Non-visual Effects of Light on Humans: Spectral Tuning and Light Distribution with Freeform Optical Structures

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Nowadays most people spend the majority their day inside, where they are exposed to artificial lighting, which are mainly provided by LED luminaires. Light is the most important "Zeitgeber" for the circadian rhythm of our inner clock [1]. It triggers non-visual effects such as alertness, cognitive performance and sleep. Sunlight, upon which humans have evolved, changes its spectrum and intensity through the day. In accordance, many studies have investigated the non-visual effects of the spectrum and the intensity of light on humans. Sunlight is also dynamic in its direction. It is known that the distribution of non-visual photoreceptors in the retina is non-uniform. This shows the potential to develop professional lighting with respect to non-uniform illumination. The project aims to produce optimized illumination patterns for non-visual effects using freeform optical structures.

Analysis of metameric lighting

Light is known to influence humans' circadian rhythms through the so-called ipRGCs (Intrinsically photosensitive retinal ganglion cells) whose sensitivity peaks at 460-484 nm wavelength (*i.e.*, blue-shifted compared to that of the visual photoreceptors). This effect is nowadays exploited using color-tunable lighting solutions that attempt to mimic the color correlated temperature, CCT, of sunlight throughout the day.

The CCT is also a fundamental parameter from a visual perspective. In several applications is preferable to keep it fix at a predetermined value (typically 4'000K). We have investigated the possibility to influence circadian rythems by tailoring the spectral power distribution, SPD, of the light at a preset CCT, *i.e.*, using metameric light stimuli. Metamers are optical stimuli that are spectrally different but chromatically equivalent (*i.e.*, perceived as same color). An additional constraint was implemented namely a Color Rendering above 80.

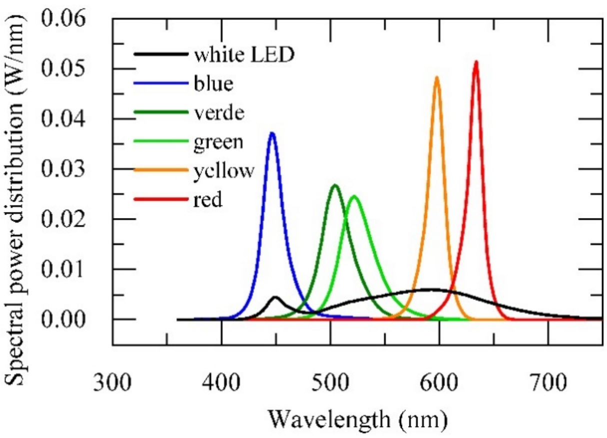

Figure 1: SPDs of the five-colored narrow-band LED (red (624 nm), yellow (594 nm), green (530 nm), verde (505 nm) and blue (455 nm) and a white LED of 3600 K, which are combined in different ratios.

For this goal, different SPDs were generated by mixing the SPD of several commercially available narrowband (colored) and broadband (white) LEDs (shown in Figure 1). The SPDs were optimized for non-visual effects with the constraint of CRI>80. In order to quantify the non-visual effects, we use the so-called circadian stimulus (CS) [2], which quantifies melatonin suppression (melatonin is the hormone that regulates our sleep-wake cycle). We show that the particular choice of LED combination, namely a broadband white LED and few narrowband colored LED can be used in lighting application to trigger non-visual circadian effects as well as maintaining required visual color rendering quality

Freeform optical structures

Angular light distribution is a fundamental parameter in classical (*i.e.*, visual) lighting design and several studies have indicated its importance from a non-visual perspective. Therefore, the possibility to realized customized light distributions is very attractive for visual and non-visual applications. Freeform optical components, designed with no constrains in symmetry, enable fully customized light distributions. Several methods exist to design macroscopic freeform lenses for imaging and non-imaging applications

On the other hand, optical microstructures are, compared to the macroscopic counterparts, much lighter and lower volume. And hence, much easier to integrate and manufacturable using cost-effective processes. However, the design of freeform optical microstructures faces several challenges which currently limits their application to for example collimated sources and relative simple distribution such as square/rectangular uniform illuminance.

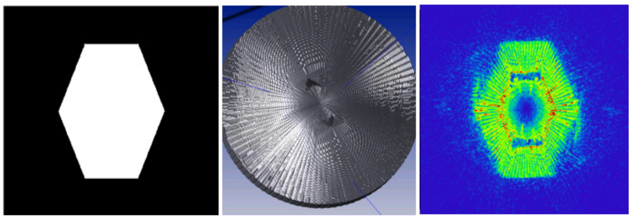

Figure 2: Left: Hexagonal target irradiance pattern. Middle: Designed freeform optical microstructures. Right: Irradiance pattern produced by the designed solution as predicted using raytracing software ZEMAX.

We are developing algorithms for the design of freeform optical microstructures based on the ray mapping concept.The preliminary results, (an example given in Figure 2) show the promising results achieved so far and indicate that further development is still needed in order to design high-quality lighting solution.

[1] C. Cajochen, *et al.*, "Circadian and light effects on human sleepiness–alertness." Chapter 2 in Sleepiness and Human Impact Assessment, Springer, (2014).

[2] M. Rea, *et al.*, "Modelling the spectral sensitivity of the human circadian system," Lighting Research & Technology 44, 386–396 (2012).