A comparison of metrics proposed for circadian lighting and the criterion adopted in the WELL Building Standard.

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Abstract

Since the discovery that intrinsically photosensitive retinal ganglion cells influence the body's circadian rhythms, there has been a desire to quantify this effect in terms helpful to lighting designers. The effect of lighting on occupants' circadian rhythms has implications for their health and well-being, and, for the workplace, this can affect productivity and absenteeism. There is not yet a universally agreed way to account for how different lighting choices might determine these effects. Various models have been proposed that attempt to quantify, at least relatively, these effects; in each case adopting some form of action spectrum associated with melatonin suppression, as this hormone is known to be critical in the circadian process. It is has been established that the effects vary according to the wavelength of the light, and the total effect is normally modelled as a weighted sum, despite evidence that effects from different wavelengths combine non-linearly or even in opposition. Different metrics are compared for various real light sources but these are shown not to agree, thus different design choices would be made according to the model adopted. The WELL Building Standard has adopted the use of Equivalent Melanopic Lux to formulate lighting criteria. Consequences for the selection of light sources and the specification of internal illuminance are examined.

Keywords

circadian lighting, WELL Building Standard, melanopic

1.0 Introduction

The lighting community has in recent years been rapidly developing the understanding of the function of the recently discovered intrinsically-photosensitive retinal ganglion cells (ipRGC) in the eye. These are different from the well-known rods and cones that provide our visual capability, and instead are apparently non-image forming receptors. The signals from ipRGC inform the brain's regulation of the body's circadian pattern, and this has biological and metabolic significance. It has been shown, for example, that disturbed circadian rhythms may be associated with increased cancer risk (1). It is important for designers to consider the likely effects of lighting design decisions on health and well-being, and not just the appearance of the visual environment and the performance of visual tasks.

The non-image forming effects of ipRGC stimulation include: circadian entrainment, increased alertness and activity, and determination of onset of sleep. The circadian rhythm would have a period of more than 24 hours in the absence of external stimuli (2). The principle stimulus that regulates this period is mediated by the ipRGC, and appropriate diurnal stimulus enables the circadian rhythm to be entrained to local time (3). Otherwise, insufficient stimulus in the day allows a drift in circadian phase, and too much stimulus in late afternoon or early evening delays the phase relative to local time (4). This effect has been shown with illuminance as low as 1.5 lux (5). The level of stimulation of ipRGC depends on the irradiance at the eye, but ipRGC sensitivity varies with wavelength. This has led to a number of attempts to refine an 'action spectrum' to account for the variation in a way analogous to the photopic vision spectrum used to quantify visual effects.

In this paper, different circadian effects models are used to assess spectra from a number of typical lamps, and the results compared to assess the level of agreement. In other words, the aim is to ascertain if the choice of model matters. Notably, one model has been adopted in the WELL Building Standard (6), which is used to specify criteria intended to ensure adequate daytime stimulus for circadian entrainment.

2.0 Proposed metrics

Our understanding of the mechanisms by which circadian effects are stimulated is still evolving and various models have emerged to attempt to quantify and predict the effect. However, Lucas et al (7) have concluded that there is no one-dimensional measure yet available, but measures may be approximated that are sufficient for guidelines to be drafted. Most proposed measures of circadian effects use nocturnal melatonin suppression as a marker, which is at least measurable. It is assumed that this correlates to other daytime phenomena, such as increased alertness and circadian entrainment. The earliest data sets were based on narrow band sources and, critically, showed that melatonin suppression was wavelength dependent (8, 9). This naturally leads to a desire to identify an action spectrum to deal with conventional sources radiating multiple wavelengths.

In order to account for the total effect of a broadband mixture of wavelengths, various additive models have been proposed. Each model attempts to provide a convenient, usable assessment method, though it has been suggested that no one model has yet emerged as ideal (10). The models are based on the relative sensitivity of the circadian response to different wavelengths, λ, which would be formulated as a function of wavelength, e.g. $C(\lambda)$. For sources of these models see the Appendix. Then the circadian stimulus is calculated for a power spectrum, $P(\lambda)$ thus:

$$\text{stimulus} = \int_{\lambda} P(\lambda) C(\lambda)\, \mathrm{d}\lambda$$

Assuming some criterion for the desired amount of aggregate stimulus can be agreed, then the corresponding amount of radiation required from a given source can be determined. As the spatial distribution of light radiation is already quantified using luminous flux, it is useful to relate the quantity of circadian stimulus to the luminous flux generated from the same source. Thus the values are commonly normalised for use with conventional photometric calculations of luminous flux and illuminance.

For a given spectral power distribution $P(\lambda)$, a conversion factor is calculated from the source spectrum thus:

$$\text{conversion factor} = k \frac{\int_{\lambda} P(\lambda)C(\lambda)\,\mathrm{d}\lambda}{\int_{\lambda} P(\lambda)V(\lambda)\,\mathrm{d}\lambda}$$

where the choice of scaling constant *k* depends on the way that the function *C* was originally scaled.

It should be noted, however, that circadian effects are not simply proportional to the metrics. They are measuring a spectrally weighted irradiance at the cornea, but this relates in a non-linear way to the circadian stimulus assessed by acute nocturnal melatonin suppression (2). Thus, at best, they provide measurements on ordinal scales. The different normalisation and scaling used make direct comparison between scales not meaningful but each metric's scale, being ordinal, can be used to rank sources by their circadian stimulus potential. What is of interest here is whether it matters which metric is used to compare the circadian potential of different lamps, providing the same illuminance.

2.1 Circadian action factor

Gall and Bieske (11) developed an action spectrum that was fitted to earlier measurements (8, 9), and scaled to have its peak at 450 nm equal to one. Then, a circadian action factor, a_{cv}, is calculated as the ratio of circadian action to photopic action for the same spectrum. Gall and Bieske suggested that their action spectrum resembles the colour-matching function, $\bar{z}(\lambda)$ (12). Since the photopic flux is proportional to the chromaticity coordinate, *y*, a_{cv} might be estimated directly from the ratio of source chromaticity coordinates *z/y*. This approach has been used to encode circadian assessment within a Radiance simulation (13), and is attractive for its ease of use as the chromaticity coordinates are more readily available than spectral data.

2.2 Melanopic sensitivity

The photosensitivity of the ipRGC is understood to result from the properties of the protein melanopsin. Study of the spectral sensitivity of melanopsin receptors in the eye has led to a melanopic sensitivity function $V_z(\lambda)$ (14) and has since been used to underpin a wider assessment framework, accounting for age effects for example (15). Work was carried out on mice but then values were corrected for the different filtering in the human lens and ocular medium. This can then be used in a way analogous to the photopic function $V(\lambda)$ (12) to determine "melanopic illuminance". But the authors note that melanopic quantities relate specifically to melanopsin activation, and not necessarily the behavioural or physiological response 'downstream' of this. They note that human cones might also contribute, but that it is difficult to provide a "one size fits all" correction to the melanopic function to take account of cone influence.

This approach has been adopted in the 2017 WELL Building Standard (6), which uses a melanopic function (7) with data scaled such that values would be identical to the standard definition of lux for a light spectrum of perfectly uniform energy, i.e. CIE Standard Illuminant E.

2.3 Melatonin Suppression Index

Aubé et al introduced further metrics to assess and compare various impacts of sources of different spectra including their melatonin suppression index, MSI (1). This is evaluated using a melatonin suppression action spectrum derived by curve fitting to the 2001 data (8, 9) and is scaled to measured data normalised to CIE Standard Illuminant D65. The index then provides a relative measure of circadian effect, again based on melatonin suppression.

2.4 Circadian light

It has been observed that there are problems with the action spectrum approach as effects from a mix of wavelengths are not simply additive, and allowance might need to be made for the way that signals from the rods and cones may 'interfere' with the ipRGC response. Consequently, the melanopic function proposed by Enezi et al (14) does not appear to characterise the empirical data well, and an alternative nonlinear model of "circadian light" has been formulated (10). It has been proposed that the influence of rods and cones might be accounted for if a model can include spectral opponent input from the blue-yellow channel (2, 3, 16). While this provides an action spectrum, an alternative model for wide spectrum sources is offered that accounts for the sub-additive effect of longer wavelength. This has been used for example by Bellia et al (17) and Dai et al (18). The subsequent relationship between circadian light and the level of circadian stimulus has been modelled by Rea et al (16).

2.5 Correlated colour temperature

Finally, it has been suggested that correlated colour temperature might be used as an indicator of relative circadian effect (11). If this is so, it is important because, while details on spectrum are not always readily available, CCT generally is. Similarly for *z*, provided that chromaticity coordinates are known, or might be estimated from Planckian radiator with the same CCT. It is envisaged that difficulty in accessing detailed spectra for lamps could be a barrier to the proper use of the spectral-based circadian measures.

3.0 Example lamp results

The objective in this section is to compare outcomes from the different metrics applied to a sample of lamps' spectra to see if the choice of model actually matters. The metrics relate to the relative spectral sensitivity of ipRGC so, as noted above, these offer only an ordinal scale of measurement. However, such metrics would still serve to compare different lamps by ranking them.

Evaluation of the metrics for any given lamp requires the lamp spectrum, and any difficulty in accessing these may be a barrier to the proper use of the metrics. Spectra might be sourced in various ways.

- They may be measured, but for compliance with a standard this would need properly controlled conditions and use of meters calibrated to traceable standards. It is unlikely that designers would have easy access to such measuring facilities.
- Lamp manufacturers may publish these data, but more often this is merely graphical rather than numerical.
- For this paper example spectra for typical white lamps published by Aubé and Roby (19) have been used.

3.1 All lamp types

Using action spectra or spreadsheet tools offered by the advocates of the different measures, and available via the links in the Appendix values were calculated for the range of typical lamps. These have each been calculated relative to related photometric quantity, flux or illuminance using the second equation above. Results are shown in Table A.

lamp type	CCT(K)	WELL	MSI	z/y	a_{cv}	CL per lux
fluorescent	2700	0.36	0.28	0.29	0.26	0.60
led	2700	0.43	0.30	0.33	0.31	0.79
incandescent	2700	0.47	0.30	0.28	0.31	0.85
fluorescent	2900	0.46	0.34	0.41	0.35	0.84
led	3000	0.42	0.28	0.30	0.29	0.77
incandescent	3000	0.49	0.32	0.30	0.33	0.89
led	3500	0.44	0.32	0.39	0.33	0.81
fluorescent	4000	0.56	0.43	0.55	0.45	0.98
led	4000	0.68	0.50	0.64	0.54	0.66
led	4288	0.72	0.63	0.90	0.66	1.00
led	4440	0.59	0.54	0.80	0.56	0.78
led	4803	0.63	0.62	0.73	0.55	0.70
led	5000	0.62	0.59	0.84	0.60	0.83
fluorescent	5000	0.73	0.65	0.84	0.65	0.77
led	5896	0.75	0.70	1.00	0.72	1.12
fluorescent	6400	0.86	0.73	0.99	0.76	1.01

key: WELL WELL Building Standard conversion factor
MSI melatonin suppression index
z/y ratio of chromaticity coordinates
a_{cv} circadian action factor
CL per lux ratio of circadian light to photopic light

Table A – Calculated circadian measures for typical lamps

If a metric was to be chosen to specify a criterion for circadian stimulus, then the conversion factor could be used to determine, for a given illuminance, whether a lamp's output was sufficient. If the different metrics were not significantly different from each other, then there would be agreement in how they ranked lamps for circadian stimulus potential. If lamps are ranked by CCT value, as shown in Table A, then it is evident that the other measures are correlated with CCT but not so as to preserve the ranking. Thus CCT would appear to be a poor indicator of relative circadian effect. With the exception of circadian light, the other, purely melanopsin-based, metrics follow a similar trend, as might be expected. The level of agreement in ranking the lamps for circadian effect can be assessed through the Spearmann rank correlation coefficient. This has been calculated and shown in Table B.

	CCT	WELL	MSI	z/y	a_{cv}	CL per lux
CCT	1.00					
WELL	0.88	1.00				
MSI	0.93	0.96	1.00			
z/y	0.92	0.89	0.96	1.00		
a_{cv}	0.92	0.95	0.99	0.97	1.00	
CL per lux	0.30	0.40	0.40	0.40	0.46	1.00

Table B – Spearmann rank correlation coefficients for all lamps

There is poor agreement between circadian light and the other measures. WELL, MSI and a_{cv} are in close agreement and there is therefore little to choose between these for making decisions between alternative lamps. The much simpler CCT and *z/y* measure derived purely from chromaticity information do not perform as well and might be considered as unreliable measures for decision making, but remain attractive for their ease of derivation.

In practice, then, the significant decision would be between the measures based on melanopsin action spectra, and the circadian light measure, as this clearly would lead to quite different decisions when selecting lamps.

3.2 Lamp types considered separately

For fluorescent lamps, all of the measures apart from CL agree perfectly on ranking so would be equally acceptable, including simply using CCT.

For LED lamps all of the measures differ notably, except that the a_{cv} and *z/y* are in full agreement, as shown in Table C.

	CCT	WELL	MSI	z/y	a_{cv}	CL per lux
CCT	1.00					
WELL	0.72	1.00				
MSI	0.87	0.90	1.00			
z/y	0.87	0.85	0.95	1.00		
a_{cv}	0.87	0.85	0.95	1.00	1.00	
CL per lux	0.38	0.35	0.52	0.63	0.63	1.00

Table C – Spearmann rank correlation coefficients for LED lamps

3.3 Summary

Evidently the choice of metric matters. The melanopic based metrics clearly differ significantly from circadian light. Even within the former, the WELL metric correlates least well. For the fluorescent lamps there is better agreement, so much so that they might be ranked simply by CCT. For LED lamps the position is more uncertain. However, until there is a greater body of evidence for the daytime circadian effects and not just nocturnal melatonin suppression it might not be possible to identify one metric as superior.

4.0 WELL Building Standard criteria

The WELL Building Standard (6) has adopted minimum “equivalent melanopic lux” (EML) criteria to gauge circadian impact as part of its wide-ranging consideration of occupants’ well-being. As noted previously, photopic illuminance can be calculated conventionally and then a conversion factor applied in order to determine the melanopic quantity. Some examples of factors were tabulated in the Standard but these are not useful for design as the factor is entirely dependent on the particular lamp spectrum. In this calculation it is implicitly assumed that the spectrum remains constant for direct and indirect illuminance. Potentially, indirect illuminance will have a spectrum altered from that of the source depending on the reflective properties, i.e. the colour, of room surfaces (13, 17).

The criteria for work areas have been arrived at based on evidence for strength of circadian stimulus and entrainment, though it is not clear if this stimulus is necessary daily (4).

Either of these criteria will satisfy the standard:

- 200 EML every day on vertical plane perpendicular to direction of view 1.2 m AFFL at 75% of workstations from artificial lighting and daylight from 9am to 1pm;
- 150 EML from artificial lighting alone at 100% of workstations.

Vertical face illuminance is conventionally addressed with design criteria for cylindrical illuminance at head-height, though this is specified for different reasons to do with the appearance of people engaged in face-to-face communication. A mean value of 150 lux is specified in BS EN 12464 (20), which would go some way towards meeting the WELL criteria for light sources with a factor close to one. However, as shown in Table A , the factors for typical light sources fall short of this; and the spatial uniformity criterion is only 0.1, so even the 150 lux would not be assured over all work stations. Lastly, cylindrical illuminance is not direction specific, but is averaged over 360° of orientation, so it does not assure a value in the particular direction of view.

At most work stations workers will be spending many hours viewing computer screens. The circadian effect of screen use has been noted for some time, and is a concern when this occurs late in the day (21). During the early part of the day, however, the screen output may aid in delivering EML. For example, a typical 300 cd/m^2 luminance from 0.1 m^2 screen spaced 0.75 m away from the face could provide approximately 50 lux. Conversion to EML will depend on what is on screen, but many have significant short-wavelength content from the use of LED back lighting, and might therefore have high factors.

Finally there may be a useful contribution from Cuttle’s perceived brightness (18, 22) criteria. He argues that the perceived brightness for a space is determined by the mean room surface exitance (MRSE), i.e. the average output of reflected flux from the room surfaces. Cuttle suggests that MRSE of 100 lm/m^2 is the minimum acceptable for a space not to appear dim, which we should normally expect to be exceeded in conventional work spaces. The MRSE equates to the average indirect illuminance in the space in lux. A bright appearance would have 300 lm/m^2, at which point the cylindrical illuminance will average at least this as there would be direct illuminance to add. Possibly, then, adoption of Cuttle’s approximate guide would

help in securing facial illuminance approaching the levels needed to deliver the required EML value.

Therefore, currently, artificial lighting should deliver an average 150 lux cylindrical illuminance at head height. An additional 50 lux may be delivered to the worker's eye from computer screens, so 200 lux is a reasonable expectation before considering daylight. The conversion of this to an EML value will depend not only on the lamps used, but any spectral shift resulting from the reflection from room surfaces, and the nature of the screen lighting. Daylight may be included in satisfying the first WELL criteria, but this likely to be indirect because the viewing direction would be oriented to avoid sunlight glare from windows, and again the effect of surface colour might need attention.

5.0 Conclusion

From the small sample of lamps examined here, it is evident that the assessment by ranking of the relative potential for lamps to influence the circadian rhythms depends on the model used. In particular, it needs to be established how and whether the additional effects of rod and cones on the ipRGC stimulus can be effectively accounted for in a single metric, such as in Circadian Light. It will be important also for future research to improve understanding of the link to daytime circadian effect, and not just rely on nocturnal melatonin suppression measurements.

If the melanopic response is used for assessing circadian effects, then for the sample of lamps used here the alternative metrics, circadian action factor, MSI, and the WELL factors are similar. For assessment of older fluorescent lamp based lighting, reference to CCT might be sufficiently accurate, but this cannot be recommended for LED lighting. However, since full spectral data may not be easily available to designers, there may be some utility in approximate metrics, such as CCT or *z/y* that do not require full spectral data until such time as lamp manufacturers calculate and publish metrics on an agreed standard basis.

Eventually a standard approach will need to be agreed that provides a valid and reliable measure of circadian effects sufficient to safeguard occupants' well-being. Once agreed this would allow lamp manufacturers to provide data on the circadian conversion factors, and designers would be able assess circadian effects in each design without the need for detailed lamp spectra.

Finally, there is a convergence possible between the various lighting criteria affecting the vertical illuminance experienced at eye level. Traditional lighting design used to fixate on horizontal working plane illuminance, but it might be timely to concentrate on vertical face illuminance. Thus ensuring:

- adequate circadian stimulus, though this might need to be moderated later in the afternoon;
- facial illuminance to facilitate comfortable face-to-face communication; and
- the visual environment has a bright appearance.

In each of these outputs, indirect illuminance will be especially important as the direct facial illuminance would be limited by the need to control glare. Therefore the importance of surface colours on the circadian effect would need to be carefully considered.

References

(1) Aubé M, Roby J, Kocifaj M, Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility, *Public Library of Science One*, 2013 8(7): e67798 doi:10.1371/journal.pone.0067798

(2) Rea MS, Figueiro MG, Bierman A and Bullough JD, Circadian light, *Journal of Circadian Rhythms* 2010, 8:2 doi:10.1186/1740-3391-8-2

(3) Rea MS and Figueiro MG, A Working Threshold for Acute Nocturnal Melatonin Suppression from "White" Light Sources used in Architectural Applications, *Journal of Carcinogene Mutagene*, 2013, 4: 150 doi: 10.4172/2157-2518.1000150

(4) Konis K, A novel circadian daylight metric for building design and evaluation, *Building and Environment*, 2017, 113: 22-38 doi: 10.1016/j.buildenv.2016.11.025

(5) Wright Jr KP, Hughes RJ, Kronauer RE, Dijk DJ, Czeisler CA, Intrinsic near-24-h pacemaker period determines limits of circadian entrainment to a weak synchronizer in humans. *Proc Natl Acad Sci USA*, 2001, 98(24): 14027–14032.

(6) WELL Building Standard® v1, Q4 2017 version, International WELL Building Institute.

(7) Lucas RJ et al, Measuring and using light in the melanopsin age, *Trends in Neurosciences*, 2014, 37(1): 1-9 doi: 10.1016/j.tins.2013.10.004

(8) Brainhard GC, Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor. *Journal of Neuroscience* 2001, 21: 6405-6412

(9) Thapan K, An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans, *Journal of Physiology*, 2001, 535: 261-267

(10) Rea MS, Figueiro MG, Bierman A and Hamner R, Modelling the spectral sensitivity of the human circadian system, *Lighting Research and Technology*, 2012, 44: 386-396 doi: 10.1177/1477153511430474

(11) Gall D, Bieske K, *Definition and measurement of circadian radiometric quantities,* Light and health - non-visual effects : proceedings of the CIE symposium '04, Vienna, Austria, 30 September - 2 October 2004

(12) British Standards Institution, BS EN ISO 11664-1:2011 *Colorimetry. Part 1: CIE standard colorimetric observers*, London: BSI, 2011

(13) Geisler-Moroder D, Dür A, *Estimating Melatonin Suppression and Photosynthesis Activity in Real-World Scenes from Computer Generated Images*, Conference on Colour in Graphics, Imaging, and Vision, Joensuu, Finland, Society for Imaging Science and Technology, 2010

(14) Enezi J, Revell V, Brown T, Wynne J, Schlangen L and Lucas R, A "Melanopic" Spectral Efficiency Function Predicts the Sensitivity of Melanopsin Photoreceptors to Polychromatic Lights, *Journal of Biological Rhythms*, 2011, 26(4): 314-323 doi: 10.1177/0748730411409719

(15) Amundadottir ML, Lockley SW and Andersen M, Unified framework to evaluate non-visual spectral effectiveness of light for human health, *Lighting Research and Technology*, 2017, 49: 673–696 doi: 10.1177/1477153516655844

(16) Rea MS, Figueiro MG, Bullough JD and Bierman A, A model of phototransduction by the human circadian system, *Brain research Reviews*, 2005, 50: 213-228 doi:10.1016/j.brainresrev.2005.07.002

(17) Bellia L, Pedace A and Barbato G, Indoor artificial lighting: Prediction of the circadian effects of different spectral power distributions, *Lighting Research and Technology*, 2014, 46: 650–660 doi: 10.1177/1477153513495867

(18) Dai Q, Cai W, Shi W, Hao, L, Wei M, A proposed lighting-design space: circadian effect versus visual illuminance, *Building and Environment*, 2017, 122: 287-293

(19) *Lamp Spectral Power Distribution Database*, last accessed 18 August 2017, http://galileo.graphycs.cegepsherbrooke.qc.ca/app/en/lamps

(20) British Standards Institution. BS EN 12464-1:2011 *Light and lighting – Lighting of work places. Part 1: Indoor work places*, London: BSI, 2011

(21) Cajochen C, et al. Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance, *Journal of Applied Physiology*, 2011, 110: 1432–1438 doi:10.1152/japplphysiol.00165.2011

(22) Cuttle C, *Lighting Design: A Perception-based Approach*, Routledge, 2015

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Appendix – Resources for calculating metrics

Action spectra data or calculation tools are available from the flowing sites.

Circadian action factor:
https://www.tu-ilmenau.de/fileadmin/public/lichttechnik/Publikationen/2003/teil2.pdf

Melanopic sensitivity:
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4699304/#SD1

MSI:
http://galileo.graphycs.cegepsherbrooke.qc.ca/lpds/index.php?n=Site.Products

Circadian light:
http://www.lrc.rpi.edu/programs/lightHealth/