Spectral Tuning of LED Sources for Improved Lighting Quality

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Abstract: Placement of radiant power at different wavelengths within the visible spectrum affects our visual perceptions, such as color perception, brightness perception, and whiteness perception. In recent years, with the development of light emitting diodes (LEDs), it is becoming easier and easier to produce highly-structured spectra—spectra have sharp changes in slopes, spikes, or discontinuities—through spectral tuning. This paper reveals the benefits and importance of spectral tuning for LED sources through several psychophysical studies. It then introduces the recent development and challenges in characterizing lighting quality under these sources with highly-structured spectra and the trend of spectral-tunable systems for improved lighting quality.

1. Introduction

Light is a type of electromagnetic radiation, covering a wide range of wavelengths. Only a small part of the entire electromagnetic spectrum is visible to the human eye, which is called the visible spectrum. It is generally considered that visible spectrum covers between 360 and 830 nm. People have investigated how our visual system responds to light at different wavelengths since 1850 [MacAdam, 1970], when Helmoholtz first developed spectral color-sensitivity curves to describe the three color-sensitive fibers in our visual system.

In the lighting field, photometry and colorimetry are the two systems for evaluating light and color. Photometry is "a measurement of quantities referring to radiation as evaluated according to a given spectral luminous efficiency function, e.g., $V(\lambda)$ or $V'(\lambda)$"; colorimetry is "a measurement of color stimuli based on a set of conventions" [CIE, 2015]. Photometry is based on the luminous efficiency function; colorimetry is based on color matching functions.

Both luminous efficiency function and color matching functions are describing visual responses to optical radiation at different wavelengths. However, both of them have limitations, which causes the failure to use photometry or colorimetry to accurately characterize our visual responses. For example, the luminous efficiency function was derived using step-by-step photometry or flicker photometry, which minimize the contributions of chromatic channels in our visual system [Wyszecki and Stiles, 1982; Houser, 2001]. Color matching functions were derived based on the additivity assumption [Wyszecki and Stiles, 1982], which was found to fail sometimes [Thornton, 1992a; Thornton, 1992b; 1992c; 1992d].

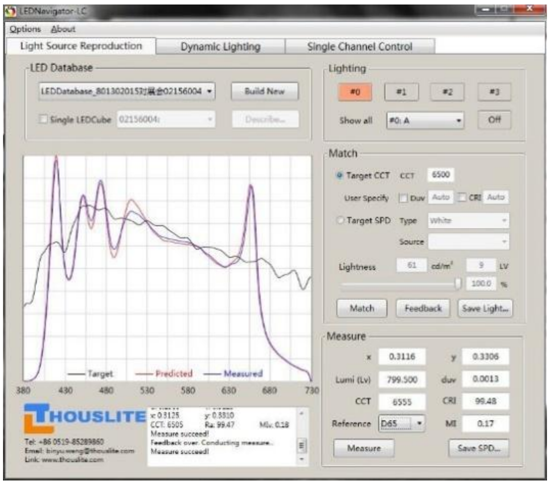


Fig.1 An example of multi-channel LED spectral-tunable source

Compared to conventional light sources, LED has a lot of freedom to create highly-structured spectrum, which has sharp changes in slopes, spikes, or discontinuous. The measures based on photometry and colorimetry have more serious problems for these highly-structure spectra. At the same time, spectral-tunable LED lighting system has more freedom and opportunities to achieve better lighting and environmental quality by placing radiant power at different wavelengths, especially for multi-channel LED system (as shown in Fig. 1).

This paper reveals the benefits and importance of spectral tuning LED lighting system, including brightness perception, whiteness perception, color perception, visual comfort, and non-visual effect.

2. Effects of spectral tuning on visual responses

2.1 Brightness perception

In illuminating engineering, luminance is always used as a proxy to quantify how bright the source or a surface is, which may be true when talking about a same light source. However, when two sources with different spectral power distributions have equal luminance, they may have different brightness perception. For example, when comparing a monochromatic blue light with a white light at equal luminance, the blue light will appear much brighter, which is actually caused by the luminous efficiency function V(λ) [Berman and others, 1990].

The effect of spectral power distribution on brightness perception has been widely accepted and investigated [Houser and others, 2009; Fotios and others, 2013]. A latest metric used to predict the relationship between brightness perception and spectrum is the ratio between scotopic and photopic lumen output (a.k.a., S/P ratio), which was found to be not valid for LED sources [Houser and others, 2009; Fotios and others, 2014].

A fluorescent lamp with diminished yellow emission was found to be perceived brighter compared to a tri-phosphor fluorescent lamp at the same illuminance level [Wei, 2011]. A similar concept was employed in an LED product to enhance brightness and color perception [Wei and others, 2014a]. Thus, LED sources with careful spectral tuning can provide higher brightness at certain illuminance level, so that equivalent brightness can be achieved with lower illuminance level leading to lower energy consumption.

2.2 Whiteness perception

In order to enhance the appearance of white objects, most of them contain fluorescent whitening agents (FWAs), a material absorbing radiation in the violet or UV part of the spectrum and reemit in the blue part of the visible spectrum. Such a fluorescent effect can help to enhance the luminance and also create a blue tint, leading to a whiteness enhancement. Most of the conventional light sources, such as incandescent lamps, fluorescent lamps, or HID sources, contain a certain amount of radiation in the violet or UV part of the spectrum to active the FWAs, which does not cause any problem to achieve whiteness enhancement.

Currently, the dominant way to produce white-light LED is to use a blue LED as a chip and a phosphor, which is called blue-pumped LEDs. These blue-pumped LEDs do not have any violet radiation, which causes the problem to render white objects. Such a problem cannot be characterized by CIE whiteness index.

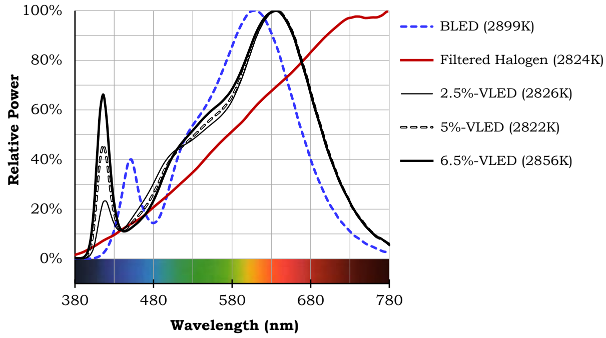
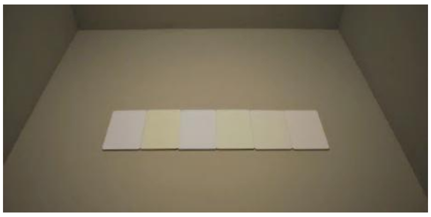


Fig.2 Relative SPDs of the five different lamp types included in the experiments, normalized to peak power [Houser and others, 2014]

A psychophysical experiment was conducted to investigate spectrum engineering on whiteness perception [Houser and others, 2014]. Five sources—a typical blue-pumped LED, a halogen lamp, and three violet-pumped LEDs with different violet emission levels—were included in the study, as shown in Fig. 2. Six calibrated whiteness standards were used in the experiment, which contained different amounts of FWAs to mimic different white objects around us. The observers were asked to arrange these six standards based on their whiteness appearance under each of the five sources. Figure 3 shows the six standards in identical order under two light sources.

(a)



(b)

Fig.3 Appearance of the six whiteness standards in same order under two types of light sources. (a) a typical blue-pumped LED; (b) a violet-pumped LED

The results from the psychophysical experiments [Houser and others, 2014] and a numerical computation study [Wei and others, 2014b] revealed that blue-pumped LED cannot render white objects due to the lack of violet emission. Even for those violet-pumped LED, an appropriate level of violet emission is necessary to activate FWAs.

Furthermore, the activation of FWAs does not mean the light source can render white objects in a preferred way. In other words, whiteness perception is different from whiteness preference. In a recent study, two sources were compared; observers were asked to evaluate whiteness perception and whiteness preference of a white shirt [Wei and others, 2015], as shown in Fig. 4.

Fig.4 The side-by-side viewing booths used for the evaluation of the colored objects [Wei and others, 2015]

The results shown in Fig. 5 indicate that higher whiteness does not mean higher preference. A careful spectral engineering is necessary to achieve whiteness rendition in a preferred way.

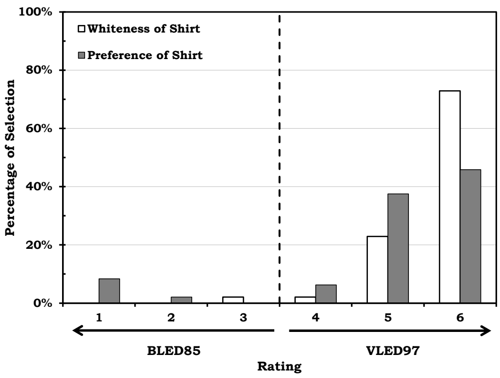


Fig.5 Grey bars: Ratings of preference for the appearance of the white shirt on a six point scale of 'strongly prefer', 'moderately prefer' and 'slightly prefer'. White Bars: Ratings along a six-point scale of 'significantly whiter', 'moderately whiter' and 'slightly whiter'. The figure illustrates that the preference for the appearance of the white shirt was not identical to the ability to distinguish differences in the whiteness of the shirt [Wei and others, 2015]

2.3 Color perception

Color rendition of a light source is always characterized by the general color rendering index (Ra), although its shortcomings and problems have been well documented [Houser and others, 2013]. With the availabilities of LED spectral-tunable sources, we can create spectrum in different ways to enhance color perception for different lighting applications.

A set of highly-structured spectra were created using a 16-channel LED system, as shown in Fig. 6 [Wei, 2015]. The study was designed to investigate chroma shift and hue shift between different lighting applications. Observers were asked to evaluate color preference of the objects and the skin tone of the face observed in the mirror, as shown in Fig. 7.

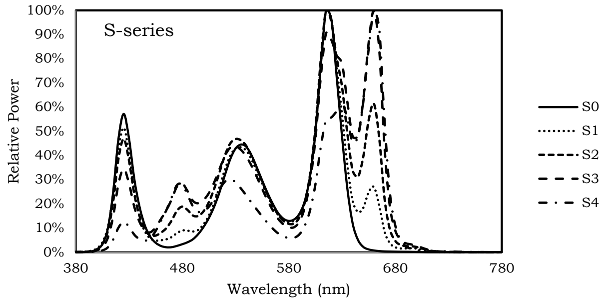


Fig.6 The spectral power distribution of different light stimuli created by a spectral tunable source [Wei, 2015]

Fig.7 The layout of the objects in the booth, viewing behind where the observer sits [Wei, 2015]

The results shown that the preferred spectrum for skin tone and food were different. In other words, color preference depends on lighting applications, which cannot be simply characterized by any measures. Spectral tunable sources can be used to create different spectra for different lighting applications.

2.4 Visual comfort

The introduction of daylight into an interior space is becoming more and more popular in the past decade. The output of electric light can be reduced based on the amount of daylight in the space using a photosensor, so that the amount of light in the space or on the work plane can be kept constant. However, light level is not the sole consideration for us to evaluate the lighting quality in a space. The compatibility of the electric light and daylight is also important.

There is no doubt that most of time daylight has a high CCT level, which motivates us to use the lamps with high CCT. However, a recent field study found that fluorescent lighting with high CCT caused the occupants feel uncomfortable. The occupants evaluated the 5000 K lamps to be less comfortable than 3500 K lamps, which affected their work productivity [Wei and others, 2014c]. The implementation of spectral-tunable source for office lighting is becoming more and more popular, which is believed to be able to help improving well-being, productivity, and visual comfort. Creating spectra in the right way so that daylight and electric light will be compatible to each other is important.

3. Effect of spectral tuning on non-visual response

The fact that light affects circadian rhythms and health has been recognized due to the existence of intrinsically photosensitive retinal ganglion cells (ipRGCs) in the retina. Although it has not been fully investigated which region(s) of the spectrum that ipRGCs are sensitive to, studies have been conducted to support that providing blue light in the morning as a type of light therapy can help seniors to improve cognitive functioning [Royer and others, 2012].

Fig.8 A photograph taken during the light therapy experiment

By using multi-channel LED spectrum tunable source and smart control, a lighting system can easily provide high quality visual responses together with non-visual responses based on different time in a day, as shown in Fig. 9.

Fig.9 A prototype of spectral-tunable LED lighting system with smart control for photobiological effect

4. Conclusions

The development of LED lighting and lighting control systems provide more and more opportunities for LED spectral tuning. The importance and benefits of spectral tuning on visual and non-visual effects have been revealed in the past couple years, which cannot be accurately characterized by the existing measures or metrics.

The maximization of the benefits of spectral tuning can only be achieved by carefully selecting the optimal wavelengths for LED channels, better understanding human responses to optical radiation, and better characterizing a luminous environment with daylight.

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