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# Human centric lighting luminaires: practical design

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**Abstract**

Discoveries in medicine concerning the influence of light on human physiology provoked the creation of the Human Centric Lighting (HCL) approach. Research dedicated to this mainly focuses on optimally matching light parameters to human needs, e.g. increasing concentration, relaxation, etc. However, only a properly designed light source is capable of meeting HCL goals. This paper focuses on the LED luminaire design used in HCL systems. A review of LEDs dedicated to HCL systems was performed. Their advantages and disadvantages are discussed. The Tunable White (TW) design is shown to be the most universal solution for HCL systems because it enables regulation of the colour temperature and spectrum, depending on user needs. However, TW is also the most complex in design. The problems that might arise during TW luminaire design are discussed. Example strategies on how to solve them, focusing on colour mixing and LED arrangement are given. Practical examples of TW luminaire design are also described, each one with a commentary covering encountered issues and their solutions.

**Keywords:** human centric lighting, luminaire, circadian rhythm, LED, tunable white, colour mixing

## 1. Introduction

Since prehistoric times, artificial light has been crucial for human life. It allowed the extension of functioning hours and improved safety. The technology of artificial light has been developing intensively, striving to increase user comfort and decrease the resources needed. Illumination methods changed from fire (burning wood in campfires, candles and kerosene lamps) to electrical lighting (incandescent bulbs, discharge lamps, and finally LEDs) (Guarnieri 2018; Weisbuch 2018; Hebda 2022).

The development of electrical lighting has had a great impact on the environment and humanity. Many papers have been devoted to the investigation of the influence of artificial light on humans. The research can be divided into two branches. The first branch is the influence of light on human vision (image forming effects, not to be confused with imaging optics). The key parameters for this branch are the colour rendering index (CRI) and illuminance. An example of such research is a paper (Aarts 2017) focusing on the influence of lighting conditions on the performance of hospital personnel.

The second branch is the influence of light on the human body (non-image forming effects of light, not to be confused with non-imaging optics used in illumination), of which an important parameter is the correlated colour temperature (CCT). A review of state-of-the-art research on the non-image forming effects of light is presented in the work of L. Tähkämö (Tähkämö 2017). Artificial light can be one of the causes of diseases like cancer, Parkinson's disease, obesity and others. Many disease-causing mechanisms resulting from artificial lighting (e.g. illumination at night) are not yet fully understood. However, they are associated with disturbances to the circadian rhythm and cooperating hormone levels, i.e. melatonin and cortisol (Salgado-Delgado 2011; Gale 2011; Shanmugam 2013). More specifically, higher amounts of blue light inhibit melatonin production and start the production of cortisol, serotonin and dopamine, causing the subject to feel more awake and improving their levels of concentration (Keis 2014; Lledó 2019). In turn, a lack of blue light triggers the production of melatonin and promotes relaxation and sleep (Lledó 2019).

Based on the newest discoveries in the field of research on the influence of light on human health, the idea of Human Centric Lighting (HCL) has arisen. HCL can be defined as an approach to illumination design in order to meet human needs. It is known that properly designed illumination can improve efficiency as well as mental and physical well-being, and can even speed up recovery from ill health (Glotzbach 1993; Salgado-Delgado 2011; Bedrosian 2013; van Bommel 2022). The spectral characteristic and intensity of natural sunlight are unique, and are the most effective with regard to the stimulation of photosensitive cells, thus naturally controlling the circadian rhythm of the human body (Shanmugam 2013). In the HCL approach, lighting designers and manufacturers try to mimic natural sunlight and its changes in order to match the daily needs of the human body. Additionally, mimicking natural sunlight directly correlates with the best CRI values (sunlight – 100 CRI), leading to improved quality of observed colours. This makes HCL luminaires unparalleled in the field of illumination.

Recently, the HCL illumination market has been growing intensively. According to Zissis (Zissis 2021), the HCL market was estimated at 445.9 million USD in 2017 and is anticipated to reach 3.91 billion USD by 2024 growing at a CAGR of 35.2% during the forecast period. Such intense interest in HCL products might unfortunately provoke the creation of low-quality "HCL" luminaires, which appear to function (i.e. change light colour) but actually have poor light parameters (e.g. improper spectrum) and so might not have the expected results on human health.

A common HCL setup usually consists of a light source, sensors, and a control unit, which can be managed via an app to select an illumination mode (Yoon 2020). As discussed above, the main focus of research is controlling


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the light source to match the light intensity and spectrum to human needs (e.g. Jato 2016; Yoon 2020; Houser 2021). The light source itself is the key element because if the light source is unable to produce the required parameters, even the best control unit won't be able to change them. A poorly designed light source will negate all advantages of an HCL setup. The main optical design issues of any LED lighting are luminous efficiency, controllable light pattern and spatial colour uniformity (Wang 2017). The troublesome part of designing a light source for HCL application is connected with providing good light quality regardless of the colour setting. Most commonly, the role of the light source in an HCL setup will be filled by a luminaire, a complex item comprised of many components of which key HCL functions are fulfilled by LEDs and optical elements like lenses, reflectors and diffusers.

This article presents a discussion of the basic problems that can be encountered during an HCL-ready luminaire optical design and their solutions.

## 2. Biological basis of the HCL approach

Circadian rhythm regulation is strictly connected with retinal ganglion cells stimulation (Shanmugam 2013). Berson (2022) showed that specific kinds of retinal ganglion cells (ipRGCs, intrinsically photosensitive retinal ganglion cells) are sensitive to blue light. Thus, ipRGC is a third type of photoreceptor, aside from rods and cones. The peak of ipRGC spectral sensitivity is close to 484 nm (Fig. 1). However, unlike the image-forming rods and cones, these cells don't contribute to vision and only transmit blue light level information into the brain, functioning in a non-image forming manner.

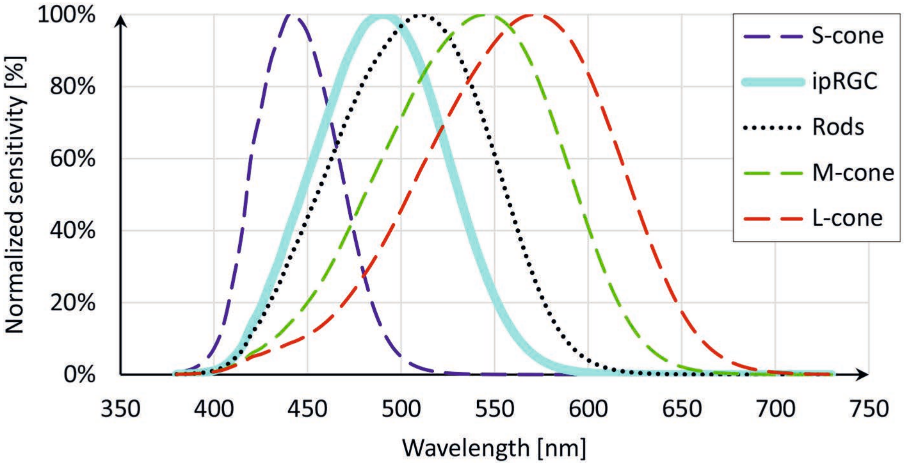


**Fig. 1.** Spectral sensitivity of human photoreceptors (source: CIE TN 003:2015)

The influence of light on the circadian rhythm can be verified in many ways, and every research facility recommends different methods. One of the most accurate parameters to measure is CS (Circadian Stimulus) (Rea 2005), based on the previously developed CLA (Circadian Light) (Rea 2005), quantifying the melatonin suppression property of light. Its creators, Lighting Research Center, included many variables in calculations, including duration of exposition, source spectrum, and balancing blue light with yellow light (Lighting Research Center 2023). Another popular parameter is the Melanopic Ratio, which is simpler to calculate, as it is just a ratio of melanopic light to photopic light (Brown 2020). EML (Equivalent Melanopic Lux) is also worth mentioning , which is directly connected with ipRGC sensitivity. Melanopic ratio and EML are often used by luminaire manufacturers to describe HCL luminaire properties (Brown 2020). Some example changes in the Melanopic Ratio for 2700 K, 4000 K and 6500 K of an LED light source are presented in Table 1 below, based on results obtained from routine tests performed in the laboratory of LUG Light Factory Sp. z o.o.

**Table 1.** Example changes of the Melanopic Ratio depending on the CCT of an LED light source (source: own study)

| CCT | Melanopic Ratio |
|---|---|
| 2700 K | 0.458 |
| 4000 K | 0.757 |
| 6500 K | 1.052 |

Based on the physiological reaction of the human body to light, there are two common colour combinations that can be applied in HCL. The first approach is to simply match the phases of sunlight, providing the human eyes with natural, peaceful stimulation by using cool light during the day and warm light in the morning and evening, as recommended by LightingEurope (LightingEurope 2017) (Fig. 2a). The second approach comes from the modern need for a boost of the circadian rhythm, matching human cortisol levels during the day. This colour sequence increases alertness during early morning work and decreases any sleep irregularity. To achieve these results, this colour combination is comprised of cool light in the morning and warm light in the evening (Houser Boyce 2021) (Fig. 2b). The choice between these two options depends on the goals of the designer: the first option will maximise comfort, while the second option will improve human efficiency. Example applications of these settings include hotels and resorts for the first colour scheme, and factories or offices for the second scheme. Furthermore, these are not the only possible colour combinations as it is simply a matter of programming the desired sequence, it would be possible to, for example, set colours to some compromise between these two presented examples (Fig. 2c). The only condition that needs to be provided regarding the colour sequence is that there must be warm light in the evenings and any blue light removed to avoid disturbing the circadian rhythm (this is common for all three examples in Fig. 2a,b,c).

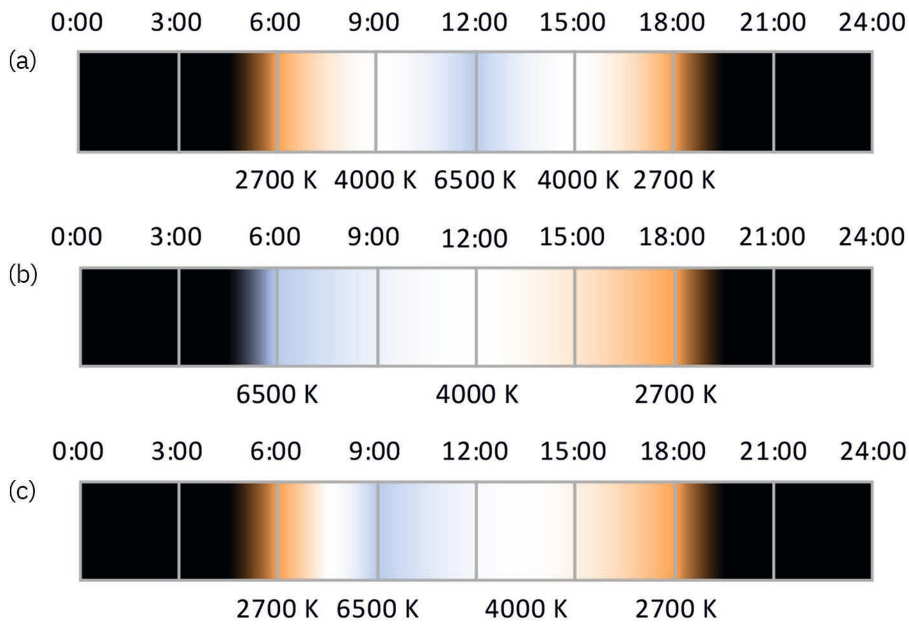


**Fig. 2.** Visualisation of basic colour combinations for HCL illumination: a) matching sunlight cycle (source: LightingEurope 2017, b) boosting the circadian rhythm (source: Houser Boyce 2021), c) compromise (source: own study)

Such sequences can be achieved in two ways, either by completely relying on artificial light with Tunable White luminaires (e.g. in hospitals), or by augmenting natural light with luminaires that have constant specific light spectrum for a defined period of time (e.g. cool white light in classrooms) (Keis 2014).

Using LEDs as a light source is the most popular and versatile solution, which makes the LEDs the main element defining the spectral parameters of artificial light. To present the spectral difference between sunlight and

LED, the spectrum of sunlight at astronomical noon (real case instead of CIE standard illuminant D65) has been measured and paired with a basic spectrum of 6500 K LED (cool daylight), as presented in the graph in Fig. 3. The 6500 K LED result comes from routine luminaire testing at the laboratory of LUG Light Factory Sp. z o.o. The sunlight measurement was performed using a Spectis 5.0 Touch spectrometer in favourable weather conditions in an area with relatively low atmospheric pollution and a clear cloudless sky. Naturally, the presented sunlight spectrum is an example result. It is important to keep in mind that the results could slightly change in different weather conditions, with different measurement method and at different times of day. Generally the sunlight spectrum can be expected to appear relatively even in the main part of the visible spectrum.

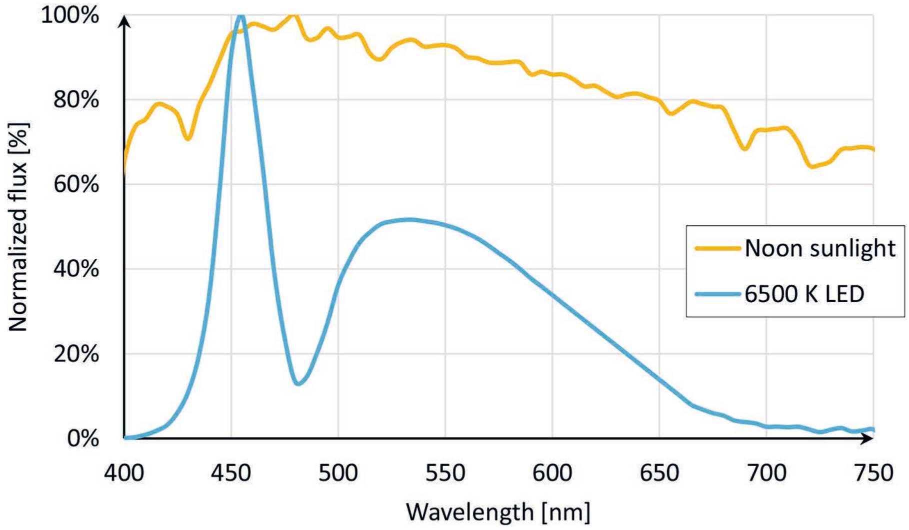


**Fig. 3.** Example of a basic 6500 K LED spectrum, and sunlight spectrum at noon (normalised) (source: own study)

It should be mentioned here that sunlight and LEDs are not the only factors to be considered regarding the light spectrum important for the human circadian rhythm. Another factor is the surrounding environment. Focusing on, for example, the office setting, the view from an office window rarely includes the direct view of the sun. More often, it presents the sky (possibly cloudy), surrounding buildings and plants, and maybe some part of pavement on the ground, all of which provide reflected or filtered sunlight from their surfaces. Not only this, office windows are usually comprised of glass and sometimes have additional filters, e.g. UV or privacy mirror films, which further change the spectrum reaching the observer. An example spectrum measurement was first performed through an open window and then in the same position through a closed window with a UV mirror filter. The measurements were performed again using the Spectis 5.0 Touch spectrometer, with the spectrometer head directed perpendicularly to the window surface.

Using the spectral data from the measurements, the transmission of the window with the filter was calculated and the obtained graph is presented in Fig. 4. IpRGC sensitivity is plotted on the same graph to emphasise the problematic influence of this filtering window. First of all, the filter lets through only approximately 30% of light, which is a significant waste. Concerning specifically the biologically active part of the spectrum (cyan), the transmission at 480 nm is only 26.6%. Such intensity may not be sufficiently stimulating for some people, and could result in sleepiness and disruption of the circadian rhythm. On a positive note, this filtering window is quite effective at eliminating UV light, so at least any UV damage is avoided.

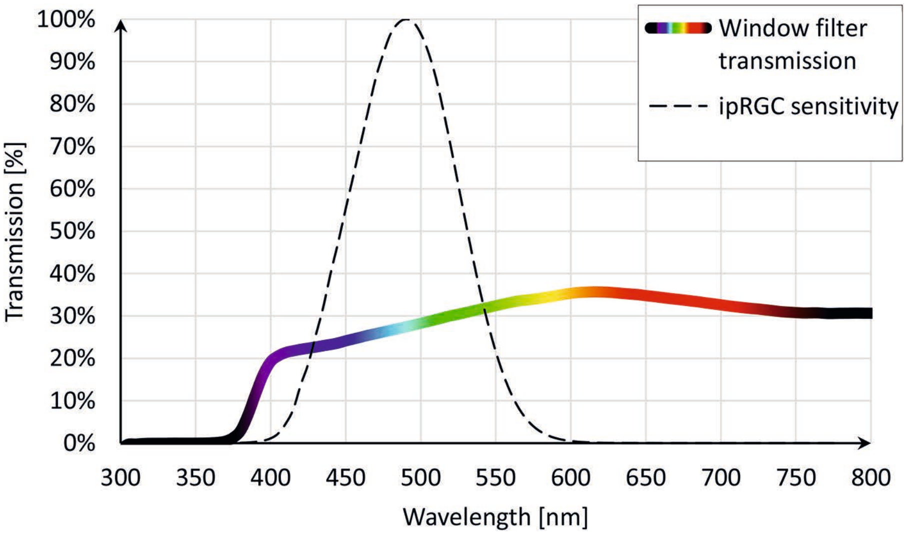


**Fig. 4.** Graph of spectral transmission of the example window with filter (source: own study)

## 3. LEDs used in HCL solutions

LED luminaires can be successfully used to improve working conditions. For Human Centric Lighting there are plenty of options available from LED manufacturers. They can be classified into three main groups: full (solar) spectrum, Equivalent Melanopic Lux (EML) optimised, and Tunable White (TW).

### 3.1. Full spectrum LED

The idea behind LEDs with a "solar" spectrum comes from the fact that the standard LED spectrum is noticeably different from that of sunlight (Fig. 3). In practice, this results in colours looking slightly different, usually some are less vibrant in LED light than in sunlight. Thus, LED manufacturers managed to come up with a different technology, creating an LED with a more natural spectrum which is closer to sunlight.

Examples of LEDs with a "solar" spectrum:

- Bridgelux Thrive (Bridgelux 2023),
- Seoul Sunlike (Seoul 2023),
- Nichia Optisolis (Nichia Optisolis 2023),
- Refond SunX (Refond 2023).

### 3.2. EML optimised LED

The second group, EML (Equivalent Melanopic Lux) optimised LED, is also motivated by the difference between the standard LED spectrum and the sunlight spectrum. However, here the LED manufacturers took a different approach – they focused on the key flaw of the LED spectrum, the "cyan gap" (wavelengths around 480 nm, between blue and green). The basic spectrum of an LED (Fig. 3) has lower intensity near the cyan colour, and the EML optimised LEDs solve this. The solution that can be applied here is to augment the white LED spectrum precisely by adding a boost of cyan light.

Examples of LEDs with EML optimised spectrum:

- Lumileds SkyBlue (Lumileds 2023),
- Luminus Salud (Luminus 2023),
- Nichia Vitasolis (Nichia Vitasolis 2023),
- Samsung Day (Samsung 2023).


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### 3.3. Tunable white

An significant flaw of both of these solutions (solar and EML optimised) is that they cannot change their spectrum to match the time of day. Additionally, high levels of blue light might work well for illumination in the morning or during the day (to increase alertness); however, using such light in the evenings or at night will lead to melatonin suppression and can disturb the circadian rhythm. The third group of Tunable White LEDs is free from this flaw.

While the previous two groups focused on improving the spectrum, this group focuses on the idea of matching the illumination CCT to human needs. To make this idea a reality, essentially at least two mixed light sources are needed (e.g. cool white and warm white) and a controller to manage light parameters. Focusing on the light source, there are two options: either enclosing two differently coloured chips inside one single LED package (Fig. 5a), or placing two LEDs next to each other (Fig. 5b).

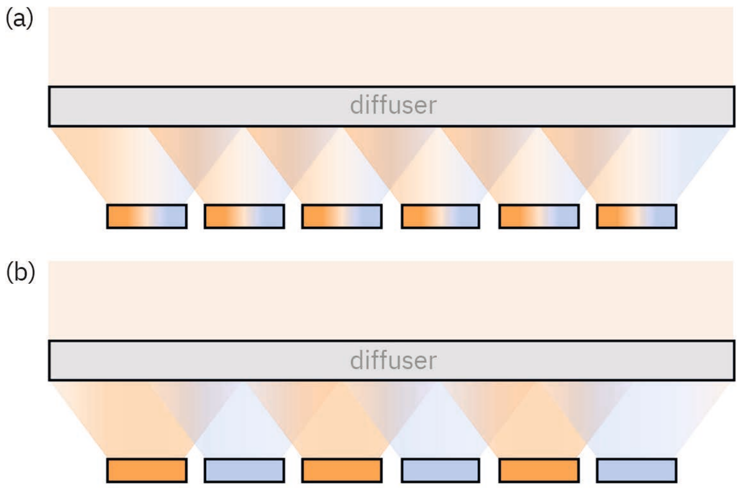


**Fig. 5.** Two approaches to Tunable White LEDs: a) single-package, b) pairs of LEDs (source: own study)

Nichia Tunable White LED is an example of a Tunable White LED in a single package (Nichia Tunable White 2023). Unfortunately other renowned LED producers don't offer this type of LED.

At first glance, it would appear that the single-package TW LED is a great design with better colour mixing. Unfortunately, the single-package approach comes with a set of problems. The main problem is accessibility – currently only one reliable manufacturer offers such a solution, so in the event of some

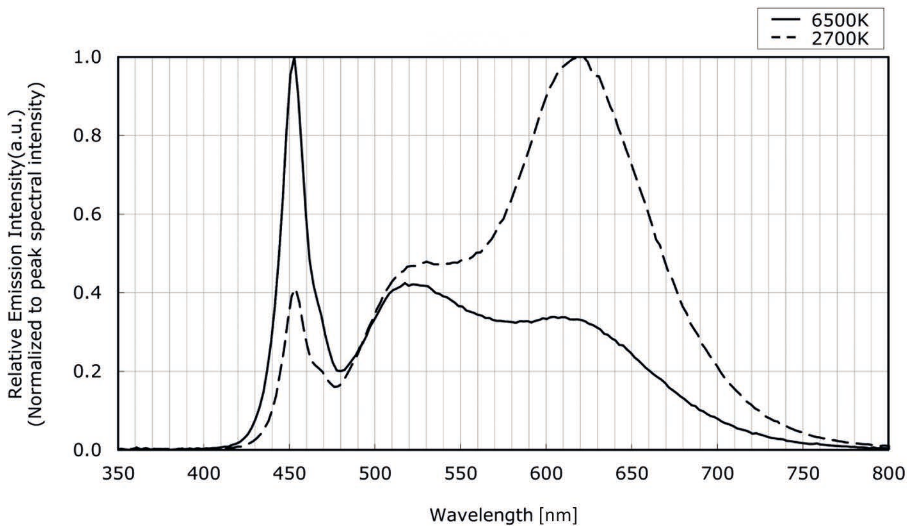


**Fig. 6.** Spectrum change of the Nichia Tunable White 90CRI (source: Nichia Tunable White (2023))

unforeseen supply problems, it will be hard to get a replacement. Concerning specifically this product, it has a noticeably lower flux, which forces a luminaire designer to fit in more LEDs on a single PCB than has been used before (in extreme cases the required number of LEDs could exceed the available space on a PCB), which leads to cost increase. Furthermore, this LED itself has a relatively higher price compared to other diodes because of the unique Tunable White design. Moreover, the spectrum of this LED is not ideal for HCL, as the cyan dip appears to change only slightly, and is quite noticeable regardless of CCT setting (Fig. 6).

The most advantageous approach is to use pairs of cool and warm white LEDs. With this approach, it is possible to minimise costs and optimise the spectrum by selecting LEDs with appropriate parameters to meet HCL requirements i.e. higher and lower values in the range of ipRGC sensitivity. An example of HCL spectra for three main CCT is presented in Fig. 7 (measurements performed in the laboratory of LUG Light Factory Sp. z o.o.).

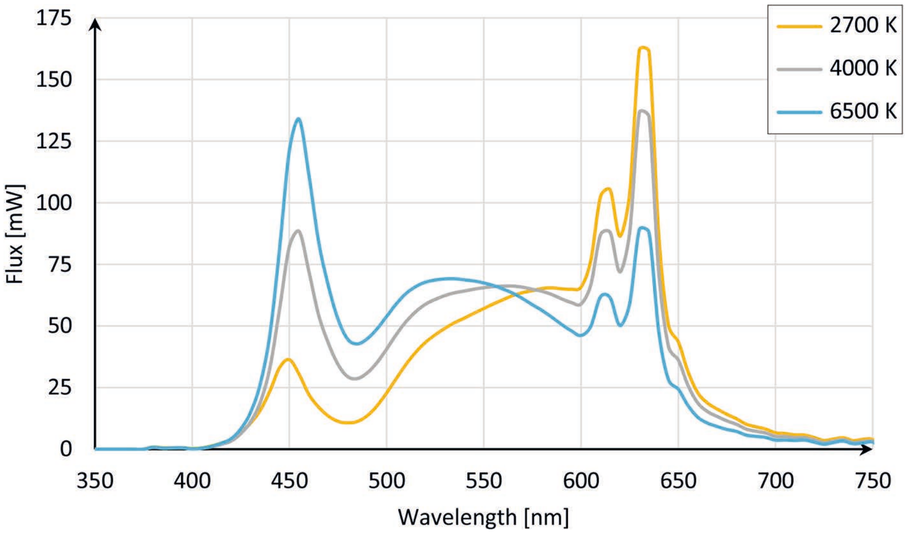


**Fig. 7.** Example spectrum differences between CCT at 90 CRI, 6500 K (cool), 4000 K (neutral) and 2700 K (warm) (source: own study)

This solution is the most universal of all the discussed options, and the lower cost of manufacturing such a luminaire results in a lower final price of the product, which in turn makes it more competitive on the market. For this reason, this article will focus on the approach of using LED pairs. To design such TW luminaires, in theory, a designer would only have to replace single colour LEDs with LEDs of two different colours. The leading problem with designing luminaires using this approach is colour mixing; this has to be taken into consideration during the PCB design and optics selection.

## 4. Colour mixing of LED pairs

The PCB design begins with LED selection. As discussed above, either a single LED with chips with different colour temperatures inside one package (Fig. 5a) or two LEDs with different colour temperatures (Fig. 5b) could be chosen. In the first case, the LED placement won't have any meaningful influence on colour mixing because both colours are coming from the same LED package, although the LED package itself might have some colour-mixing elements. In the second case, with two LED colours, the LED placement can make the difference between a smooth Tunable White transition (the goal) and a basic dual-coloured luminaire (not acceptable).

The next design step is the selection of optics. Depending on the desired illumination effect, there are various options. Regardless of this, the designer must make sure that the optics will cooperate well with the selected LEDs and match their placement, as well as making sure the resulting light will be uniformly mixed. The simplest approach is to either cover the PCB with a diffuser or to add a diffusive surface to the optics (rough surface on lens or reflector). This approach, however, will result in the widening of the light distribution, which is not always desirable. Another (more advanced) solution is the addition of a colour-mixing structure to lens or reflector surface, which is usually a pattern of concavities or convexities. Because this method provides much more control over the light beam, the resulting light distribution can be as designed.

Fig. 8 presents examples of colour-mixing optics, showing their models (top) and illumination spots (bottom). To better visualise the colour-mixing properties, an RGBW LED was used as a light source. The lens in Fig. 8a has a rough top surface for the purpose of colour mixing, while the lens in Fig. 8b has a colour--mixing structure.

(a) (b)

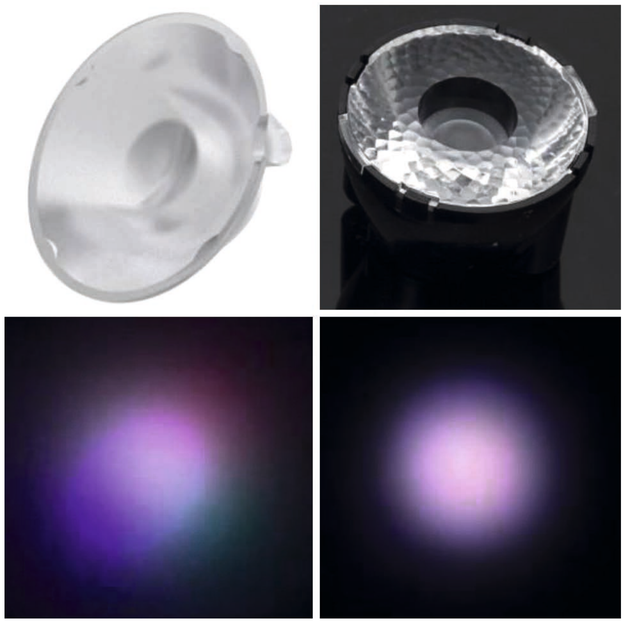

**Fig. 8.** a) Manufacturer A: frosted TIR lens (top) and its illumination spot (bottom) (source: Carclo Optic 10756 2023), b) Manufacturer B: TIR lens with mixing structure (top) and its illumination spot (bottom) (source: LEDiL CA16202 2023)

A separate problem concerning optics selection is the fact that LED optics are usually designed with the assumption that the LED source will be placed in the centre. But if differently coloured LEDs (or chips in one LED) are used, the light source will be off-centre for single LED settings, resulting in a slightly different light distribution for each LED in the pair. Usually, this problem can be somewhat remedied by placing LEDs in an alternating order (in the case of sets of two LEDs), or rotating the LEDs (e.g. each rotated 90° or 180°) with respect to its neighbours (in the case of LEDs with multicolour chips).

To demonstrate these principles, a linear lens (Fig. 9) was chosen and tested using two TW PCBs with different LED arrangements (LEDs of the same colour in two rows, and LEDs in alternating colour pairs), PCBs are presented in Fig. 10,

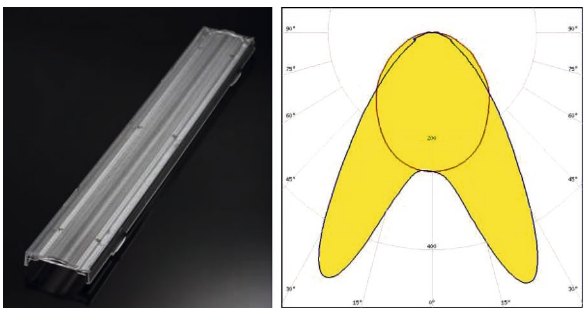

**Fig. 9.** Double-asymmetric linear lens (left) and its light distribution (right) (source: LEDiL F15860 2023)

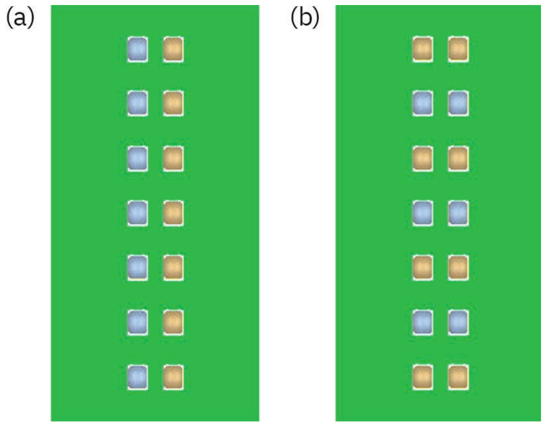


**Fig. 10.** Test PCB modules visualisation: a) 1st PCB – two rows, b) 2nd PCB – alternating pairs (source: own study)

and illumination results are presented in Fig. 11. Both cases demonstrate the problem that the light source misses the centre of the lens, thus resulting in a double-shifted light distribution. More importantly, they show a clear influence of LED arrangement on colour mixing.

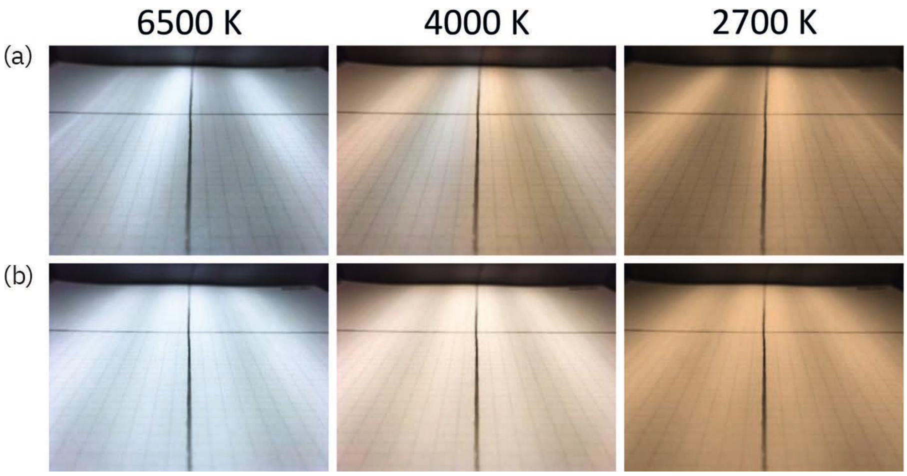


**Fig. 11.** Illumination results of F15860 LINNEA lens for settings 6500 K, 4000 K, 2700 K, obtained using: a) 1st PCB – two rows, b) 2nd PCB – alternating pairs (source: own study)

During optics selection or design, it is also important to take into consideration the basic optical properties like colour dispersion or source imaging (for very narrow light distributions). Ironically, these problems occur only if the optical setup is too perfect, i.e. ideal smooth clear lenses, closer in design to imaging optics instead of illumination optics. Below, in Fig. 12, the basic imaging principle is presented, causing unwanted projection of the

$$\frac{1}{f}=\frac{1}{s_1}+\frac{1}{s_2}$$

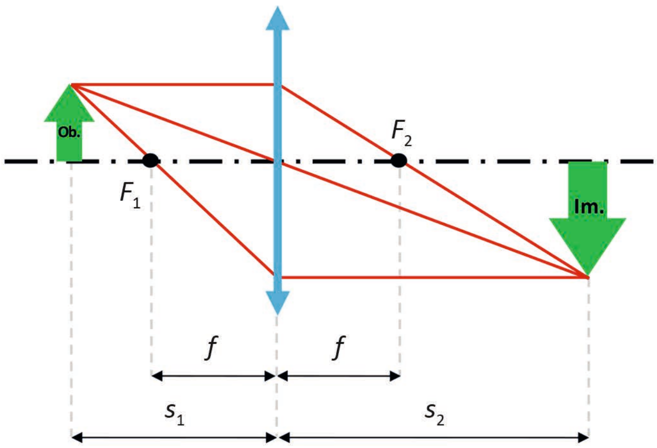


**Fig. 12.** Basic ray optics imaging principle (source: own study based on Landsberg 2003)


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LED structure (Landsberg 2003). Good illumination optics should fully mix the LED structure image, resulting in a uniform Gaussian spot; however, if a lens is similar to imaging optics, then the resulting spot can show LED structural details. This phenomenon is also known as "yellow ring", since it commonly presents as a partially blurred spot, with a white area from the projected LED die structures, surrounded by a yellow circle from projected phosphor. An extreme example of this phenomenon is visible in Fig. 13.

(a) (b) (c)

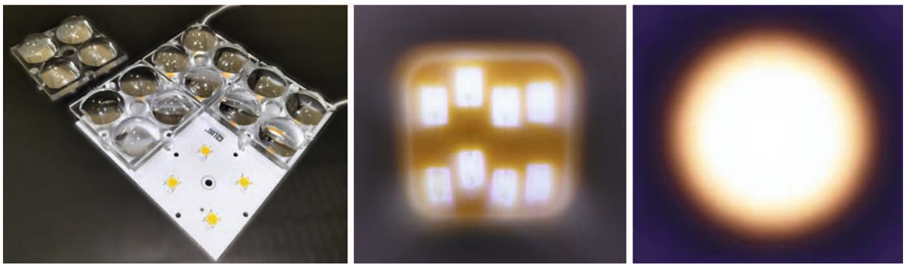

**Fig. 13.** LED structure projection by a narrow--beam illumination lens, a) PCB with lenses, b) unwanted projected LED structure, c) yellow ring spot (source: own study)

The colour-dispersion property is demonstrated on the plot in Fig. 14, showing the refractive index dependence on wavelength. As examples, two materials are used: PMMA and PC, which are common for illumination lenses. Comparing these two plots, it is possible to observe that the slope for PC is steeper than for PMMA, which suggests that the colour dispersion from PC will be more pronounced.

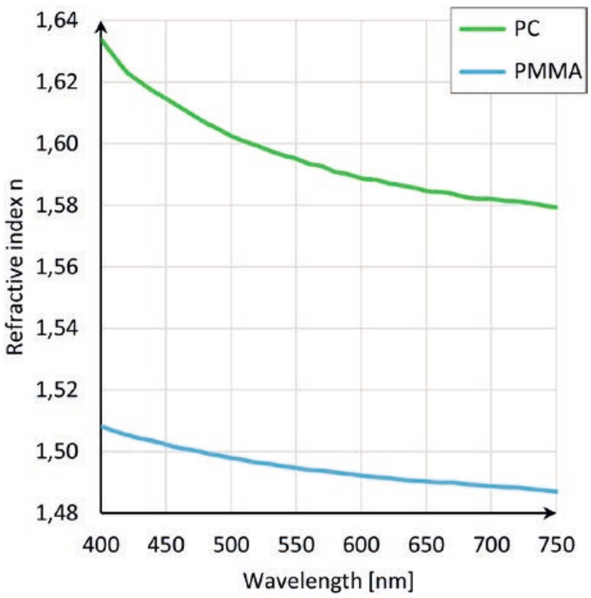


**Fig. 14.** Material refractive index dependence on wavelength in visible range, examples of PC and PMMA (source: Polyanskiy 2023)

Specifically for HCL Tunable White luminaires, these two issues could result in light distribution changes depending on the colour temperature. Even if the colours seem mixed, dispersion might accentuate the spectral differences between colour temperatures or the LED chip structures could be projected onto the illuminated surface instead of just a uniform light spot.

## 5. Practical examples

During HCL luminaire design, it is common practice to use already existing luminaire mechanical designs. In accordance with the scientific research project entitled "Industrial and experimental research development work on the development lighting solutions in the field personalization of lighting, with taking into account chronobiology – possible implications in innovation lighting fixtures". (Agreement No. RPLB.01.01.00-08.0023/19-01), under Priority Axis 1. Economy and innovation, Measure 1.1 Research and innovation of the Regional Operational Program – Lubuskie 2020, co-financed by the European Fund Regional Development , several LUG Light Factory Sp. z o.o. luminaires have been converted and are available in HCL-ready TW versions. From these, three luminaires were selected as examples in order to demonstrate problems that can be encountered during HCL luminaire design.

### 5.1. Recessed luminaire: Softielight

The Softielight luminaire contains two light sources, which emit two beam types: ambient light and direct light. Both sources have linear LED modules situated in the luminaire middle, one above the other. The direct light simply exits the middle beam, with light distribution providing low UGR. The ambient part relies on reflections inside the luminaire and side diffusers releasing the light (Fig. 15) (Softielight 2023).

**Fig. 15.** General view of Softielight luminaire (source: LUG source materials)

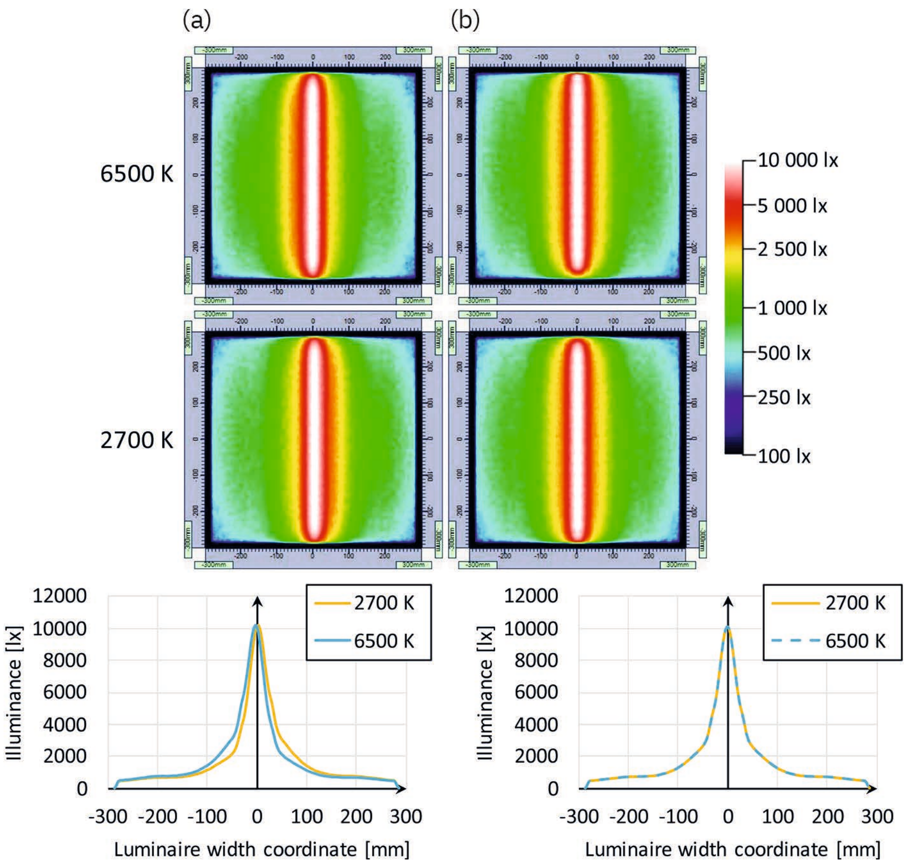


**Fig. 16.** Simulated illumination distribution (log scale) on the luminaire surface for CCT 6500 K and 2700 K (top), and middle section graphs (bottom) (source: own study)


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To convert this luminaire to TW, LED modules needed to be replaced. The first module designed was the version used in Fig. 10a, and the illumination results were slightly asymmetric, as presented in the figures below (Fig. 16a). The conclusion was that the LEDs on the module needed to be alternating (Fig. 10b). As expected, the results with such a module were uniform (Fig. 16b). These visualisations were created in professional optical simulation software.

### 5.2. Downlight luminaire: Lugstar

The Lugstar luminaire is a downlight, consisting of an LED module covered with a diffuser and enclosed in a reflector (Fig. 17) (Lugstar 2023). This solution doesn't include any lenses. However, an important restriction was that the distance between the diffuser and the PCB couldn't be changed without redesigning of the reflector, and manufacturing a new reflector is an unnecessary cost. Thus, proper colour mixing had to be achieved only by LED arrangement, while at the same time taking electrical requirements into consideration. To save the cost of manufacturing PCB prototypes, colour mixing was tested in a simulation using professional optical simulation software, and the results for two different PCBs are presented in Fig. 18, for CCT 2700 K, 4000 K and 6500 K. The initial LED arrangement (Fig. 18a), which was designed prioritising electrical simplicity, had an unsatisfactory colour mixing result. For this reason, another PCB was designed only this time with LEDs arranged in a more alternating sequence and this yielded acceptable optical simulation results (Fig. 18b) leading to this PCB being manufactured and implemented into the product.

**Fig. 17.** General view of the Lugstar luminaire (source: LUG source materials)

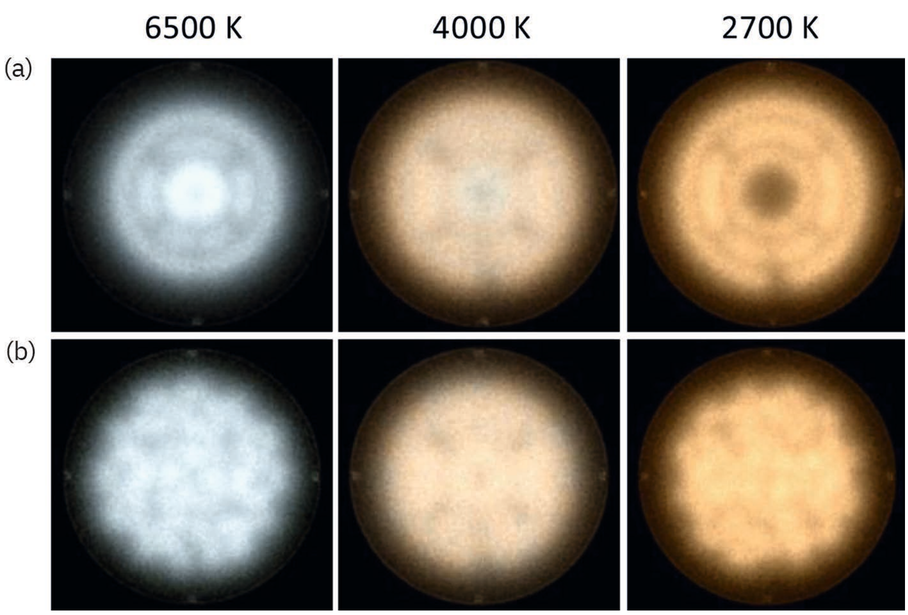


**Fig. 18.** Lugstar simulated illumination results for settings 6500 K, 4000 K, 2700 K a) initial TW PCB LED arrangement, b) final TW PCB LED arrangement (source: own study)

https://doi.org/10.37705/TechTrans/e2024002

### 5.3. Clean room luminaire: Medica

Medica is a direct light luminaire, consisting of LED modules with backlight type lenses and covered with a diffuser (Fig. 19) (Medica 2023). The challenge with this luminaire was the presence of lenses. The LED modules needed to be replaced as in the previous examples, and the new modules had TW LED pairs instead of single LEDs, which meant that the lenses were no longer able to fit.

**Fig. 19.** General view of the Medica luminaire (source: LUG source materials)

There were two solutions to this problem: either designing new lenses or removing the lenses and adjusting the distances between components, e.g. bringing the LEDs closer to each other and increasing the distance between the LEDs and the diffuser. As shown in previous research (Wang 2017), the design of lenses is a complex process that requires time and resources. Moreover, the design of a new method for fixing the lenses to the modules is required because the previously used method cannot be applied to a different lens. Furthermore, it shouldn't be forgotten that each lens has some cost, and reducing cost is always welcome. Therefore, lenses were removed and distances between luminaire parts were adjusted, keeping in mind the maximal luminaire dimensions acceptable for the customer. The visualisations were obtained using professional optical simulation software and are presented in Fig. 20.

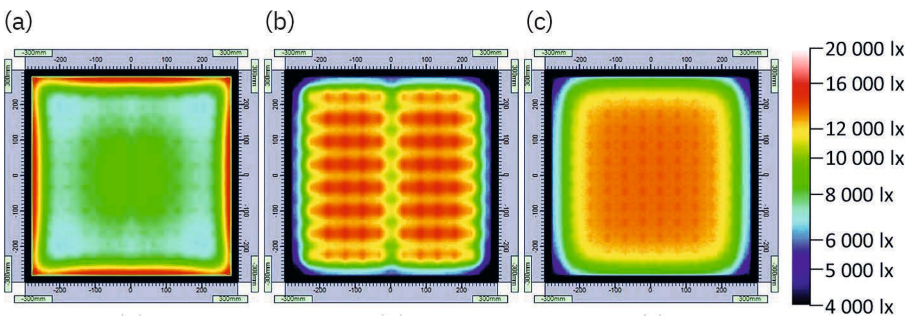


**Fig. 20.** Simulated illumination distribution (log scale) on the diffuser surface for: a) original Medica with lenses, b) original Medica without lenses and before placement adjustments, c) Medica TW after placement adjustments (source: own study)

## 6. Conclusions

Artificial light is an unavoidable part of modern human life. Its influence on human vision and the body has been a common topic of scientific research and has led to the development of the Human Centric Lighting idea. The key to HCL was sunlight, as the human body evolved to be reliant on the light intensity and spectrum of the sun. The breakthrough in this branch of research was the discovery of ipRGCs, a third type of photoreceptor that doesn't participate in vision, but plays a major role in the circadian rhythm. This photoreceptor is sensitive to light wavelengths around cyan (peak at 484 nm) and causes hormone level changes leading to alertness if a high enough amount of such light is detected, or relaxation if this light is minimised. Such data can be incorporated into the HCL colour sequence, providing relaxation or alertness depending on the time of day and the current needs.

The most optimal light source for HCL is the LED luminaire. LEDs themselves are a very efficient and good quality light source. LED manufacturers are constantly improving their properties and providing a wide variety of options that can be used in HCL luminaire designs. Solutions available on the market can be divided into sources with a constant spectrum and sources with an adjustable spectrum. HCL-specific LEDs with a constant spectrum usually have some improvements around the "cyan gap" of the LED spectrum. The adjustable spectrum in LEDs is achieved by using pairs of LEDs with cool and warm colour temperatures, commonly known as TW. Because of the ability to adjust the colour sequence to client needs, the TW solutions are the most popular.

There are common technical issues in the HCL luminaire design process. These must be worked out when designing and implementing an HCL luminaire. Moreover, it is also important that the product meets all the aesthetic requirements of the market. The light distribution and uniformity of illumination on the luminaire surface are subject to verification when the target customer comes into contact with the final product. In the context of biologically stimulating lighting, paying proper attention to the optical solution brings benefits both in terms of the level of the light's impact on the user's perception of the illuminated space and the quality of the lighting. Simulations, whether they be mechanical, electrical or especially optical, greatly accelerate the design process, allow for the avoidance of undesirable phenomena, optimise the quantity and quality of components, minimise production costs and maximise the desired results. Note that the appropriate method to achieve the desired HCL luminaire features will vary depending on the mechanical design of the luminaire, the customer's requirements and the approach to tunable white technology itself.

## References

Aarts, M.P.J., Rosemann, A.L.P., van Loenen, E.J., Kort, H.S.M. (2017). Influence of light condition on medication care in a hospital. In *Lighting for Modern Society: Proceedings of the Lux Europa 2017* (pp. 202-206). Lighting Engineering Society of Slovenia.

Bedrosian, T. A., Nelson, R. J. (2013). Influence of the modern light environment on mood. *Molecular Psychiatry*, *18*, 751–757. https://doi.org/10.1038/mp.2013.70

Berson, D. M., Dunn, F. A., Takao, M. (2022). Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock. *Science*, *295*(5557), 1070–‒1073. https://doi.org/10.1126/science.1067262

Bridgelux Thrive™ Features & Benefits. (2023). Retrieved from https://www.bridgelux.com/products/thrive#features (date of access: 2023/06/06).

Brown, T.M. (2020). Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. *J Pineal Res.*, *69*: e12655. https://doi.org/10.1111/jpi.12655

Carlo Optics. Optic 10756 Led Cree XLamp XM-L Color G2 HI RGBW. (2023). Retrieved from https://www.carclo-optics.com/optic-10756-led-cree-xlamp-xm-l-color-g2-hi-rgbw (date of access: 2023/06/06).

CIE Technical note 003 (2015). Report on the First International Workshop on Circadian and Neurophysiological Photometry.

European Commission, Joint Research Centre, Zissis, G., Bertoldi, P., Serrenho, T. (2021). *Update on the status of LED-lighting world market since 2018*, Publications Office. https://data.europa.eu/doi/10.2760/759859

Gale, J.E., Cox, H.I., Qian, J., Block, G.D., Colwell, C.S., Matveyenko, A.V. (2011). Disruption of circadian rhythms accelerates development of diabetes through pancreatic beta-cell loss and dysfunction. *Journal of Biological Rhythms*, *26*(5), 423–433. https://doi.org/10.1177/0748730411416341

Glotzbach, S.F., Rowlett, E.A., Edgar, D.M., Moffat, R.J., Ariagno, R.L. (1993). Light variability in the modern neonatal nursery: Chronobiologic issues.

*Medical Hypotheses*, *41*(3), 217–224. https://doi.org/10.1016/0306-9877(93)90234-H
Guarnieri, M. (2018). An Historical Survey on Light Technologies. *IEEE Access*, *6*, 25881–25897. https://doi.org/10.1109/ACCESS.2018.2834432
Hebda, O. (2022) Systemowe podejście do analizy niezawodności infrastrukturalnych opraw LED. *Przegląd Elektrotechniczny*, *08*, 57–62. https://doi.org/10.15199/48.2022.08.11
Houser, K.W., Esposito, T. (2021) Human-Centric Lighting: Foundational Considerations and a Five-Step Design Process. *Frontiers in Neurology*, *12*, 1–13. https://doi.org/10.3389/fneur.2021.630553
Houser, K., Boyce, P., Zeitzer, J., Herf, M. (2021) Human-centric lighting: Myth, magic or metaphor? *Lighting Research & Technology*, *53*(2), 97–118. https://doi.org/10.1177/1477153520958448
Jato, O., Weier, M., Maiero, J., Scherfgen, D., Roth, Th., Frericks, Ph., Stefani, O., Bues, M., Hinkenjann, A., Kruijff, E. (2016). OLIVE: Simulation within Human-Centric Lighting Environments. In *Virtuelle und Erweiterte Realität*. *13*. *Workshop der GI-Fachgruppe VR/AR* (pp. 45-52), Aachen: Shaker Verlag.
Keis, O., Helbig, H., Streb, J., Hille, K. (2014). Influence of blue-enriched classroom lighting on students' cognitive performance. *Trends in Neuroscience and Education*, *3*(3–4), 86–92. https://doi.org/10.1016/j.tine.2014.09.001
Landsberg, G.S. (2003). Optika. Moskwa: Izdatelskaya firma "Fiziko--matematicheskaya literatura".
LEDiL CA16202 GABRIELLA lens. (2023). Retrieved from https://www.ledil.com/product-card/?product=CA16202_GABRIELLA-MIDI-S&model=XM-L+RGBW+%28XMLDCL+HI%29 (date of access: 2023/06/06).
LEDiL F15860 LINNEA lens. (2023). Retrieved from https://www.ledil.com/product-card/?product=F15860_LINNEA-Z2T25 (date of access: 2023/06/06).
Lighting Research Center (2023). Retrieved from https://www.lrc.rpi.edu/ (date of access: 2023/06/06).
LightingEurope (2017) Joint position paper by LightingEurope and the International Association of Lighting Designers (IALD) on Human Centric Lighting.
Lledó, R. (2019). Human Centric Lighting, a New Reality in Healthcare Environments. In: Cotrim, T., Serranheira, F., Sousa, P., Hignett, S., Albolino, S., Tartaglia, R. (eds). *Health and Social Care Systems of the Future: Demographic Changes, Digital Age and Human Factors*. HEPS 2019. Advances in Intelligent Systems and Computing, (1012). Cham.: Springer. https://doi.org/10.1007/978-3-030-24067-7_3
Lugstar 3.0 Tunable White. (2023). Retrieved from https://www.luglightfactory.com/en/products/downlight-luminaires/LUGSTAR_3_0_TUNABLE_WHITE (date of access: 2023/06/06).
Lumileds Luxeon SkyBlue. Overview. (2023). Retrieved from https://lumileds.com/products/human-centric-lighting/luxeon-skyblue/ (date of access: 2023/06/06).
Luminus. Salud specialty illumination SMD LEDs. (2023) Retrieved from https://luminus.com/products/salud (date of access: 2023/06/06).
Medica 2.0 Tunable White. (2023). Retrieved from https://www.luglightfactory.com/en/products/clean-room-lighting/MEDICA_2_0_TUNABLE_WHITE (date of access: 2023/06/06).
Nichia Optisolis. Product features.(2023). Retrieved from https://led-ld.nichia.co.jp/en/product/lighting_optisolis.html (date of access: 2023/06/06).
Nichia Tunable White (2023). Retrieved from https://led-ld.nichia.co.jp/en/product/lighting_tunablewhite.html (date of access: 2023/06/06).
Polyanskiy, M.N. (2023). *Refractive index database*. Retrieved from https://refractiveindex.info (date of access: 2023/06/07).

Rea, M.S., Figueiro, M.G., Bullough, J.D., Bierman, A. (2005). A model of phototransduction by the human circadian system. *Brain Research Reviews*, *50*, 213–228. https://doi.org/10.1016/j.brainresrev.2005.07.002

Refond. Product catalogue. Retrieved from https://www.hev-electronic.com/Aton/FileRepository/Pdf/Refond%20product%20series.pdf (date of access: 2023/06/06).

Salgado-Delgado, R., Osorio, A.T., Saderi, N., Escobar, C. (2011). *Disruption of Circadian Rhythms: A Crucial Factor in the Etiology of Depression. Corporation Depression Research and Treatment*. Retrieved from https://downloads.hindawi.com/journals/drt/2011/839743.pdf (date of access: 2023/06/06). https://doi.org/10.1155/2011/839743

Samsung LM302N DAY. Tech spec. (2023). Retrieved from https://www.samsung.com/led/lighting/mid-power-leds/3030-leds/lm302n-day/ (date of access: 2023/06/06).

Seoul SunLike. Technology that returns natural light to humans. (2023.) Retrieved from http://www.seoulsemicon.com/en/technology/sunlike/lineup/ (date of access: 2023/06/06).

Shanmugam, V., Wafi, A., Al-Taweel, N., Büsselberg, D. (2013) Disruption of circadian rhythm increases the risk of cancer, metabolic syndrome and cardiovascular disease. *Journal of Local and Global Health Science*, *1*, 1–42. https://doi.org/10.5339/jlghs.2013.3

Softielight Tunable White. (2023). Retrieved from https://www.luglightfactory.com/en/products/louver-&-recessed-luminaires/SOFTIELIGHT_TUNABLE_WHITE (date of access: 2023/06/06).

Tähkämö, L. (2017) Sustainable residential lighting practices and light pollution. In *Proceedings of the 9th international conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL '17), Part III* (pp. 1147-1160). Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/113534

van Bommel, W. (2022). Human-Centric Lighting. In: Shamey, R. (Eds.) Encyclopedia of Color Science and Technology. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-27851-8_426-1

Wang, K., Liu, Sh., Luo, X., Wu, D. (2017). Freeform Optics for LED Packages and Applications. Singapore: John Wiley & Sons Singapore Pte. Ltd. https://doi.org/10.1002/9781118750001

Weisbuch, Cl. (2018). Historical perspective on the physics of artificial lighting. *Comptes Rendus Physique*, *19*(3), 89–112. https://doi.org/10.1016/j.crhy.2018.03.001

Yoon, S. H., Lee, K. S., Cha, J. S., Mariappan, V., Lee, M. W., Woo, D. G., & Kim, J. U. (2020). Indoor surveillance camera based human centric lighting control for smart building lighting management. *International Journal of Advanced Culture Technology*, *8*(1), 207–212. https://doi.org/10.17703/IJACT.2020.8.1.207