda) d\lambda, \quad (2)$$

where  $X_{e,\lambda}$  can be replaced with  $\Phi_{e,\lambda}$  or  $E_{e,\lambda}$  for calculating radiant flux or irradiance, respectively. The subscript c on  $X_e$  represent a scaling with the  $C(\lambda)$  curve and  $\Phi_{e,c}$  or  $E_{e,c}$  is given in equivalents of standard units [W] or [ $\text{W}\cdot\text{m}^{-2}$ ], respectively.

The relation to photometric values  $X_v$  is obtained as

$$X_{e,c} = K_m^{-1} \times X_v \times a_{cv}, \quad (3)$$

where the circadian action factor is defined as

$$a_{cv} = \frac{\int X_{e,\lambda} C(\lambda) d\lambda}{\int X_{e,\lambda} V(\lambda) d\lambda}. \quad (4)$$

The  $a_{cv}$  factor together with the  $C(\lambda)$  function have been used to compare the performance of different light sources (Gall and Bieske 2004, Bellia *et al.* 2011). The issue with this method is that if the  $C(\lambda)$  function is replaced with a new sensitivity function that may better approximate circadian non-visual responses, the  $a_{cv}$  values may change significantly.

### 2.2.3 Equivalent $\alpha$ -opic illuminance

Apart from calculating the melanopic illuminance or the circadian effective irradiance, another solution has been suggested that defines a new absolute measure (Lucas *et al.* 2014). Instead of normalizing the spectral efficiency functions so that the maximum height is equal to one, it was proposed to normalize the sensitivity curves to the area of the photopic luminous efficiency function,  $V(\lambda)$ , see Figure 1(c). This is done separately for each type of photoreceptor using the sub notation  $\alpha$  to distinguish between the different types,  $\alpha$  can take the value z, lc, mc, sc, and r, respectively for melanopic, erythroptic, chloropic, cyanopic, and rhodopic equivalent illuminance. In addition, five new units have to be introduced so that one equivalent  $\alpha$ -opic illuminance is equal to one photopic illuminance under equal-energy light conditions. The new equivalent  $\alpha$ -opic illuminance is obtained as

$$E_\alpha = K_N \int E_{e,\lambda} N_\alpha(\lambda) d\lambda, \quad (5)$$

where  $N_{\alpha}(\lambda)$  is the spectral sensitivity curve for photoreceptor  $\alpha$  normalized to unity-peak and  $K_N = 72\,983,25 \alpha\text{-lm}\cdot\text{W}^{-1}$  is a normalization constant derived by integrating the  $V(\lambda)$  function multiplied by the photopic luminous efficacy or  $K_N = K_m \int V(\lambda)d\lambda = \int K(\lambda)d\lambda$ . Note that the value of  $K_N$  does not change with photoreceptor type  $\alpha$  but the unit changes accordingly. Consequently the relationship between illuminance [lx] and the new units of measure [ $\alpha$ -lx]: melanopic [z-lx], erythropic [lc-lx], chloropic [mc-lx], cyanopic [sc-lx], and rhodopic [r-lx] illuminances is not consistent with the definition of luminous efficacy. This concept is similar to the circadian effective irradiance, introduced in Section 2.2.2. These absolute measures describe how effective a given light exposure is to produce an effect.

### 3 Unified framework: Key concepts

In order to evaluate the spectral effectiveness of any photoreceptor type or photoreceptive system, we developed a unit-less factor using the equal-area normalization approach described in Section 3.1. The new factor enables the evaluation of the relative spectral power distributions (SPDs) of a light source in terms of its comparative ‘brightness’ or ‘energy’ relationship to an equal-energy spectrum for any system of photoreception. The mathematical concepts of the new factor and the conversion to absolute measures are explained in Sections 3.2 and 3.3, respectively.

#### 3.1 Equal-area normalization approach

In order to assess the spectral sensitivity of a photoreceptor or a system of photoreceptors, the sensitivity curves are scaled to have equal areas under the curves as shown in Figure 1(c). The normalized sensitivity curves represent how much light ‘hits’ different types of photoreceptors with equal probability when exposed to pure white light. This type of normalization is widely used in colorimetry, for example to model the changes in cone sensitivities that occur in each type of cone during chromatic adaption (Stockman and Sharpe 2000). Furthermore, it was recently adopted by Lucas *et al.* (2014) to calculate the equivalent rhodopic, erythropic, chloropic, cyanopic, and melanopic illuminance values (see Section 2.3.3). Note, however, that these sensitivity curves do not describe the functional relationship by which light induces its effect, only what the photoreceptors are exposed to (Lucas *et al.* 2014).

The spectral sensitivity curves shown in Figure 1(c) are scaled to the area of the  $V(\lambda)$  function. The cone fundamentals (Stockman and Sharpe 2000) and the  $V(\lambda)$  function are adopted to represent the spectral sensitivity of rods and cones, respectively. The spectral sensitivity curve for the ipRGCs photoreceptor is constructed by assuming  $\lambda_{\text{max}}$  480 nm using an opsin template (Govardovskii *et al.* 2000) and a lens transmittance of a 32 year old observer (van de Kraats and van Norren 2007). Here these curves are used to demonstrate the use of the unified framework (i.e. not a recommendation for selection of sensitivity curves which is beyond the scope of this paper). The sensitivity curves are shown for wavelengths ranging from 390 nm to 700 nm, where the eye relative sensitivity is  $> 0,005$ . Although the human eye is sensitive to light  $< 390$  nm and  $> 700$  nm, the relative sensitivity at these wavelengths is extremely low. Therefore, the wavelength range  $390 \text{ nm} \leq \lambda \leq 700 \text{ nm}$  can be considered the visible wavelength range. Note that the wavelength range should be adjusted depending on the selected sensitivity curves and the desired accuracy.

#### 3.2 Relative spectral effectiveness (RSE) factors

The unit-less factor is called the relative spectral effectiveness (RSE) factor,  $\eta$ , with subscripts  $v$  and  $e$  that represent photopic and energetic relations, respectively. The,  $\eta_{v,i}$  factor is the relationship between the weighted spectral irradiance with a spectral sensitivity function,  $S_i(\lambda)$ , and the spectral irradiance weighted with the  $V(\lambda)$  function. The letter  $i$  is a general notation and can take five forms: ipRGC, l, m, s, and r that stands for ipRGCs, L-cones, M-cones, S-cones, or rods, respectively, and the respective sensitivity functions are noted as  $S_{\text{ipRGC}}(\lambda)$ ,  $S_l(\lambda)$ ,  $S_m(\lambda)$ ,  $S_s(\lambda)$ , and  $S_r(\lambda)$ , shown in Figure 1(c). It is assumed that  $\int S_i(\lambda)d\lambda = 1$ , so the five human photoreceptors have an equal probability of absorbing spectral irradiance under equal-energy radiator (a pure white light). The effectiveness factors are simple to use and useful to rate the performance of different SPDs independently of an absolute intensity of a light exposure.

The  $\eta_{v,i}$  factor for any  $S_i(\lambda)$  weighted spectral irradiance is obtained as follows

$$\eta_{v,i} = \frac{\int_{390}^{700} E_{e,\lambda} S_i(\lambda) d\lambda}{\int_{390}^{700} E_{e,\lambda} V(\lambda) d\lambda} \times K_v, \quad (6)$$

where  $K_v$  is equal to the area of  $\int V(\lambda) d\lambda = 106$ . The  $\eta_{e,i}$  factor is the relationship between the  $S_i(\lambda)$  weighted spectral irradiance and the non-weighted spectral irradiance

$$\eta_{e,i} = \frac{\int_{390}^{700} E_{e,\lambda} S_i(\lambda) d\lambda}{\int_{390}^{700} E_{e,\lambda} d\lambda} \times K_e, \quad (7)$$

where  $K_e$  is equal to the length of the wavelength range from 390 nm to 700 nm, or 310, derived by integrating the area of a rectangle with height equal to one on the interval from 390 nm to 700 nm. The area scale constants,  $K_v$  and  $K_e$ , ensure Equations (6) and (7) to return unity if the spectral power distribution of the light source has an equal-energy spectrum. By constraining the wavelength range to 390 nm to 700 nm, the effectiveness factor is fully focused on the spectral effectiveness over the visible range. It is given that irradiance outside 390 nm to 700 nm does not contribute to biological or non-visual effects of ocular light exposure.

### 3.3 Conversion to absolute measures

Spectral profiles of different light sources stimulate each photoreceptor type differently. When selecting light sources, it can be useful to convert illuminance values from a *reference* light source to a *target* light source while maintaining an equal stimulus to a specific photoreceptor. This concept, called the equivalent illuminance in the presented paper, was first published by (Pechacek *et al.* 2008), but only for one type of *reference* light source and with respect to one type of spectral sensitivity curve. Here, the equivalent illuminance is generalized in a mathematical form and extended to handle different types of *reference* light sources and photoreceptors.

The equivalent illuminance is defined as

$$E_{v,i}^{eq} = E_v \times r_{v,i} = E_v \times \frac{\eta_{v,i}^{ref}}{\eta_{v,i}^{tar}}, \quad (8)$$

where  $r_{v,i}$  is the ratio of the RSE factor for the reference light source,  $\eta_{v,i}^{ref}$ , to the RSE factor for the target light source,  $\eta_{v,i}^{tar}$ .

The equivalent illuminance is similar to the concept of 'equivalent luminance' that was introduced by the CIE as a supplement to the photometric system to scale brightness under mesopic lighting conditions (Sagawa 2006). "According to the CIE definition, the equivalent luminance is the luminance of a specified reference light that has the same brightness as the target light under consideration." Note that the meaning of the word 'equivalent' is used differently by Lucas *et al.* (2014) and Pechacek *et al.* (2008). The concept of the equivalent  $\alpha$ -opic illuminances (Lucas *et al.* 2014) is similar to the circadian effective irradiance (Gall and Bieske 2004, DIN 2009), so from here on effective illuminance will be used instead of equivalent  $\alpha$ -opic illuminance to avoid confusion. The effective illuminance is obtained by multiplying the photopic illuminance by the RSE factor

$$E_{v,i}^{eff} = E_v \times \eta_{v,i}. \quad (9)$$

The advantage of using equivalent illuminance over effective illuminance is that it provides a quantity in units of photopic illuminance [lx], which can be translated directly to adjust lighting in experimental or architectural settings using a lux meter. The equivalent  $\alpha$ -opic illuminance or effective illuminance are quantities that cannot be directly applied without a new device/tool that can measure  $\alpha$ -lx or convert  $\alpha$ -lx to lx.

In a similar way equivalent irradiance is defined as

$$E_{e,i}^{eq} = E_e \times r_{e,i} = E_e \times \frac{\eta_{e,i}^{ref}}{\eta_{e,i}^{tar}} \quad (10)$$

and effective irradiance

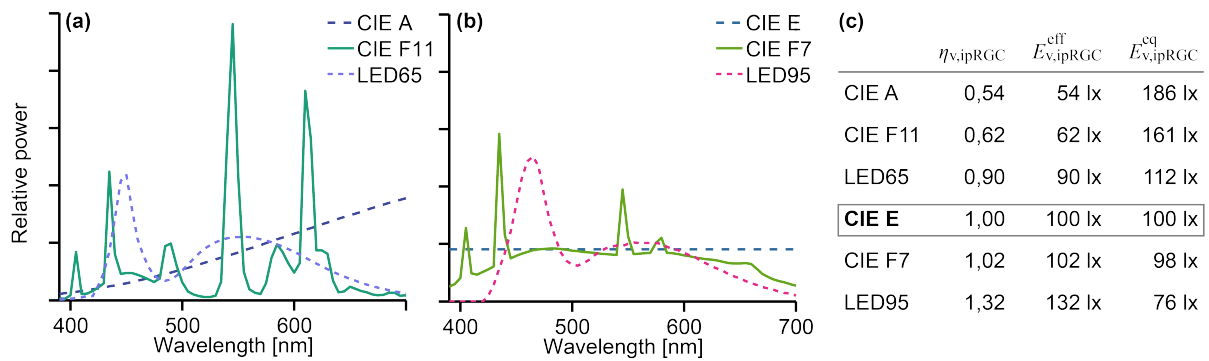
$$E_{e,i}^{eff} = E_e \times \eta_{e,i} \quad (11)$$

## 4 Results

In order to demonstrate the usage of the proposed framework, we calculate the ipRGCs effectiveness of illuminance (Section 4.1) and the non-visual (biological) effectiveness of irradiance (Section 4.2) for electric light sources having different spectral power distributions (SPDs).

### 4.1 ipRGCs effectiveness of illuminance

The  $\eta_{v,ipRGC}$  factor was calculated for six electric light sources: incandescent 2856 K (CIE A), three-band fluorescent 4000 K (CIE F11), white LED 6500 K (LED65), equal-energy 5454 K (CIE E), broadband fluorescent 6500 K (CIE F7), and blue LED 9500 K (LED95). These light sources were selected to illustrate how the  $\eta_{v,ipRGC}$  factor changes in relation to different types of light sources. Their relative SPDs are shown in Figure 2(a,b) for the visible part of the electromagnetic spectrum, between 390 nm and 700 nm. In Figure 2(c), the  $\eta_{v,ipRGC}$  factor values are compared for the above mentioned electric light sources and sorted from lowest to highest RSE factor. Values above one indicate that the corresponding light sources are more effective than an equal-energy spectrum (CIE E) for stimulating the ipRGC photoreceptors for the same illuminance. This applies to the light sources that are rich in the short-wavelength part of the spectrum. In this example, the CIE F7 and LED95 light sources are more effective than the CIE A, CIE F11, and LED65 light sources. For example the incandescent (CIE A) light source returns a factor value of 0,54, which means that twice the illuminance should give the same effectiveness as the fluorescent (CIE F7) light source that has a factor value close to 1.



**Figure 2 – (a) The relative SPDs for incandescent 2856 K (CIE A), three-band fluorescent 4000 K (CIE F11), white LED 6500 K (LED65), (b) equal-energy 5454 K (CIE E), broadband fluorescent 6500 K (CIE F7), and blue LED 9500 K (LED95). (c) The relative weight of ipRGC to photopic illuminance, the ipRGC effective illuminance of 100 lx, and the ipRGC equivalent illuminance for CIE E of 100 lx.**

If we compare the ranking of light sources obtained here using the  $\eta_{v,ipRGC}$  factor values to other studies that have used the circadian action factor (Gall and Bieske 2004, Bellia *et al.* 2011) or circadian potential (Pechacek *et al.* 2008), we see that these different values show the same relative relations. The difference is that here the sensitivity curves are normalized to equal area, so the  $\eta_{v,ipRGC}$  factor returns equal measure for any type of sensitivity curve for equal-energy (CIE E) light source.

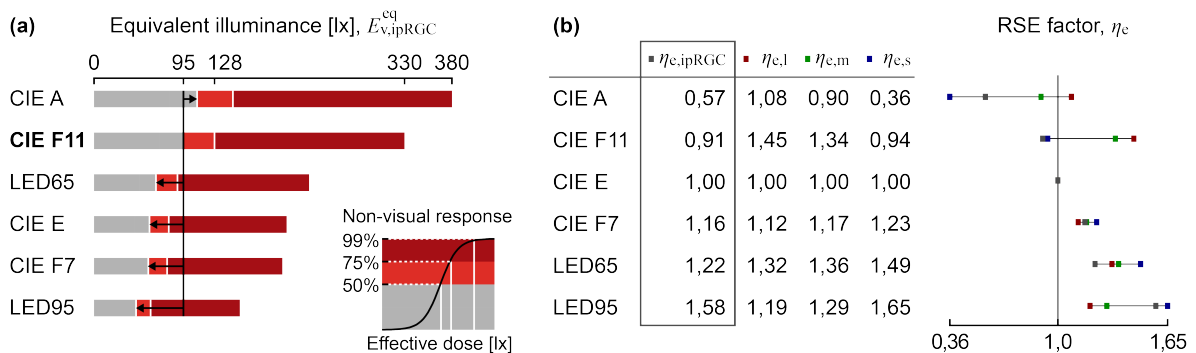
In Figure 2(c), the effective illuminance and the equivalent illuminance as explained by Equations (9) and (8) are also listed for the ipRGC photoreceptors. For a light source of 100 lx the effective illuminance is the product of 100 lx and the  $\eta_{v,ipRGC}$  factor, thus the ipRGC

effective illuminance,  $E_{v,ipRGC}^{eff}$ , shows the same relative relation as the  $\eta_{v,ipRGC}$  factor. Since illuminant CIE E is only a theoretical SPD the effective illuminance has a limited usability in practice (as it is not possible to use an equal-energy spectrum in reality). The ipRGC equivalent illuminance shows how much light is needed to produce the same effect for CIE E of 100 lux. Further, the relative effectiveness factor for other photoreceptors than the ipRGCs can also be calculated.

Figure 3(a) shows ipRGC equivalent illuminance for the *reference* light source CIE F11. The illuminance levels of the *reference* light sources (CIE F11) are tuned to return the equivalent illuminance of 95 lx, 128 lx, and 330 lx that correspond to 50%, 75%, and 99%, respectively, of subjective alertness responses derived from the dose-response relationship published by Cajochen *et al.* (2000). These values are obtained using the  $\eta_{v,ipRGC}$  factor values, see Equation (8). The conversion ratios are useful to adjust intensity levels for different types of light sources. The amount of shift in equivalent illuminance and direction from 95 lx of CIE F11 that achieved half maximum effective dose (50%) is illustrated with black arrows in Figure 3(a). For example 58 lx of CIE F7 is needed to achieve the same ipRGC effectiveness as 95 lx of CIE F11.

### 4.2 Non-visual (biological) effectiveness of irradiance

Instead of evaluating light sources in relation to the photopic visual system, it is possible to omit the  $V(\lambda)$  function and calculate the effectiveness of irradiance. The  $\eta_{e,i}$  factors are very different compared to the  $\eta_{v,i}$  factors. In Figure 3(b) the  $\eta_{e,i}$  factors are listed for ipRGCs and L-M-S-cones, ranked from the lowest to the highest based on the ipRGC RSE factor of irradiance,  $\eta_{e,ipRGC}$ . The results are no longer smoothed by the  $V(\lambda)$  function and the influence of the different spectral profiles is more visible. Of the illuminants listed the CIE F7 illuminant has the least spread in effectiveness. This is seen in Figure 3(b) where the squares show the distribution of the RSE factor values for the different photoreceptor types.



**Figure 3 – (a) The ipRGC equivalent illuminance, i.e. the amount of illuminance to achieve the same stimuli (non-visual response) for the ipRGCs for CIE F11 illuminant of 95 lx, 128 lx, and 330 lx, represented with light to dark colours, respectively. (b) The relative weight of ipRGCs and L-M-S-cones to irradiance.**

## 5 Discussion

Since spectral sensitivity curves are necessary for evaluating visual and non-visual responses to light, it is appropriate to classify existing methods into two approaches of scaling the curves: a unity-peak normalization and an equal-area normalization. According to the unity-peak normalization, the spectral sensitivity curves are scaled so that their maximum value is set equal to one. This approach is the most common representation of spectral sensitivities and is useful for comparing relative differences in peak sensitivity, not the magnitude of a response. The issue is that different photoreceptors are weighted unequally and therefore their functional relationship is distorted. As a starting point in determining how much light ‘hits’ a photoreceptor, the more appropriate approach is the equal-area normalization, where the sensitivity curves are scaled to have equal areas under the curves. The assumption is that each type of photoreceptor or photoreceptive system is given equal weight when exposed to pure white light. This approach does not examine the functional impact, since stimulating

each photoreceptor equally will not necessarily result in equal biological impact, and given that the functional contribution of the various photoreceptors will change with light intensity, duration, pattern and light history.

We developed a unit-less factor, relative spectral effectiveness (RSE) factor, which shows the relative relationship between a spectrally weighted irradiance and photopic luminous or radiant quantities. When selecting a light source it is useful to evaluate how its spectral profile may stimulate the photoreceptor types differently. The mathematical description of the new factor is designed to return unity if the spectral power distribution of the light source has an equal energy spectrum. Applying the unified framework to a light source with a non-equal energy spectrum will result in a low value (<1) of the RSE factor if the light source has low stimulus potential for the photoreceptive system under investigation, and if the light source has high stimulus potential, the RSE factor will be high (>1). The equal-area normalization allows us to compare the sensitivities of any photoreceptive systems and avoiding the problem related to the unity-peak normalization where resulting values are highly influenced by the total area of the curves, which is unequal, and cannot be directly compared for effectiveness. In order to compare spectral profiles of light sources in an absolute quantity instead of a relative scale, the RSE factor can be turned into a set of conversion ratios that determine illuminance levels resulting in equivalent stimulus to a specific photoreceptive system for a range of light sources. This is useful to convert illuminance levels from one particular *reference* light source to equivalent illuminance levels in another *target* light source. The RSE factor thus enables the evaluation of the relative spectral power distribution of a light source in terms of its comparative 'brightness' relationship to an equal-energy spectrum for any system of photoreception.

As much of research has been carried out using photopic illuminance, understanding the relationship between the spectral sensitivity of the non-visual system and the photopic visual system is important. The existing methods have suggested new metrics that are compliant with current standards (Enezi *et al.* 2011, Bellia and Bisegna 2013) or depend on the relative relation between the two systems (Gall and Bieske 2004, Pechacek *et al.* 2008, Lucas *et al.* 2014). The high value of melanopic efficacy (Enezi *et al.* 2011) is not related to a comparability of visual and non-visual biological effects and it has been pointed out that it may lead to confusion (Lang 2011, Lucas *et al.* 2014). The use of different terminology for the same measure may also be troublesome and it is important to have a unified description of both relative and absolute measure. An exclusive focus on how spectral sensitivity is rated in relation to the photopic visual system may not be the best practice. Instead of evaluating the non-visual responses as a subsystem or as an extension of the photometric system, it can be evaluated directly in relation to the radiometric system independently of the  $V(\lambda)$  function. The spectral irradiance can simply be weighted with a spectral sensitivity curve. As the human eye cannot detect different intensities in irradiance as for illuminance, however, equivalent photometric values might still be preferable among practitioners.

The human non-visual system of photoreception is functionally different from the visual system and must therefore be assessed accordingly. Defining the relative roles and contributions of the different photoreceptors types in non-visual responses to light has proven to be challenging. The magnitude of the non-visual effects of light depends not only on the spectral power distribution of the light source, but also the dynamic changes in light exposure, which are not yet fully understood. The shortcomings of the existing methods in accounting for these dynamic changes are not addressed here. It is assumed that the sensitivity of photoreceptors should not change with lighting conditions, so each photoreceptor can be evaluated separately. Under the unified framework the relative contribution can be scaled and summed as appropriate.

## 6 Conclusion

This paper describes key concepts in a unified framework for evaluating non-visual spectral effectiveness. The equal-area normalization is adapted to define a new unit-less quantity, called the relative spectral effectiveness (RSE) factor. Relevant measures from existing research literature are reviewed and explained in relation to the new RSE factor. It is demonstrated how the RSE factor can be used to evaluate and compare spectral effectiveness of different light sources in relative and absolute quantities. Following these



recommendations by reporting both absolute and relative measures will increase transparency and improve communication of study results and other research findings. We hope that this effort will help practitioners and researchers to interpret and communicate information on non-visual spectral effectiveness in a universal way.

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