NIST SPECTRALLY TUNABLE LIGHTING FACILITY FOR COLOR RENDERING AND LIGHTING EXPERIMENTS

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ABSTRACT

The National Institute of Standards and Technology has developed a spectrally tunable lighting facility to allow state-of-the-art vision experiments on color rendering and lighting. The facility is composed of two cubicles, each lit by a spectrally tunable light source that contains 1800 high power light-emitting diodes comprising 22 color channels that are used to simulate traditional and new lighting spectra. Human observers can be completely immersed in the lighting environment and completely adapted to allow for the evaluation of the color rendering of objects, including human faces and skin tones, in a real-life setting.

Keywords: color rendering, general lighting, spectrally tunable light, vision science

1. INTRODUCTION

Solid state lighting (SSL) is a promising emerging technology that is expected to fundamentally alter lighting in the future [1]. The spectra of light-emitting diode (LED) sources are dissimilar to traditional incandescent and discharge lamps, so some of the existing standards and measurement methods are insufficient or deficient for LED applications. For example, a new metric to evaluate the color rendering of light sources is being developed in a technical committee (TC1-69) in the International Commission on Illumination (CIE) to address the problems of the color rendering index (CRI) for LED light sources, and this work requires rigorous vision experiments. Further, SSL sources have much greater flexibility of spectral design than traditional lamps and manufacturers have more freedom in the selection of light source chromaticity and illumination color quality for a wide range of lighting applications. However, the interrelated effects of chromaticity, color rendering, and other aspects of light source spectra are still not well understood. The introduction of SSL is necessitating the re-visiting of many of these types of issues regarding the effects of spectra on lighting metrology.

2. SPECTRALLY TUNABLE LIGHTING FACILITY CHARACTERISTICS

To address such important issues and to allow state-of-the-art vision experiments on color and lighting, a spectrally tunable lighting facility has been developed at the National Institute of Standards and Technology (NIST) after two years of effort. The facility has two spectrally tunable lighting sources (STLS) to illuminate separate 2.5 m x 2.5 m cubicles, so that observers can be completely immersed in and fully adapted to the lighting environment. This allows for the evaluation of the color rendering of objects, including human faces and skin tones, in a real-life setting. The two cubicles allow side by side comparison of different light settings. Photos of one of the sources are shown in Figure 1.

Figure 1. Left: an STLS lowered from the ceiling (with the walls of the cubicle removed). Right: one of cubicles lit by the STLS, to be used for color rendering experiments.

Each STLS unit utilizes 1,800 high-power LEDs (375 mA max) of 22 color channels spanning the 440 nm to 640 nm region. Figure 2 shows the spectra of the 22 color channels of LEDs currently installed. Seventeen of them are narrow-band high power LEDs and five of them are phosphor-type high-power LEDs to fill the green and part of the red regions. Each color channel contains 75 LEDs (150 LEDs for some colors), which produce 5 W to 10 W of optical power per channel. The number of color channels and the spectral range are still limited, as efficient high power LEDs at certain wavelengths were not available at the time of delivery.

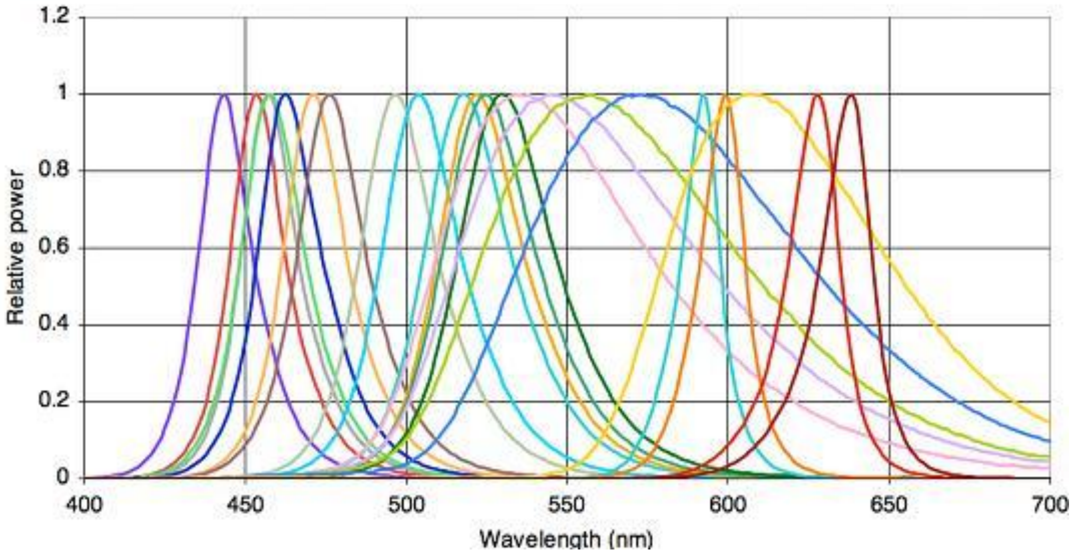

Figure 2. The spectra of the 22 color channels of LEDs currently installed in STLS.

The STLS is designed to be expanded for additional color channels in the future. The power supplies can accommodate up to 2400 LEDs and can individually address up to 400 color channels per STLS. Currently the 22 color channels are divided into six specific board types. The individual boards can be seen in Figure 3, which is a close-up photo of one STLS with the diffuser removed. Positions are available for immediate addition of two more board types. As new LEDs are developed, the boards can be easily added or replaced. In Figure 3 the five large aluminium heat sinks are visible. Above the heat sinks are cooling fans that pull ambient air across the fins of the heat sinks. Once the system warms up, which takes about 20 minutes; the system can switch between spectra instantly (within 20 ms) and is stable immediately (to within 1 % in illuminance and 0.001 in chromaticity u'v' over 30 min).

Figure 3. The six LED board types mounted on the heat sinks installed in the STLS.

3. SPECTRALLY TUNABLE LIGHT SOURCE CONTROL ALGORITHMS

The system is currently controlled by several computer programs. The actual spectral power distribution is measured with a stray-light corrected spectroradiometer. The first program simply controls the individual color channels using intensity sliders. Any given set spectrum can be saved to a file and retrieved when needed for experiments. The overall illuminance can be changed by simply entering the desired value (in lx). In the second program, the user chooses which of the 22 color channels are to be active and selects a correlated color temperature (CCT), a Duv (distance from the blackbody locus) and an illuminance level. The range of CCT is 2000 K to 10000 K, of Duv is -0.02 to 0.02, and of illuminance is 0 lx to 1000 lx. The program will automatically balance the active channels to create a spectrum that meets the CCT, Duv and illuminance values specified. The user may select all the channels or subset of the channels in the red, blue, and green regions.

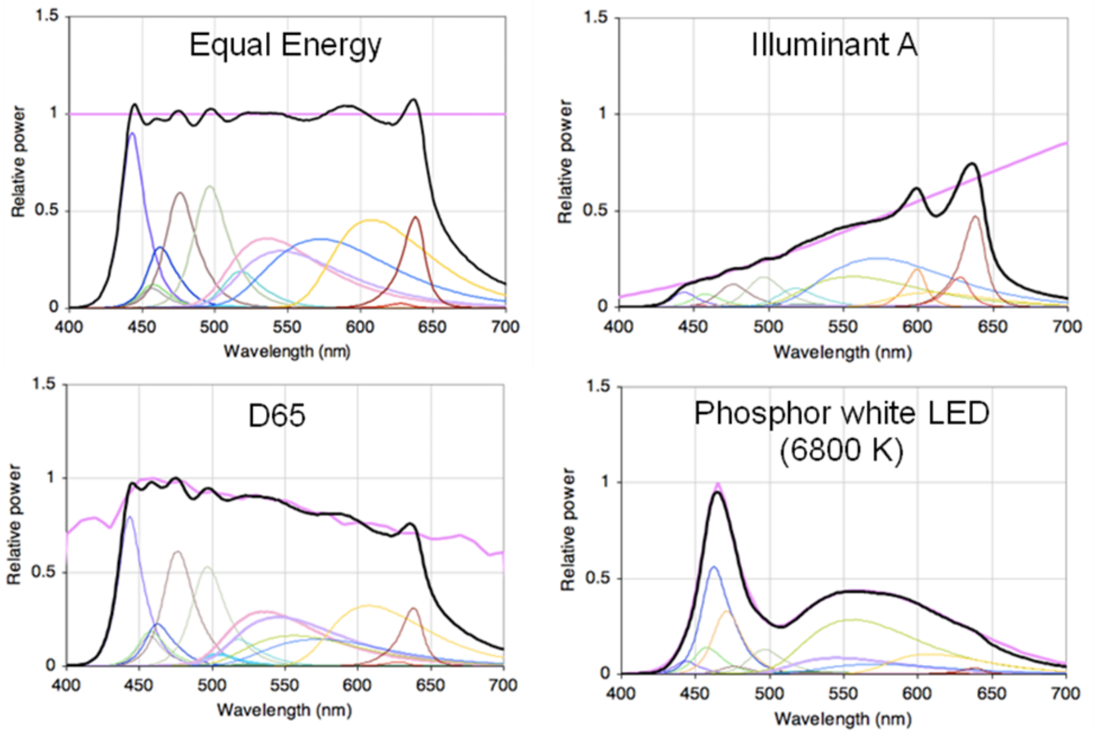

Figure 4. Spectral matching of the STLS to standard illuminants and an LED spectrum.

A third program performs a spectral matching algorithm using all of the color channels to match a spectral power distribution provided in a file. Figure 4 shows some an example of the spectral matching to standard illuminants and an LED spectrum. In an attempt to match special spectra such as a neodymium lamp, it was realized that the best spectral match did not give values for characteristic metrics, including CCT, Duv, Color Rendering Index (CRI) [2] and Color Quality Scale (CQS) [3], that would accurately correspond to the real lamp. Figure 5 shows the spectrum of the real neodymium lamp (top figure) and the STLS spectrum using the spectral matching algorithm (middle figure). The figures on the right side show the calculated color coordinates (*a**, b* in CIE 1976 L*a*b* (CIELAB) space [4]) of the 15 object color samples used in the CQS, illuminated by the test light and by Planckian radiation at the same CCT. The simulated spectrum does not exhibit the chroma enhancement, seen when using the real neodymium lamp. Table 1 shows the calculated results for several parameters describing the two spectra. The spectral match result shows large differences in all these parameters from those of the real neodymium lamp

Table 1. Comparison of color metrics for neodymium lamp and matched spectra

Spectrum	CCT	Duv	CRI	R9	CQS
Real Neodymium	2757	-0.005	77	15	88
Spectral match	3014	0.002	92	85	97
Object color match	2760	-0.005	76	9	88

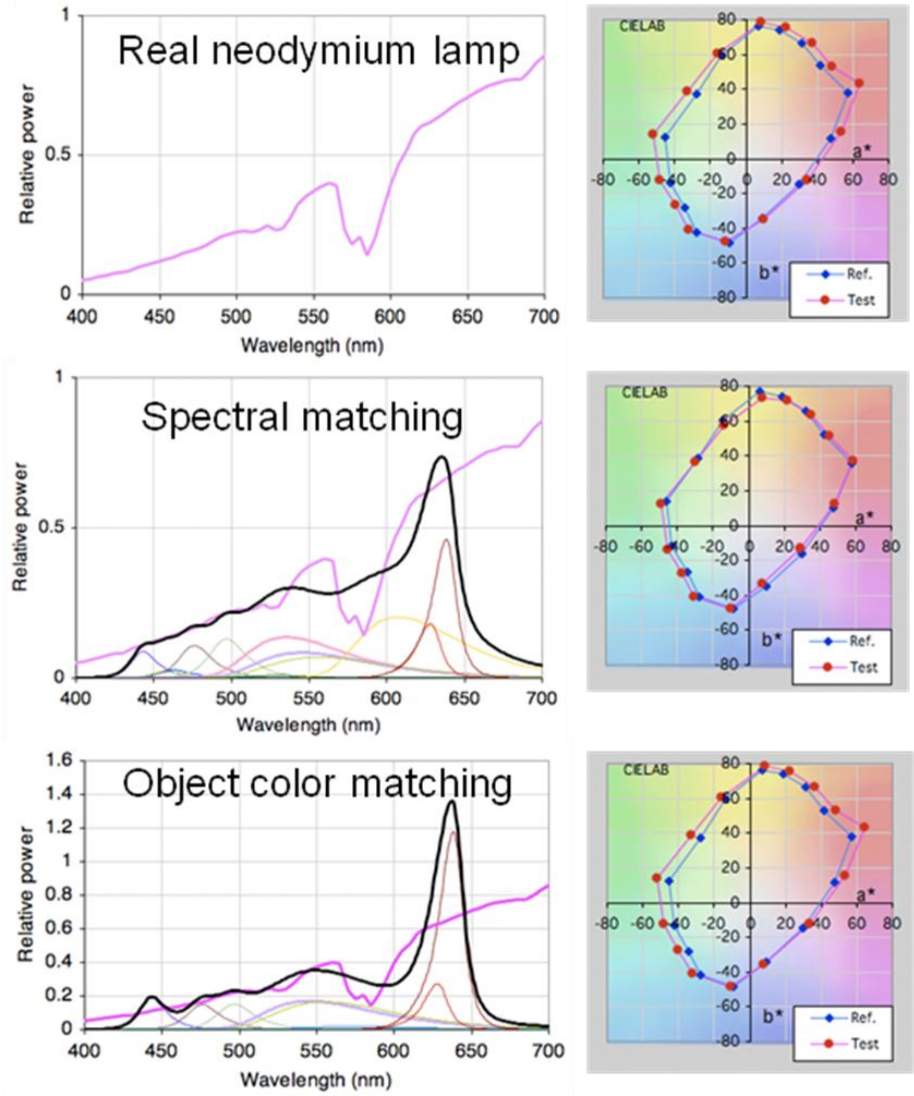

Figure 5. The spectrum of the neodymium lamp (top), the STLS spectrum using the spectral matching algorithm (middle) and the spectrum from the object color matching algorithm (bottom). The CIELAB plots show the change in chromaticity coordinates for the 15 object colors used in the CQS referenced to a blackbody.

In response to this problem, a fourth software program has been developed to match spectra for the exact CCT and Duv of the real lamp and also minimizes the differences in ΔE^{*}ab of the 15 object colors (used in the CQS calculation) from those of the real lamp. The STLS spectrum is adjusted until the differences between the objects are minimized between the STLS spectrum and the target spectrum. Figure 5 (bottom) and Table 1 (bottom row) show the results for the object color matching for the same neodymium lamp as an example. The resulting object color matched spectrum has nearly identical values of CCT, Duv, CRI and CQS. This object color matching program is used successfully to simulate color rendering of other traditional lamps (fluorescent and HID lamps), while spectral matching for these light sources is difficult due to the limitations of STLS.

Currently, the STLS control programs and the spectroradiometer run separately, and all the controls are feed-forward control, and final STLS spectra to be used for vision experiments are adjusted manually from the spectroradiometer readings of CCT and Duv. Work is in progress to incorporate the spectroradiometer program into the control program to implement feed-back control of STLS based on the direct readings of the spectroradiometer, which will allow easier tuning of the spectra and even better stability of illuminance and chromaticity of output light.

4. FUTURE VISION SCIENCE EXPERIMENTS

The current and immediate future vision science experiments using the STLS seek to test and validate the CQS through the evaluation of color fidelity, color preferences, and color discrimination. Future vision science experiments will include studying effects of illuminance levels on color quality, testing the limits of chromatic adaptation, investigating the effects of light source chromaticity, and other various spectral effects of lighting, particularly related to solid state lighting.

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ACKNOWLEDGEMENTS

The authors would like to thank the NIST director for the STLS funding provided through the Innovations in Measurement Science program.

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