Circadian lighting in a space daylit by a tubular daylight device

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Circadian lighting in a space daylit by a tubular daylight device

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Abstract This study demonstrates an experimental example of application of time-lapse high dynamic range images for analyzing variations in correlated color temperature (CCT) and circadian lighting in an interior space daylit using a tubular daylight device (TDD). Previous studies have shown that the spectral composition of daylight affects human circadian rhythms, with emphasis on wavelengths towards the blue region of the visible spectrum. Spectrally based metrics such as CCT can therefore aid in evaluating the circadian impact of daylight. TDDs redirect daylight towards interior spaces with changing light levels and color temperatures during the daylight hours. This paper details the color temperature and circadian lighting metrics (circadian luminance and illuminance) in an interior space throughout a period of several days in a mid-latitude, temperate, sunny climate. An automated time-lapse HDR photography apparatus was modified to allow for calculation of CCT and circadian lighting metrics using state-of-the art techniques available in the literature. Prior to the measurements in the space with the TDD, this device was calibrated against a spectrophotometer. Results indicate the level of daily variation in CCT and circadian lighting metrics that can be expected in interior spaces daylit by TDDs without any other sources of daylight. Besides showcasing the use of HDR techniques, these results could be used to support design decisions involving daylighting in interior spaces. These techniques can also be used outside the laboratory in the evaluation of the circadian impact of lighting throughout the built environment.

1.Introduction

Studies have shown the effect of correlated color temperature of space lighting on occupant's health, well-being and productivity [1]. There are very few studies that analyzed the variability of circadian

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lighting in built environment. Previous studies have shown several applications of High Dynamic Range (HDR) photography in the field of building research [2]. Studies show that calibrated HDR photography could be processed to allow the calculation of various metrics such as luminance, illuminance, glare, irradiance, and correlated color temperature [3]–[6]. In this study, we analyze the variations of correlated color temperature in an experimental interior space daylit by tubular daylight devices. Calibrated High Dynamic Range (HDR) photography is validated to measure the variation in correlated color temperature of the interior scene.

2. METHOD

2.1 Experimental set-up

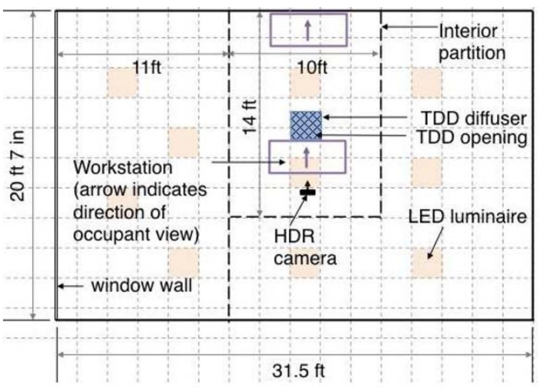
For our study, we used rotating test cell B of FLEXLAB (flexlab.lbl.gov) at Lawrence Berkeley National Laboratory located in Berkeley, California, United States (latitude 37°4′ N, longitude 122°1′ W) during the month of June 2018. FLEXLAB is a building technologies test facility with the capability to assess real-time side-by-side comparisons of component and system technologies. The rotating test cell has a north facing entrance door and south facing window as oriented for this study.

2.1.1 Test room

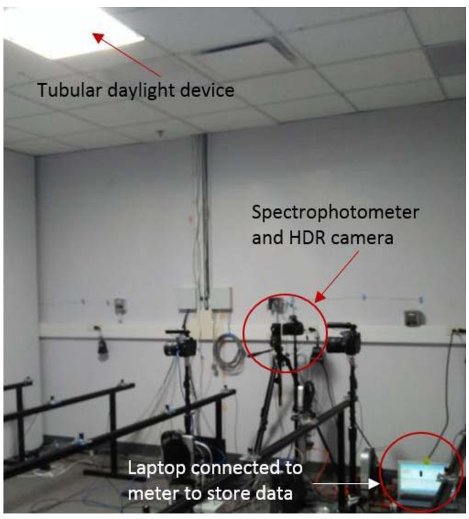
For this test, a smaller test space was created inside the rotating test cell by using partition panels. In this way, the daylight coming inside the space is from the tubular device opening alone. The test room is equipped with a tubular daylight device (TDD), High Dynamic Range (HDR) camera with vertical illuminance sensor, and a spectrophotometer. Interior surface reflectance of the floor, walls, partition, and ceiling, are 0.135, 0.57, 0.59, and 0.74, respectively, as measured by a spectrophotometer using a grey reference card. The test room was unoccupied during the study. The configuration of the test room is shown in Figure 1a. Following are the descriptions of equipment used during experiment:

a) Tubular daylight device

Tubular daylight devices have optical domes that capture the sun's rays at the rooftop level and can then transfer the light more than 50 ft through the highly reflective tubing with a reflectance of 90% or higher. Diffusers at the bottom of the tube then disperse the daylight throughout the interior space. In this study two different TDDs were used: Velux 22" Suntunnel with a Suncurve dome, and a Solatube 750DS. Both TDDs have Fresnel lens diffusers at the bottom to disperse the diffused light. The location of TDD inside the test room is shown in Figure 1a.



1a



1b

Figure 1a. Configuration of test room and 1b. Setup done for calibration part

b) HDR camera

A Canon 5D digital SLR camera with *Sigma 8mm f3.5* fisheye lens was used to capture the daylight from TDD. The camera has a *Li-cor LI210* photometer sensor mounted just above the camera lens to measure vertical illuminance and calibrate the images. An Apple Mac Mini processor was also mounted on the tripod that runs the software to automate the camera. It also runs the scripts to combine low dynamic range images taken at series of exposure values to make a high dynamic range image at every 5-minute interval. Post-processing scripts crop and correct each captured HDR image for geometric and vignette correction, and calibrate the vertical eye illuminance of image. Camera was mounted at eye height while sitting at working desk that was 4' (305cm).

c) Spectrophotometer

A Konica Minolta CL-200A spectrophotometer was set adjacent to HDR camera at same elevation for measuring the Correlated Color Temperature (CCT), CIE XYZ and CIE xy measurements. Measurements were automated and stored at every 5 minutes to match the interval of image capture. This data was gathered for two days (June 09 -10) for the purpose of calibration of CIE XYZ obtained from HDR images. Location of tubular daylight device, HDR camera, and spectrophotometer inside the test space are shown in Figure 1b. Only one HDR camera was used for this experiment. Additional instruments that appear in Figure 1b are for additional data collection for other related experiments.

2.2 Calibration

The calibration procedure was performed with a similar configuration as mentioned in previous section but without furniture or use of electric lights, and a different but similar TDD as shown in Figure 1b. Data from camera and spectrophotometer was gathered for two days (299 data points). Calibration method used in this study is adapted from the study done by Mehlika Inanici et al.[4], [7]). Since the spectrophotometer provides measurements in CIE XYZ format, therefore to calibrate the RGB pixel values obtained from the HDR image, first they are converted to CIE XYZ format. The Radiance [8] daylight simulation tool is used to obtain X, Y and Z pixel values from post processed HDR images. The Radiance program *Ra_xyze* converts between Radiance RGBE (red, green, blue, exponent) and XYZE (CIE X, Y, Z, exponent) formats. Then, the Radiance program *pvalue* converts the pixels from picture format to text format. A text file with all the pixel values of an HDR image and their positions is then processed in a Python script. Only the pixels under the circular area of HDR image (Figure 2) are considered for this calculation, the black region is removed. For each HDR image, we got a set of average X, Y and Z values by computing the cosine-weighted mean of the circular area of fisheye image for respective channels. To compute the cosine-weighted mean, each pixel is weighted as a function of pixel's distance from the center of the image. This was done to align the measurements taken from the spectrophotometer.
After this, mean values are multiplied by a factor of π since circular area of a fisheye image correspond to the 180° hemispherical data from spectrophotometer. Photographically obtained CIE XYZ values from this computation are compared with the measured values from spectrophotometer in order to get a calibration factor.

2.3 Measurements

Images were captured over a period of 14 days from June 13 to June 26, 2018 and a total of 2216 data points were gathered in the setting shown in Figure 1b. This setting represents an office condition with two working desk and monitors. During this time, two ceiling mounted LED fixtures were running on a schedule as given in table 1. This schedule was devised in order to best approximate the lighting schedule in the Table G-I in user manual for ASHRAE 90.1 standard. Two sample HDR images with lights switched on and off are shown in Figure 2. A calibration factor was applied to the CIE XYZ values calculated from HDR images as determined by the calibration process. Photographically obtained calibrated CIE XYZ values and CCT values are plotted for two weeks to analyze variations.

Table 1: Lighting schedule from June 13 to June 26, 2018

Day	LED On	LED Off
Mon-Fri	7:00 - 7:30, 8:00 - 12:30, 13:00-17:30, 18:00 - 20:00	Lights were off rest of the time
Saturday	7:00- 7:20, 8:00 - 9:30, 11:00 - 12:30	Lights were off rest of the time
Sunday	7:00- 7:20, 8:00 - 8:47, 13:00 - 13:48	Lights were off rest of the time

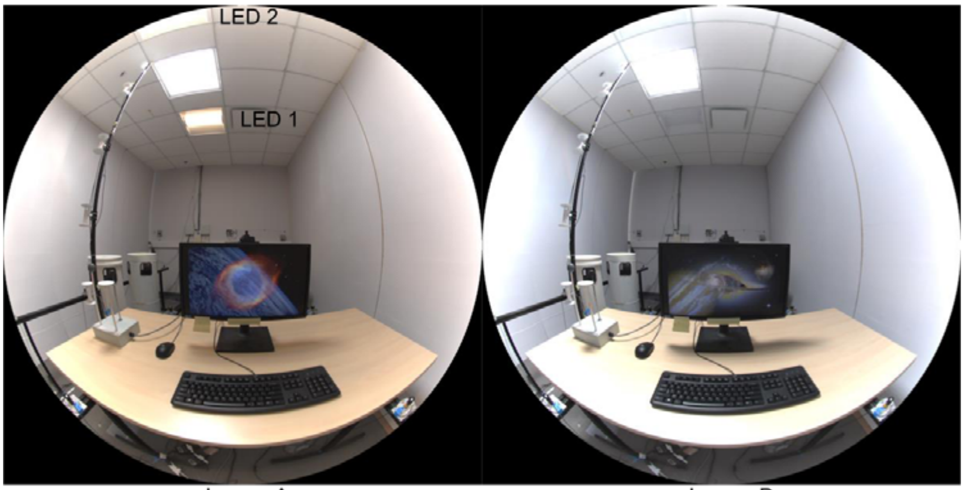


Image A
Two LED lights were on
Time: 8:25 AM

Image B
None LED lights were on
Time: 12:30 PM

Figure 2 Sample calibrated HDR images captured on June 13, 2018

3. RESULTS AND DISCUSSION

3.1 Calibration and comparison

3.1.1 Measured and captured CCT comparison

To calculate CCT from CIE XYZ values, McCamy's method [9] is used. First the chromaticity coordinates x and y are calculated using CIE XYZ values as shown below:

$$x = X / (X+Y+Z) \quad (1)$$
$$y = Y / (X+Y+Z) \quad (2)$$

Then, correlated color temperature is calculated as per McCamy's method:

$$n = (x - 0.3320) / (0.1858 - y) \quad (3)$$
$$CCT = 449 \times n^3 + 3525 \times n^2 + 6823.3 \times n + 5520.33 \quad (4)$$

The following graph (Figure 3) compares the measured CCT data from spectrophotometer and captured CCT data from HDR camera over the course of the calibration period (June 9 and June 10, 2018). Maximum CCT recorded is 7887K at 7:20AM on June 10 and minimum CCT is 5260K at 7:30AM and 6:50 PM on June 10. In Figure 3, we can observe high CCT values during early morning and late evening time. This is probably because before sunrise and after sunset the TDD is only capturing light from the blue sky, which has a much higher CCT than light from a sky that includes the sun. Although, both the curves follow each other, it can be observed that captured CCT values are higher than measured CCT values. Therefore, calibration factor is required to get more accurate CCT predictions from HDR images.

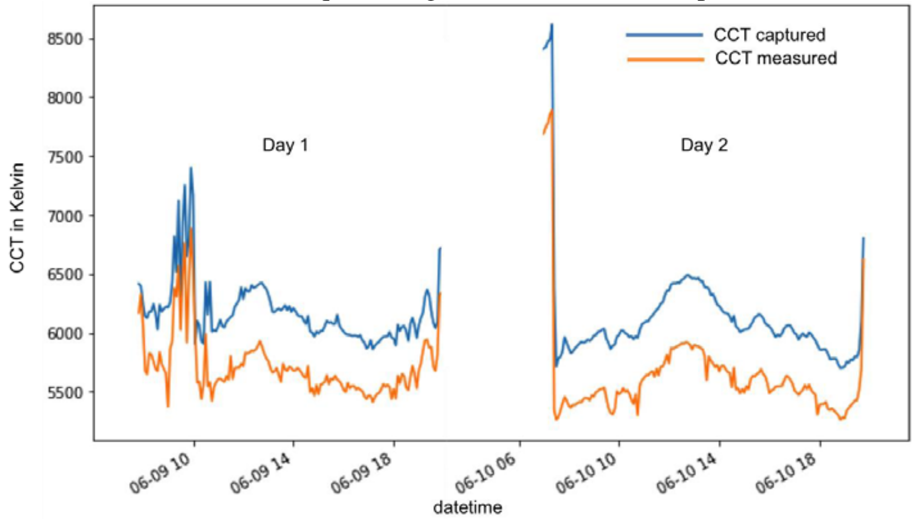


Figure 3 Pre-calibration comparison between CCT measured and CCT calculated

3.1.2 CIE XYZ calibration

Photographically obtained CIE XYZ values are plotted against respective measured CIE XYZ values using spectrophotometer over the course of two days. The R-squared value for the X, Y and Z are respectively 0.993, 0.993 and 0.994.

Following graphs (Figure 4) represent the measured and captured CIE XYZ values relation plot of 299 data points for two days (June 9 and June 10, 2018).

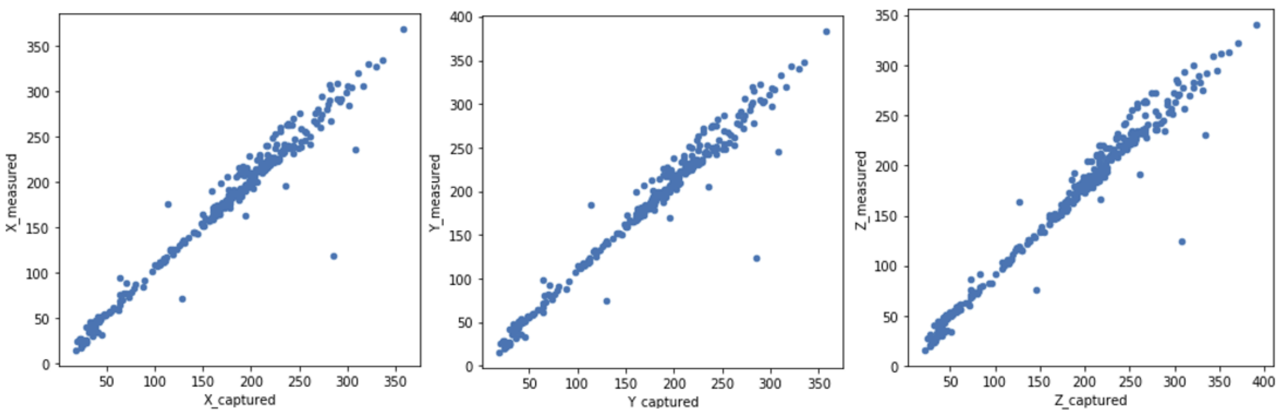


Figure 4 Correlation plot between measured and captured CIE X, Y and Z values

After applying the calibration factor to captured CIE XYZ values, CCT is calculated again using McCamy's method. Figure 5 represents the comparison of captured and measured CCT values after calibration. CCT values calculated using HDR images lies within ±9.54% of measured CCT values.

Results show that captured and measured values are in very good agreement with each other. This also indicates that applications of HDR photography can be extended to measure CIE XYZ values and CCT values of a scene.

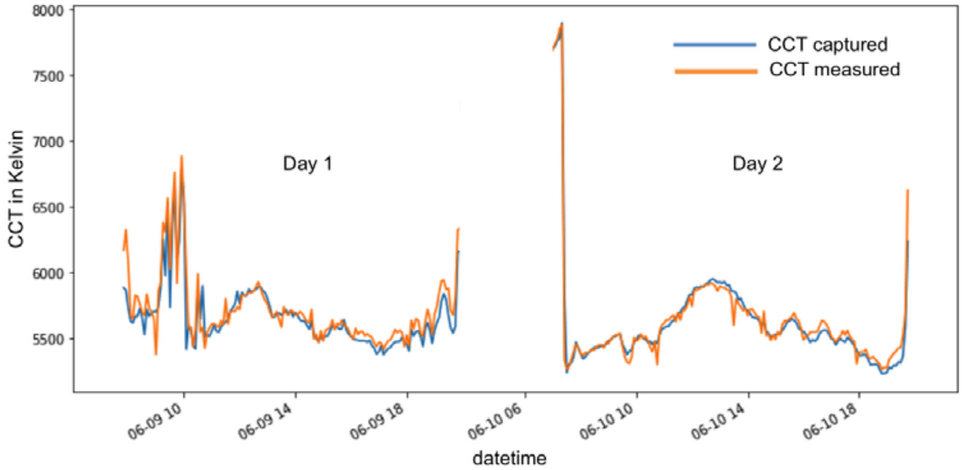


Figure 5 Post-calibration comparisons between measured CCT and captured CCT

3.2 Calibrated CCT Measurements Over 2 Week Period

Calibrated CIE XYZ values from HDR images are obtained following the method described in previous section and these values are further used to calculate CCT. Images are captured for 14 days from June 13 to June 26, 2018. Lighting schedule for this duration is as per table 1. During this time, maximum-recorded CCT is 12349K at 7:20AM on June 23 and minimum recorded CCT is 3110K between 8:30PM to 8:45PM on June 13. The following graph shows the variation in CCT throughout these 14 days.

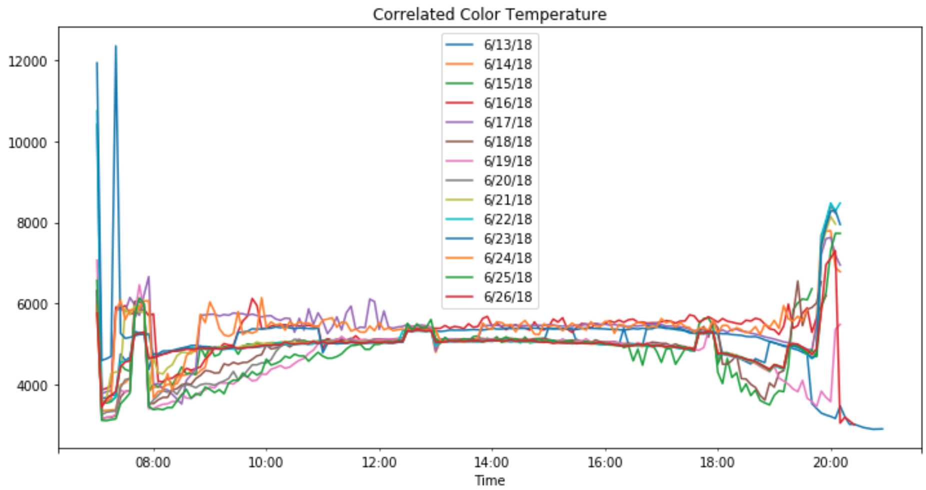


Figure 6 CCT measured from 7AM to 8PM for 14 days

Few unusual peaks of high CCT can be observed in the plot during morning hours between 7AM to 8AM. This is due to the change in artificial lighting schedule during those hours. With reference to table 1, LED lights were off between 7:30 AM to 8:00 AM in morning, and only light coming through TTD was from blue sky, this explains the high CCT in Figure 6 during sunrise. To understand the variation better, CCT data is plotted and discussed below for one weekday (06/13/2018) and for Saturday (06/23/2018) in relation to respective lighting schedule. These two days were days with clear sky. Figure 7 shows the variation in CCT on June 13 and June 23. CCT increases when lights are off and decreases when lights are turned on again. On weekend average CCT tends to be higher than CCT on weekdays due to less hours of artificial lighting switched on. Results indicate the level of daily variation in CCT that can be expected in interior spaces daylit by TDDs without any other sources of daylight.

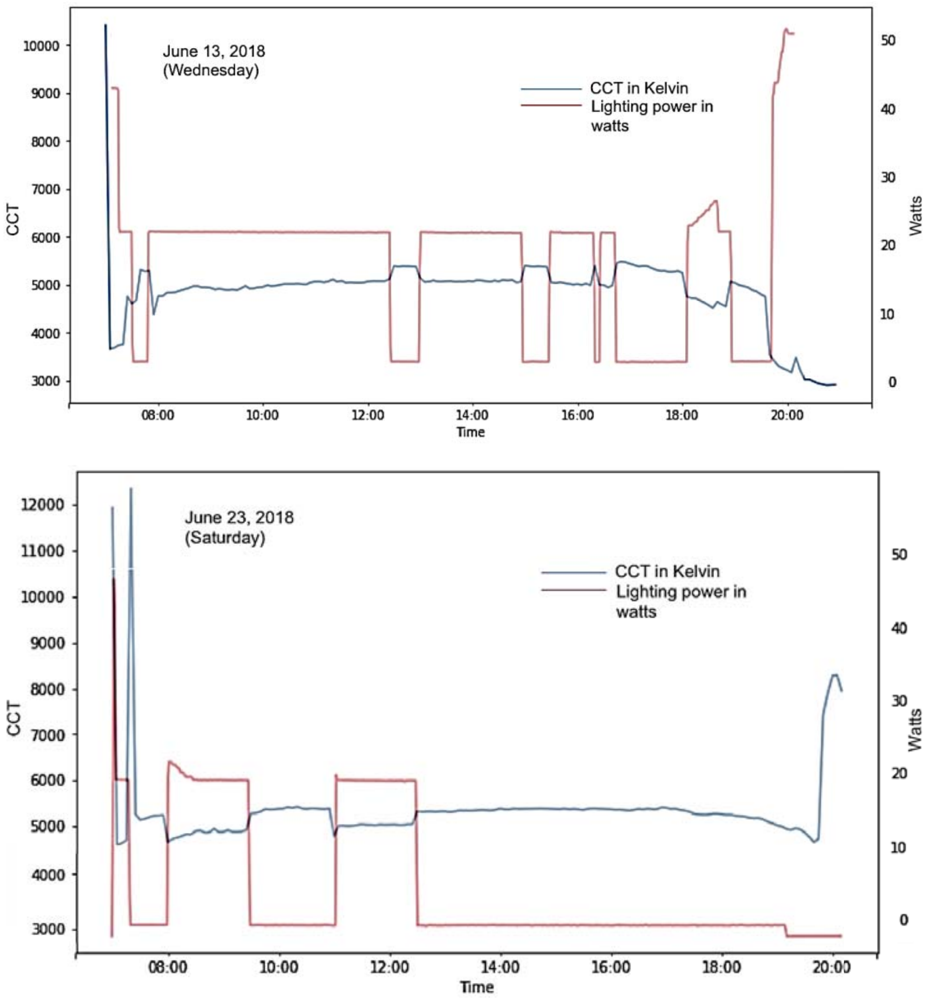


Figure 7 Variations in CCT levels in comparison with lighting on/off status as per weekday and weekend schedule respectively.

4. CONCLUSION

This study demonstrates the variations in correlated color temperature calculated from time-lapse automated HDR images in the presence of a tubular daylight device in a test room over a period of 14 days. This study presents a methodology that could be employed to analyze CCT of various daylight devices and artificial lighting and help stakeholders to take informed decision while installing lighting devices in a space. The calibration process used ensured sufficient accuracy for most general lighting purposes and this process is likely to be suitable for any situation where time-lapse HDR photography is feasible. This method may not be suitable in situations where very frequent movement is expected, as this affects the accuracy of the HDR generation process. The CCT of the light provided by the TDD was generally found to be higher than that of the electric lights in test room. Also, the CCT of the TDD light appears to vary significantly throughout the day. Further work is needed in order to characterize this behavior in more detail and determine how significantly it impacts the occupants' perception of the space.

5. ACKNOWLEDGEMENT
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