Studying Chromaticity Binning: What should we expect from today's LED light sources?

Generally, people expect two light sources with the same rated color appearance to appear identical when installed in their homes and businesses. Obvious variation often leads to dissatisfaction, complaints and product returns. To avoid these issues, it is important that light sources have sufficient chromatic consistency to ensure color matching for most people. Currently, the lighting industry relies on binning for correlated color temperature (CCT) and Duv to address this issue.

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Due to the construction process of typical LEDs, there is some level of variation in the color of light being produced by each emitter. To limit the difference in appearance of the light being produced, fixture manufacturers will select LED emitters that produce light within a certain range of chromaticity, a process known as "binning." However, there is a lack of data on what level of variation in light color is visible to most people. This makes it difficult to know with certainty that the final fixture will achieve the chromatic uniformity goals.

These issues and others formed the basis for a multi-year research program conducted by the California Lighting Technology Center, with support from the California Energy Commission, aimed at improving the adoption of energy-efficient LED lighting products. This article presents results from one piece of this work focused on identifying the level of chromatic variation that avoids perceptible levels of color difference among today's LED light sources.

To gather the consumer input needed to research this issue, 46 study participants were shown 40 lighting scenes using four light sources. After assessing each scene, the participants were asked to indicate when they noticed a difference in the appearance of one of the four light sources. Data was collected and analyzed to determine a "just-noticeable difference" (JND) threshold that most study participants were able to observe.

Correlated Color Temperature & Duv. CCT is defined by the American National Standards Institute (ANSI) and the IES in ANSI/IES RP-16-17, *Nomenclature and Definitions for Illuminating Engineering*, as "The absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source." In simple terms, a blackbody radiator is an object that produces specific colors of light based on its temperature. On a chromaticity diagram, such as the 1976 CIE Chromaticity Diagram shown in **Figure 2**, the spectrum of visible light produced by the reference "black body" is known as the Planckian locus. Changes in CCT are typically described as "cooler" versus "warmer" within the lighting industry (**Figure 1**).

The distance of the chromaticity point from the Planckian locus is called Duv. Duv is defined by ANSI C78.377-2015 as "the closest distance from the Planckian locus on the (u', 2/3v') diagram, with '+' for above and '-' for below the Planckian locus." Perceptually, changes from the Planckian Locus are typically described as "green" for positive changes in Duv or "pink" for negative changes in Duv.

Just-Noticeable Difference of Color Appearance. CCT and Duv provide a common language in which to discuss the "just-noticeable difference," or JND, of light-source color appearance. For color appearance, the JND is the threshold at which most people are able to detect a difference in color between two similar light sources. There is no current industry standard for JND of light-source color appearance, perhaps because a metric to quantify this JND involves many complex considerations. For example, for each observer of the same lighting scene, the ability to perceive a color difference is contextually dependent on the level of effort expended, and the observer's focus and judgement.

Additionally, an observer might see a difference when there is none, called a false positive observation. For instance, the observer's eyes may be adapting when the observation is made. This would make two identical sources seem subtly different when viewed sequentially. Or the observer may be shifting focus between two sources, which causes different parts of their eyes to react, which may result in apparent but nonexistent perceived color variation.

Considering these variables, any qualitative JND metric for color appearance should be based on how frequently an average observer correctly detects a difference in color between two light sources. The metric should also consider how frequently that observer experiences a false-positive observation. For this study, CLTC defined JND as the level of difference that is correctly observed twice as frequently as the rate of false positive observations.

Study Methodology. To quantify the JND threshold for color appearance, CLTC prepared an immersive test environment, where study participants were shown four custom table

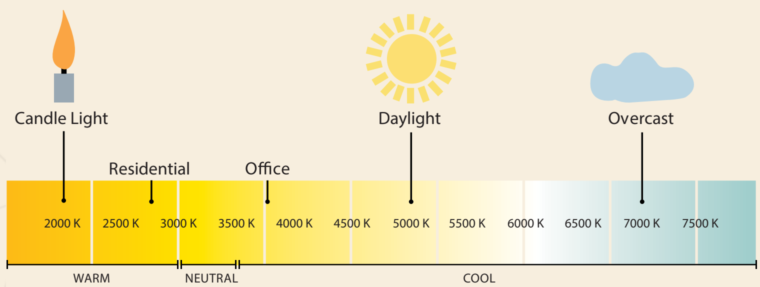

Figure 1: Approximate color temperature of various light sources.

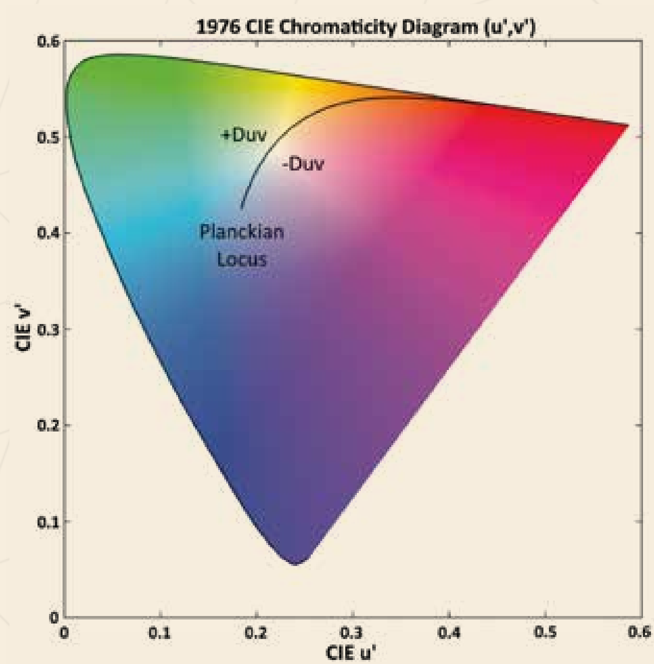

Figure 2: CIE 1976 Chromaticity Diagram with Planckian locus and Duv labeled.

lamps. Participants were positioned so that the diffuser filled a 10-deg viewing angle. The participants were shown a series of lighting scenes using these table lamps to determine the JND threshold in terms of CCT and Duv. The table lamps were placed in cells painted black to create a theoretical worst-case visual environment that correlated with the study participant's maximum ability to see changes in light color. In an attempt to prevent the participant from observing a sudden change in the light sources, they were asked to look away from the table lamps as the lights were changed to the next scene.

In each scene, three of the table lamps were set to produce identical color metrics. The randomized fourth table lamp was configured to be different from the other three lamps using either the CCT or Duv metrics (**Figure 3**). After each scene was observed, study participants were asked to identify which lamp was different. Participants were allowed to state that there was no difference between the lamps. Their answer was recorded for each scene.

To address both residential and commercial applications, the same methodology was used for both 2700K and 4000K reference light sources. The CCT and Duv differences shown to the study participants are provided in **Table 1**. These changes

Figure 3: Participants were presented with four table lamps and asked to identify which one had a different color of light.

Table 1: CCT and Duv changes shown to study participants. Values calculated using the 1964 10-deg standard observer.

2,700 K CCT Change	*4,000 K CCT Change*	*2,700 K Duv Change*	*4,000 K Duv Change*
-24.3	-36.3	-0.0007	-0.0009
20.8	37.3	0.0010	0.0012
-41.7	-76.7	-0.0019	-0.0020
40.9	71.9	0.0019	0.0020
-83.7	-152.5	-0.0033	-0.0032
81.0	154.2	0.0036	0.0036
-143.6	-277.6	-0.0067	-0.0060
143.7	268.4	0.0069	0.0062

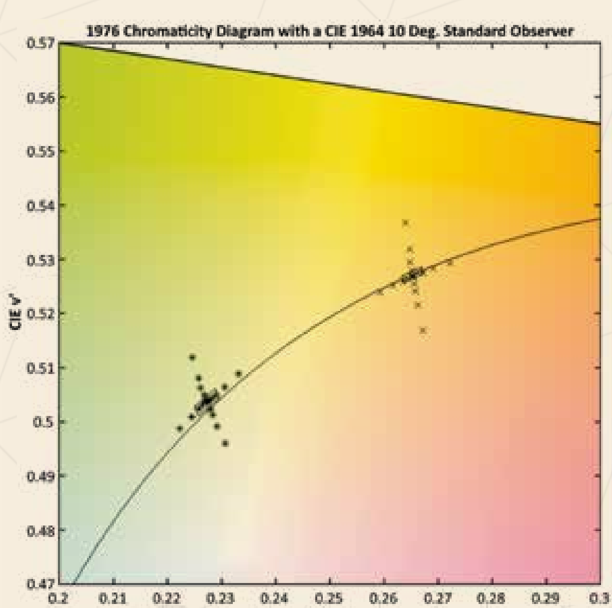

Figure 4: Scene locations in 1976 Chromaticity Diagram with a CIE 1964 10-deg standard observer. Background colors are approximate.

are from the center of each CCT bin. The scenes in Table 1 were selected to produce nominally equal intervals in the CIE 1976 chromaticity diagram (u’, v’). The location of these 32 scenes are provided in **Figure 4**.

In addition to these scenes, each participant was shown scenes where all table lamps emitted the same color of light for a total of 40 scenes (16 scenes with one lamp being different and four with all lamps identical for both 2700K and 4000K).

To analyze the data, CLTC compiled the responses of study participants and calculated the percentage that correctly identified the scene change. This percentage, or frequency observed, is provided in **Table 2** for each CCT scene.

The percentage at which the participants correctly identified each Duv scene change is provided in **Table 3**. These data points were used to identify the JND of color appearance by fitting a logistical model to the frequency at which the magnitude of changes was observed. Logistical models are frequently used to describe perceptual responses and provided an excellent fit to the experimental data gathered by CLTC from the participants. The selected logistical model is shown fitted to the response to the magnitude of change in **Figure 5**.

To determine the JND of color

2700K CCT Change		4000K CCT Change	
-24.3	4%	-36.3	22%
20.8	13%	37.3	2%
-41.7	17%	-76.7	9%
40.9	9%	71.9	4%
-83.7	65%	-152.5	63%
81.0	72%	154.2	70%
-143.6	98%	-277.6	91%
143.7	98%	268.4	93%

Table 2: Percentage of observers who identified the CCT changes.

2700K Duv Change		4000K Duv Change	
-0.0007	31%	-0.0009	22%
0.0010	53%	0.0012	28%
-0.0019	93%	-0.0020	72%
0.0019	84%	0.0020	63%
-0.0033	98%	-0.0032	91%
0.0036	100%	0.0036	93%
-0.0067	100%	-0.0060	98%
0.0069	98%	0.0062	98%

Table 3: Percentage of observers who saw each Duv change scene.

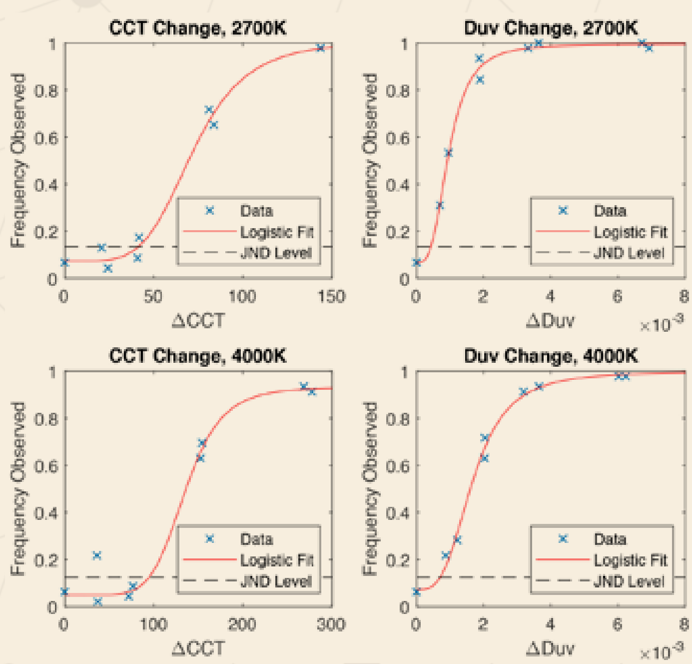

Figure 5: Four-parameter logistical models fit to frequency of observed change.

Table 4:
Size of just-noticeable observable bins.

	ΔCCT	ΔDuv
2,700 K	41.4K	0.00043
4,000 K	94.7K	0.00070

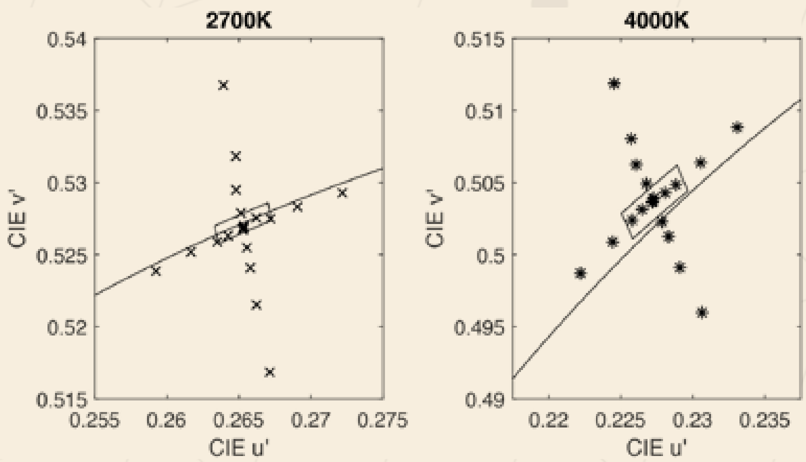

Figure 6:
Just-noticeable difference observed bins for 2700K and 4000K compared to the scene locations shown in Figure 4.

appearance, the false-positive rate was identified from the data collected from scenes which had no change. In Figure 5, the value of frequency observed at zero change is the false-positive rate. Based on the qualitative definition of JND used in this study, the magnitude of change at which the fitted model equals twice the false positive rate is then the just-noticeable difference. Based on this correlation from Figure 5, the size of the observed bins is given in **Table 4** and is shown on the chromaticity diagram in **Figure 6**.

Conclusions. The chromaticity bins identified through this research are useful for industry and lighting designers alike in understanding what today's average consumer is able to detect with respect to color appearance variation. It is recommended that results from this study and others like it be used to inform future product development efforts and establish best practices for lighting design. Additionally, the bins can be used as a tool for determining uniformity requirements moving forward, which is especially useful with today's spectrally tunable lighting systems. ◎

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