CIRCADIAN LIGHTNING (EYANTRA) WEEK 1

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TECHNOLOGY – THE ENABLER

In recent years, there has been a surge of interest in human-centric lighting (HCL). The key reason behind this growing interest is the advancements in technology, particularly LED lighting. LED technology opens up numerous possibilities that were previously unavailable, allowing us to tune both the spectrum and intensity of lighting. This flexibility makes LEDs an excellent foundation for human-centric lighting.

Human-centric lighting should be more than just dimmable—it must be tunable. By combining hardware and software, lighting manufacturers now offer solutions that let users adjust and program both light intensity and spectrum. This adaptability is crucial for creating environments that support our natural circadian rhythms.

THE HISTORY OF CIRCADIAN RHYTHMS AND HUMAN EXPOSURE

For Before the industrial revolution, humans were exposed to minimal light at night. Technological advances have introduced new sources of light into our world including electronic screens (~40 lux), lighting in homes (100–300 lux), and residential street lamps (15 lux) (Gaston et al., 2013). In contrast, the light from a full moon only emits 0.1–0.3 lux (Gaston et al., 2013). Indeed, 99% of Americans experience significant light pollution, defined as the alteration of natural nighttime lighting conditions (Falchi et al., 2016)

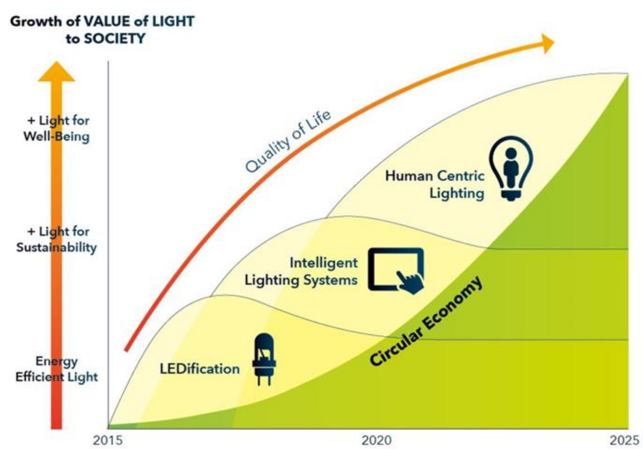

Image: The Strategic Roadmap 2025 of LightingEurope was published in March 2016. It demonstrates the increasing growth in the value of light to society

With the advent of artificial lighting, especially in the last century, our exposure to natural light has drastically decreased. People started spending more time indoors, relying on artificial light that does not mimic the dynamic nature of sunlight. This shift has had profound effects on our circadian rhythms, leading to disruptions that impact mental and physical health.

For example, having lights on in living spaces after dark delays the release of melatonin and may contribute to trouble sleeping (Gooley et al., 2011). Additionally, the wide prevalence of mobile phones with access to the Internet (i.e., smartphones), has led to light exposure throughout the day and night. Roughly 85% of US individuals own smartphones (Center, 2021), and many use their phones before bedtime (Hysing et al., 2015). The use of electronic screens delays the onset of sleep and decreases wakefulness the following day (Šmotek et al., 2020).

WHAT ARE CIRCADIAN RHYTHMS?

Circadian rhythms are 24-hour cycles that regulate various bodily functions, including sleep, wakefulness, hormone release, and metabolism. These rhythms are primarily influenced by the natural light-dark cycle of the environment. The brain's "master clock," located in the suprachiasmatic nucleus (SCN) of the hypothalamus, helps synchronize these rhythms with the day and night cycle.

During the day, light signals the body to be awake and active, while darkness at night triggers the release of melatonin, a hormone that promotes sleep. This natural cycle ensures that bodily functions like sleep, digestion, and hormone production occur at the right times.

However, the widespread use of artificial lighting, especially since the 19th century, has disrupted this natural synchronization. Artificial light, particularly at night, can confuse the circadian system, leading to a misalignment between our internal clocks and the external environment. This disruption can cause sleep disorders, metabolic issues, and increased susceptibility to mental health problems like depression.

In environments where people are exposed to artificial light at odd hours, such as in shift work or in regions with long periods of darkness, the natural circadian rhythms can be severely disrupted, leading to various health problems.

HEALTH CONSEQUENCES OF CIRCADIAN DISRUPTION

The health consequences of circadian disruption are vast, ranging from increased fatigue and lack of focus to cardiovascular diseases and certain cancers. One of the most common effects of disrupted circadian rhythms is altered sleep. Artificial light exposure, especially at night, impairs the ability to fall asleep and shortens sleep duration (Šmotek et al., 2020). Disrupted circadian rhythms can affect cognition and mood and may lead to increased anxiety and depression. Depression, characterized by mood changes and diminished pleasure, is often accompanied by sleep disruptions (Belmaker & Agam, 2008), implicating circadian disruption as a key feature of depression and other mood disorders (Walker et al., 2020).

Typically, individuals performing shift work will adjust to their nontraditional schedules and their rhythms will shift to match the time that they are awake (Andlauer et al., 1979).

However, anywhere from 10% to 30% of individuals performing shift work are never able to adapt and instead develop shift work disorder, characterized by extreme sleepiness during work hours and insomnia during rest hours (Waage et al., 2009). Interestingly, individuals who have performed shift work for many years may lose tolerance (as shown by increased digestive issues, fatigue, and impaired sleep) (Andlauer et al., 1979)

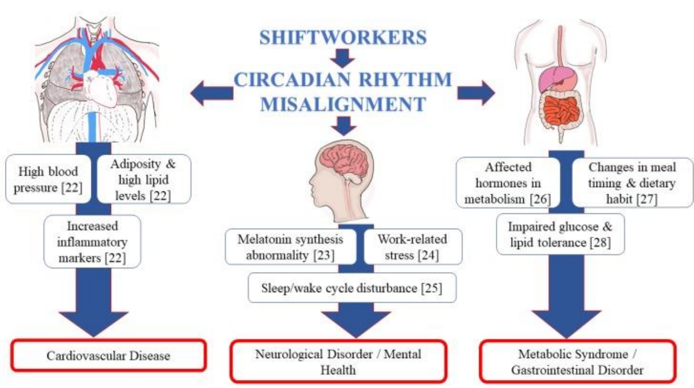

Image: Scematic diagram on the effect of circadian rhythm disruption on different body systems

Mohd Azmi NAS, Juliana N, Mohd Fahmi Teng NI, Azmani S, Das S, Effendy N. Consequences of Circadian Disruption in Shift Workers on Chrononutrition and their Psychosocial Well-Being. Int J Environ Res Public Health. 2020 Mar 19;17(6):2043.

OUR FIRST PROPOSAL (WEEK 1)

This project aims to develop a circadian lighting system that adapts to the natural rhythm of the human body by adjusting the lighting in a room according to the time of day. The system will utilize a lookup table that maps the time of day to ideal color temperature and light intensity based on circadian rhythms. The goal is to ensure that the lighting in the room syncs with these rhythms, even accounting for the current lighting conditions.

KEY COMPONENTS

LOOKUP TABLE (TIME ZONE SPECIFIC):

Time of Day: The table maps each hour to an ideal color temperature and intensity.

Color Temperature: Reflects the optimal light for circadian alignment at each hour.

Intensity: Derived from the sun's position data for the specific time zone, ensuring appropriate light levels.

Example of a lookup table: (Naive implementation)

Time of Day	Lighting	Intervention	λmax (nm)	EV (lux)	CS
6:00 a.m. - 8:00 a.m.	Cool Blue Light	Blue-Enriched	480	100	0.50
8:00 a.m. - 10:00 a.m.	Cool Blue Light	Blue-Enriched	480	200	0.60
10:00 a.m. - 12:00 p.m.	Bright White Light	White (6500K)	N/A	500	0.45
12:00 p.m. - 1:30 p.m.	Natural White Light	White (5500K)	N/A	400	0.35
1:30 p.m. - 3:00 p.m.	Warm White Light	Warm White (3000K)	N/A	200	0.20
3:00 p.m. - 5:00 p.m.	Warm Red Light	Red-Enriched	630	50	0.10
5:00 p.m. - 7:00 p.m.	Dim Red Light	Red-Enriched	630	30	0.05

Circadian Stimuli (CS) is a metric used to quantify the effectiveness of light in stimulating the human circadian system. It was developed to measure how much a given light source affects the circadian rhythm, particularly in regulating sleep-wake cycles, alertness, and mood.

SENSORS

Light Intensity Sensor: Detects the current light level in the room.

Ambient Light Sensor: Measures the color temperature of the existing light.

Time Zone Data Input: Provides sun position data to calculate the required temperature.

ALGORITHM:

The system will compare the detected light intensity with the ideal intensity from the lookup table.

If the room's current light intensity is lower than the ideal, the system will add a delta amount of light to reach the target intensity.

This algorithm will also convert the desired color temperature and intensity into RGB values using suitable for driving LEDs.

Inspiration for algorithm was borrowed from here, and modified since this did not give optimal results:

ColorTemp to RGB using Relative Intensity, Planck's Intensity Formula and L, M, S Receptors data of Humans

Actual algorithm used is similar to this and can be found on our GitHub Repo, but after finding out the Intensity of light through the Planck's method, we use the predefined Color Matching Functions from the CIE 1931 specification dataset (.csv), which provides a few constants to map the Intensity to the XYZ color space for each wavelength from 360nm to 830nm in steps of 1. These XYZ values are then converted to the sRGB space (which is close enough to RGB) through a linear transformation.

Proposed Method for Converting Color Temperature to RGB for LEDs

Converting the color temperature of light (measured in Kelvin) to RGB values (used in LED displays) is a complex but fascinating process that combines physics, color science, and mathematical transformations. Smith's method, which we'll explore, leverages the CIE 1931 color matching functions to accurately translate a given color temperature into the familiar RGB format.

1. Understanding Color Temperature and RGB

Color Temperature: The color temperature of a light source is expressed in Kelvin (K) and describes the hue of the light. For example, a lower temperature (e.g., 1900K) emits a warm, reddish light (like a candle), while a higher temperature (e.g., 6500K) produces a cooler, bluish light (like daylight).

RGB: RGB is a color model used in digital displays, where colors are created by mixing Red, Green, and Blue light at various intensities. The challenge is to convert a given color temperature (a physical property) into specific RGB values that can be used by LEDs.

2. The Role of the CIE 1931 Color Space

The **CIE 1931 color space** is a mathematical model that represents human color perception. It was developed by the International Commission on Illumination (CIE) in 1931 and is foundational to color science.

The core of this model is the **CIE 1931 XYZ color matching functions**. These functions describe how the human eye perceives light of different wavelengths and are used to convert physical light properties (like those described by Planck's Law) into a format that corresponds to human vision.

3. The Conversion Process in Smith's Method

Step 1: Calculate Spectral Radiance Using Planck's Law

Planck's Law describes the intensity of light emitted by a black body (an idealized physical body) at a given wavelength and temperature. For a specific color temperature, we calculate the spectral radiance across the visible spectrum (approximately 380 nm to 780 nm).

Mathematically, this is expressed as: $L(\lambda, T) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$

Where:

- λ is the wavelength of light.
- T is the color temperature in Kelvin.
- h is Planck's constant.
- c is the speed of light.
- k_B is Boltzmann's constant.

Step 2: Integrate with the CIE 1931 Color Matching Functions

The spectral radiance calculated for each wavelength is then integrated with the CIE 1931 XYZ color matching functions. These functions (denoted as $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$) represent the sensitivity of the human eye's color receptors (cones) to different wavelengths.

The integration across the visible spectrum yields the XYZ tristimulus values:

$$X = \int L(\lambda, T) \cdot \overline{x}(\lambda)\, d$$

$$Y = \int L(\lambda, T) \cdot \overline{y}(\lambda)\, d$$

$$Z = \int L(\lambda, T) \cdot \overline{z}(\lambda)\, d$$

These XYZ values are a direct representation of the color as perceived by the human eye.

Step 3: Convert XYZ to RGB Using a Transformation Matrix

The final step is to convert the XYZ values to RGB values using a linear transformation matrix specific to the RGB color space (e.g., sRGB).

The transformation is performed as follows:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.2406 & -0.9689 & 0.0557 \\ -1.5372 & 1.8758 & -0.2040 \\ -0.4986 & 0.0415 & 1.0570 \end{pmatrix} \begin{pmatrix} X \\ Y \\ B \end{pmatrix}$$

The resulting RGB values are then normalized and scaled to the 0-255 range typically used in digital displays.

4. Practical Application for LEDs

Once the RGB values are determined, they can be directly applied to control the intensity of red, green, and blue LEDs to reproduce the desired color corresponding to the input color temperature.

5. Example: Converting 6500K to RGB

Let's walk through an example of converting a 6500K color temperature (daylight) to RGB:

1. **Calculate Spectral Radiance**: Use Planck's Law to determine the intensity of light across the visible spectrum.
2. **Integrate with CIE 1931 Functions**: Combine this spectral data with the color matching functions to derive the XYZ values.
3. **Transform XYZ to RGB**: Apply the transformation matrix to obtain RGB values.

For 6500K, the process might yield RGB values close to [255, 255, 255], which represents white light—consistent with what we expect from daylight.

Conclusion

Smith's method, which uses the CIE 1931 color space and Planck's Law, is a robust and accurate way to convert color temperature to RGB values. It's widely used in fields like digital imaging, display technology, and LED lighting design, ensuring that the colors we see on screens or through lighting match our natural perception of those colors in the real world.

CHALLENGES WE MIGHT FACE

Since color temperature is an abstract value and we do not know of any hardware that can sense this quantity directly, we might have to use simple machine learning models like SVM, or simple classification models that at least tell us the range of color temperatures based on the data's location, sun position, weather and temperature, etc.. This color temperature is useful in the case where we want to adjust our lookup tables to be specific to that location. The algorithm for displaying a specified color temperature to an LED is based on an approximation and may be computationally expensive to run on hardware like the Arduino UNO. So, the algorithm is run on a computer and then the generated lookup tables are to be copied to the microcontroller. Although the case could be different if we are using more powerful microcontrollers like Raspberry Pi. The algorithm converts color temperature to RGB by first calculating the spectral radiance using Planck's Law, then integrating it with the CIE 1931 color matching functions to get XYZ values, which are finally transformed into RGB using a standard matrix. This approach ensures accurate color representation for LEDs based on human color perception.

NAIVE IMPLEMENTATION IN TINKERCAD (NOT YET INTEGRATED WITH THE ALGORITHM)

A brief idea of how the basic structure or working can be found here in a Tinker CAD Simulation where 24 hours of day are simulated in 24 seconds. (Data and Color temperatures were just hardcoded as of now, can apply the mentioned algorithm in the coming days). Here is the link: TinkerCad Simulation