Light and the biological clock

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Introduction

Temporal rhythms can be found throughout the whole natural world. The circadian (from Latin circa – around, dies – day) have been discussed in the magazine Svetlo (The Czech word for Light) several times, for example no. 1 and 3/2005 or 5 and 6/2008. The expression circadian was introduced in the 50's by Franz Halberg, one of the founders of chronobiology, the science of temporal order in the living realm. From Czech chronobiologists, Prof. Helena Illnerová and her team are the most well known for the discovery of melatonin secretion variation in rats which depends on light exposure changes over the four seasons, as well as for the discovery of photosensitivity in the biological clock in suprachiasmatic nuclei in hypothalamus [2].

In the autonomous nervous system of mammals, the Central Biological Clock is found under the crossing of optical nerves in the suprachiasmatic nuclei (SCN) which controls hormone levels in blood, body temperature, sleep and alertness to name just a few. Melatonin is the hormone governing sleep and body re-generation, whilst Cortisone is the hormone connected with activity, stress and motion. Examples of levels observed, courtesy of [3], are shown in Fig. 1. The patterns of the curves vary slightly each day.

The Central Clock is synchronized by light, but food intake also matters. In young humans, this clock has a circa of 24 hours when running free of light synchronization, which is the origin of the term 'circadian'. Individual organs have their local clock synchronized with the SCN 'master' clock. The event of adjusting the clock (also known as the Zeitgeber) can be the illumination. A dose of several luxes of suitable spectral distribution for several minutes can already cause level of melatonin in blood to decrease.

Effects of light on living organisms

Professor Fritz Hollwich, an author of an Ophthalmology textbook and inventor of many procedures in ophthalmology, has studied these effects closely. In his inaugural dissertation from 1948, he distinguishes the visual and energetic (non-visual) function of the eye. He found that patients suffering blindness due to cataracts had different levels of certain hormones and other markers in the blood, compared to the normally sighted population. When the patients regained their sight after an operation, the levels returned to normal. He also found that some distributions of light, lack of light or excess light or it's invariance have adverse effects on organisms.

In the last few years, a novel photoreceptor – intrinsic photosensitive retinal ganglion cells (ipRGC) is often discussed. These had already been found in mice back in 1991 and in humans as late as 2007. ipRGC contain melanopsin pigment, which maximum sensitivity is reported between 450 – 482 nm (rarely also between 420 nm and 491 nm). These cells project the synchronization event to the Central Clock, they also play a part in the pupil reflex and they may also contribute to the visual sensation. They are spread all over the retina, but are more numerous in its lower part. They are called the circadian sensor or blue-sky sensor for their high sensitivity to blue and spatial distribution on the retina.

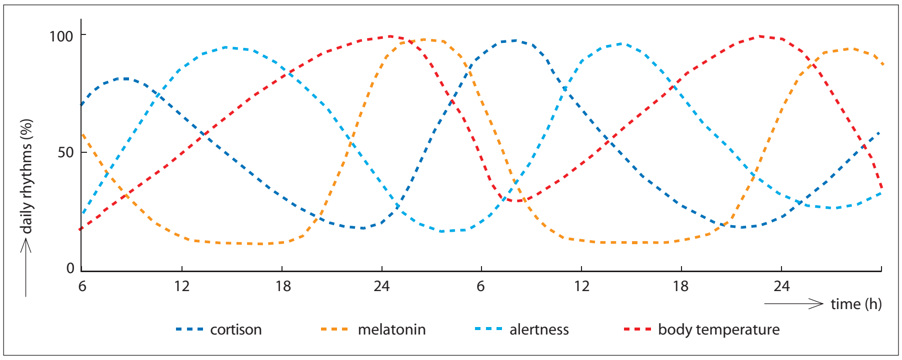

Fig. 1 - Daily rhythms of the human body

The latest research [5] shows that the synchronization signal is also assisted by the cones and the exposition time also plays an important part. The effects of two narrow-band lights with wavelengths of 460 nm and 555 nm were compared:

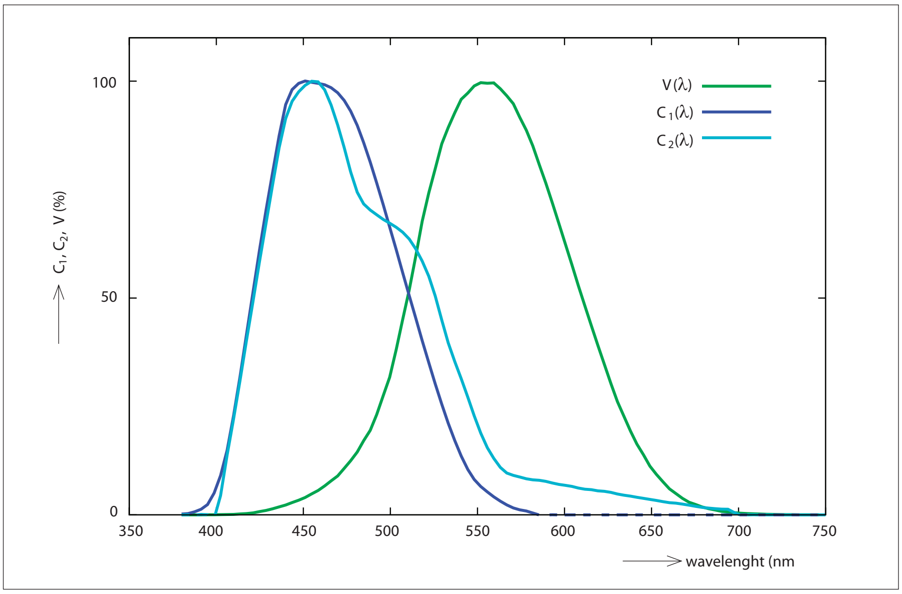

Fig. 2 - Possible shapes of relative sensitivity (efficiency) of circadian sensor C(λ) and the V(λ) curve

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their initial effect on melatonin decrease was almost the same, however, in the case of the green light, the effect ceased after about 90 minutes, while the blue light effect persisted. $C_1(\lambda)$ hence shows the long-term sensitivity while the $C_2(\lambda)$ takes the short-term effects into account. Two effects are observed: melatonin level decrease and phase-shift of the Central Clock.

In [6] and [7], a construction of circadian dosimeter (Daysimeter, LuxBlick) is described. It's a small instrument that are worn like spectacles. Two photodiodes are used as sensors, one corrected by a filter to V(λ) and the second to C(λ). Measured values are stored along with timestamps in intervals of tens of seconds. Analysis of the data can show whether the user gets a sufficient dose of the light affecting the nervous system and whether or not he/she is disturbed by light at night. Critical points can be localized in time so a remedy may be suggested. Data from additional sensors like an accelerometer or a thermometer can make interpretation of the light data easier.

Decreasing of the melatonin level in the morning and keeping it low during the day is naturally beneficial as it starts a number of processes that lead to higher alertness, activity and concentration. Light sources of higher chromatic temperature can provide spectrum rich in the circadian-efficient band. According to the Kruithoff curve, we can expect the users to require higher levels of light in their place of work, which can be also aided by local luminaries. Higher illuminance and higher chromatic temperature can have tangible economical output in the workplace thanks to a better quality of workmanship [8], lowering stress [4], better use of work time or lowering sick leave.

Melatonin is a hormone of sleep and regeneration of the organisms. It scavenges free radicals and kills cancer cells in the body. So it's most beneficial to let it do its job undisturbed during the night. The means for lowering the disturbing night light include a more sophisticated design of street lamps, curtains, window blinds, shutters or red night light.

White LEDs are mostly blue LEDs with a phosphor that converts part of the blue light into yellow, which then mixes with blue making white. This introduces a risk of disturbing the night dark by LED streetlights. Blue light gets far more scattered in the atmosphere than the longer wavelengths, so disturbing scattered light should also be considered.
According to [9], LEDs with a low chromatic temperature (2,600 K) are suitable for street lighting. However, even in this case, the portion of circadian-efficient light is three to four times higher than in the more commonly used high-pressure sodium lamps. (Tab. 1)

Table 1 – Examples of Ac values

Light source		Specification	A_c (–)
daylight		D65	100
black body		2 700 K	36
		4 000 K	64
		5 000 K	82
		6 500 K	100
		8 000 K	116
		20 000 K	156
		100 000 K	181
fluorescent	warm white 827	2 700 K	27
	cool white 840	4 000 K	55
	daylight 95	5 000 K	83
	cool daylight 965	6 500 K	95 to 105
	blue	Philips TL-D Blue	740
incandescent	general	2 800 K	36
	halogen	2 900 K	40
LED	warm white	2 850 K	36
	cool white (daylight)	6 800 K	90
	blue	450 nm	875
	green	520 nm	52
	red	630 nm	0.4
arc lamp	sodium	high pressure	8 to 13
	sodium	low pressure	0.2
	metal halide 942	4 200 K	69
	metal halide 965	6 500 K	100

Calculation and Measurement

Circadian values are introduced in parallel with photometric values in [10]. Function V(λ) is replaced with C(λ) and index c is used with the values. In this way, we can consider 'circadian illuminance' for example.

Circadian illuminance can be measured with a luxmeter corrected to circadian efficiency C(λ). For coarse relative measurements, a Lee #120 gel filter can be used. Another option calculation from the spectrum or establishing a factor to convert 'photopic lumens' to 'circadian lumens' for a given light source.
A factor of circadian efficiency a_{cv} (German zircadianer Wirkungsfaktor) is introduced [10]. This is calculate for light of relative spectral distribution of power according to Equation 1.

$$a_{cv}\{X(\lambda)\} = \frac{K_m \int_{380}^{780} X(\lambda)C(\lambda)\mathrm{d}\lambda}{K_m \int_{380}^{780} X(\lambda)V(\lambda)\mathrm{d}\lambda} \qquad (1)$$

acv is a factor for converting photopic values into circadian values for a given light source. It can be used to compare different lights or light sources from the perspective of their effect on our nervous system.

The shape of the curve C(λ) and the area under it are not exactly known yet.

This is why another factor can be introduced to allow comparison of the results calculated with presently known shape of C(λ) and those based on an updated C(λ) in future. The factor can be defined in different ways, for example the equality of areas under C(λ) and under V(λ) or by equality of luminous and circadian flux for CIE illuminant A (incandescent bulb model) [10]. The option proposed here for discussion is Circadian Activation Index A_C (CAI). Its value is defined = 100 for CIE D65 illuminant.
A_C is calculated according to Equation 2.

$$A_c\{X(\lambda)\} = = 100\frac{K_m \int_{380}^{780} X_{D65}(\lambda)V(\lambda)\mathrm{d}\lambda}{K_m \int_{380}^{780} X_{D65}(\lambda)C(\lambda)\mathrm{d}\lambda} a_{cv}\{X(\lambda)\} \approx \approx 106.25 a_{cv}\{X(\lambda)\} \qquad (2)$$

A_C makes it easy to compare the impact of different lights on the nervous system. For the reference light – daylight – it has a value of 100. Values for some common light sources and black body temperatures are tabulated in Table 1.

Besides the daily rhythms, physiological rhythms of high/low tide, weekly rhythms, lunar and annual rhythms are known. Lack of light during winter contributes to sleepiness and need for longer sleep, but also to seasonal affective disorder (SAD), known as winder depression. This can be also treated by bright light therapy (phototherapy). 10,000 lux at eye level for 30 minutes is a proven efficient dose [11]. For personal application, Sunshine simulators are used. In contrast to industrial sun simulators, these are luminaries for illuminating the eyes and face. Desk or wall luminaries with fluorescent lamps are well known (usually providing 10,000 lux at the diffuser). Portable battery--powered luminaries with white or blue LEDs are also on the market. Less known are light visors with embedded LEDs for illuminating the eyes. These aids can easy the start of a new day, but for a permanent effect, lighting with sufficient circadian effect is needed all day long.

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