Smartphone-based measurement of the melanopic daylight efficacy ratio

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Abstract

Recently, the CIE published a new standard in which the so called 'melanopic daylight efficacy ratio' (abbreviated to melanopic DER) is introduced. This number is helpful in estimating the impact that a light source may have on our circadian rhythm. Although the melanopic DER can be directly calculated from the spectral power distribution, in case the latter is unknown a spectrophotometer or similar instrument is required, which is usually unavailable to the general public. Here we demonstrate how the melanopic DER can be accurately estimated from a smartphone image of two selected color samples. In addition, using the smartphone's camera parameters we provide a method to estimate the illuminance. Combined these measurements allow an evaluation of the absolute melanopic stimulation.

Introduction

Bibliographic data (www.dimensions.ai) and trend analysis on search terms (Google Trends) both show that there is growing interest in the non-visual or non-image-forming effects of light, such as the effect on our circadian rhythm. The same conclusion, based on PubMed data, was reached in a recent review on the role of melanopsin in visual and non-visual function [1]. Effects like this can impact our performance and well-being and are therefore important to study and understand. One of the mechanisms involved is melatonin suppression, the reduction of the release of melatonin during the evening and night. Melatonin is a hormone that is known to be involved in the regulation of our sleep-wake cycle. The suppression is initiated by the absorption of light in the melanopsin photopigment [2], present in the retinal ganglion cells (intrinsically photosensitive Retinal Ganglion Cells or ipRGCs).

To quantify the potential of a light source (illuminant) to evoke such biological effects, the CIE recently published an international standard [3]. Among other things, it defines the Melanopic Daylight Efficacy Ratio, here abbreviated to melanopic DER. It is the ratio of the melanopic efficacy of luminous radiation (for a source), $K_{mel,v}$, to the melanopic efficacy of luminous radiation for D65 daylight, $K_{mel,v}^{\mathrm{D65}}$:

$$melanopic\ DER = \frac{K_{mel,v}}{K_{mel,v}^{\mathrm{D65}}} = \frac{\Phi_{mel}/\Phi_v}{\Phi_{mel}^{\mathrm{D65}}/\Phi_v^{\mathrm{D65}}} \quad (1)$$

in which Φ_{mel} represents the melanopic radiant flux and Φ_v the luminous flux. Superscript indicates the illuminant, being either the source (empty superscript) or D65. When the source is daylight D65, the melanopic DER equals 1. Further, we have

$$\Phi_{mel} = \int SPD(\lambda)\, s_{mel}(\lambda)\, d\lambda \quad (2)$$

$$\Phi_v = K_m \int SPD(\lambda)\, V(\lambda)\, d\lambda \quad (3)$$

with $SPD(\lambda)$ the spectral power distribution of the source, $s_{mel}(\lambda)$ representing the action spectrum of ipRGCs due to their photopigment melanopsin, and $V(\lambda)$ the photopic luminous efficiency function, both shown in Fig. 1. K_m is the maximum spectral luminous efficacy of radiation for photopic vision, K_{m} = 683 lm·W^{-1}. The denominator in eq.(1), $K_{mel,v}^{\mathrm{D65}}$, has a constant value of 0.0013262 W·lm^{-1}, so we can simplify eq.(1) to

$$melanopic\ DER = 754.03 \left(\frac{\Phi_{mel}}{\Phi_v}\right). \quad (4)$$

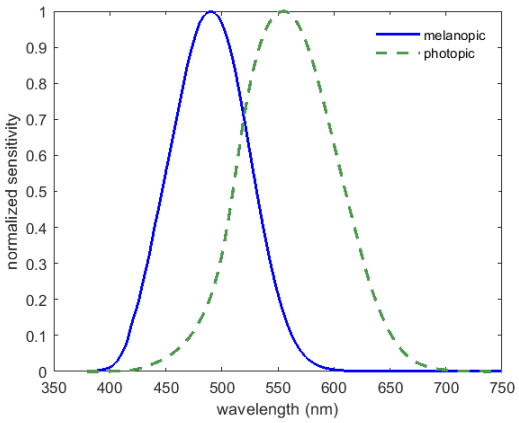

Figure 1. *Photopic (V_λ) and melanopic spectral weighting functions, normalized to their peak sensitivities.*

When the spectral power distribution (SPD) of a light source is known, the melanopic DER can be readily calculated according to equation (4). When the SPD is unknown, however, one would first have to measure it with a spectrophotometer or a similar instrument. For the general public a spectrophotometer is not available. To solve that problem, we here show how to estimate the melanopic DER with a smartphone and two commercially available color samples.

Method

The melanopic flux and the luminous flux as defined by equations (2) and (3) are in fact obtained by calculating the area under the curves, where the curves are the spectral (wavelength-by-wavelength) product of the illumination and the spectral weighting functions shown in Fig.1. Our method incorporates a similar approach by measuring the intensity of the light reflected from two samples having spectral reflectances similar to the spectral weighting functions shown in Fig.1. Therefore, the spectral product of illumination and reflection mimics the spectral product of illumination and ipRGC sensitivity. The intensity of the reflected light is derived from the samples' colors as captured by a smartphone's camera and sensor.

Selection of color samples

We searched for commercially available, off-the-shelf color samples that have spectral reflectances resembling the spectral

weighting curves shown in Fig. 1. The two samples that we found are shown in Fig. 2, where the normalized spectral reflectances of the two samples are plotted together with the spectral weighting functions of Fig.1. The two samples, Pantone 3272 C and Sikkens K2.40.70 will be referred to as the 'melanopic' and 'photopic' sample, respectively. As Fig.2 shows, the matches to the spectral weighting functions are not perfect, in particular at both ends of the wavelength range. Probably a closer match can be obtained when searching in more databases or when a proper spectral match is formulated by mixing paint or inks. We will show however that with the current selection of samples a very good approximation of the melanopic DER can already be obtained.

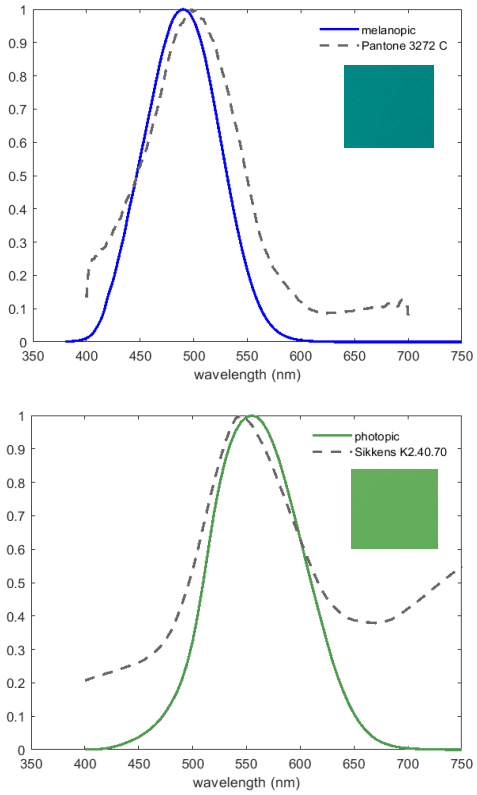

Figure 2. *Reflectance of color samples (dashed curves) found for matching the melanopic (top) and photopic (bottom) spectral weighting functions. All functions are normalized to their respective maxima. A color impression of the samples under white light is given below the legends.*

Set-up

The two color samples were placed on the bottom of a wooden light box (Fig.3), the interior of which was painted a neutral white. Light was projected through a 30 × 30 cm opening by a LEDCube (Thouslite, Changzhou, China) mounted directly on top of the box. In Fig.4 the normalized spectral emission of the 11 LED channels is shown. Eight narrow-band LEDs are present, having peak emissions at 420, 450, 475, 500, 520, 595, 635 and 655 nm, respectively. Another 3 broad-band LEDs deliver warm-white, cool-white and lime-green light. We varied the spectral power distribution of the illumination by sending random drive values (in 10 bit) to each of the 11 LED channels. To increase variation in the resulting illumination spectrum (i.e. the summed light output from the 11 channels), the normalized drive values, varying between 0 and 1, were raised to the power of 3 to produce slightly more extreme values. This way, we could more easily produce varying levels of melanopic DER in the actual spectrum. The latter was measured with a JETI Specbos 1211 spectroradiometer (JETI Technische Instrumente GmbH, Jena, Germany), pointed at a white diffusely reflecting calibration patch. From the spectral measurement, the melanopic DER values were calculated using eq. (2).

Figure 3. *Light box with the melanopic and photopic patch positioned on the bottom. A LEDCube 11-channel LED system on top provided the illumination, images of the patches were recorded by a smartphone (left tripod). The actual spectral power distribution of the illumination was measured by a spectrophotometer (right) pointed at a white calibration patch.*

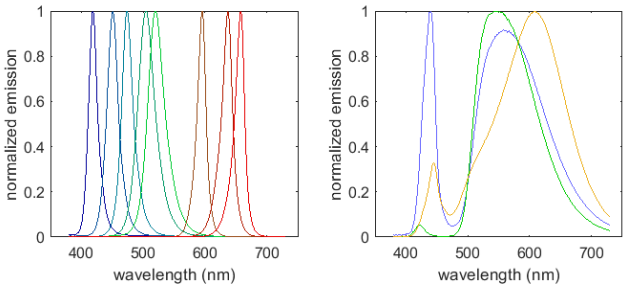

Figure 4. *Normalized spectral emission of the 11 LED channels of the LEDCube system. Left: 8 narrow-band channels. Right: 3 broad-band channels.*

Smartphone recordings

Three smartphones were selected, an iPhone SE (running on iOS), a Huawei P20 and an HTC One A9 (both running on Android). The smartphones were stabilized on a tripod, their rear-facing camera pointing towards the melanopic and photopic patches which were placed side by side. We made two sets of recordings per smartphone. In one, the images were recorded in RAW format, and in the other (separate) recording in JPG format. For the RAW format all camera setting were put on automatic. To get to the RAW image files, the *Camera+ 2* app was installed on the iPhone, the Android camera pro settings allowed direct access to it. For recording the JPG images the white balance was fixed on 2700K for the HTC and the iPhone, and on 2800K for the Huawei. Fixating the white balance for the JPG images was necessary to keep the illumination-induced color differences in the image of the two samples.

For each phone we captured 200 images, 100 in RAW and 100 in JPG image format. These images resulted from illuminations created with randomized drive values for the LED channels, as explained above. Figure 5 gives some examples of the resulting images under various illuminations. As is clearly visible, with changing illumination also the reproduced color and intensity of the melanopic and photopic patches change. This makes it possible to derive a relationship between the melanopic DER and the RGB values for the two patches.

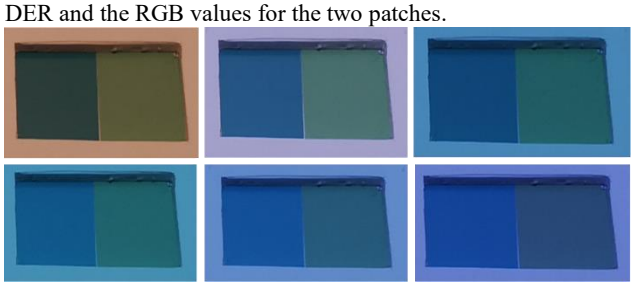

Figure 5. *Selected examples of the recorded JPG images of the melanopic patch (left half) and the photopic patch (right half) under various illuminations. Note the difference in color and brightness appearance of the patches. Melanopic DER values from upper left to bottom right: 0.34, 0.7, 0.9, 1.1, 1.3, 1.5.*

Color processing

The recorded RAW images were transformed into DNG format with Adobe's Digital Negative Converter, Windows version 10.3.0.933 (downloadable from Adobe's website). Following the MATLAB image processing pipeline approach as outlined in [4], the mean R,G,B values of the central area (about 10% of the total patch) in the images of the melanopic and photopic patches were determined. From the spectral measurements with the spectrophotometer, the melanopic DER values were calculated. Using standard fitting techniques we found regression formulas to describe melanopic DER based on the two pairs of R,G,B values of the two color patches. The general formula that we used is

$$melanopic\ DER = k\left(\frac{m_1R_m+m_2G_m+m_3B_m}{p_1R_p+p_2G_p+p_3B_p}\right)^n \qquad (5)$$

with:
R_m, G_m, B_m : *mean R,G,B values for the melanopic patch*
R_p, G_p, B_p : *mean R,G,B values for the photopic patch*
$k, m_1, m_2, m_3, p_1, p_2, p_3, n$: *regression parameters (to be estimated).*

The logic behind this formula is the summation of the R,G,B intensities of the melanopic and photopic patch, to approximate the melanopic and photopic intensities like in equations (2) and (3). The additional parameters m_i and p_i allow for weighting of the R,G,B values, and the exponent n accounts for some nonlinearity. In the case of the JPG images, the same formula shown in eq. (5) was used. However, the R,G,B values of the melanopic and photopic patches were first normalized to range between 0 and 1, and then inversely gamma corrected (raised to the power of 1/2.2).

Results

Because of practical relevance for lighting applications we restricted the melanopic DER range to a maximum value of 1.5. This means that for the 100 measurements, some 10-20% of the measurements made fell outside of this range. For the remaining data points, 50% was randomly selected and used for training the model parameters, the other 50% was used for testing. Table 1 shows the estimated parameter values and performance measures for both data sets. Shown are the number of data points (N), the percentage explained variance (adjusted R^2), the mean absolute error (MAE) and mean percentage error (MPE). Table 1 refers to processing of the RAW images, Table 2 shows the results for the processing based on JPG images.

For the regression based on the analysis of the RAW images, very high values for the adjusted R^2 are obtained, resulting in a mean percentage error of 2.6 for the Huawei and the iPhone, and 4.0 for the HTC. In Figure 6 we show scatterplots of the actual and predicted melanopic DER values for the best and worst performing smartphone. For the JPG images, the adjusted R^2 values are lower, resulting in a mean percentage error of about 5 for the Huawei, and 8.7 and 12.4 for the iPhone and HTC respectively (see Figure 7 also).

Table 1: Regression parameters and performance measures for RAW images. MAE: mean average error. MPE: mean percentage error.

Parameter (eq.5)		iPhone SE	Huawei P20	HTC One A9
m_1		1.10	1.78	3.31
m_2		0.87	0.81	0.85
m_3		1.75	0.90	1.09
p_1		0.84	1.56	1.75
p_2		1.03	0.93	1.02
p_3		1.13	0.65	0.99
k		1.52	1.12	1.85
n		2.67	2.50	3.34
train	N	43	45	39
	adj R^2	0.99	0.99	0.96
	MAE	0.024	0.024	0.044
	MPE	2.60	2.39	4.28
test	N	42	45	39
	adj R^2	0.99	0.99	0.95
	MAE	0.027	0.025	0.040
	MPE	2.62	2.59	4.01

Table 2: Regression parameters and performance measures for JPG images (fixed white balance). MAE: mean average error. MPE: mean percentage error.

Parameter (eq.5)		iPhone SE	Huawei P20	HTC One A9
m_1		0.00	0.43	0.41
m_2		1.64	4.61	3.97
m_3		0.80	2.61	0.28
p_1		0.48	0.95	0.42
p_2		2.36	5.17	4.44
p_3		-0.82	1.87	-1.24
k		0.36	1.17	0.27
n		2.14	7.42	4.54
train	N	43	45	46
	adj R^2	0.90	0.96	0.94
	MAE	0.055	0.039	0.099
	MPE	6.53	5.00	11.0
test	N	42	45	45
	adj R^2	0.87	0.97	0.89
	MAE	0.074	0.043	0.114
	MPE	8.68	5.09	12.4

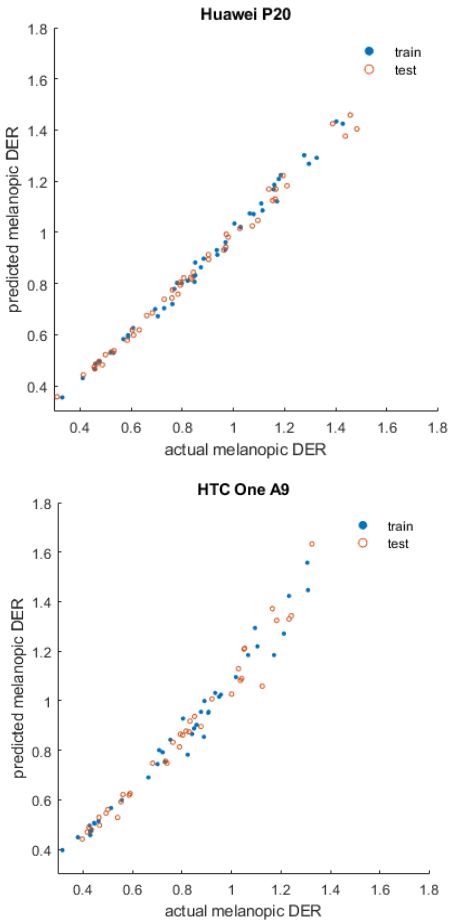

Figure 6. *Best (top, Huawei P20) and worst (bottom, HTC One A9) result obtained for RAW images. Actual melanopic DER is calculated from the spectral power distribution of the illumination, the predicted melanopic DER is based on eq.(5).*

Estimating the light level

To estimate the effects of light on the circadian rhythm (as mentioned in the Introduction), knowing the melanopic DER for a light source is not enough. The melanopic DER is a ratio, a dimensionless number, and is independent of the intensity of the light. To calculate the 'melanopic illuminance', the melanopic DER needs to be multiplied with the illuminance level. Here we show that the illuminance can be estimated from the smartphone camera parameters which are stored as metadata with an image file. Equation 6 shows a formula to predict the illuminance E (in lux) from the camera parameters:

$$E = 248 + \frac{1.84 * G_p * \log(ISO) - 310}{G_m * Exposuretime} - 1.5 * Aperture * ISO \qquad (6)$$

in which G_m and G_p are the RAW green channel values for the melanopic and photopic patch respectively, and *ISO, Aperture* and *Exposuretime* are the camera parameters. The formula in eq.(6) was obtained by applying machine learning (symbolic regression) to the actual illuminance values (derived from the spectrophotometer measurements) and the pooled smartphone measurements. With eq.(6), the mean percentage error in predicted E is 6.5% (evaluated on the test set, i.e. 50% of 300 data points). For our set of measurements E varied from about 150 to 3250 lux. Higher performance measures, i.e. lower mean percentage errors, are obtained when deriving a formula per smartphone. Depending on the complexity of the formula that one allows in the symbolic regression, the mean error can then be as low as a few percent. For processing of the RAW images, we found mean percentage errors of 1.7, 2.4 and 2.8 for the Huawei, iPhone and HTC respectively. However, the solution space of symbolic regression needs some validation on physical correctness. A formula like eq.(6) at least has the expected basic dependencies: higher illuminance levels require shorter exposure times, smaller apertures and lower ISO values.

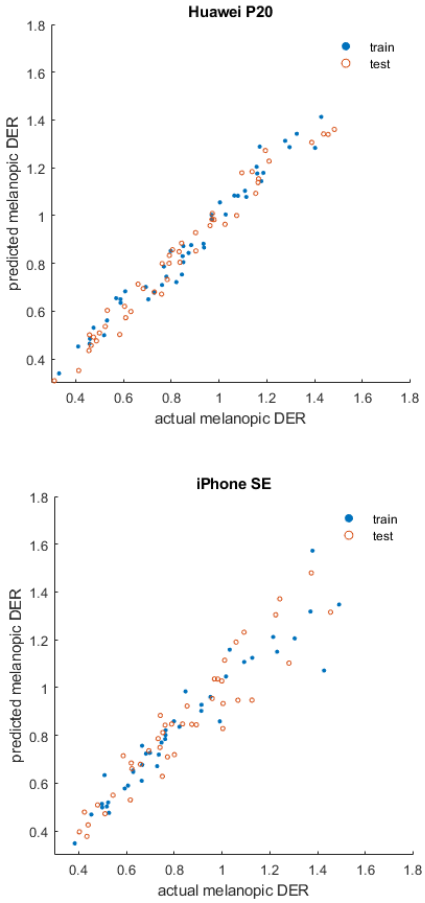

Figure 7. *Best (top, Huawei P20) and worst (bottom, iPhone SE) result obtained for JPG images. Actual melanopic DER is calculated from the spectral power distribution of the illumination, the predicted melanopic DER is based on eq.(5).*

Discussion

We showed that the melanopic DER of a light source or illuminant can be successfully estimated using a smartphone and two commercially available color samples. Of the three smartphones that we tested, the iPhone and the Huawei showed best performance in terms of predicting the actual melanopic DER. The performance of the HTC One was lower (for the RAW images), which might be expected based on its age and quality level. Of course, we do not know the performance of other smartphones yet, but we may expect that future cameras and sensors implemented in smartphones will still increase in quality. With less than 3% average error in the RAW measurements for the two most recent smartphones, this is already more than enough to measure relevant differences in practical lighting situations. For

instance, a ‘high’ melanopic DER value of 1 and a ‘low’ value of 0.6, which is a 40% difference. Even a 10% measurement error could suffice in this case. Indeed, our own experiences with a custom smartphone app (running on Android) which implements the JPG version of our method confirmed the usability for distinguishing between high and low melanopic DER situations.

The performance for the RAW images is higher than for the JPG images. This was an expected result, because JPG images are subject to more (and possibly manufacturer-specific) image processing. However, with an average percentage error of 5-7 this would still enable the possibility to distinghuish between higher and lower melanopic DER levels. The estimated melanopic DER combined with an estimate of the illuminance level as obtained from the camera parameters, opens the possibility to make quantitative predictions on the effect of light on the circadian system. What needs to be checked, though, is how the method performs under more widely varying changes in illumination, both spectral changes and illuminance levels. Perhaps a more sophisticated colorimetric characterization approach is needed, like worked out for a set of digital cameras [5].

On a final note, our lab has recently contributed to published evidence for the mentioned relationship between high melanopic DER light stimulation and melatonin suppression [6].

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Marcel Lucassen received his MSc in Technical Physics from Twente University (1988) and his PhD on color constancy from Utrecht University (1993). Since then he has worked with Akzo Nobel Coatings, TNO Human Factors, Lucassen Colour Research and the University of Amsterdam, with the focus on basic and applied color research. He is currently a senior scientist with Signify Research.

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Tobias Borra received his MSc in Cognitive Neuroscience from Leiden University in 2003 and his PhD in psychophysics from Utrecht University (2012). Since then he has fulfilled positions as post-doc at Physics of Man and Experimental Psychology (Utrecht University). He is currently a scientist with Signify Research.