Towards a uniform specification of light therapy devices for the treatment of affective disorders and use for non-image forming effects

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Research paper

Towards a uniform specification of light therapy devices for the treatment of affective disorders and use for non-image forming effects: Radiant flux

M.P.J. Aarts (Mariëlle)*, A.L.P. Rosemann (Alexander)

Chair Building Lighting, Unit Building Physics and Service, Eindhoven University of Technology, The Netherlands

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ABSTRACT

Background: For treating affective disorders like SAD, light therapy is used although the underlying mechanism explaining this success remains unclear. To accelerate the research on defining the light characteristics responsible for inducing a specific effect a uniform manner for specifying the irradiance at the eye should be defined. This allows a genuine comparison between light-affect studies. An important factor impacting the irradiance at the eye are the radiant characteristics of the used light therapy device.

Method: In this study the radiant fluxes of five different light therapy devices were measured. The values were weighted against the spectral sensitivity of the five photopigments present in the human eye. A measurement was taken every five minutes to control for a potential stabilizing effect.

Results: The results show that all five devices show large differences in radiant flux. The devices equipped with blue LED lights have a much lower spectral radiant flux than the devices equipped with a fluorescent light source or a white LED. The devices with fluorescent lamps needed 30 min to stabilize to a constant radiant flux.

Limitations: In this study only five devices were measured. Radiant flux is just the first step to identify uniform specifications for light therapy devices.

Conclusions: It is recommended to provide all five α -opic radiant fluxes. Preferably, the devices should come with a spectral power distribution of the radiant flux. For the devices equipped with a fluorescent lamp it is recommended to provide information on the stabilization time.

1. Introduction

Light therapy is the treatment of a disorder by exposure to electromagnetic radiation in and close by the visible spectrum (i.e., visible, ultraviolet and infrared radiation). Depending on the type of ailment, treatment is mediated through the skin or through the eyes. This paper only focus on light mediated through the eyes, used in the treatment of Seasonal Affective Disorder (SAD) or circadian related issues like jet-lag.

Radiation that is considered from the point of view of its ability to excite the human visual system is called light (CIE, 2011). However, new insights show that light excites not only the human visible system (Image Forming, IF) but as well the non-image forming (NIF) system. The IF system is mediated via the cones and rods enabling respectively photopic and scotopic vision. Activation of the different types of cones (L,M and S-cones) are required for color vision. The NIF system is known for taking cues from the absence or presence of light for example to entrain or adjust the human internal clock to daily (circadian) and seasonal rhythms (Czeisler, 1999; Czeisler et al., 1989; Khalsa et al.,

2003; Spoelstra et al., 2015; St Hilaire et al., 2012). The photosensitive retinal ganglion cells (ipRGCs) are considered to be the main photoreceptors to mediate light to the NIF system, although the cone and rod cells also contribute (Gooley et al., 2010). Light therapy is successfully applied to re-adjust the internal 24 h clock, e.g. in sleep disorders (van Maanen et al., 2016) or to regulate it, e.g. for jetlags and shift work (Kakooei et al., 2010; Veitch et al., 2003). Moreover, light therapy is successfully applied to treat seasonal affective disorders (SAD; winter depression), other forms of mild depression (Lieverse et al., 2011; Mårtensson et al., 2015; Meesters and Gordijn, 2016), and to enhance cognitive performance or to prevent agitation in patients with dementia (Riemersma-van Der Lek et al., 2008; Sloane et al., 2007; van Hoof et al., 2012).

A guideline on the treatment dose of Seasonal Affective Disorders (Lam and Tam, 2009) suggests that the higher the illuminance, the shorter the necessary exposure time per day: 10.000 lx for 30 min, 5000 lx for 45–60 min and 2500 lx for 1–2 hours. When analyzing the literature on light therapy for SAD, positive results for treating SAD were also found out of the suggested dose boundaries. In Fig. 1, the different

* Corresponding author.

E-mail address: m.p.j.aarts@tue.nl (M.P.J. Aarts).

Fig. 1. Exposure used for SAD studies based on literature. Each dot represents one study. According to the outcome measures defined by the authors, the combination of exposure (expressed in illuminance) and duration, resulted in a positive result. Similar colors represent the same study, in some cases the placebo condition. The gray area depicts the assumed relationship between the illuminance and the time (Lam and Tam, 2009).

dots represent studies which show positive results (Anderson et al., 2009; Avery et al., 2001; Danilenko and Ivanova, 2015; Gordijn et al., 2012; Meesters et al., 2011; Song et al., 2015). This indicates that the dose for treating SAD is different as earlier suggested. These six studies were included based on the criteria that information should be given about the time and light exposure, more than 10 human subjects over 18 years old without eye problems and other forms of depression participated per intervention, light was the only dependent variable, a standard and comparable diagnose and severity tool was used, and published after 2000.

Although light therapy is used as treatment for diverse (affective) disorders, there is currently no consensus in literature on a particular effective radiant exposure (dose depending on the amount, duration and spectral composition) that a light therapy device needs to provide.

In the above mentioned affective studies, the light exposure is described in different quantities, restricting a comparison between these studies. It is therefore essential for bringing Affective Disorder studies with light therapy to the next level, to describe the light exposure of future studies in similar and comparable quantities.

Currently there are numerous (> 200) different light therapy devices available without medical prescription. The devices vary in characteristics such as size, light source, light output, recommended placement of the device, ultraviolet blocking screens (Baczynska and Price, 2013) and price. Most devices come with some technical specifications while others lack any. Relevant information indicating the purpose of a device for a specific affect is missing in many cases. Some devices lack a user manual while other products indicate the preferred distance between the user (eyes) and the device as well as the recommended duration of a light therapy session. According to the manual of some devices, the viewing direction is not relevant as long as 'the light reaches the eyes'. In general, the specifications and information accompanying the light therapy devices are not standardized, non-uniform, and incomplete.

Considering the above and the technical information provided in different non-comparable quantities it becomes close to impossible for a researcher or a medical practitioner to base a purchase or prescription of a device on an informed decision.

The impact of light therapy from the technical perspective depends on the effective irradiance received by the eyes (energy and spectral composition) in relation to the timing and duration of the exposure

(Lucas et al., 2014).

Since a light therapy device could potentially serve different purposes, the timing and duration of the exposure needs to be based on the aimed effect and consequently also on the individual needs and (ocular) conditions, for example due to the biological ageing of the eye.

As for standard photometry, the illuminance or irradiance at eye level depends on:

1. The radiant characteristics like the radiant flux of the device, the directionality, the luminous surface of the device;
2. The position of the eyes relative to the position of the device;
3. The room characteristics.

When assessing the influence of the eye position relative to the device, one has to consider the direct as well as the indirect radiation (i.e. via multiple reflections) reaching the eye. When light therapy is given in a highly reflective white room, the reflected radiant flux adds significantly to the total irradiance. This is similar for the photometry where the total illuminance is the sum of the direct luminous flux and the reflected luminous flux. In a dark room with low reflective surfaces, the direct component will mainly contribute to the total effective irradiance on a certain position. Therefore the impact of light therapy is dependent on the radiant characteristics of the device, the room characteristics and the position of the device related to the eyes see Fig. 2. Additionally, also the compliance of patients to undergo medical treatment is essential for the impact, and depends on flicker, safety, luminance, colours and its design (Baczynska and Price, 2013).

When considering NIF, it is acknowledged ((Aarts et al., 2017; CIE, 2015a; Lucas et al., 2014) that photometric quantities cannot be used. According to the definition of the International System of Units (SI), "a photobiological or photochemical quantity is defined in purely physical terms as the quantity derived from the corresponding radiant quantity by evaluating the radiation according to its action upon a selective receptor. The quantity is given by the integral over wavelength of the spectral distribution of the radiant quantity weighted by the appropriate actinic action spectrum" (BIPM, 2006). For the visibility the action spectrum is the spectral sensitivity of the human eye for photopic vision, the $V(\lambda)$ curve. With that action spectrum and the maximum of luminous efficacy K_m , one can convert a radiometric quantity X_e to a photometric quantity X :

Fig. 2. Different technical aspects impacting the outcome of light therapy.

$$X = K_m \cdot \int_{\lambda} \frac{\partial X_e(\lambda)}{\partial \lambda} \cdot V(\lambda) d\lambda \quad (1)$$

Instead of referring to the spectral distribution of a quantity via the differential, this is often simplified by referring to this differential using the symbol $X_{e,\lambda}$.

The International Commission on Illumination (Commission Internationale de l'Eclairage, CIE) proposes in their technical note TN002 (CIE, 2014) definitions of new terms relating photochemical quantities to photometric quantities using the same weighing of the radiant quantity with the action spectrum of one of the different effects of light. As an example this technical note gives the blue light hazard weighted radiance, which mathematically is expressed as in Eq. (2):

$$L_B = \int L_{e,\lambda}(\lambda) \cdot B(\lambda) \cdot d\lambda \quad (2)$$

where

L_B the blue light hazard weighted radiance
 $L_{e,\lambda}$ the spectral radiance
 $B(\lambda)$ the blue light hazard spectral weighting function

Since the impact of the different photosensitive cells in the eye on NIF effects is not fully comprehended, it has been suggested to use not one action spectrum, like for photometric quantities, but five. The ipRGC are considered to be the dominant photoreceptors of the NIF system. The ipRGC combine their melanopsin based photosensitivity with the photoreception signals of the rods and cones in the ipRGC network (Lucas et al., 2014). In the CIE TN003 (CIE, 2015a) the spectral sensitivity functions are defined, based on the spectral efficiency of the five photopigments detected in the human photoreceptor cells and the spectral transmission properties of the eye:

- Melanopsin is the photopigment of the ipRGC with a peak sensitivity, $\lambda_{\max}$ around 480 nm. Human pre-receptor filtering (in the standard observer) shifts $\lambda_{\max}$ around 490 nm.
- Rhodopsin is the photopigment of the rod photoreceptors with $\lambda_{\max}$ around 498 nm. Human pre-receptor filtering shifts $\lambda_{\max}$ around 505–510 nm, the peak for scotopic sensitivity.
- Three cone opsins are the photopigments of the cone photoreceptors; the S-cone opsin cyanolabe with $\lambda_{\max}$ around 420 nm, the M-cone opsin chlorolabe with $\lambda_{\max}$ around 534 nm, and the L-cone opsin erythrolabe with $\lambda_{\max}$ around 564 nm. Human pre-receptor filtering shifts $\lambda_{\max}$ towards 440 nm, 545 nm, and 570–575 nm respectively.

The CIE proposes the use of five α -opic weighted irradiances when describing light in relation to NIF effects, mathematically calculated in the same way as in Eq. (2), weighing the spectral irradiance with the

action spectrum of the above mentioned photopigments, see Eq. (3).

$$E_{e,\alpha} = \int E_{e,\lambda}(\lambda) \cdot s_{\alpha}(\lambda) \cdot d\lambda \quad (3)$$

where

$E_{e,\alpha}$ the α -opic irradiance
 $E_{e,\lambda}$ the spectral irradiance
 $s_{\alpha}(\lambda)$ the α -opic spectral efficiency function

Similar to the description for the α -opic irradiance, the α -opic radiant flux can be described. With this metric the radiated energy emitted by the device, related to a specific action spectrum can be determined (see Eq. (4)).

$$\Phi_{e,\alpha} = \int \Phi_{e,\lambda}(\lambda) \cdot s_{\alpha}(\lambda) \cdot d\lambda \quad (4)$$

Where

$\Phi_{e,\alpha}$ the α -opic radiant flux
 $\Phi_{e,\lambda}$ the spectral radiant flux
 $s_{\alpha}(\lambda)$ the α -opic spectral efficiency function

The aim is to propose uniform specifications for light therapy devices. This will enable researchers studying the effects of light therapy to compare a dose, independent of the device used. Using one set of metrics for describing the (light) exposure characteristics enables the comparison between studies. This will accelerate the research on defining the light characteristic for inducing a specific effect. Introducing a uniform set of specifications for light therapy devices will also help consumers to reach an informed purchase decision.

The study described in this paper focusses on the radiant characteristics of a device.

2. Method

When considering the radiant characteristics, a parallel can be drawn between the specifications of luminaires. These specifications provide the relevant information for making a lighting design, aiming to fulfill the visual requirements of the users. These include, among others, the luminous flux ('quantity derived from the radiant flux, Φ_e , by evaluating the radiation according to its action upon the CIE standard photometric observer' (CIE, 2011)). An important difference between visual system and NIF is that instead of photometric quantities, light therapy devices need to provide characteristics based on radiant quantities. In order to indicate the deviation between the devices the five α -opic radiant fluxes as proposed by CIE TN003 (CIE, 2015a) will be determined for different light therapy devices.

Table 1
Specifications of light therapy devices used in this study as provided in the manual. A dash (-) indicates that information was missing.

	Type light source	Light sources	Nominal Irradiance	Illuminance	Dimensions
Device A	LED	LED, single peak wavelength 470–475 nm	1.5–2.5 mW/cm (46 cm)	350–400 lx	–
Device B	LED	–	1.9 W/m ² (50 cm)	220 lx (50 cm)	14.3 × 14.3 × 3.5 cm ³
Device C	LED	–	29 W/m ² (50 cm)	2750 lx (50 cm)	29.4 × 37.6 × 4.1 cm ³
Device D	Fluorescent	PLL/36 W/840	–	–	–
Device E	Fluorescent	PLL/ 36 W/ 865	–	10,000 lx	–

2.1. Light therapy devices

The light therapy devices used for this study have been selected based on the following criteria:

- 1. The manufacturer reported that it effectively treats SAD;
- 2. Different types of lamps (white LED, blue LED, fluorescent) and therefore different spectral distributions;
- 3. Freely available for purchase in the country where this study has been performed (the Netherlands).

Based on these criteria five devices have been selected. An overview of the specifications provided in the manual of the device are listed in Table 1.

2.2. Measurement set-up

The spectral distribution of radiant flux of each device was measured by using an integrating sphere with a diameter of 3 m. The measurement setup in the integrating sphere can be found in Fig. 3.

The measurements were conducted in the photometric lab according to the guidelines described in LM-79-08 (Iesna, 2008). The spectrometer used for these measurements was the Torus-25-OSF (bandwidth 360–825 nm). The raw measurement data was internally post-processed with the Spectrasuite software package. Both, the device and the software, are products from Oceanoptics.

Before starting the actual measurement, the influence of the device itself was determined by performing an absorption measurement. Throughout the absorption measurements, the device was switched off while placed in the center of integrating sphere (position L, Fig. 3), the only light source switched on was the calibrated auxiliary lamp (A). The TORUS spectrometer was placed at point F. The baffles (B) ensured that

no direct measurements can be taken at position F. The absorption measurement of each device was directly processed in the result of the actual measurement to correct for the dimensions of the device. For the actual measurement, the device was switched on. A reading was taken every five minutes for a total duration of 30 minutes, the recommended duration of a light therapy session. These five minute interval time series measurements were conducted to check for potential stabilization effects. During the measurements, the air temperature in the sphere was 26 °C and the relative humidity was 32%.

The spectral radiant flux, was measured with a spectral resolution of less than 1 nm for a 2° degree standard observer. The values were converted into the five α-opic values, by using the CIE toolbox (CIE, 2015b), a Microsoft Office Excel sheet developed alongside the CIE Technical Note (CIE, 2015a). As the spectral radiant flux was measured for wavelength intervals of less than 1 nm, the measurement data had to be averaged for a 1 nm range resolution to match the resolution of the α-opic action spectra. The toolbox calculated the α-opic radiant fluxes in accordance with Eq. (3).

2.3. Data analyses

All the measurement data were provided in MS Office Excel-files. The CIE toolbox (CIE, 2015a) to calculate the α-opic-related values is a tool developed in MS Office Excel. The data processing is described in paragraph 2.2 Measurement set-up. Post data processing of all data was conducted using MS Excel 2013 and Matlab2013a. The graphs were made in Matlab2013a.

3. Results

The spectral distribution of radiant flux of the different light therapy devices is shown in Fig. 4. The two on the top are the light therapy

Fig. 3. Left: Measurement setup in an integrating sphere. Right: the integrating sphere used for these measurement. During the measurements the sphere is closed. The device is placed in the center and the picture was taken after the measurements, with the device still turned on.

Fig. 4. The spectral power distribution of radiant flux of the devices. Left: a picture of the device in the integrating sphere. Right: the spectral power distribution of the device. Devices D and E were measured every 5 min until stabilization was reached after 30 min.

devices with a blue LED, showing its characteristic monochromatic peak. Device C, equipped with a white LED, shows a smooth curved graph with a peak around 450 nm. The spectral power distribution graphs of Device D and device E show the typical band-width spectrum of a fluorescent lamp. The graphs of both devices show typical peaks at around 450 nm (Blue), 550 nm (Green), as well as 600 nm (Red). The stabilization time is illustrated by the different colored lines based on measurements taken every 5 min until constancy was reached.

Fig. 5 shows the five α -opic radiant fluxes for all devices in order to

demonstrate the individual differences between the five light therapy devices. Table 2 gives an overview the different radiant fluxes as well as the photometric quantity, luminous flux.

The radiant flux of the three LED devices remained constant over time. The two devices with fluorescent light sources reached stable conditions after 30 min. Table 3 shows the deviation of the melanopic radiant flux over time relative to the stable condition.

Fig. 4. (continued)

Fig. 5. The five α -opic radiant fluxes of the measured light therapy devices.

4. Discussion

Table 2 shows the differences in α -opic radiant fluxes and luminous fluxes between the five therapy devices. Device A and Device B were developed to trigger a melanopsin response with its peak sensitivity in the bluish part of the spectrum. This explains why the melanopic radiant flux is higher than the other α -opic radiant fluxes of both devices. Additionally, expected was that the melanopic radiant flux would be

similar for all five devices but the opposite was found; the melanopic flux of Devices A and B were lower than that of Devices C, D and E. The difference of melanopic radiant flux between all five devices is close to a factor six. This is rather large when considering all devices are to generate a similar effect. This also implies that since the dose is higher, the exposure time for the devices with the highest values might be reduced. Since it currently remains unclear which α -opic action spectrum contributes to what extent to which affective disorder or other NIF effect, it is recommended to determine all five α -opic radiant fluxes of a device. The highest overall values are emitted by Device D and the lowest by Device B.

The measurements over a period of 30 min after switching the device on indicate that devices with a fluorescent light source do not have a constant radiation over time. The other, LED-based, devices are and maintain stable after ignition. Both devices D and E remain nearly stable after 15 min (Table 3). Device D at ignition gives a lower melanopic radiant flux than the stable value but after 5 min gives a slightly higher output. The clinical relevance of this effect for Device D will probably be minor. For Device E, the radiant exposure at ignition is 48% higher than after 30 min.

The instable character of Devices D and E are most likely caused by the temperature; the luminous flux of fluorescent light sources depends on the ambient temperature (Pritchard, 1999). The thermal condition inside the device takes a considerable amount of time to reach thermodynamic equilibrium.

The limitation of this study is that only five devices were measured. Radiant flux is the first step to identify uniform specifications for light therapy devices. The next step would be to identify the (weighted)

Table 2
 α -opic radiant fluxes of the different light therapy devices.

Device	Cyanopic radiant flux in W	Melanopic radiant flux in W	Rhodopic radiant flux in W	Chloropic radiant flux in W	Erythropic radiant flux in W	Spectral Radiant flux in W	Luminous flux in lm
A	0.66	0.86	0.72	0.41	0.23	1.13	80.5
B	0.22	0.53	0.46	0.29	0.17	0.60	68.7
C	0.62	0.89	1.21	1.64	1.84	3.24	1116.0
D	1.85	2.93	4.03	5.37	6.19	11.15	3714.9
E	0.90	0.93	1.06	1.14	1.11	2.50	656.3

Table 3
 The deviation of the melanopic radiant flux from the stable condition over time.

	0 min	5 min	10 min	15 min	20 min	25 min	30 min
Device D	– 8.5%	15.7%	11%	5.5%	1.8%	1.2%	0%
Device E	49%	30%	8%	5%	1%	0%	0%

irradiance at the eye.

5. Conclusion

For scientific research that aims to identify a relationship between light therapy and an affect, it is clear that merely mentioning the used device is not sufficient.

The results of this study clearly show that the five radiant fluxes of the five tested light therapy devices are not identical. Therefore it is suggested to provide all five α -opic radiant fluxes. Preferably, the devices should come with a spectral power distribution of the radiant flux. This enables researchers to determine the radiant flux for any spectral efficiency function, not limited to these five.

Another finding was the impact of thermal stabilization of the devices equipped with fluorescent lamps. Light therapy devices are typically used for treatment purposes during the warm-up period since users may not wait for devices to warm up before starting treatment. Future standards should consider how this is to be addressed when making comparisons between different treatment lamps. The three devices equipped with LED lamps, do not need any stabilization time.

The next procedure in order to enable a comparison of the impact of light therapy devices from a technical perspective, is to define the influence of the room characteristics and the position of the viewer related to the device.

Contributors

Both authors contributed in the research and in the preparation of this article. The role of the first author was to set-up the study protocol, perform the data analyses and prepare the article. The role of the second author was to give input on the methodology, check the data analyses and prepare the article.

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Statement on additional research data

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