

Dynamic Lighting System for Workplaces at Northern Latitudes

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Abstract. In this article the author analyzes quality parameters of the ergonomic lighting systems and forms a model of an ideal indoor lighting. Based on the literature review and author's measurements of the natural daylight, the model's principal features are 1) dynamic spectrum and 2) dynamic color temperature. The model prescribes these parameters to follow the characteristics of the natural daylight in the course of a day and throughout the year. The relevance of these parameters and the connection to human wellbeing is argued in support to the model.

Keywords: dynamic lighting, spectrum, color temperature, indoor lighting.

I. INTRODUCTION

In developing a dynamic lighting system fit to northern latitudes, the author sees it necessary that such lighting system's spectrum and color temperature follow the same parameters of natural daylight in the corresponding geographical region. As for example, when observing spectrum and color temperature throughout the year and day in south-European latitudes they have a great difference to those observed in northern Europe. The latter region is where the study was performed and the current model produced for. The author presents the findings from the literature and argues the necessity of each parameter to be included in the system.

The aim of this study is to develop a model for an indoor ergonomic lighting system that would best match the natural daylight, which is considered as a standard for high-quality lighting systems.

Millions of years of the human evolution is a process that the sunlight has been an integral part of. Therefore it is not difficult to understand that natural daylight is a type of light that we, humans are most custom to. The scientific body of research is continually pointing out the important role the Sun and natural daylight are playing in human wellbeing. Be it a simple regulation of circadian rhythms or a complex mechanism of driving the organism's immune system – the Sun is proven to make it all happen. A term “mal-illumination” has even been produced to describe a health condition where a person, due to a limited access to the daylight, has developed a mixture of health symptoms, something similar to chronic fatigue syndrome. Being acquainted with the relevant daylight biological effects studies, one could not underemphasize the relevance of the light in an everyday environment. However, most modern workplaces fail to consider all the characteristics of the light, expect one – the illuminance level. And even if the correct

illuminance level is maintained, being in compliance with the relevant standards, this level would not even get close to the natural daylight's levels at the better part of the day.

In author's opinion, nowadays a major problem of widespread lighting systems is an inadequate spectrum. In sunlight all colors are represented in relatively same amounts, producing continuous spectra. Whereas, the artificial lighting would either have a shifted color spectra (towards red in case of a filament light bulbs) or a fragmentary spectra (in case of excited gas technologies). Only few of the lighting technologies come near to natural daylight in reproducing its spectra, which are usually much more expensive.

The underlying principle for developing an ergonomic lighting system is to follow the characteristics of the natural daylight as closely possible. The scientific body of research has shown when the indoor lighting deviates from such characteristics the human wellbeing or performance may suffer.

Recent biomedical studies have shown that besides visual function, light plays also an important role in entering the eyes and having a biological effect for human wellbeing. Due to the recent discovery of a novel photoreceptor in the eye the necessity for dynamic lighting has become clearer. Light is signaling the time of the day by the means of the newly discovered photoreceptor cells and a separate nerve system to our biological clock, which in turn regulates the circadian (daily) and circannual (seasonal) rhythms of a large variety of bodily processes (Bommel 2006).

These 24h rhythms have a major impact on our health both physically and behaviorally: sleep/wake cycles, alertness, performance patterns, core body temperature, production of hormones (Bellia et al 2011). This new kind of photoreceptor contains the melanopsin, the pigment that is most sensitive to the blue light, which if received in the eye for a period of time stimulates a wide range of physiological responses associated to the neuroendocrine and neurobiological systems, like resetting the timing in the circadian pacemaker, suppressing nocturnal melatonin production and improving alertness (Bellia et al 2011; Daurat et al 1993).

Research done in the field of photobiology has demonstrated that bright light can be successfully used for treating SAD (seasonal affective disorder). The cause for the SAD to kick in is widely believed to be deficiency or complete lack of natural daylight, especially in the winter period. Symptoms of the SAD include:

- Depression,

- Lack of energy,
- Decreased interest in work or important activities,
- Increased appetite with weight gain,
- Carbohydrate and sugar cravings,
- Increased need for sleep and excessive daytime sleepiness,
- Social withdrawal,
- Extreme afternoon slumps with decreased energy and concentration,
- Decreased sex drive (Holick and Jenkins 2009).

Next to using bright light in treating SAD, it has also been found to improve social behavior. People who were exposed to light exceeding 1000lx were reported to have less quarrelsome activity, more agreeable behaviors and overall better mood (Rot et al 2008).

Even his colleagues concluded in their systematic review that bright light therapy is an excellent for treatment nonseasonal depression today and as adjuvant therapy for antidepressant medication (Even et al 2008).

As reversing the symptoms of SAD has been established with confidence, the mechanism of it is still under investigation. Some researchers claim that blue component of the light is a key factor in diminishing SAD. Others have shown that as well as the blue also the white light at high intensities can be used for SAD treatment. Some researchers even claim that the color of the light used for SAD treatment doesn't matter as long as the light is of high intensity. Recent research has even indicated that intense blue light having a damaging effect for human eyes (Gagne et al 2011).

On the other hand, Glickman tested whether blue LED (Light emitting diode) daily usage has an effect on persons suffering from SAD (Seasonal Affective Disorder) and found that symptoms of major depression were reversed (Glickman et al 2006). The same effect was however not observed for a control group that underwent the same therapy using dimmer red LEDs (Glickman et al 2006).

Thorn however points out with their recent study, that SAD is connected to the cortisol awakening response (CAR) and there was no difference in cortisol levels during the rest of the day between controls (Thorn et al 2011). The study concluded that during the shortened daylight period in winter the cortisol response to awakening is attenuated in SAD persons (Thorn et al 2011).

Again, in supporting the blue light, Brainard with his colleagues doing their research on SAD found that in the same light intensities (2.3×10^{15} photons cm^{-2}) white light had greater therapeutic benefit than red or blue light (Brainard et al 1990). Although their study was done with a small sample size ($n=18$), it and other studies would imply that best results in light therapy are achieved with high intensity white light.

Not all people can be considered to be affected by the SAD, only a certain percentage of the population are vulnerable for the reduction of natural lighting which in turn has now been widely accepted to be the trigger for SAD. Blue light is seen to

affect SAD through modulating emotion brain processing in healthy people (Vandewalle et al 2011). Vandewalle's team's conducted a study that showed enhanced responses to auditory stimuli in the posterior hypothalamus in SAD patients, at the same study, green light decreased these responses and the effects of blue or green light were not observed in healthy controls (Vandewalle et al 2011). Vandewalle's study was innovative in pointing out posterior hypothalamus as the neurological substrate involved with SAD, including a distinctive response to light and altered emotional responses (Vandewalle et al 2011). Therefore by now we know that light with its special spectral characteristics has a direct effect on emotional brain in SAD persons.

II. METHOD

In order to develop an ergonomic lighting system model the author performed 1) a literature analysis and 2) a series of measurements. The aim of the literature analysis was to determine whether the author's hypothesis is supported by the scientific body of knowledge. Literature review especially focused on the human effects in regard to the light spectrum and color temperature. The goal of the measurements was to record the characteristics of the natural daylight from winter solstice to summer solstice – a period from when the sun is at its lowest and to when at its highest. On a measurement instance the following sunlight characteristics were recorded:

- Spectrum;
- Color temperature (Kelvins);
- Illuminance level (lux);
- UV-A and UV-B radiation (mW/cm^2).

Additionally on-site air temperature and relative humidity level were recorded. The exact time and position was also marked as to later calculate the sun elevation and closeness to the sea –which both may have a noticeable effect on the main parameters of interest in this study.

To perform the task the author included following instruments:

- Optical spectrometer ASEQ Instruments LR-1, capable of distinguishing 3653 unique wavelengths in the range of 279 to 974 nanometers (nm). But for the purposes of this study mostly visible range was used from 390 to 710 nm registering light intensities for 1717 unique wavelengths. Spectrometer's signal-to-noise ratio is 300:1. The spectrometer has also a built-in option for calculating color space XYZ coordinates which in turn were used to calculate the color temperature (in Kelvins). The spectrometer produced both the graphical output of the spectrum curve and also a text-file output for later analysis and spectral matching.
- Laptop PC for a real-time data recording and spectrometer control.
- Lux meter 1330B, with the maximum measuring range of 200 000 lux, with the tolerance $\pm 5\%$ rdg ± 10 dgt.

- UV meter Waldmann 585 100, capable of measuring three UV ranges: UVA 320 - 410 nm; UV6(UVB) 280 - 360 nm; UV21(UVB) 280 - 350 nm. Maximum measurement range: UVA 199.9 mW/cm², tolerance +/- 5%; UVB 19.9 mW/cm², tolerance +/-10%.
- Infrared thermometer to record measurement site's ambient temperature.

Measurement days were selected so that to minimize the influences from other weather conditions such as clouds, rain etc. The methodology aimed to minimize measurement errors from other environmental factors so that the main deviation in measured readings would only be from the parameters of interest.

Local weather station (national grid) online data was used to obtain relative humidity readings. The importance of recording this parameter is as the light spectrum is dependent on the level of humidity – the more water molecules there are in the air the more distorted is the spectrum (EMHI).

For calculating the Sun's elevation at the measurement site an online calculator was used (SunEarthTools).

The literature analysis mapped what health effects and cognitive effects are known from afore-mentioned lighting parameters. The purpose of the literature analysis was to support the proposed model with research data.

Taking into account the literature findings and the measurements' analysis the author formed an ergonomic lighting system model.

III. RESULTS

A. Measurements

The natural daylight measurements were conducted in the latitude of 59 degrees North (city of Tallinn).

Throughout the entire year (from oct 2011 to sept 2012) the entire cycle of sun was metered. Having a look into the daylight characteristics year-round is important in order to encompass the sun at the lowest and at the highest elevation angle.

Altogether 91 measurement instances took place. The measurements were usually about metering the sunlight characteristics at the noon, but also all-daylong measurements were done where the same characteristics were metered hourly.

Common knowledge that the sunlight's color temperature is in a functional relationship with Sun's elevation angle can also be seen from the author's measurements in Figure 1. Based on the measurement data obtained at the given coordinates and calculated Sun elevation angle the author derives all other color temperature models.

In Figure 1 an effect from the air humidity can be seen as having an effect on the color temperature level – measurements conducted on the same Sun elevation angle throughout the year often do not match. A narrow line in Figure 1 represents color temperature level at the specified

Sun elevation angle with minimum distortion effect from the humidity. Therefore this narrow color temperature line is used for deriving the color temperature for the daylong and year-round models.

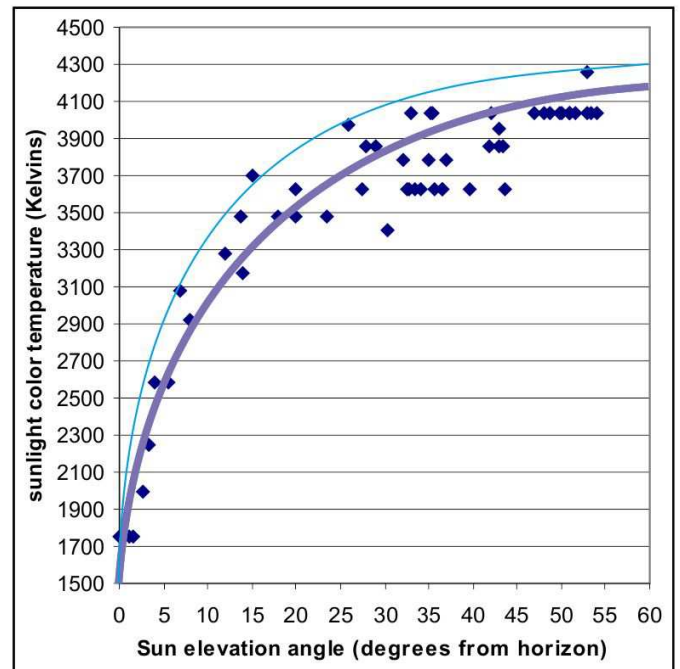


Fig. 1. Sunlight's color temperature as a function of Sun elevation angle – measurements distribution graph and modeled average and maximum color temperature curve (author's measurements).

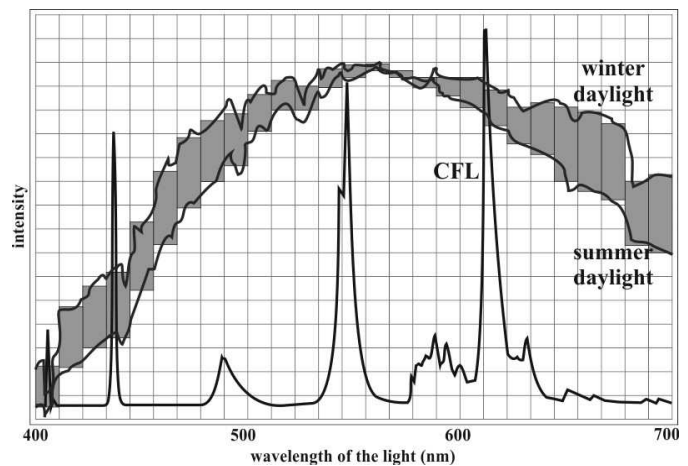


Fig. 2. The author's measurements for the spectrum of the summer sun, the winter sun and the compact fluorescent light bulb.

Figure 2 presents a comparison of three different lighting conditions: winter sunlight, summer sunlight and the compact fluorescent light bulb (CFL) spectrum. The difference of the summer and winter spectra is highlighted – this illustrates also the Sun's color temperature being higher in the summer and lower at the winter. Comparing sunlight's spectra to the one of a CFL leads to dramatic conclusion – it is pseudo white, as it creates an illusion of being a white light, but most of the wavelengths of the visible spectrum range are missing.

As the natural daylight may either be a direct sunlight or a diffused light from the atmosphere, all relevant natural light sources/mediums were metered: sunlight directly, sunlight through the clouds and clear sky zenith. Also in the wintertime, sunlight reflecting from the snow was metered. A comparison of these different cases is presented in figure 3.

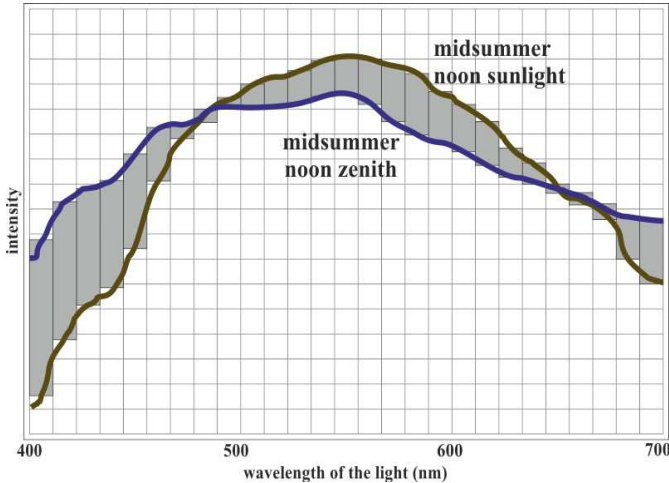


Fig.3. Spectral difference of midsummer noon sunlight, and midsummer noon zenith.

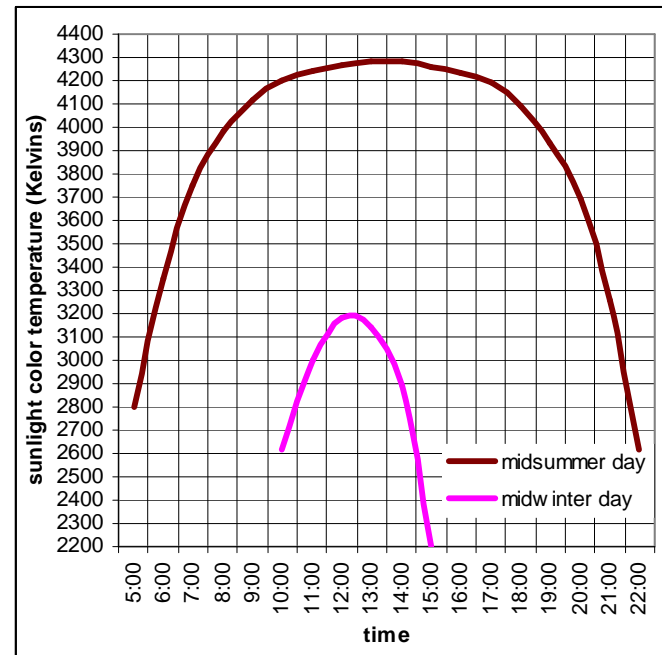


Fig.4. sunlight color temperature during the course of the day from sunrise to sunset (modeled based on author's measurements)

Figure 5 indicates the maximum color temperature of the sunlight per each month. The values were modeled based on the Sun's elevation angle at noon per each month and author's measurements that prescribe maximum color temperature per Sun's elevation angle (Fig. 1).

Considering the current capabilities of artificial lighting technologies, it is obvious that the model's suggested

spectrum cannot be precisely reproduced; therefore the proposed spectrum should be used as a guide in developing best possible spectrum solution.

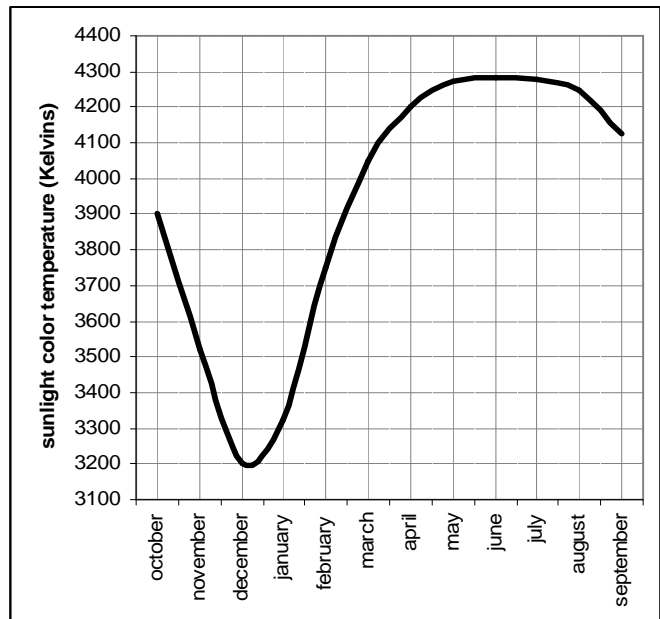


Fig.5. Noon (maximum) sunlight color temperature throughout the year.

B. The model

Based on the literature review and the author's measurements the proposed model can be described by two main parameters:

1) continuous spectrum distribution, similar to what is pictured in figure 3 – either noon sunlight spectrum for direct lighting and/or noon zenith spectrum for indirect lighting;

2) dynamic color temperature throughout the day and year-round changing from 2200 to 4300 Kelvins depending on the time of day and month, as pictured in Figure 4 and 5. Whereas figure 5 sets a maximum color temperature for the noon and corresponding to the period of year, Figure 4 prescribes the fluctuation of the color temperature during the course of the day. One might notice that on the darkest time of midwinter actual sunlight does not cover all the working hours, in such case the color spectrum curve is to be stretched vertically until the whole workday is encompassed. This adjustment could be also applied for other special working hours that are not covered by the graph. One of such examples might be the night shift, which in itself is a major contributor to workers' stress due to the messed up circadian rhythms. Currently proposed model of dynamic color temperature might very well offer some relief also to the night shift workers, helping their bodies to get custom to the artificial day. Nowadays for example light is being used as pre-lunch countermeasure to circadian and sleep disruption in astronauts (Fucci et al 2005). The same research group found the spectrum range of 446-477 nm to be most potent in suppressing plasma melatonin, which in turn is a major contributor to circadian rhythm mechanism (Fucci et al 2005).

The above mentioned are the main parameters addressed by the model. In addition the following parameters should be

mentioned, as they are associated with the high-quality lighting systems:

- Controlled UV exposure;
- Sufficient illumination level;
- Harmonious brightness distribution;
- Glare limitation;
- Avoidance of reflections;
- Personal control;
- Daylight integration.

The author sees it unnecessary to have a dynamic illuminance level, as it is unattainable and needless to pursue illuminance levels those of a natural daylight. For comparison: a recommended illuminance level (maintenance value) for office workplaces is commonly 500lx, whereas the illuminance from the midsummer midday sun at northern latitudes is measured to be over 100 000 lx. Having this in mind, the author suggests to maintain the suggested illuminance level, based on the specific workplace type, according to the relevant standards, for example such as the European standard EN 12464-1.

A controlled UV exposure is found to be a necessary complement to indoor lighting system, especially if the outdoor time for these workers is limited. UV radiation is necessary for cell division – if a person is lack of UV light, the normal cell growth is disturbed, which can lead to cancer (Moritz 2010).

Figure 6 represents an approximate UV power density at the selected latitude throughout the year. In comparison, the widely used PHILIPS facial solarium UV-radiation output at the distance of 30cm was recorded to be as follows UV-A 3,3 mW/cm²; UV6 (UV-B) 0,11 mW/cm²; UV21 (UVB) 0,12 mW/cm² (author's measurements). The highest recorded UV-readings of the midsummer sun at noon were significantly higher: UV-A 4,1 mW/cm²; UV6 (UV-B) 0,37 mW/cm²; UV21 (UVB) 0,42 mW/cm² (author's measurements).

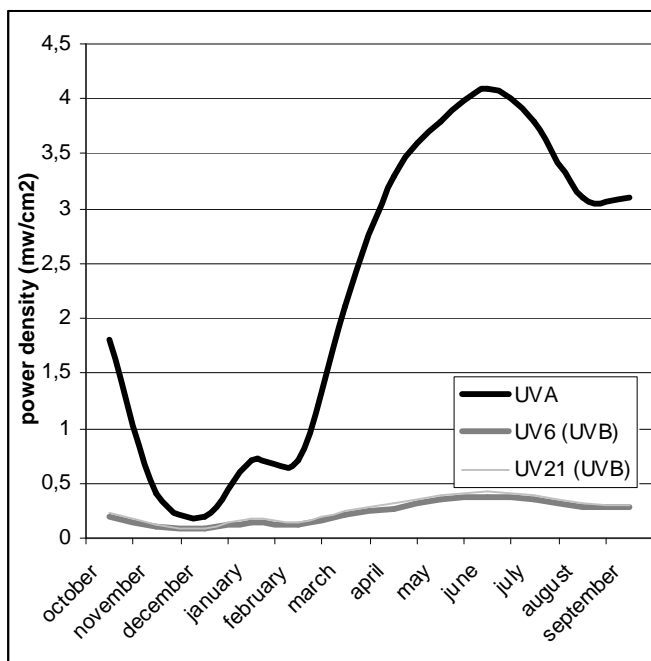


Fig.6. UV radiation output throughout the year (authors measurements).

IV. CONCLUSIONS AND DISCUSSION

In this article the author formed a model for dynamic indoor lighting system that best matches the natural daylight characteristics. The author argued why this model would suit the human in the work environment better than majority of the lighting system in use at present time. This article provides a theoretical basis, grounded with instrumental measurements for the future studies in developing and analyzing the benefits of such dynamic lighting systems that match natural daylight characteristics.

The essential idea behind the author's proposed principles is to support human day/night circadian rhythms and the year-round (summer/winter) rhythm of the northern latitude. This is achieved by following as closely as possible the daylight color temperature of the corresponding time of the year. Next to following the seasonal spectrum the model prescribes a color temperature for the course of the day. Not less important is the achieving the full spectrum for indoor lighting – a human being needs all wavelengths of the daylight. The basic principle behind the day variance follows the findings of the literature – having a yellowish tone at the morning, white at noon and yellowish again by the end of the day. The described color tone shift might be unnoticeable but does affect the circadian rhythms of the human body, telling when it's time to be active and when it's time to prepare to rest.

The author still believes that the best alternative to all artificial lighting systems is natural daylight. Spending time outside is proven to benefit one's health and social behavior. Therefore, even having installed a state of the art dynamic lighting system can never replace sunlight in its complexity.

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