Public Lighting, Public Health

Lenka Maierová
University Centre for Energy Efficient Buildings, CTU in Prague
Buštěhrad, Czech Republic
lenka.maierova@fsv.cvut.cz

***Abstract*—Impact of artificial light at night on sleep and health of humans and other living species is discussed among scientists. This paper analyses the properties of several commercially available light sources with regards to their effects on wildlife, human sleep, and health. A novel, environmentally considerate LED light source is introduced. Further, integration of this light source into the pilot biodynamic street lighting system is described. Based on the season and time of day, a control system changes the spectral composition of the light in order to provide healthy, sustainable lighting without compromising on safety, psychological needs or energy savings.**

Keywords—Circadian rhythm, LED, light at night, non-image forming light perception, spectral power distribution, biodynamic lighting, advanced control system

I. Introduction

Life on the Earth evolved under the influence of regular alternation of day and night, i.e. light and darkness. Physiology of nearly all living species, including humans, is strongly affected and perfectly adapted to this 24h rhythmicity.

A. Eye, Light and Entrainment

Two perception systems sensitive to the exposure to light have evolved in the eye. The visual image of the surrounding environment is created in the brain thanks to the signals from rods and cones, originally alternating to provide daytime (cones) and night-time (rods) vision, gradually overlapping around the time of sunrise / sunset, see Fig. 1.

In parallel, the system of intrinsically photosensitive retinal ganglion cells (ipRGCs, [1]) provide information about the light intensity to several regions of our brain, responsible for the regulation of our sleep, mood, cognitive functions and many others [2]. This, so called non-image forming (nonvisual) light perception system, is essential for entrainment of endogenous subjective time (circadian time) of the organism to the 24-hours light-dark cycle in the external environment on the planet [3]. This mechanism also enables adaptations to changes in the length of the photoperiod during the year.

Most pronounced adaptation to the difference between day and night is the daily rhythm of sleep and wakefulness. For example, the neurohormone melatonin is produced only during the subjective night-time and in the darkness. This hormone is involved in the synchronization of the circadian rhythms within the body, acts as a powerful antioxidant and improves immune defense. Light at night, mainly its blue spectral component causes immediate systematic suppression of the melatonin synthesis [4]. As an effect, incontrovertible evidence has been found, that the repeated disruption of the dark phase of the night significantly increases the risk of the so-called civilization diseases, such as psychiatric disorders including depression, sleep disorders, memory disorders, cardiovascular disease, insulin resistance and obesity, and in particular some

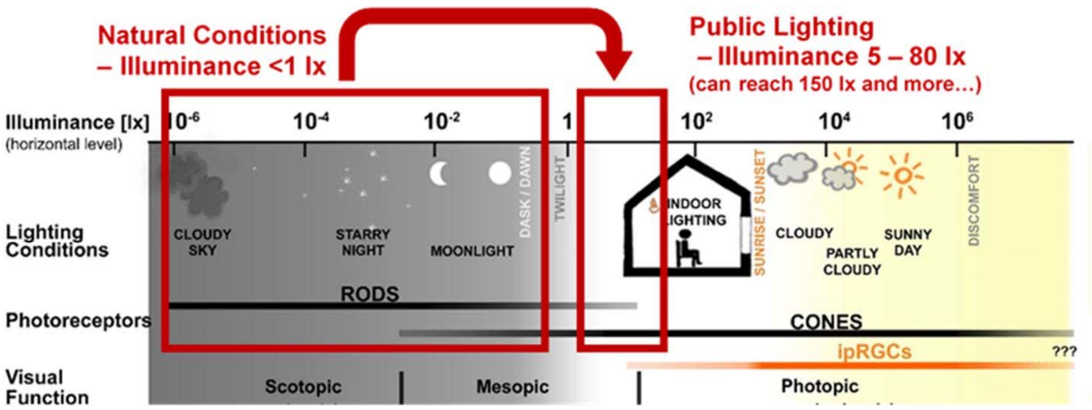

Fig. 1. Examples of possible outdoor lighting; illuminance on the horizontal plane (lux), the range of sensitivity of the human eye and the activity of photoreceptors. Arrow indicates the change of from the natural condition under the night sky to the public lighting. Adapted from [23].

This work has been supported by the Ministry of Education, Youth and Sports within National Sustainability Programme I, project No. LO1605.

types of tumors [5, 6]. For these reasons, light at night (LAN) is among experts globally perceived as a significant negative factor for human health, night shift work is classified as a presumably carcinogen due to causing circadian disruption [7, 8]. Not only humans are sensitive to light at night, LAN induced significant changes in natural behavior and physiology were reported for many wildlife animals [9].

B. The Loss of the Dark Sky

The process of urbanization combined with the increasing levels of public lighting along roads, shopping centers and also in residential areas reduced the night. Due to the worldwide campaign on energy savings, high-pressure sodium lamps (HPS) commonly used in the past are being gradually replaced by modern sources with Light-Emitting Diodes (LED). Change of the light source is usually connected with an increase in illuminance. Streets with standard sodium lamps were originally illuminated to about 5 to 10 lux on the walkway. A set of measurements in situ confirmed that after the replacement with LEDs illuminance values reach mostly 30 to 80 lux on the horizontal plane (Fig. 2), but it is not uncommon to find illuminance exceeding 100 lux. Recent scientific measurements of the dark sky confirmed that 99 % of the population in Europe lives in an environment with light pollution [10]. Electric street lighting, although much dimmer than indoor lighting, still illuminates the night hundred times brighter than the nature during the extreme of full moon [11], see also Fig. 1. Compared to natural conditions, artificial lighting is constant in its quantity and quality, without timing or seasonal information. This missing cue may explain results of population behavioral studies, which find artificial lighting in the highly urbanized European areas as a factor of limited synchronization of daily activities entrainment to the daylight, even if compared to the some less urban regions in Europe [12]. For example, outdoor illuminance was identified as one of the three key factors postponing sleep onset in adolescents [13], which may cause sleep deprivation and chronic social jet-lag associated with the shifted sleep phase. These are linked with all above mentioned symptoms of disrupted circadian rhythms and have a negative impact on life quality in general [14]. In response to these findings, the American Medical Association (AMA) published a statement, which recommends minimizing the negative impact of the public lighting on human health [15]. It is important to recognize the importance of darkness during the night. To protect from disturbing street light entering into the living rooms and bedrooms in urban areas, total blackout curtains are often installed. Unfortunately these curtains also prevent the access of light of the dawn. Morning light however acts as, an essential cue for good synchronization of the internal biological clock in humans. It helps to prevent further phase delay of sleep/wake rhythm in individuals with already delayed sleep phase, so-called ‘late birds’ [12], which becomes a frequent issue in most developed societies.

C. Light Sources on the Market

In contrary to existing HPS, LED technology offers sources with a selectable spectral power distributions (SPD), affecting the hue of the emitted light. Among the newly installed LEDs, still the most frequent types are cold or neutral white LED with Correlated Color Temperature (CCT) of 4000K and higher [16]. High CCT is selected mainly for its high potential on energy savings that is generally required by the investor.

LED technology also can produce sources of "warm light," or “warm-warm light” i.e. with CCT of 3000 K or lower. This light is visually similar to the traditional HPS, while it offers a higher Color Rendering Index (CRI) and its energy consumption is accordingly higher than that of cold and neutral LEDs. Another light source on the market, which is suitable for night lighting, could be LEDs of a specific color, which contains only long wavelengths, such as for example, LED PC Amber. The CRI of this light is low. Further, affordable low-cost, low energy consumption LED technology has increased the popularity of outdoor decorative lighting, with rising luminous flux and wide use of color lights throughout the night. As an example of new, in the natural environment non-native and potentially disturbing element can be the monochromatic light source with dominant light emission in the shortwave region around 460 - 480 nm, (blue). Such lighting source (Fig. 3) produces visually low-intensity light with surprisingly high effect on the circadian system. The consequences should be considered.

II. ANALYSES OF BIOLOGICAL IMPACT

The biological impact of light depends not only on the

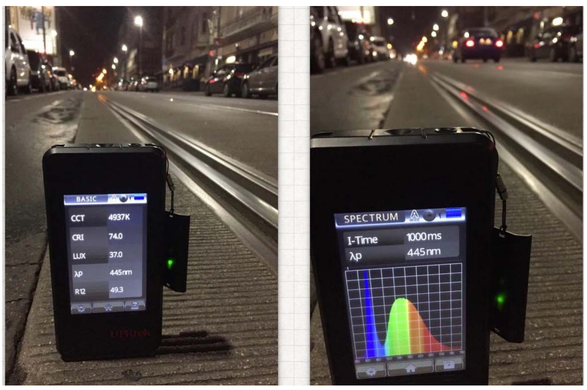

Fig. 2. Typical illuminance in the urban area. Light contains significant representation of blue part in the spectra. Illuminance (37 lux) significantly exceeds required standard. Photo Medřický, published with permission.

Fig. 3. Advertising and decorative lighting in the open landscape. Monochromatic blue light disturbs the circadian system of humans and all living organisms in nature. Photo Medřický, published with permission.

illuminance. Due to the shift in the peak sensitivity between the classes of photoreceptors (caused by spectral sensitivity of specific photopigments), the impact of light exposure is dependent on the spectral composition of the light. Whereas the photopic vision combines the stimuli from three types of cones and its peak sensitivity is in the green part of the spectra, approximately 555 nm and scotopic vision sensitivity peaks around 500 nm, the ipRGCs are highly sensitive to the blue part of the spectrum, with a peak at 460 – 480 nm [4, 17].

A. Methods

To illustrate the impact of the light selection on humans, we analyzed spectral properties of common, commercially available LED light sources, used for public lighting: cold white, neutral white, warm white, warm-warm white, phosphor converted (PC) amber, nearly-monochromatic blue light used in decorative lighting, and a newly developed source of shortwave containing LED light. LED sources were compared to the natural light sources – CIE defined standard sky D75 and D55, moonlight, and traditional light sources: candle and HPS lamp. SPD of these were used as defined from CIE (source 1, 2). SPD of streetlights were taken from manufacturers (source 5 - 11) or measured under controlled condition in the laboratory (source 12) with calibrated Radiospectrometer Uprtek MK350S Premium.

For graphical comparison of the light sources (Fig. 4), data was expressed relative to the dominant wavelength of each source. For calculation (see table at Fig. 5), characteristic

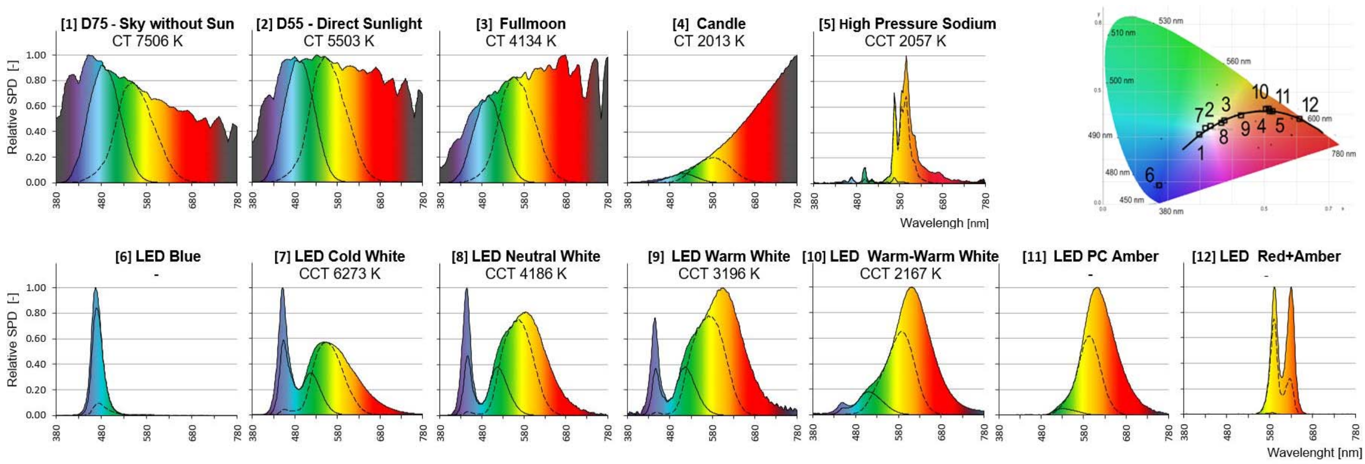

Fig. 4. Graphic comparison of natural and electrical light sources used for public lighting. Color space = the entire spectrum; dashed line = visually effective portion of the spectra according to V(λ); solid line = biologically effective portion of the spectra according to Lucas et al. 2015 [17]. Position of the light source within the color chromaticity diagram is indicated at the upper left.

TABLE I
MEASUREMENT OF THE LIGHT SOURCES – COMPARISON OF THE MELANOPIC EFFICACY

	Light Source	E_{phot} [lx]	CT (CCT) [K]	CRI [%]	Human retinal photopigment complement [W·lm^{-1}] $E_{S\text{-}p}$	$E_{M\text{-}p}$	$E_{L\text{-}p}$	E_{rod}	E_{mel}	E_{phot} / E_{mel}	E_{mel} / $E_{mel,\ HPS}$	E_{mel} / $E_{mel,\ moon}$
1	D75 – Sky without sun	>5 000	7506	100	5 740	6 050	5 338	4 989	5 938	119%	> 4 000	> 30 000
2	D55 – Direct sunlight	>50 000	5503	100	50 305	44 083	50 261	49 538	49 890	100%	> 34 000	> 250 000
3	Full moon	0.25	4134	99	0.213	0.147	0.234	0.247	0.200	80%	0.14	
4	Candle	1	2013	94	0.462	0.128	0.739	1.025	0.343	34%	0.23	1.71
5	HPS – High pressure sodium	10	2057	17	2.559	0.663	7.128	10.299	1.468	15%		7.33
6	LED Blue	1	n.a.	n.a.	5.582	7.428	2.898	1.557	7.780	778%	5.30	38.85
7	LED Cold White	30	6273	75	28.048	28.467	29.544	28.635	26.607	89%	18.13	132.84
8	LED Neutral White	30	4186	71	21.157	20.517	26.597	28.735	17.751	59%	12.10	88.63
9	LED Warm White	30	3196	81	18.598	14.046	25.161	29.388	15.146	50%	10.32	75.62
10	LED Warm-Warm White	30	2167	78	12.891	3.641	22.396	30.458	9.176	31%	6.25	45.8
11	LED PC Amber	10	(1849)	n.a.	2.216	0.042	6.417	10.547	0.955	10%	0.65	4.77
12	LED Red+Amber	10	(1286)	n.a.	1.057	0.009	5.867	11.038	0.213	2%	0.14	1.06

Fig. 5. Characteristics of light sources. E_{phot} = Effective (visual) illuminance on horizontal plane according to the V(λ); CT = Color temperature; CCT = Correlated color temperature; CRI = Color rendering index; S-p = S-photopic (S-cone), M-p = M-photopic (M-cone), L-p = L-photopic (L-cone), rod = Scotopic, mel = Melanopic (ipRGC); EC, HPS = Ratio of melanopic efficacy of the light source to HPS lamp; EC, moon = Ratio of circadian illuminance of the light source to moonlight. All calculation based on Lucas 2015 et al. [17]

(visual) illuminance (E_{phot}, based on photopic sensitivity [17]) of each light source has been chosen according to the common natural condition or the typical installation: 30 lux for white LED streetlight, 10 lux for HPS and long-wave LED light, 1 lux for decorative blue LED and candle, 0.25 lux for full moon. Based on equivalents of effective illuminance for 5 known photoreceptors in human eye, calculated according to Lucas et al 2015 [17, 18], we expressed ratio of melanopic to photopic sensitivity (E_{phot} / E_{mel}), ratio of E_{mel} for each light source compared to HPS lamp ($E_{mel,\ HPS}$) and to the full moon ($E_{mel,\ moon}$).

B. Results and discussion

Results of the calculation are summarized in Table 1. It demonstrates the biological impact of all sorts of LEDs, which are nowadays commonly installed in public lighting. As confirmed by measurement in situ, it typically overshoots the full moon illuminance more than 100 times. Natural full moon with 0.25 lux maximum illuminance [19] should be seen as an extreme lighting condition, which occurs maximally once per 29 days for few hours. Our calculation shows that the biological impact of the warm 3200 K LED white light with 30 lux exceeds the impact of the full moon by 75 times, not mentioning the rest of the lunar period, when the lighting levels decrease under 0.001 lux [11]. The type of source matters, higher CCT during night means significant increase of biological toxicity.

Even if compared to the existing HPS lamps, the biological impact of LED exceeds HPS several times. The warm-warm white LED light with CCT of 2167 K source has twice higher biological impact than traditional HPS, if compared in situation with the same illuminance, and 6 times higher if the illuminance has been increased to 30 lux. Impact of neutral white light (CCT 4000 K) under the same conditions increased more than 10 times.

Therefore, new long-wavelength based LED sources have been developed: PC Amber and Red+Amber. Content of wavelengths shorter than 500 nm in these sources is close to zero and their biological impact is minimal. Visually it may resemble the HPS, which is generally well accepted for the night lighting [16]. PC Amber LED was successfully tested in protected areas of natural heritage such as Canary Islands, where biological parameters prevailed over higher energy consumption (increase of roughly 20% compared to standard white LED). The newly developed Red+Amber LED light source has an even lower biological impact and, thanks to the additive approach in light composition, it achieves reasonably high efficacy. With an advantage over traditional light sources, Red+Amber LED could be easily coupled with other LEDs, could be attached to the same regulation system, controlled, dimmed etc.

Last but not least, new available sources of color light with large representation of blue wavelengths (LED Blue) create biological impact nearly eight times higher than the visual. Such light perceived through the eye seems to be dim, but it carries a strong alarming stimulus to our internal circadian clock. Unfortunately, exactly due to the visually dim appearance, popularity of Blue or Green LED is fast increasing, and is associated with all the adverse biological consequences.

III. MODULATION OF THE BIOLOGICAL IMPACT AS NEW PARAMETER FOR LIGHTING REGULATION

If we would consider biological impact solely, and if the target average illuminance should be kept above 5 lux, nothing but light sources with absence of blue spectral component (such as HPS and LED Amber sources) are appropriate for night public lighting.

A. Safety and visual comfort on the streets

It is obvious, however, that the modern lifestyle, with a lot of evening traffic and activities, is not in line with very dim lighting. Quality public lighting needs to provide good visibility to support visual comfort and safety on the streets. Studies and public surveys investigating the satisfaction of the residents with the public lighting confirm, that the illuminance as it is on the streets of European cities is generally perceived as sufficient [20] and no further global increase of illuminance is necessary. Responders to the population survey [21] are three times more likely willing to pay for ecological sustainability of the public lighting than to more brightness. In urban areas, about one-third of responders feels uncomfortable with artificial light. About 75 percent of the responders are at least occasionally affected by least one light source. In consistency with the survey, laboratory studies [22] show spatial distribution of the light to be the important factor for visual comfort under low illuminance. Avoidance of light glare in the direction of view and an even light distribution without frequently changing light and dark areas allow the eye to adapt to the lower lighting intensity. Last but not least, strong opposition to the cold white light from the residents grew up in several districts. Powerful, too bright, disturbing cold light sources were not always well accepted. In some cases, such as Rome, re-installation of the traditional HPS or at least change for warm white LED has been strongly demanded.

B. Time-dependent controller

Novel biodynamic technology offers a solution to fulfill visual needs while reducing biological risks of artificial light in night, with only a few compromises. Thanks to an improved understanding of the dual system of light perception in the eye, we can now tune the properties of the light according to the actual needs. Since new LED luminaires are able to integrate more than one type of light source, they are able to switch between multiple modes. In the periods of heavy traffic, more powerful sources with higher CCT and CRI could be used while later in the night, when there is almost no activity in the streets, light without blue spectral component could be used to protect the wildlife and not disturb the sleep of the residents. Based on the time of the day (night) and/or the season of the year, smart regulation and advanced control systems tune the intensity and spectrum of the light sources to create biodynamic public lighting.

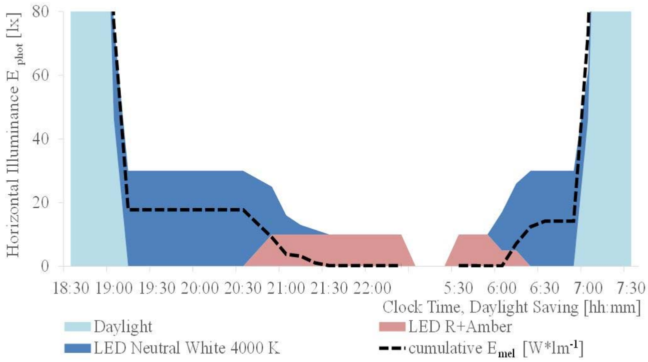

Fig. 6. Biodynamic street lighting in Řevnice - example of regulation for time around the equinox, during daylight saving time. Dashed line presents cumulative biological impact E_{mel} of all light sources, natural and artificial, calculated in $W*lm^{-1}$. Daylight properties according to Spischan [11]

C. Test-bed of biodynamic lighting

Example of the timing regulation for the recently developed biodynamic lighting is presented in Fig. 6. The first test-bed has been built in Czech town Řevnice. Six biodynamic light sources were installed along the walkway connecting new residential development with the central area. Lighting installation provides biologically stimulating (LED neutral white light, $E_{mel} > 15$ $W*lm^{-1}$) light during the evening and morning rush hours, and non-stimulating illumination (LED Red+Amber, $E_{mel} < 0.5$ $W*lm^{-1}$) for resting during the night time. One hour of gradual transition is set between the two modes. So far, the tested installation received positive feedback, but more research will follow in order to optimize the setup.

IV. CONCLUSION

The technology of light-emitting diodes allows us to set up not only the quantity of light, but also control the quality, such as the spectral composition. Cold and neutral LEDs produce light that visually resembles natural daylight and has alerting effect on live beings. Light with lower or no content of short wavelengths is more suitable for use in the vicinity of natural environments and in residential areas with lower traffic volumes. To increase visibility during periods after sunset and before sunrise, when the traffic is still/already high, biodynamic lighting could provide the solution. Via integration of advanced control systems it is possible to integrate several light sources and tune the resulting intensity and spectral composition based on the time of the day and the season of the year. Taking into account the biological processes in the human body, proposed smart regulation supports (or at least does not decrease) the stability and synchronization of the circadian clock. Based on the recent scientific findings such systems will be beneficial to health and increase the quality of life in urban areas as well as limit the negative impact of light at night in the countryside and natural locations. This could be achieved without excessive deterioration of visual comfort or energy efficiency.

REFERENCES

[1] S. Hattar, H.W. Liao, M. Takao, D.M. Berson, K.W. Yau, “Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity”, Science. 2002 Feb 8; 295(5557):1065-70.

[2] R. G. Foster, M. W. Hankins, “Circadian vision”, Curr Biol. 2007 Sep 4; 17(17):R746-51.

[3] T. Roenneberg, S. Daan, M. Merrow, “The art of entrainment”, J Biol Rhythms. 2003 Jun; 18(3):183-94.

[4] C. Cajochen, M. Münch, S. Kobialka, K. Kräuchi, R. Steiner, P. Oelhafen, S. Orgül, A. Wirz-Justice, “High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light”, J Clin Endocrinol Metab. 2005 Mar; 90(3):1311-6.

[5] C.A. Czeisler, “Perspective: casting light on sleep deficiency”, Nature 23; 497(7450), p13, (2013).

[6] S. M. Pauley, “Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue”, Med Hypotheses. 2004; 63(4):588-96.

[7] F. Falchi, P. Cinzano, C.D. Elvidge, D.M. Keith, A. Haim, "Limiting the impact of light pollution on human health, environment and stellar visibility", J Environ Manage. 2011 Oct; 92(10):2714-22.

[8] A. Haim, B. Portnov, “Light Pollution as a New Risk Factor for Human Breast and Prostate Cancers”, Springer, 2013.

[9] K. J. Gaston, J. P. Duffy, S. Gaston, J. B. Thomas, W. Davies, “Human alteration of natural light cycles: causes and ecological consequences”, Oecologia 2014; 176: 917.

[10] F. Falchi, P. Cinzano, D. Duriscoe, C.C. Kyba, C.D. Elvidge, K. Baugh, et al., “The new world atlas of artificial night sky brightness”, Sci Adv. 2016 Jun 10;2(6):e1600377.

[11] M. Spitchan, G. K. Aguirre, D. H. Brainard, A. M. Sweeney, “Variation of outdoor illumination as a function of solar elevation and light pollution”, Sci Rep. 2016 Jun 7; 6:26756.

[12] T. Roenneberg, C.J. Kumar, M. Merrow, “The human circadian clock entrains to sun time,” Curr. Biol.2007, 17, R44–45.

[13] C. Vollmer, U. Michel, C. Randler, “Outdoor light at night (LAN) is correlated with eveningness in adolescents”, Chronobiol Int. 2012 May; 29(4):502-8.

[14] Jones J.M. In U.S., 40% get less than recommended amount of sleep. GALLUP 2013. In: http://www.gallup.com/poll/166553/ lessrecommendedamountsleep.aspx

[15] American Medical Association, “AMA adopts guidance to reduce harm from high intensity street lights”, online at: https://www.ama-assn.org/ama-adopts-guidance-reduce-harm-high-intensity-street-lights

[16] Smart Outdoor Lighting Alliance, “Public lighting trends for 2017”, online at http://volt.org/public-lighting-trends-for-2017/

[17] R.J. Lucas, S. Peirson, D.M. Berson, T.M. Brown, H.M. Cooper, C.A. Czeisler, et al, “Measuring and using light in the melanopsin age”, Trends in neurosciences 2014; 37.1.

[18] CEN/TR 16791: 2017 Quantifying irradiance for eye-mediated non-imageforming effects of light in humans, September 2017.

[19] C. C. M. Kyba, A. Mohar, T. P. Longscore, “How bright is moonlight?” Astronomy & Geophysics 2017; 58 (1), 1.31–1.32.

[20] S. Fotios, J. Unwin, S. Farrall, “Road lighting and pedestrian reassurance after dark: A review”, Lighting Res. Technol. 2015; Vol. 47: 4, 449 – 469.

[21] A. Besecke, R. Hänsch, “Residents‘ perception of light and darkenss“, in Urban lighting, light pollution and society, Routledge, Taylor & Francis 2015; 224-48.

[22] T. Uchida, Y. Ohno, “Defining the visual adaptation field for mesopic photometry: Effect of surrounding source position on peripheral adaptation”, Lighting Res. Technol. 2017; Vol. 49: 763–773.

[23] L. Maierova, “Lighting environment in buildings, nonvisual light perception and inter-individual differences”, Ph.D. thesis, CTU in Prague, 2015.