Human Perceptions of Color Rendition Vary with Average Fidelity, Average Gamut, and Gamut Shape

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Abstract

An experiment was conducted to evaluate how subjective impressions of a light source's color quality depend upon the details of the shifts it causes in the color appearance of illuminated objects. Twenty-eight participants each evaluated 26 lighting conditions in a 3.1 m by 3.7 m room filled with objects selected to cover a range of hue, saturation, and lightness. Illuminating Engineering Society (IES) TM-30-15 Fidelity Index (R_f) values ranged from 64 to 93, IES TM-30 Gamut Index (R_g) values from 79 to 117, and IES TM-30 Hue Angle Bin 1 Chroma Shift ($R_{cs,h1}$) values from -19% to 26%. All lighting conditions had the same nominal illuminance and chromaticity.

Participants were asked to rate each condition on eight point scales for saturated-dull, normal-shifted, and like-dislike, as well as classifying the condition as one of saturated, dull, normal, or shifted. The findings suggest that gamut shape is more important than average gamut area for modeling human preference, with red playing a more important role than other hues. Average fidelity alone is a weak predictor of human perception, especially Commission Internationale de l'Eclairage (CIE) R_a (i.e., CRI). Nine of the top 12 rated products had a CIE R_a value of 73 or less, which indicates that the criteria of CIE $R_a \geq 80$ may be excluding many preferred light sources.

1 Introduction

Quantifying color preference is a challenge for lighting metrology, especially when the goal is to determine optimal spectra for light sources. Like preference for art, food, or clothing, color preference is a subjective experience that is highly dependent on the individual, culture,[1, 2] age,[3, 4] and application.[5, 6] It may also change with time or day or duration of the experience, among many other factors that have not been systematically investigated. Nonetheless, two important goals are to enable lighting specifiers and consumers to select sources that enable preferable object appearance and to make tradeoffs between color quality and other performance attributes.

In developing measures for assessing the overall effects of light source spectrum on object color appearance, which is known as color rendition, it is relatively simple to quantify *objective* characteristics, such as average color fidelity (the overall similarity of colors illuminated by a test and reference source) or average change in color saturation (which is sometimes called vividness). This is done with Illuminating Engineering Society (IES) TM-30-15, *IES Method for Evaluating Light Source Color Rendition* (TM-30),[7] in the form of the Fidelity Index (R_f) and the Gamut Index (R_g), which are similar in intent to other previously developed measures.[8-11] However, it is less clear how these average measures may translate into value for the end user in an actual application. While averaging distills complex information to an easily used value, it also discards key information, such as how particular hues or samples may be affected.

Several researchers have identified the benefit of using multiple, independent, average measures to more fully characterize human assessments of color rendition.[9, 10, 12-15] Some work has suggested the need for supplementary information, going beyond averages, in the form of graphical representations or numerical sub-indices for fidelity and saturation of specific hues.[1, 16, 17] While the focus of most research has been average values—especially the concept of supplementing an average color fidelity value with an average color gamut value[6, 10, 12, 14, 15]—the results of this work suggest that hue-specific information is quite important, corroborating the hypothesis of de Beer and colleagues.[17] This work takes a deeper look at the relative importance of shifts across different hues, using the term *gamut shape* to describe this attribute of color rendition.

In this report, TM-30 Hue Angle Bin Chroma Shift values ($R_{cs,hj}$) are used as a numerical indicator of gamut shape. TM-30 $R_{cs,hj}$ values are derived from the TM-30 Color Vector Graphic. They correspond to the purely radial difference between vectors for the test and reference condition in each of the 16 hue bins (*j*). A positive value indicates an average increase in chroma for the samples in the hue angle bin, whereas a negative value indicates an average decrease in chroma for the samples in the hue angle bin. Complete calculations are available in the TM-30 Advanced Calculation Tool and the TM-30 Basic Calculation Tool.

1.1. Past Experiments Focusing on Color Preference and Other Subjective Impressions of Color Rendition

When designing color rendition experiments, researchers must decide on all contextual factors (age, culture, gender, application, and illuminance), as well as the light source(s) under which the judgment is made, weighing innumerable options against the constraints of limited resources. This has led to different tradeoffs being made in the numerous experiments in this field.

The quantity and type of objects included in color rendition experiments has varied considerably. Some narrowly-focused experiments (or parts of experiments) have focused solely on the appearance of skin tones,[1, 6, 18-20] while others have focused on printed images or color checker cards.[2, 14, 21-24] Some have primarily examined fruits and vegetables,[2, 6, 15, 25-28] while others have included a broader variety of consumer goods.[1, 5, 29-31] Other than Smet and colleagues,[31] Islam and colleagues,[23] and Jost-Boissard and colleagues,[32] most recent literature on color preference includes only very limited discussion of the attributes of the objects, despite the fact that they are critical to the stimulus being evaluated. An object set that is not similar to the samples used for an average color rendition measure may not exhibit the same shifts that the measure predicts, and therefore the measure should not be expected to be an effective predictor of psychophysical responses. Further, models or recommendations based on such experiments may have internal validity, but should not be expected to have external validity (generalizability) unless they are only used for similar object sets.

Most of the previously noted experiments have used a relatively small number of objects (less than 20) presented in a viewing booth, but a few have used more objects presented in full-size spaces.[1, 5, 29, 30] This contextual factor may also influence participant responses. Rea and Freyssinier point out that with a large number of objects, some observers may focus on one particular color while other observers may give an overall response to the objects in the field of view.[14] Further, while modern color difference calculations are based on extensive experimentation, the meaningfulness of different color shifts in immersive, polychromatic environments is an important consideration that is not addressed in small-scale experiments.

Most recent research on color rendition has emphasized variations in spectral power distribution (SPD). However, most studies have examined only a limited number of SPDs (≤ 8).[1, 5, 6, 14, 15, 18-22, 24-26, 31, 33, 34] While fewer SPDs allow for methods that can provide stronger statistical results, it also reduces granularity and the capability to consider a wide range of color rendition conditions. A few studies have used color tunable luminaires with fixed primaries, either with preset conditions[23, 27, 30, 35-37] or allowing for user variation;[2, 27, 38] these studies have focused on creating a variety of color rendition properties using existing average measures of color rendition. Fewer studies have focused on systematically changing the spectral features of the light source,[20, 39-42] which allows for different types of inquiry, such as the effects of systematic changes in SPD on visual perception.

Importantly, none of the reviewed studies systematically examined a wide range of combinations of fidelity, gamut, and gamut shape that could be utilized in an architectural interior, as was done for this study. One of two studies that varied both average gamut and average fidelity did not include any sources in the range most preferred in this study.[15] The other did not systematically vary either attribute.[6] We know of only one body of work that isolated gamut shape independent of average fidelity and average gamut.[36, 37]

Despite the wide range of methodologies used to study color rendition, one finding seems to be relatively consistent: preference is correlated with saturation.[1, 2, 6, 20, 23, 28, 30, 32, 34, 43, 44] Others have illustrated that preference is related to both saturation and fidelity,[5, 15, 31, 36] which suggests that there is a limit to the amount of increased saturation that is acceptable/preferred.[28, 37] In general, two measures have been shown to be more useful than one at predicting multiple subjective perceptions.[6, 10, 15]

Some studies have shown that color fidelity alone is not a strong predictor of naturalness ratings,[23, 28, 31] while others have found the opposite.[2, 6, 27, 32] Accordingly, one area with inconsistent findings is whether naturalness and preference are related to one another: some studies suggest they are correlated,[15, 23, 28, 31] while others suggest they are not correlated.[2, 27, 32] No studies have found that average color fidelity alone is highly correlated with preference,[9] although high color fidelity has been considered important by some.[45]

The various contexts of the reviewed studies—including applications, cultures, illuminance levels, chromaticities, adjacent illumination, evaluated objects, duration of viewing, and time of day—may contribute to the range of findings, further highlighting the link between context and preference. Some of these contextual factors, such as application, culture, and chromaticity, have been investigated, whereas others, such as viewing duration and time of day, have not.

1.2. Goals and Hypotheses

The main goal of this experiment was to relate human perceptions of color rendition to the measures included in TM-30. The SPDs designed and used for this experiment covered the range of R_g possibilities for which R_f exceeds 63, at the specified chromaticity. Since using only R_f and R_g will not fully characterize a SPD, two SPDs with different gamut shapes were studied at each combination of R_f and R_g, minimizing and maximizing saturation of reds, as characterized by $R_{cs,h1}$. The *a priori* hypotheses included: 1) as R_f increased, colors would be judged as more normal (measured on a normal versus shifted rating scale), 2) as R_g increased, colors would be judged as more saturated (measured on a saturated versus dull rating scale), 3) higher levels of R_g would be more preferred than lower levels of R_g (measured on a like-dislike scale), and 4) higher levels of red saturation would be more preferred. Additional post hoc analysis expanded beyond these specific hypotheses, using the full suite of TM-30 measures to develop best-fit models for normalness, saturation, and preference. These models are intended for testing additional datasets and for future hypothesis development; strictly applying them in practice based on the results from a single experiment would be premature, and few commercially-available light sources are similar to these carefully engineered sources.

2 Methodology

2.1 Apparatus and Test Space

2.1.1 Lighting Equipment

A spectrally tunable luminaire, the ETC Source Four Series 2 Lustr, was used to create 26 different lighting conditions that were colorimetric metamers to the Commission Internationale de l'Eclairage (CIE) 1931 Standard Observer. The luminaire had seven independently controlled LED channels (**Figure 1**). The luminaires were controlled via a DMX-based digital control interface connected to a laptop computer running Nicolaudie Easy Stand Alone 2 (ESA2) software, which allowed for manual programming of DMX channels between 0 and 255.

2.1.2 Objects for Evaluation

Objects were selected to provide a reasonable distribution within all three dimensions of the color volume (hue, chroma, and lightness), while simultaneously maintaining an environment that, as a whole, was not readily identifiable as a specific type of architectural space. Four categories of objects were chosen: printed artwork, clothing, consumer goods with packages containing inks or dyes, and natural objects such as flowers and produce. Two mirrors were also provided to allow participants to assess the color appearance of their own faces. Spectral reflectance functions (available upon request) were measured for each of the objects using a factory calibrated Minolta CM-600d spectrophotometer (SN: 21011777). Polychromatic objects, such as artwork or complex packaging, were characterized based on measurements of up to seven of the most prominent colors, at the discretion of the experimenters.

2.1.3 Room Layout

The windowless experiment room was approximately 3.1 m by 3.7 m with a ceiling height of approximately 3 m. It had two fixed walls (north and west), one temporary wall (south), and an open end (east) for entering and exiting. The open end was fitted with a black curtain that was closed when participants were performing

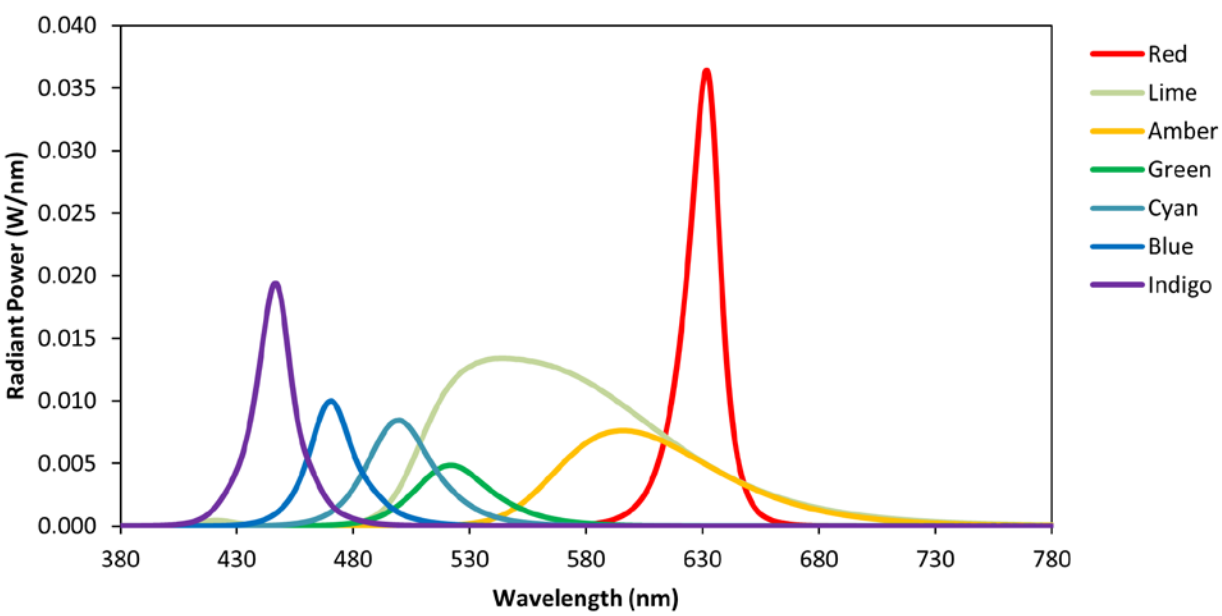


Figure 1. Spectroradiometric measurements of each channel of the ETC Source Four Series 2 Lustr luminaire at full output, as measured in an integrating sphere according to IES LM-79-08.

their evaluations. Objects were placed in specific areas of the room according to their category, as shown in **Figure 2.**

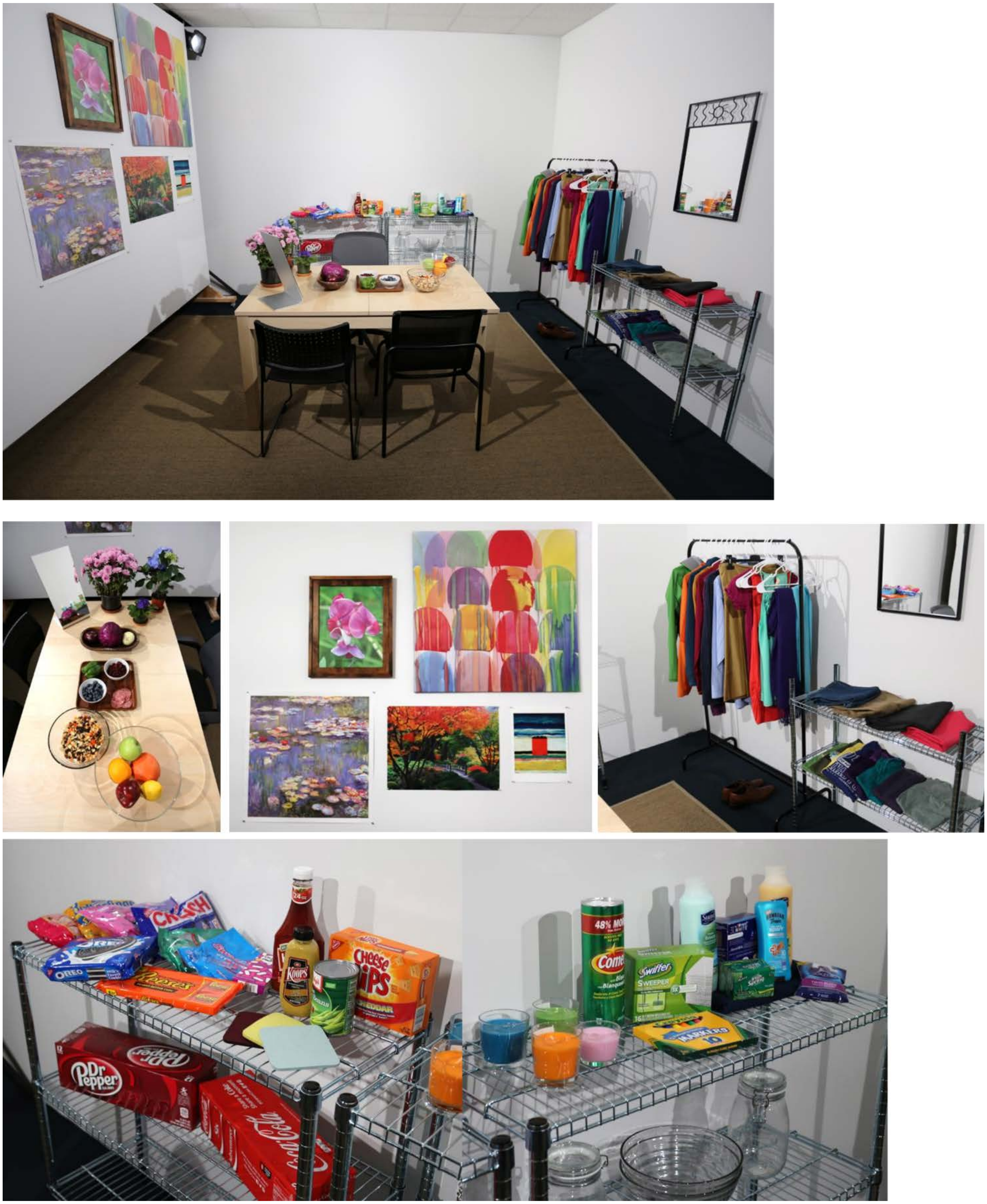


Figure 2. Photographs of the experimental room. One of the luminaires can be seen at the upper left of the top photograph. The other three luminaires are behind the camera at a similar height, at the upper left corner, middle, and right corner of the room. The four object groups include the artwork (left wall), consumer goods (rack along far wall), clothing (racks along right wall) and natural objects (table in center).

2.2 Lighting Conditions

Twenty-six SPDs were selected to produce a range of TM-30 R_f and R_g values, with R_f values ranging from 63 to 93 and R_g values ranging from 79 to 117 (see Table 1). Thirteen nominal combinations of R_f and R_g were based on four levels of fidelity and up to five levels of gamut, with two SPDs at each point corresponding to different gamut shapes (i.e., different individual shifts leading to the same average values of R_f and R_g).

Calculations, based on photometric measurements of individual channels, estimated the relative intensity of the seven LED channels necessary to produce the specified R_f value, R_g value, and chromaticity under two different constraints: maximizing or minimizing TM-30 $R_{cs,h1}$, the chroma shift in hue angle bin 1, which is nominally red.[†] Final refinements of each lighting condition were made in-situ using a calibrated Minolta CL-500A illuminance spectrophotometer (SN: 100020008). All objects were removed from the space for the final measurement to ensure that the characterization was of the SPD itself, as is the intended use of TM-30. Summary numerical attributes of each SPD are provided in **Table 1**. More data for each source can be found in Appendix A.

Table 1. Characteristics of the 26 lighting conditions.

				IES TM-30-15			
ID	LER	CCT (K)	D_{uv}	R_f	R_g	$R_{cs,h16}$	R_a
1	322	3514	-0.0001	66	79	-19%	73
2	309	3520	0.0003	67	83	-11%	77
3	299	3478	-0.0003	67	89	-8%	72
4	294	3531	0.0005	65	92	4%	68
5	292	3515	0.0006	67	99	5%	65
6	289	3500	0.0003	65	102	15%	56
7	290	3489	-0.0002	66	109	14%	56
8	286	3502	-0.0002	64	112	22%	46
9	290	3480	-0.0004	67	119	22%	50
10	287	3511	0.0000	64	120	26%	43
11	352	3504	-0.0003	73	88	-13%	72
12	307	3491	0.0001	74	92	0%	81
13	351	3502	0.0000	75	99	-5%	78
14	298	3487	0.0000	73	102	11%	68
15	301	3484	-0.0002	76	108	9%	70
16	301	3496	-0.0003	74	111	17%	60
17	305	3489	-0.0004	77	116	16%	68
18	299	3485	0.0000	74	117	20%	60
19	337	3520	0.0005	83	91	-13%	80
20	328	3483	0.0002	84	93	-6%	91
21	343	3513	0.0005	83	98	-7%	84
22	311	3506	0.0007	84	102	7%	83
23	309	3504	0.0000	83	111	14%	73
24	332	3498	0.0000	85	109	6%	90
25	328	3491	0.0001	93	100	-3%	95
26	321	3502	-0.0001	93	101	2%	95

[†] Although the conditions were created to maximize and minimize $R_{cs,h1}$, fidelity and chroma shift values in all 16 hue bins were considered when examining the best regression models. The range of variation in each hue angle bin followed similar trends to evaluation over large datasets. Increasing chroma is more easily achieved in some hue angle bins than others. The range of possible conditions in this experiment are similar to those of identified by Žukauskas and colleagues,[27, 46, 47] who also examined LED sources, and consistent with the work of Ohno and colleagues,[28] who noted that "it was difficult to produce [saturating] lights for yellow and blue at this time".

The vertical illuminance at 1 m above the floor at the center of the west wall—the main calibration point and the center of the consumer goods group—was 214 lux ± 4 lux. The illuminance distribution throughout the space was consistent between lighting conditions, but was not perfectly uniform, so the illuminance on the objects varied throughout the space by as much as 30% (approximate). Because the objects always remained in the same location, the illuminance on each object was nominally the same for each lighting condition.

Although the 26 lighting conditions represent a wide range of R_f and R_g values, neither the TM-30 values nor the SPDs themselves are the true experimental independent variables, because the participants were viewing the interaction of the SPDs and the objects. This effect was examined by comparing custom average fidelity and average gamut measures, based on the reflectance measurements of the experimental objects, to standard TM-30 calculations. Due to the careful selection of the objects, the match was sufficient to justify using the TM-30 measures as a characterization of the visual stimulus. In other words, there was little difference between the custom and standard calculations, and no material difference between the regression models. If the experimental objects had very different properties from the standard color evaluation samples of TM-30, such as might occur with a bowl of fruit, TM-30 would not be an appropriate characterization of the visual stimulus, and the results would be less applicable outside of the specific context.

2.3 Participants

Twenty-eight people participated in the experiment, 12 males and 16 females. None of their professions was related to lighting. Ages ranged from 19 to 65 years, with a mean of 40 years (44 years for men and 38 years for women). Before participating, each person completed a color vision test (Ishihara 24 plate). Visual color deficiency (red-green colorblindness) was noted for one of the male subjects, but he was not excluded from the study; review of his responses did not demonstrate abnormalities beyond the variance of the other data.

2.4 Participant Ratings (Dependent measures)

For each lighting condition, participants completed a paper response form that had three semantic differential rating questions, each with an eight-point scale, and one multiple choice question. The first two semantic differential questions required participants to circle a response, from 1 to 8, indicating whether they felt the lighting made the color of objects appear normal (1) or shifted (8), and whether they felt the lighting made the color of objects appear saturated (1) or dull (8). The third semantic differential question asked whether their overall opinion was that they liked (1) or disliked (8) the way the lighting made the objects appear. The multiple choice question required participants to choose one of four options that best described how the lighting made the objects look: dull, normal, saturated, or shifted.

At the conclusion of the experiment, the participants completed a brief questionnaire to describe their experience, and to provide insight into which objects or colors were the most influential in determining their judgments. The questions were structured similar to other studies on color preference,[15, 35-37] in order to allow for comparisons based on the different methodologies.

2.5 Procedure

2.5.1 Pre-Experiment Preparation

Each session had one or two participants. Upon arrival, participants went into a daylit conference room with a researcher to review and sign an informed consent form and complete a color vision test. Participants were then directed to the experimental room in a different part of the building. A second researcher provided a white lab coat for each participant to wear, to minimize any effect of the color of the participants' clothing on their assessments. The researcher and participants entered the experimental room, which was preset to lighting condition 26. The researcher provided instructions for several minutes, before showing the participants four conditions that demonstrated the range that would be experienced (conditions 1, 10, 5 and 26). A minimum of four minutes elapsed while the participants were in the room but before the first experimental trial was viewed, allowing for sufficient chromatic adaptation,[48-51] although long-term color contrast adaptation artifacts cannot be completely accounted for in a short-term laboratory experiment.

2.5.2 Experimental Trials

Two announced practice trials (conditions 20 and 15) and one unannounced practice trial (randomly selected) were completed before beginning the 26 experimental trials. The participants were told that the third practice trial was the beginning of the experiment. For each trial, participants were instructed to enter the experimental room, move about the room to consider the color appearance of the different objects, and wait for the researcher to instruct them that they could complete their ratings (after 30 seconds of viewing). Once they completed their ratings, the participants stepped out of the experimental room and handed their forms to the researcher, who gave each participant another blank form. After the researcher changed the lighting condition to the next setting, participants re-entered the room and repeated the process. The area outside of the experiment room was dimly lit with a reading light to allow the researcher to check that the response forms were completed properly.

The order of presentation of the 26 experimental conditions was randomized for each session. After the final experimental trial, the researcher set the lighting condition back to condition 26, and the participants entered the room to complete the concluding summary questionnaire. Each experimental session required a total of about one hour.

3 Results

3.1 Data and Variance

The mean, range, and standard deviation for each rating question at each stimulus condition, are shown in **Table 2**. The mean Standardized Residual Sum of Squares (STRESS) values[52-54] between each observer's rating of the 26 conditions and the average rating of the 26 conditions was 0.35 (for normal versus shifted, range 0.14 to 0.63), 0.29 (for saturated versus dull, range 0.13 to 0.50), and 0.34 (for like versus dislike, range 0.15 to 0.56). STRESS is not commonly used for experiments on the perception of color rendition, but the values seen here are similar to those reported by Smet and colleagues.[54]

The responses to the final questionnaire revealed three different items that were frequently cited as very influential (flowers, Coke and/or Dr. Pepper packaging, and a green bell pepper), but more than 25 objects were mentioned at least once. Another likely contributor to the variance is the order in which participants viewed the conditions, due to a stronger memory of the immediately preceding condition and the effects of

Table 2. Summary of participants' responses. For question 4, the shaded cells with red font have the greatest selection rate (mode).

	Q1: Normal-Shifted				Q2: Saturated-Dull				Q3: Like-Dislike				Q4: Pick a Word			
ID	Min	Mean	Max	SD	Min	Mean	Max	SD	Min	Mean	Max	SD	**Dull**	**Normal**	**Saturated**	**Shifted**
1	1	5.30	8	2.1	1	5.84	8	1.7	1	5.66	8	2.0	54%	14%	11%	21%
2	1	4.86	8	2.2	1	5.82	8	1.8	1	5.68	8	1.7	64%	11%	4%	21%
3	1	4.70	8	2.2	2	5.57	8	1.8	1	5.39	8	2.2	29%	32%	4%	36%
4	1	4.77	8	2.3	1	3.89	8	1.9	1	4.54	8	2.5	18%	25%	25%	32%
5	1	4.34	8	2.2	1	4.41	8	1.9	1	4.27	8	2.1	29%	43%	14%	14%
6	1	4.23	8	2.4	1	3.29	7	1.8	1	3.32	7	2.1	4%	36%	36%	25%
7	1	4.00	8	2.2	1	3.68	7	1.7	1	3.77	8	2.0	7%	37%	33%	22%
8	1	4.04	8	2.2	1	2.64	5	1.4	1	3.66	8	2.2	4%	22%	63%	11%
9	1	3.91	8	2.2	1	2.68	7	1.5	1	3.57	8	1.9	7%	14%	64%	14%
10	1	4.27	8	2.4	1	2.23	8	1.5	1	3.88	8	2.1	4%	21%	64%	11%
11	1	4.79	8	2.3	2	5.86	8	1.8	1	5.29	8	1.9	64%	25%	0%	11%
12	1	3.70	8	2.0	1	4.66	8	1.6	1	4.00	8	1.8	29%	50%	7%	14%
13	1	4.59	8	2.2	1	5.79	8	1.8	1	5.11	7	1.8	43%	36%	0%	21%
14	1	3.89	7	1.9	1	3.55	7	1.5	1	3.82	8	2.1	21%	39%	32%	7%
15	1	3.25	7	2.2	1	3.61	8	1.7	1	3.14	8	2.0	14%	61%	14%	11%
16	1	3.79	7	2.1	1	3.13	6	1.2	1	3.25	6	1.6	7%	39%	46%	7%
17	1	3.59	8	1.8	1	3.59	6	1.3	1	3.05	6	1.5	14%	50%	29%	7%
18	1	3.52	8	2.0	1	3.14	7	1.6	1	3.34	8	2.0	11%	36%	50%	4%
19	1	4.89	8	1.7	2	5.66	8	1.2	2	5.41	8	1.5	68%	18%	0%	14%
20	1	3.88	7	1.8	2	5.11	8	1.7	1	4.41	8	1.9	54%	29%	7%	11%
21	1	4.32	8	2.1	1	5.32	8	1.9	1	5.02	8	2.1	54%	25%	7%	14%
22	1	2.73	6	1.8	1	3.63	6	1.2	1	3.05	6	1.6	4%	75%	21%	0%
23	1	3.54	7	2.1	1	3.54	8	1.7	1	3.25	8	1.8	7%	41%	37%	15%
24	1	3.21	8	2.2	1	4.11	8	1.5	1	3.32	7	1.6	18%	64%	7%	11%
25	1	3.38	7	1.9	1	4.73	7	1.5	1	3.79	7	2.0	43%	46%	7%	4%
26	1	2.79	7	2.0	2	4.29	8	1.6	1	3.11	8	2.0	14%	71%	7%	7%

visual adaptation. The conditions were presented in a random order to reduce and counterbalance these effects in the aggregate data, but all such effects cannot be removed.

3.2 Color Shifts and Their Influences

The main purpose of the final questionnaire was to begin to understand *why* the participants made the judgments that they did; this provides context for understanding the computed models discussed in this article. The responses indicated that object group and hue group had varying influences on the participants' ratings.

As shown in **Figure 3**, over two thirds of the participants identified either the consumer goods or natural objects as the most influential object group. These are likely the objects with color properties that were most familiar to the participants—something that was mentioned as an unsolicited comment by at least three people. This finding may help explain different results from past experiments, where either familiar or unfamiliar objects may have been featured exclusively.

As shown in **Figure 4**, the three most influential object hues were red, orange, and green, all of which were noted by more than 63% of the participants. These results are generally consistent with the findings of others who used a similar questionnaire, [15, 35-37] although there are some differences that likely stem from different prevalence of objects in the scene, as well as different types and magnitudes of color shifts caused by the interaction of SPDs and objects' spectral reflectance functions. For this experiment, the prevalence of object hues was balanced across the hue range.

Critically, the relative influence of different hues may be influenced by particular objects that changed color more than others. These shifts are caused by the interaction of the spectral reflectance functions with the SPDs, as evaluated by the human color vision system. For example, 9 of the 10 objects showing the greatest color shift across the 26 lighting conditions were in the nominally red and orange hue angle bins (16, 1, 2,

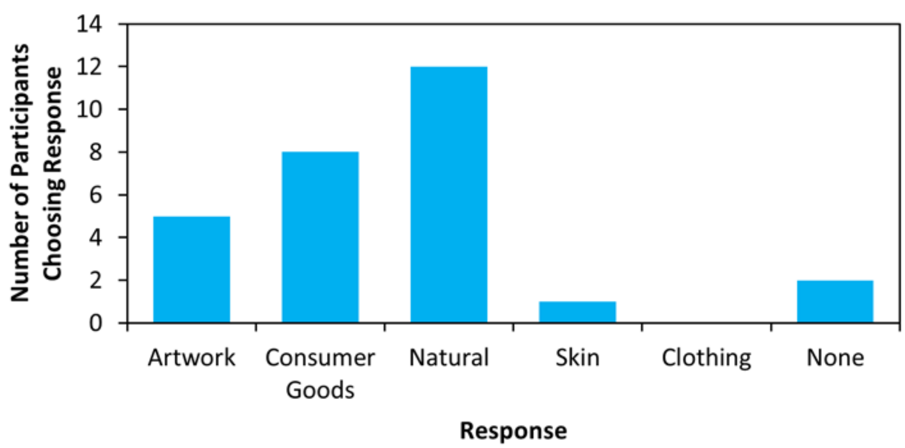


Figure 3. Responses to the post-experiment question: Which group of objects, if any, influenced your overall opinion of each condition the most? The natural objects and consumer goods were the most frequently cited groups, followed by the artwork. Skin tones were only mentioned by one participant and clothing was not mentioned by anyone. Potential contributing factors to the differences include participants' familiarity with the objects (or an associated memory of the color of the object), the presence of specific objects that shifted more than others, the position of the object groups within the room, or the differences in object chromaticities within each group.

and 3), with one in a nominally blue bin (13). In contrast, 5 of the 10 objects that exhibited the least color difference were in nominally yellow hue angle bins (4 and 5), although several of the objects, such as the walls, would more appropriately be classified as nominally white. In general, the hue angle bins with the highest and lowest color stability for the combination of this set of SPDs and the TM-30 color evaluation samples tend to reflect the response of the observers regarding influential hues in this experiment. These results do not necessarily suggest that observers are more sensitive to certain hues than TM-30 suggests. Rather, in this experiment, observers were more influenced by hues that had the greatest change in rendition when illuminated by this range of sources.

3.3 Modelling of Perceptions

The central goal of this work was to improve understanding of the relationship between color rendition measures calculated from spectral data and human perceptual responses. This article focuses on the measures provided in TM-30,[7, 55, 56] although others were considered, including CIE R_a,[57] gamut area index (GAI),[14] and the Q_f and Q_g values from the color quality scale.[58] In general, the TM-30 method was more effective at characterizing the three perceptual attributes examined than the other methods, primarily because it extends beyond average values and uses a more uniform color space than past measures. Initial analyses to test hypotheses for each perceptual attribute were performed using linear regression models; in each model R_f, R_g, and $R_{cs,h1}$ were fitted as continuous predictors and participant as a categorical predictor. $R_{cs,h1}$ was specifically studied because of the *a priori* hypothesis that enhanced saturation of objects with a red hue might be important. Subsequent analyses focused on a deeper examination of the underlying perceptual influences and the strength of relationships, using the mean responses for each SPD to help reduce the numerical noise associated with the substantial variability for individual samples.

3.3.1 Perceived Normalness

The initial analysis of predictors, testing *a priori* hypotheses for R_f, R_g, and $R_{cs,h1}$ and their relationship with perceived normalness, showed that both R_f ($p < 0.001$) and $R_{cs,h1}$ ($p < 0.001$) were significant factors. In this combined model, R_g was not a significant predictor of normalness ($p = 0.789$), likely due to collinearity with $R_{cs,h1}$ ($r^2 = 0.59$). These results confirm the hypothesis that higher fidelity is perceived as more normal, but also suggest that the relationship is more complex.

Best subset analysis was subsequently used to identify more complex models that better explain the variation in the ratings. The inputs included only first order terms for the TM-30 measures. Linear regression models for mean normalness rating using R_f and R_g alone had r^2 values of 0.35 and 0.32 and Mallows C_p

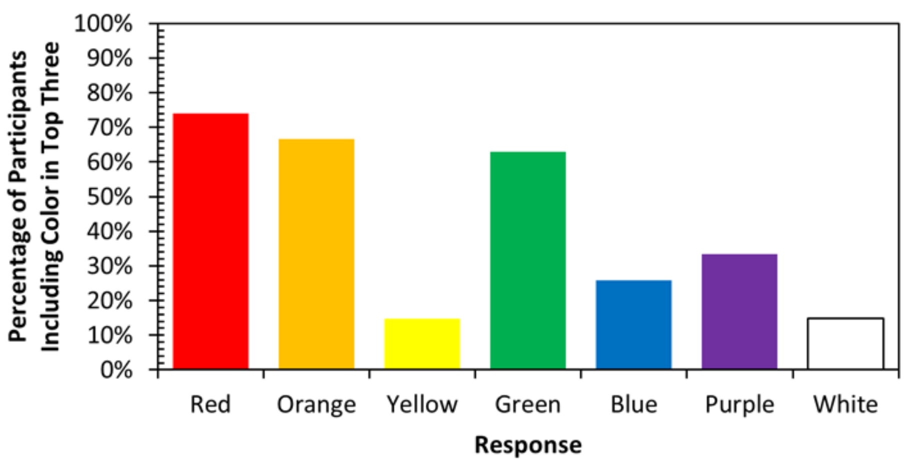
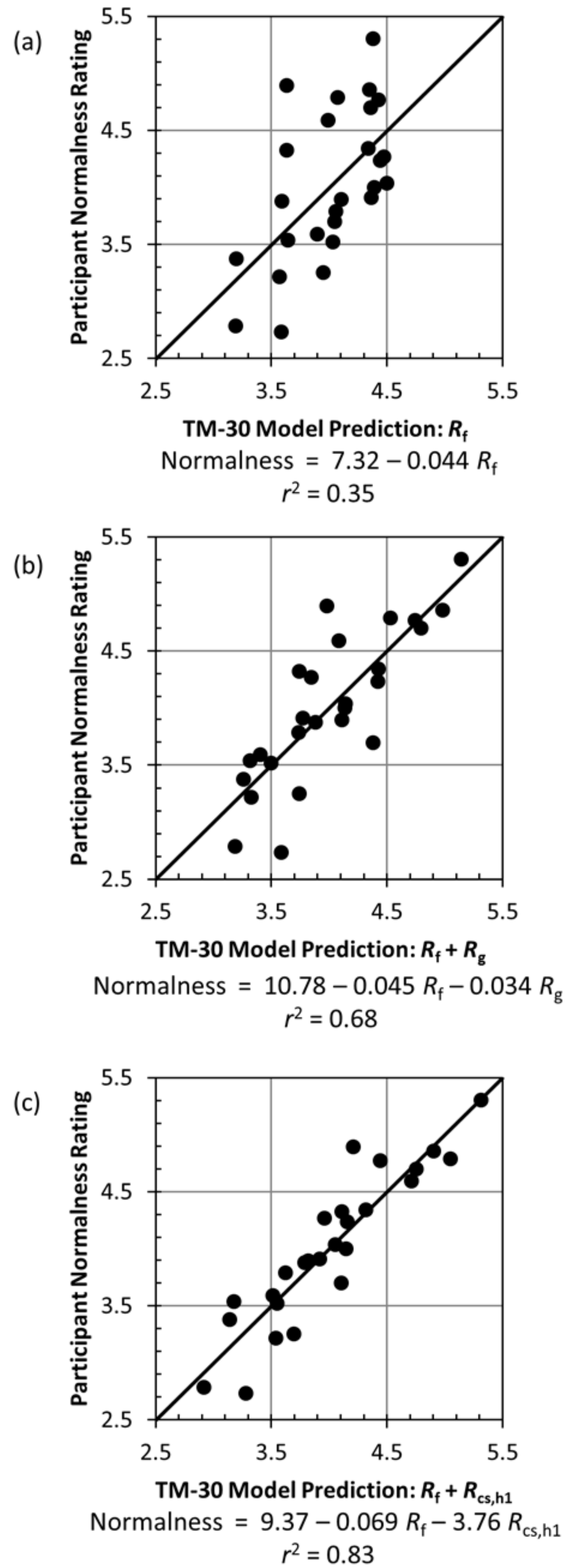


Figure 4.
Percentage of participants for which a color was ranked in the top three based on having the most influence on the participant's judgments. One participant did not respond to this question.



values[59§] of 33.3 and 33.8, respectively. The r^2 value for CIE R_a was just 0.06. These results are consistent with the findings of Smet and colleagues,[9] who compiled data from several color perception studies. Despite being a statistically significant predictor of normalness rating, R_f shows only moderate utility for explaining the variation in mean normalness ratings. Utilizing R_f and R_g together in a linear regression model of mean normalness rating improved the correlation (r^2 = 0.68, Mallows C_p = 12.3), which is again consistent with the findings of Smet and colleagues. These models for perceived normalness are shown in **Figure 5**.

An even better model of mean rated normalness (r^2 = 0.83, Mallows C_p = 3.4) can be built using R_f and $R_{cs,h1}$. Both predictors have p values less than 0.0001 in the regression model, which is also shown in **Figure 5**. Notably, $R_{cs,h1}$ alone (r^2 = 0.14) is not a better predictor of normalness than the other measures, even when including up to third-order terms (r^2 = 0.36), but it has more incremental value when paired with R_f than does R_g. The influence of reds has been noted in past lighting research,[1, 28, 36, 37, 60, 61] and the psychological importance of red is well documented.[62] The importance of $R_{cs,h1}$ as a predictor is also recognizable because two sources with the same average fidelity and gamut value can render colors very differently; this was an

Figure 5.
Linear regression models and associated coefficient of determination (r^2) values for the relationship between various TM-30 measures and the means for participant normalness ratings. (a) R_f is weakly correlated with normalness ratings. **(b)** The linear combination of R_f and R_g is moderately correlated with the normalness ratings, but there are several outlier points. **(c)** The model built from TM-30 components that was most strongly correlated with rated normalness was the linear combination of R_f and $R_{cs,h1}$. A one point increase in average fidelity (R_f) leads to approximately the same increase in perceived normalness as a two percent increase in deep red chroma shift ($R_{cs,h1}$).

§ Mallows' C_p helps identify regression models that are relatively precise and unbiased. A value of Mallows' C_p close to the number of predictors in the model plus the constant indicates that the model may be useful for predicting future responses. For a model with two terms and a constant, a value of Mallows C_p of about 3 would indicate a very good fit.

important consideration in choosing the 26 spectral power distributions, and is discussed further in Section 3.4.

3.3.2 Perceived Saturation

The initial analysis of predictors for perceived saturation showed that R_g ($p = 0.022$) and $R_{cs,h1}$ ($p < 0.001$) were significant factors. In this test, R_f was not a significant predictor ($p = 0.06$). These results confirm the hypothesis that higher gamut is perceived as more saturated, but again suggest that the relationship is more complex—and tied to the relationship between average gamut area and red saturation in this set of conditions. The regression coefficient for R_g indicates that a one point increase in R_g provides a change of 0.02 (on the 8-point scale of dull-saturated) towards being perceived as more saturated, whereas an increase of 1% for $R_{cs,h1}$ provides a change of 0.07 towards being perceived as more saturated.

In subsequent best subsets analysis of mean rated saturation, red chroma shift was clearly a superior predictor, especially $R_{cs,h16}$ ($r^2 = 0.95$), as indicated in **Figure 6**, which also shows a lower correlation between mean rated saturation and R_g ($r^2 = 0.75$). Other measures of red and red-orange saturation ($R_{cs,h1}$, $R_{cs,h2}$, and $R_{cs,h3}$) were also strongly correlated with mean rated saturation; they were also correlated with one another due to the features of the SPDs, such that increasing saturation in one of those four bins almost always dictated increased saturation in the adjacent bins. Importantly, the fit of a linear model for mean rated saturation using the chroma shift measures was not strongly correlated with the range of chroma shift values in that hue angle bin, as shown in **Figure 7** ($r^2 = 0.21$). Thus, the influence of reds cannot be attributed solely to the inclusion of $R_{cs,h1}$ as a variable in the SPD development process. Similarly, the fit of the chroma shift measures is not strongly correlated with the mean color difference across the 26 conditions for the actual objects in each hue bin, which is also shown in **Figure 7** ($r^2 = 0.35$).

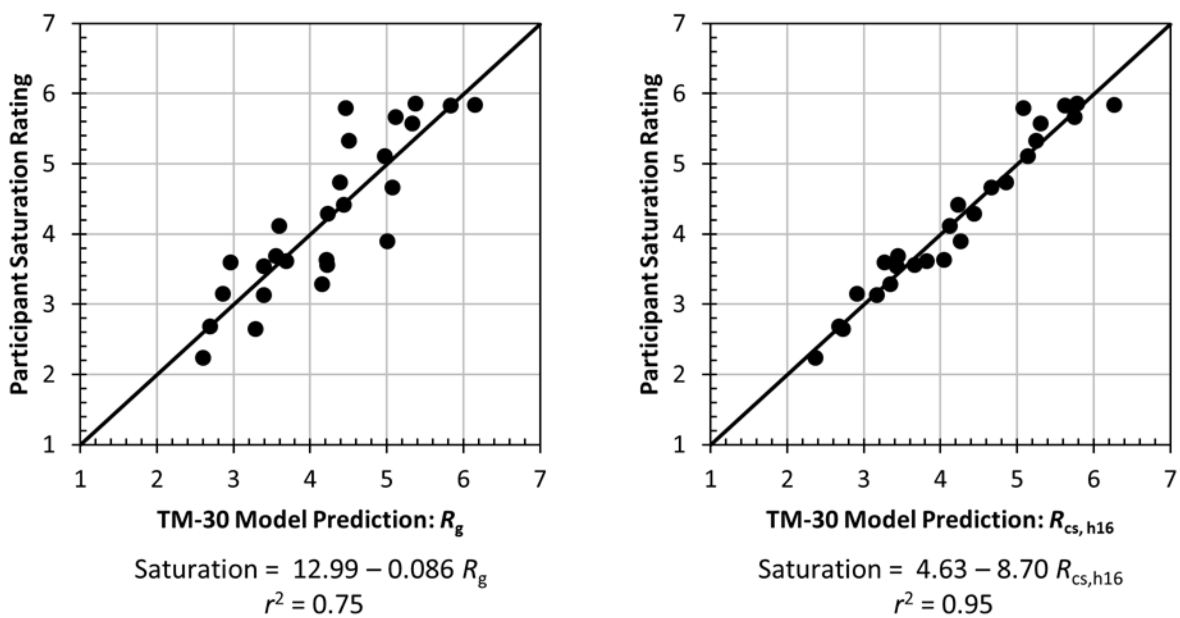


Figure 6. Linear regression models and associated coefficient of determination (r^2) values for the relationship between various TM-30 measures and the means for participant saturation ratings. Red chroma shift ($R_{cs,h16}$) was a stronger predictor for perceived saturation than average gamut area (R_g).

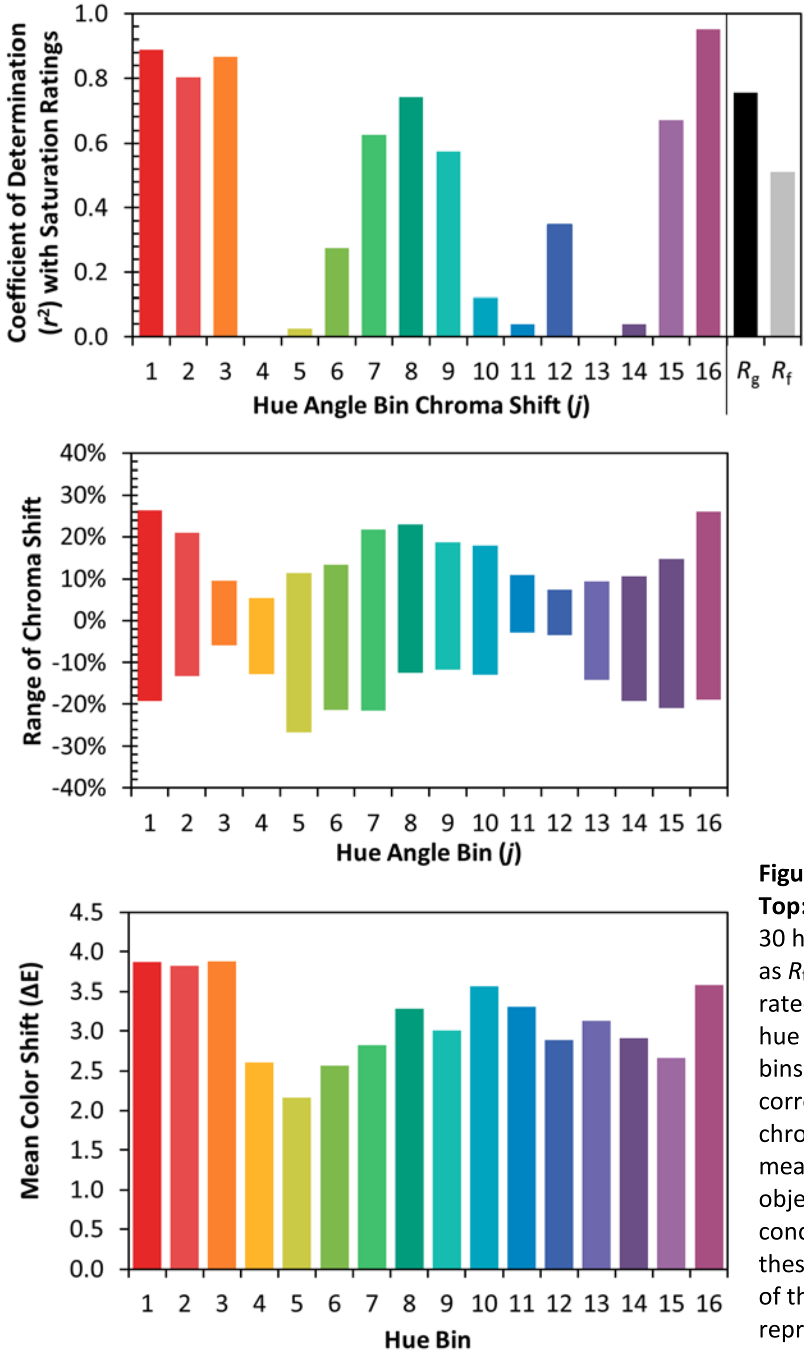


Figure 7.
Top: Coefficient of determination (r^2) for all TM-30 hue angle bin chroma shift measures, as well as R_f and R_g, in a linear regression model with rated saturation. The top four models use the hue angle bin chroma shift measures for hue bins 16, 1, 3, and 2. The strength of the correlation is not dependent on the range of chroma shift across the 26 SPDs **(middle)** or the mean difference versus the reference for all objects in each bin across the 26 lighting conditions **(bottom)**, although by definition these two are related to each other. The colors of the bars in the charts are approximate representations of the hue angle bins.

3.3.3 Perceived Preference

The initial analysis of predictors for perceived preference showed that R_f ($p < 0.001$) and $R_{cs,h1}$ ($p < 0.001$) were significant factors. In this combined model, R_g was not a significant predictor ($p = 0.70$). This result is similar to that for normalness, and may be related to the collinearity of R_g and $R_{cs,h1}$. If used alone in a single-predictor model, R_g does achieve statistical significance. These results confirm the hypothesis that preference is tied to red saturation, and suggest that R_g alone is not an ideal predictor of preference.

Further analysis of possible models offers substantial insight into the importance of different hues and the nonlinear response to changes in saturation. Best subsets analysis of linear regression models for mean rated preference show variable utility of the TM-30 measures when used in isolation. The r^2 values for linear models with R_f, R_g, and $R_{cs,h1}$ as lone predictors were 0.06 (Mallows C_p = 188.9), 0.62 (Mallows C_p = 63.3), and

0.51 (Mallows C_p = 88.6), respectively. Past results suggest that too much saturation is not desirable;[28, 36, 37] which was confirmed in the present study: rated preference increased with increasing saturation over a range of saturation values, but then decreased when saturation exceeded a certain level (see **Figure 8).** Consequently, single-predictor *linear* models are unlikely to provide good predictive power. Combining R_f and R_g or R_f and $R_{cs,h1}$ improves the correlation, with r^2 values of 0.68 (Mallows C_p = 50.8) and 0.88 (Mallows C_p = 7.6), respectively. Illustrations of the effectiveness of these models are provided in **Figure 9**, using colors corresponding to the ratings of each combination.

Importantly, the correlation between hue angle bin chroma shift and preference was unique to the red hue bins, as shown in **Figure 10**, which summarizes an expanded investigation of potential non-linear models for predicting mean rated preference. The most strongly correlated regression model for mean rated preference (r^2 = 0.94), shown in **Figure 11**, is the combination of R_f and a third-order polynomial fit for $R_{cs,h16}$, which is a measure of nominally red saturation. This model more strongly captures the nonlinear relationship between preference and saturation:

$$\text{Preference} = 7.446 - 0.041\, R_f - 9.99\, R_{cs,h16} - 0.90\, R_{cs,h16}^2 + 106.6\, R_{cs,h16}^3 \qquad \textbf{Equation 1}$$

Note that a second order term for $R_{cs,h16}$ in this model is not statistically significant, but was retained to maintain a hierarchical model. A model without the third-order term has an r^2 of 0.89, which is minimally better than the two-variable linear model including R_f and $R_{cs,h1}$. Apparently, for this dataset, the inclusion of R_f in the preference model acts to mitigate the effect of oversaturation, leaving minimal room for improvement when including higher-order terms.

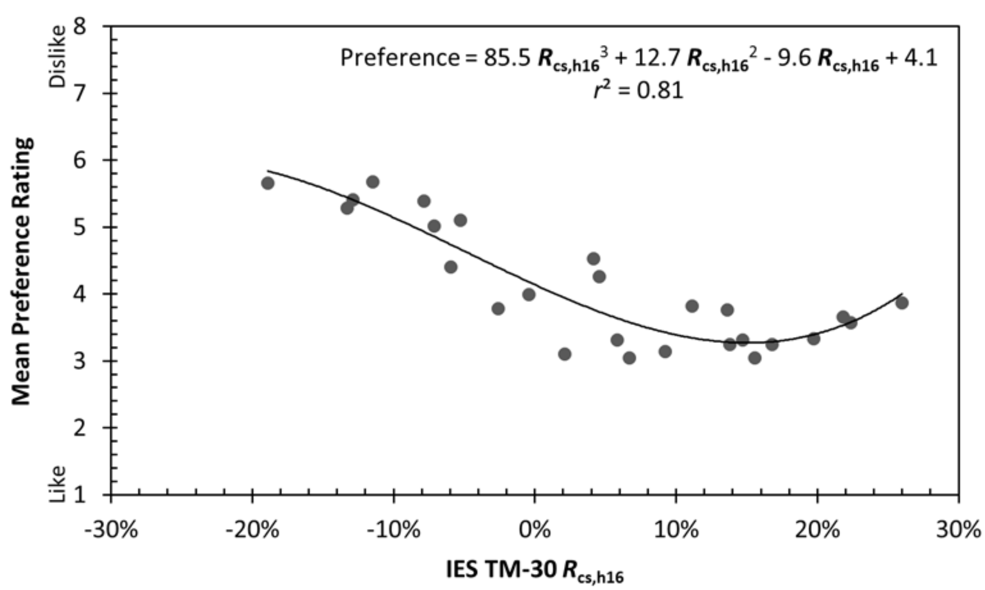


Figure 8. A single-predictor polynomial model of color preference shows the ideal hue angle bin 16 chroma shift to be 15%. However, conditions including sources with $R_{cs,h16}$ between 2% and 16% were all similarly rated. The polynomial relationship, where preference decreases again at high levels of saturation, is corroborated by past research. Note that a similar model using $R_{cs,h1}$ had a lower r^2 value of 0.59, even though that was the variable that was modulated during the experimental design phase. For both preference and saturation ratings, $R_{cs,h16}$ was more strongly correlated for this set of experimental conditions. This is perhaps due to the influence of a flower photograph and the chrysanthemum flowers, both frequently noted by the participants and both in hue angle bin 16.

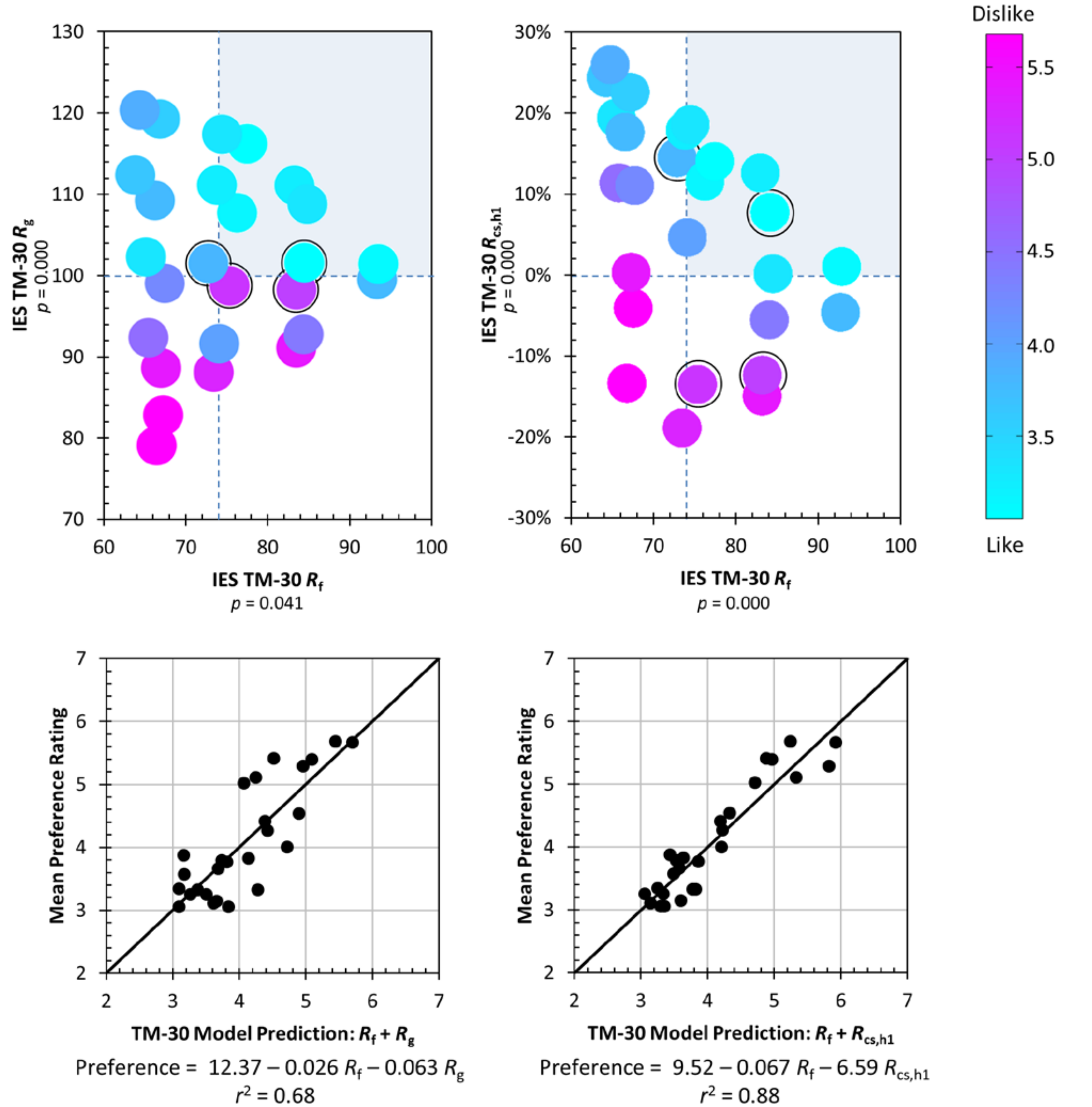


Figure 9. Two-measure plots of color rendition, with each point colored according to its preference rating. The points with black outlines are those that correspond to nominal R_g values of 100, where contrasts in gamut shape were most prevalent (see Figure 13). The shaded areas identify the region where products would meet both of the potential criteria (dashed lines).

3.4 Influence of Gamut Shape on Findings

The data for all three rating scales demonstrate the influence of gamut shape—or specific shifts which are more influential than others—which diminishes the value of average gamut values. **Figure 12** shows a plot of mean saturation rating versus $R_{cs,h16}$, as well as mean saturation rating versus R_g. $R_{cs,h16}$ is highly correlated with R_g (r^2 = 0.85) for this set of SPDs—and moderately correlated for a larger set of 212 commercially available sources in the TM-30 Advanced Calculator Tool library (r^2 = 0.49). However, $R_{cs,h16}$ (r^2 = 0.95) shows

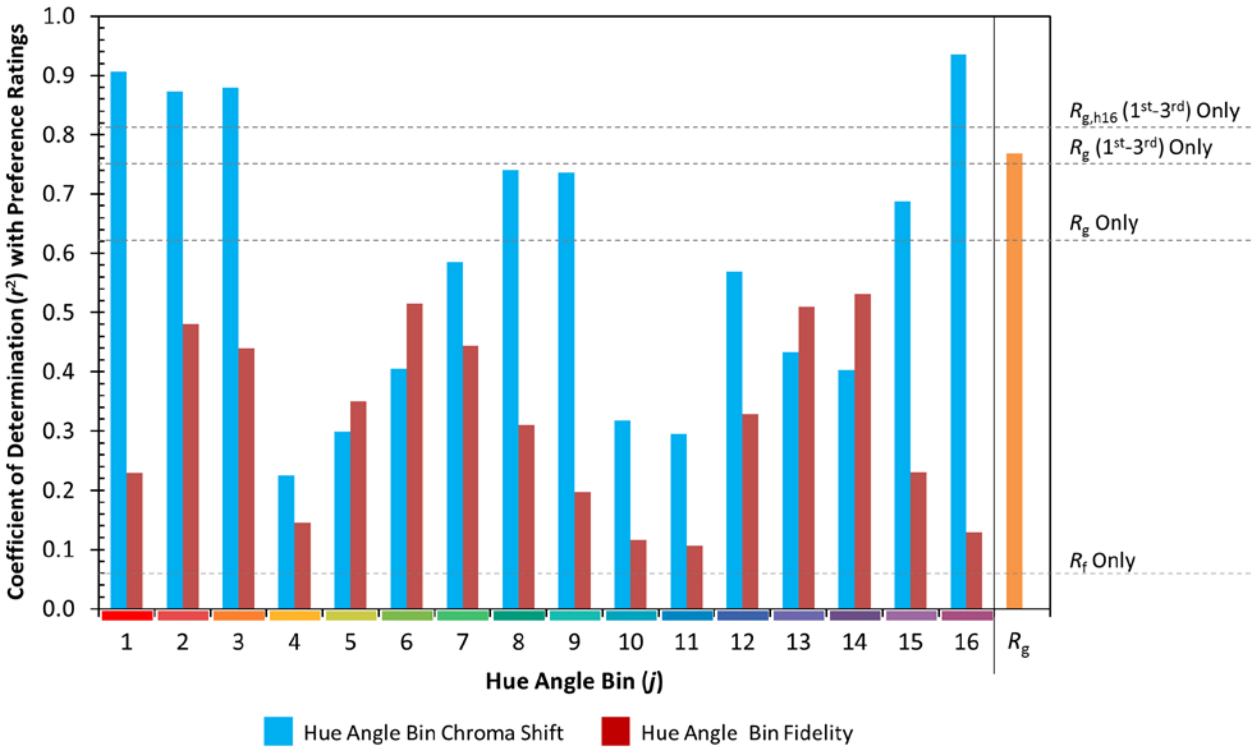
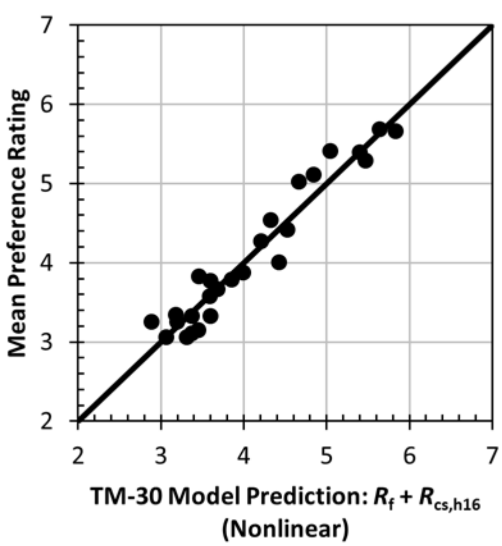


Figure 10. Comparison of the coefficient of determination for mean preference ratings versus 33 different TM-30 measures paired with R_f. First through third-order terms for all predictors were included. The horizontal dashed lines indicate the coefficient of determination for models that include only one predictor, as indicated. A higher r^2 value indicates better ability for the given model to explain the variation in the mean preference ratings. Models that include a measure of red saturation ($R_{cs,hj}$ for hue bins 16, 1, 2, or 3), paired with R_f, provide the best predictions of rated preference.



$$\text{Preference} = 7.45 - 0.041\,R_f - 9.99\,R_{cs,h16} - 0.90\,R_{cs,h16}^2 + 106.6\,R_{cs,h16}^3$$

$$r^2 = 0.94$$

Figure 11. Best fit regression model and associated coefficient of determination (r^2) value for the relationship between various TM-30 measures and the means for participant preference ratings. This model includes up to third-order polynomial terms for $R_{cs,h16}$, which better captures the nonlinear relationship between red saturation and preference, as shown in Figure 8.

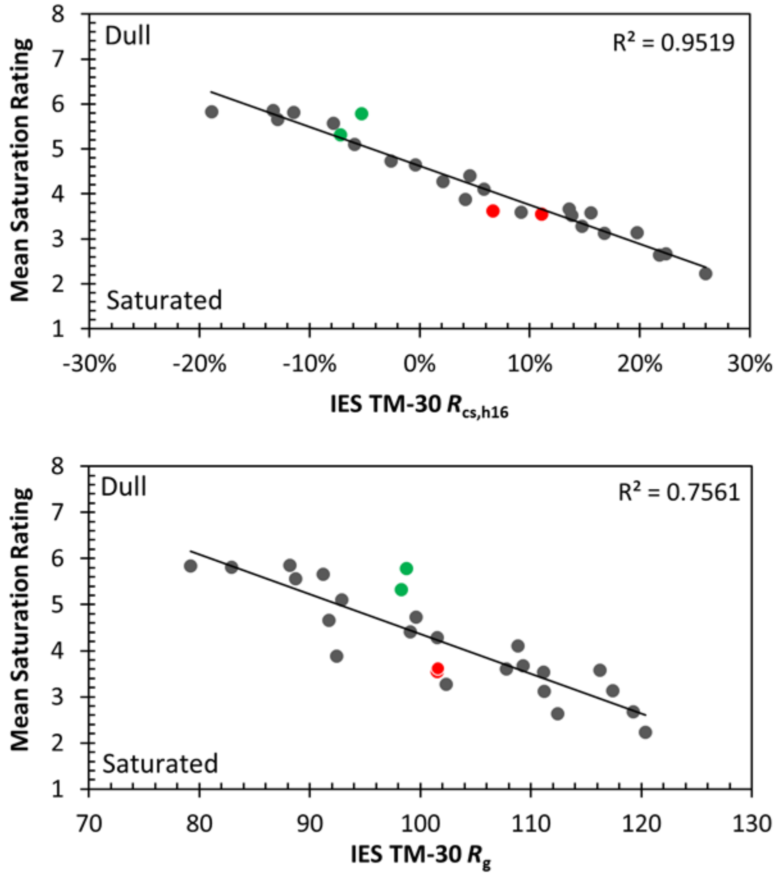


Figure 12. Linear regression model for mean saturation rating versus $R_{cs,h16}$ and R_g. A particular weakness for R_g as a predictor of saturation can be seen for SPDs with contrasting gamut shapes when average gamut is the same. The contrast is particularly strong for conditions 21 and 22 and 13 and 14 (see Figure 7), which are shown as colored points: the red dots saturate reds the most, whereas the green dots saturate yellow-greens the most. The strength of $R_{cs,h16}$ as a predictor is consistent with the participants' responses to the most influential hues (see Figures 4 and 5).

stronger correlation with rated saturation than R_g (r^2 = 0.75), and is a more useful predictor because it is able to distinguish between sources with the same average fidelity and gamut, which were rated significantly different. **Figure 13** shows the TM-30 Color Vector Graphics for conditions 13, 14, 21, and 22, which are also highlighted as colored points in **Figure 12**. Conditions 13 and 21 were rated as significantly less saturated than conditions 14 and 22 (both p <0.01 as tested by paired t test), which were at the same nominal R_f and R_g values but had SPDs that produced an increase in red saturation. Given the limitations of the luminaires used in this study, these two nominal R_f-R_g points were the only ones where a strong contrast in gamut shape could be created. As such, additional research with a new set of experimental conditions is needed to further examine and validate the role of gamut shape, and more specifically red saturation, on overall perceptions in polychromatic environments. Notably, there are no examples of sources with approximately equal $R_{cs,h16}$ values that the participants rated significantly different for saturation.

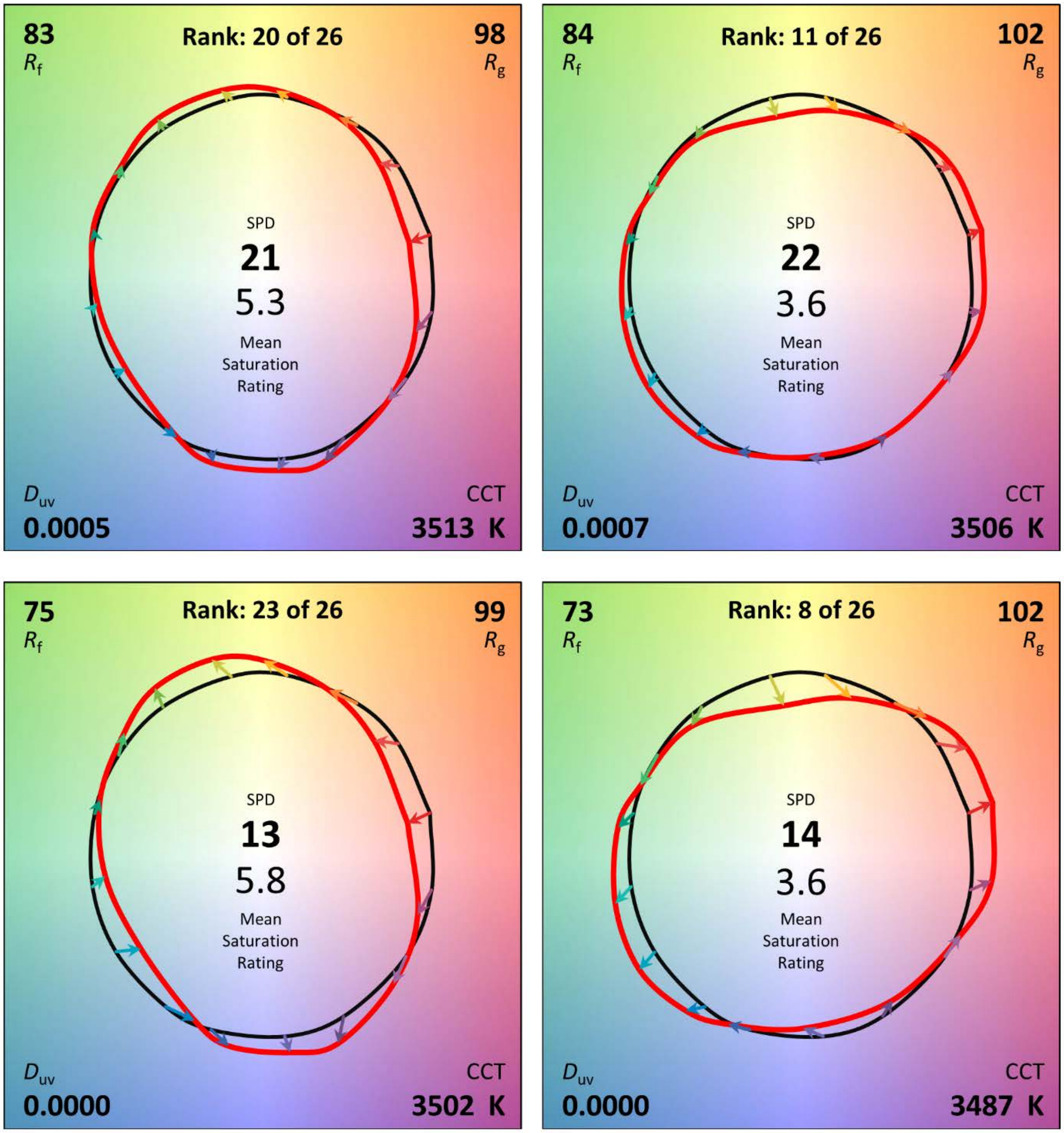


Figure 13. TM-30 Color Vector Graphics and mean saturation statistics for SPDs 21, 22, 13, and 14. SPDs 21 and 22 have approximately equivalent scores for average gamut (≈100) and fidelity (≈84). SPDs 13 and 14 also have approximately equivalent scores for average gamut (≈100) and fidelity (≈74). As shown, the SPDs in each pair differ in gamut shape, with SPDs 22 and 14 saturating reds and desaturating greens and yellow, and the approximate inverse for SPDs 21 and 13. The conditions including SPDs 22 and 14 were rated significantly more saturated than the two conditions including the SPDs 21 and 13 (i.e., lower mean rating), suggestive of the importance of the rendition of reds to judgments of saturation, which aligns with the results shown in Figure 4. The listed rankings are based on the rank-order of the mean saturation ratings, with a lower value indicating higher perceived saturation. The small differences in the fidelity and gamut values arise from limitations in the granularity of DMX control.

Similar results were seen in these same pairs of conditions for ratings of preference and normalness, with saturation likely being the underlying cause of the difference in ratings. There was a statistically significant difference in preference rating for SPDs 21 and 22 ($p < 0.001$) and SPDs 13 and 14 ($p = 0.018$), which is especially relevant because this region of R_f-R_g space is home to a majority of sources used to illuminate architectural interiors. SPD 22 was the second most liked source, whereas SPD 21 was the 20th most liked source (of 26). Likewise, there was a statistically significant difference in normalness ratings for SPDs 21 and 22 ($p = 0.004$); however, difference between SPDs 13 and 14 did not reach statistical significance ($p = 0.205$). While both normalness and preference ratings favored increases in red saturation, the range of ideal values was lower for normalness (approximately 0% to 8%) than preference (approximately 2% to 16%).

4 Discussion

This experimental data, combined with past work,[6, 9, 10, 12-16, 27, 35, 58] highlights the substantial benefit of using two measures simultaneously to predict color preference. This experiment was designed to carefully test this concept, while also evaluating the possible challenges of using only average color metric values for this purpose. This was done by designing and producing distinctly different SPDs having the same average values, but different gamut shapes. Importantly, this approach of using paired SPDs with different gamut shapes led to improved correlation for models that included a hue angle bin chroma shift value rather than average gamut area.

Hue angle bin chroma shift measures are particularly interesting because, more than just an individual value, they help describe the broader gamut shape, at least for this dataset. It is not possible to characterize gamut shape using fidelity sub-indices, such as CRI's R_9 or TM-30's $R_{f,h1}$. Although the Color Vector Graphic is an even more complete characterization of gamut shape, visual depictions have limitations, such as not lending themselves to regression analysis. The significant effect of gamut shape was suggested in TM-30,[7, 55] expanded upon by Houser and Royer,[8] and is corroborated by Wei and colleagues.[36, 37] It was also alluded to by Teunissen and colleagues,[6] who stated "it is not straightforward to identify, from our study, universal areas of high preference in this two-dimensional representation [using average fidelity and gamut values]. Apparently, other factors in the SPDs also contribute to preference…" and that sources with equal average values "are not always perceived equally attractive", despite advocating for a two-measure system of average values.

Khanh, Vinh, and Bodrogi[63] showed that when combined, R_f and R_g are moderately correlated with single-number indices intending to characterize color preference, such as CQS Q_a[58] and MCRI,[31] using a set of theoretical SPDs. Similarly, the results of this experiment demonstrate that R_f and R_g can be combined to provide a moderately effective characterization of color preference. However, a two-measure system using average fidelity and average gamut area cannot distinguish between the types of red-saturating sources that were strongly preferred in this experiment and sources that desaturate reds. In fact, from a practical perspective, the design and use of red-saturating sources could be inappropriately disincentivized when considering only average values, because they tend to have slightly reduced luminous efficacy of radiation (LER). **Figure 14** shows that LER is variably correlated with saturation in different hue bins.

Looking at specific examples, **Figure 15** provides Color Vector Graphics and average color rendering characterizations for four typical commercially-available products, which were ostensibly developed to balance CIE R_a and energy efficiency. These four products, all nominally 3500 K with minimal D_{uv} values, all have gamut shapes that would be predicted to be disliked in the context of this experiment, based on **Equation 1**. Even existing products designed for enhanced gamut, shown in **Figure 16**, do not necessarily provide enhanced red saturation, as would be preferred, because average gamut is a limited characterization.

Figure 17 shows the CIE R_a, R_f, R_g, and $R_{cs,h16}$ for each lighting condition. In each, the lighting conditions are ordered from highest mean preference rating (left) to lowest mean preference rating (right). Also shown are provisional criteria that could be used to identify the most favored sources: $R_f \geq 74$, $R_g \geq 100$, $R_{cs,h16} \geq 0$. Importantly, these criteria are not necessarily relevant to preferred sources in other contexts, but are shown to demonstrate the possible effectiveness of a set of criteria based on the measures included in TM-30. **Figure 17** also demonstrates the ineffectiveness—and potential disservice—that would arise if one were to try to use criteria based on CIE R_a to identify preferred sources, as evidenced by the fact that 9 of the 12 highest rated products had a CIE R_a value less than 73—and as a low as 45. This occurs because CIE R_a

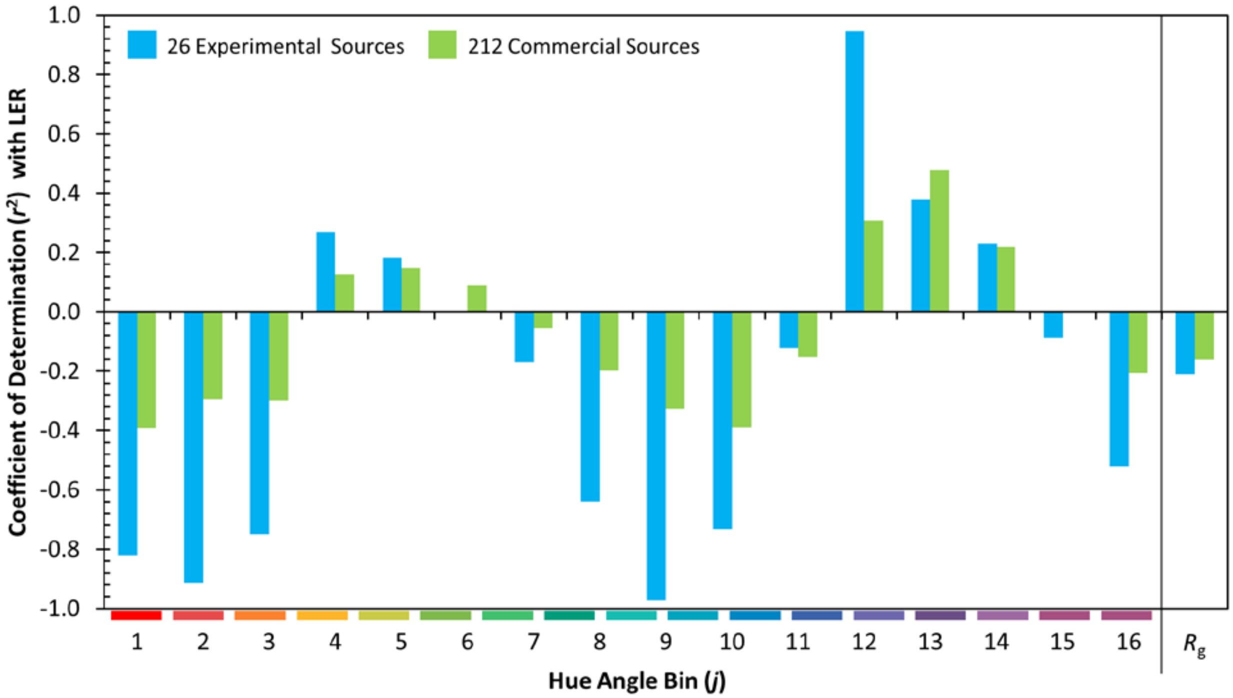


Figure 14. Comparison of coefficient of determination (signed to indicate positive or negative linear correlation) between hue angle bin chroma shift and luminous efficacy of radiation (LER) for the 26 experimental sources and the 212 commercially-available sources of the TM-30 Advanced Calculator Tool library. LER shows a regular pattern of correlation depending on the hue angle bin: the correlation is negative with red and green saturation, but positive with yellow and blue saturation. This is an important consideration because preference is positively correlated with red saturation.

systematically penalizes sources that increase red saturation compared to R_f, principally due to the non-uniformity of the 1964 CIE U*V*W* color space used for the calculations.[64] This shortcoming cannot be overcome by pairing CIE R_a with an average gamut area measure.

4.1 Limitations and Future Research Questions

The experimental room used in this work did not provide an identifiable application, which may influence what color shifts are preferred. Additionally, all SPDs had the same chromaticity; the validity of the results at other chromaticities must be verified, although some studies reported that CCT did not affect preference.[28, 65, 66] Likewise, only one illuminance level was used. Due to the Hunt effect,[11, 67] it is possible that preferred saturation levels may change with illuminance. Additional investigation is necessary using sources with a greater diversity of spectral features, and with additional emphasis on gamut shape. None of the current results should be applied to sources with $R_f < 60$, because that region was not explored in this study. The applicability of these short-term evaluations to long-term perceptions is unverified. Given these considerations, guidance or thresholds derived from this experimental data should not be indiscriminately applied to other contexts.

New studies focusing on preference in specific applications, with real-world viewing conditions (e.g., long exposure durations, complex polychromatic environments, and unique adaptation conditions) are warranted. This study has shown that the measures of TM-30, when used in combination, are effective in communicating context-specific preferences, which is important for the development of new research.

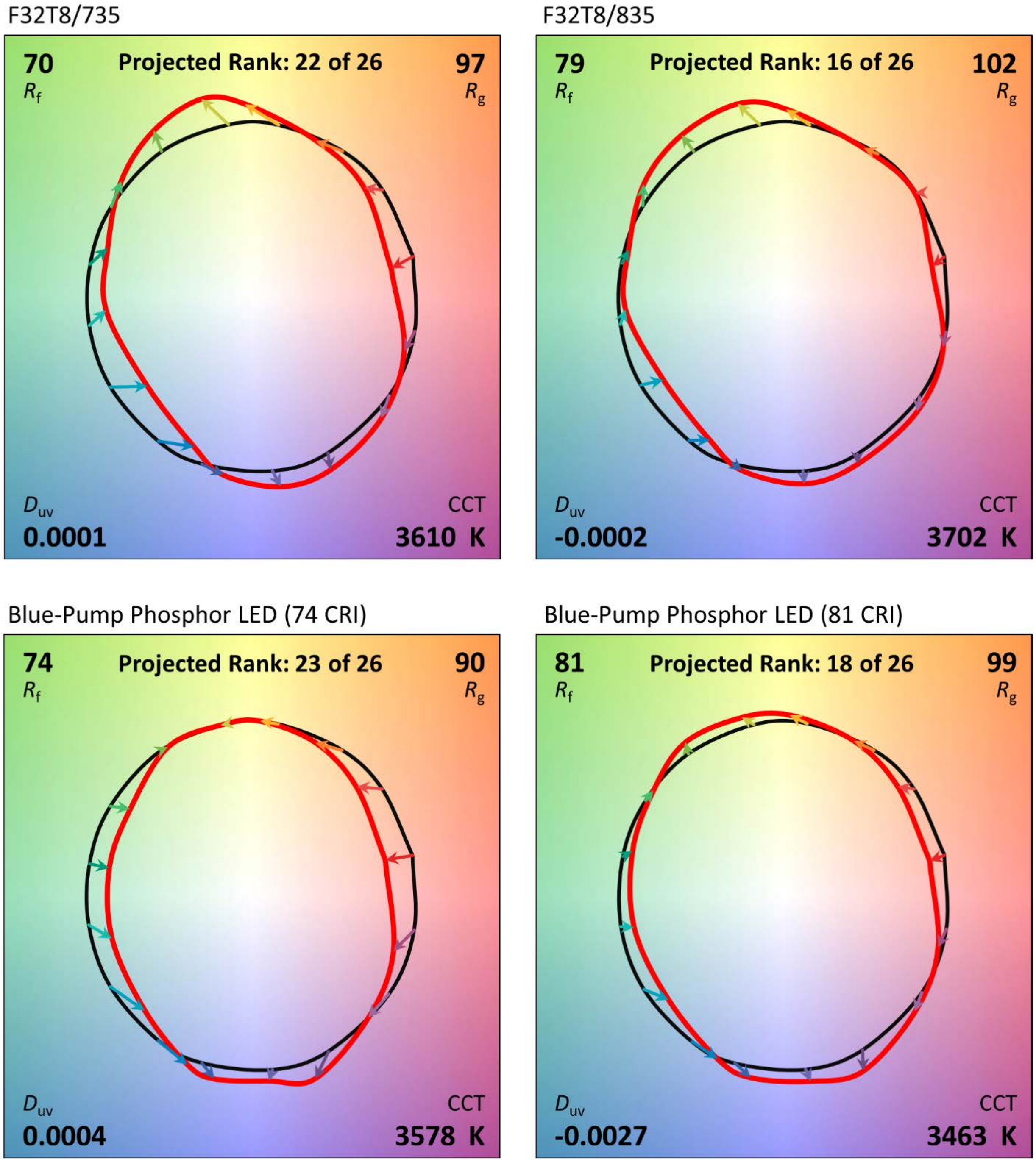


Figure 15. TM-30 Color Vector Graphics for four typical, commercially available sources, with predicted preference rank based on the predictive model expressed in Equation 1. All four sources feature elongation of the gamut shape approximately along the *b*' axis. Note that these four sources all have similar chromaticity coordinates compared to the experimental sources.

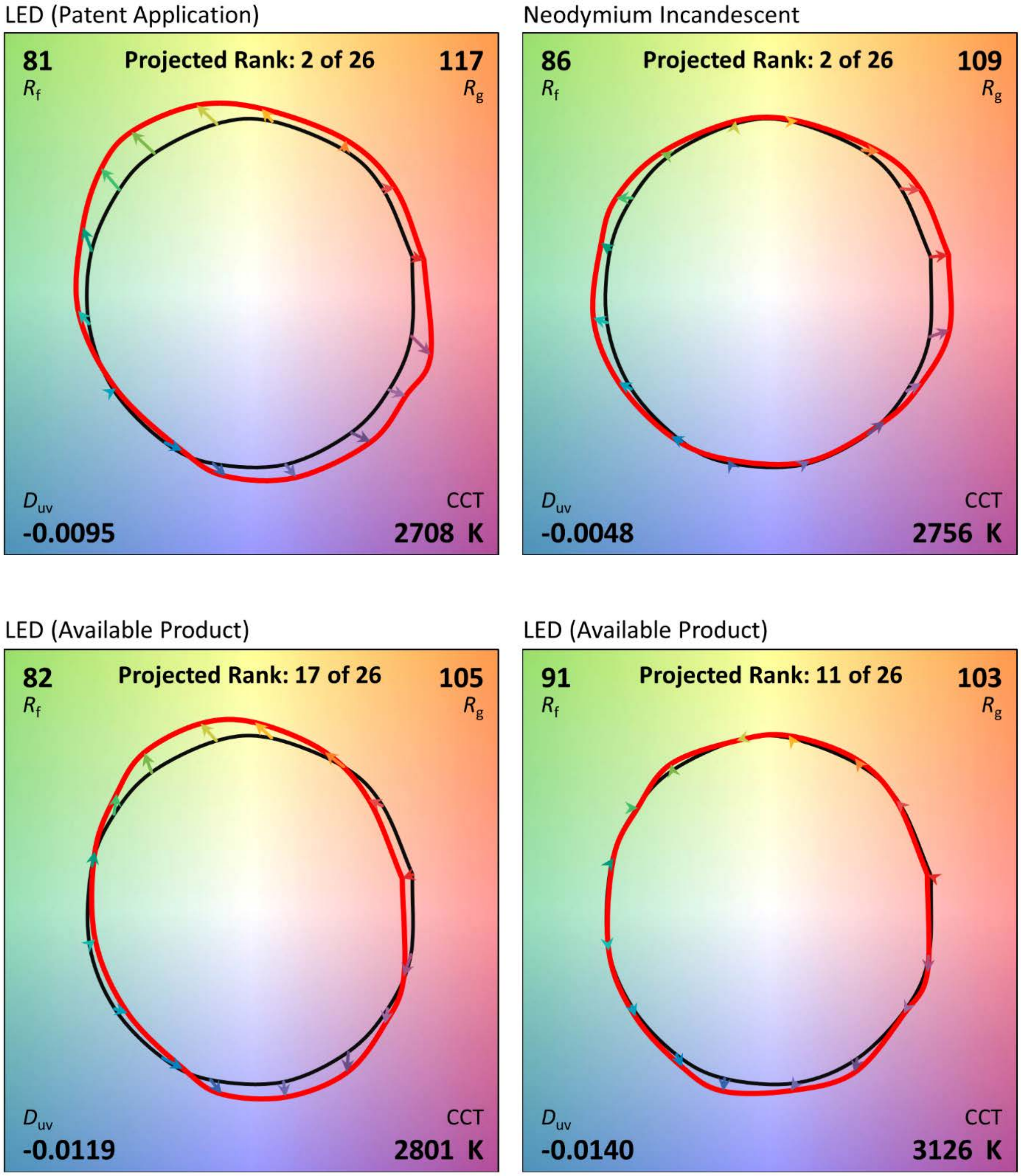


Figure 16. TM-30 Color Vector Graphics for four enhanced gamut sources, with predicted preference rank based on Equation 1. One of the four sources features elongation approximately along the b’ (vertical) axis, which is generally less preferred but is still rewarded by average gamut measures. Note that the chromaticity coordinates of these sources is not similar to those used to develop Equation 1; its application here is currently speculative.

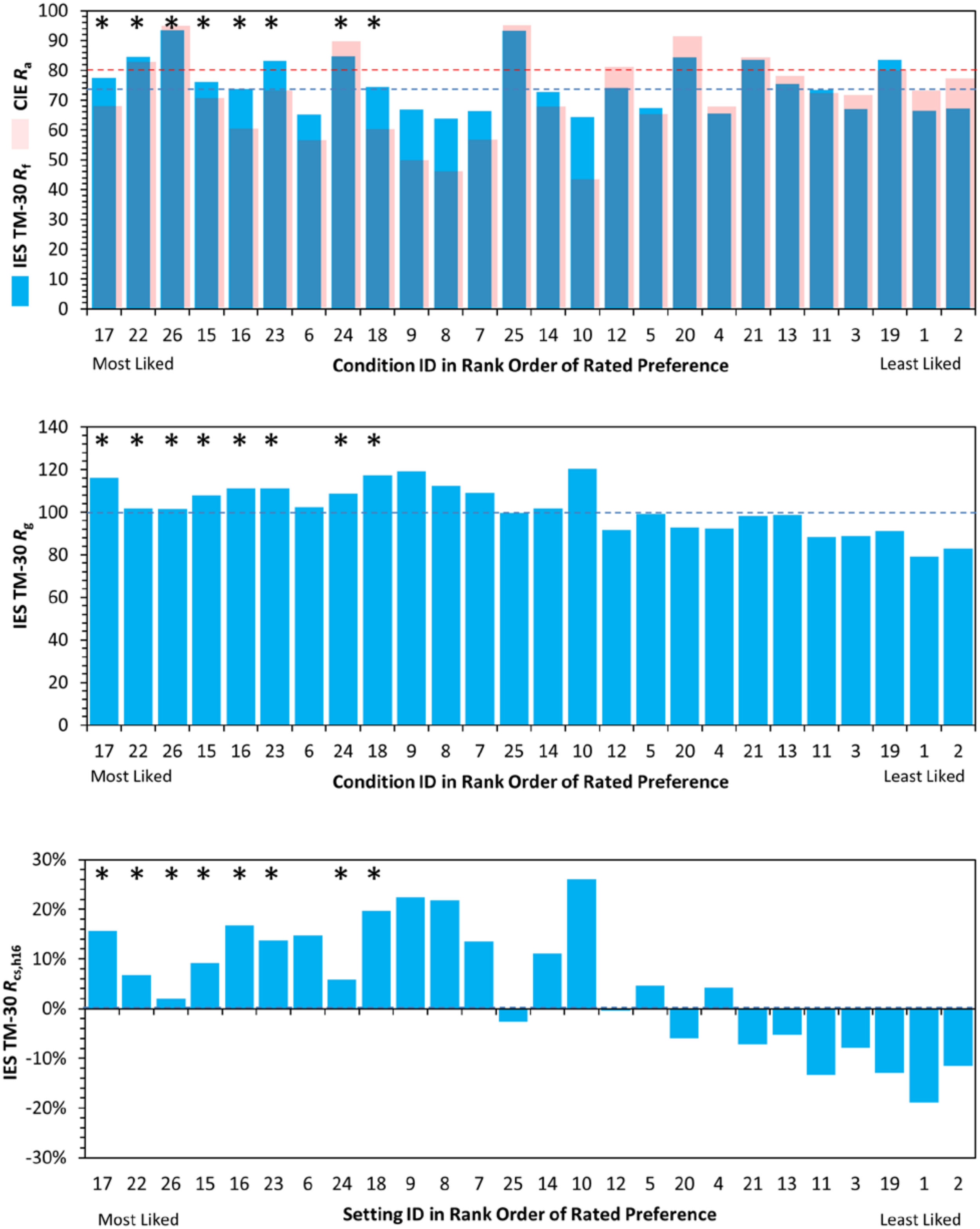


Figure 17. R_a, R_f, R_g **and** $R_{cs,h16}$ **for each condition, with the conditions plotted from left to right in decreasing order of mean rated preference.** The blue dashed lines show prospective specification criteria, with the asterisks indicating SPDs that would exceed all three criteria. The red dashed lines show the most commonly used existing criterion for CIE R_a for architectural interiors.

5 Conclusions

This article examines the usefulness of the TM-30 measures for characterizing subjective perceptions of preference, saturation, and normalness. The carefully considered environment was illuminated with a wide range of SPDs having fixed chromaticity and fixed lumen output. Age and gender of the participants represented a cross-section of most populations. The type of architectural space was intentionally undefined, although the objects were typical of a consumer-oriented space.

When combined in regression models, the TM-30 measures demonstrated excellent correlation with participants' mean ratings for normalness (r^2 = 0.83), saturation (r^2 = 0.95), and preference (r^2 = 0.94). This experiment also demonstrated that sources with equivalent average fidelity and gamut values can elicit statistically different perceptual responses. Thus, a visually-detectable difference in average fidelity and average gamut area values is zero points.

In particular, increased saturation of reds was more liked, whereas increased saturation of yellows was less liked. This is particularly relevant because it is counter to the goals of increasing LER, which has resulted in many existing commercially available light sources being engineered to achieve a certain level of CIE R_a, but less-preferred gamut shapes. It is also important because the existing CIE R_a is biased against red saturation; for this reason, a majority of the 14 most favored sources (i.e., the top half) had CIE R_a values below 73. For this experiment, the maximum preference occurred with conditions where $R_{cs,h16}$ was between about 2% and 16%.

This report provides evidence to support the effectiveness of the TM-30 method, which extends beyond average fidelity and average gamut area. Still, TM-30 is a tool, not an answer. It must be combined with other information—such as chromaticity, intensity, distribution, efficacy, and cost—when choosing a light source.

6 References

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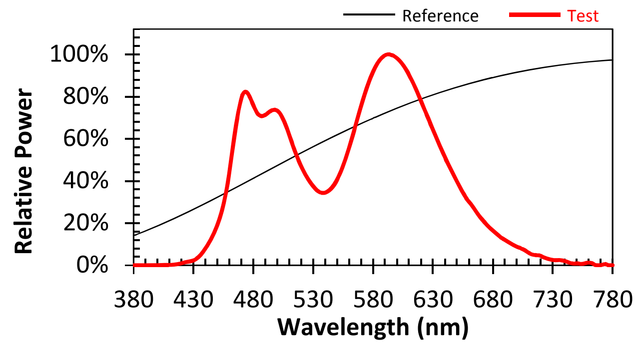
Appendix A: Light Source Data

Color Rendition Report

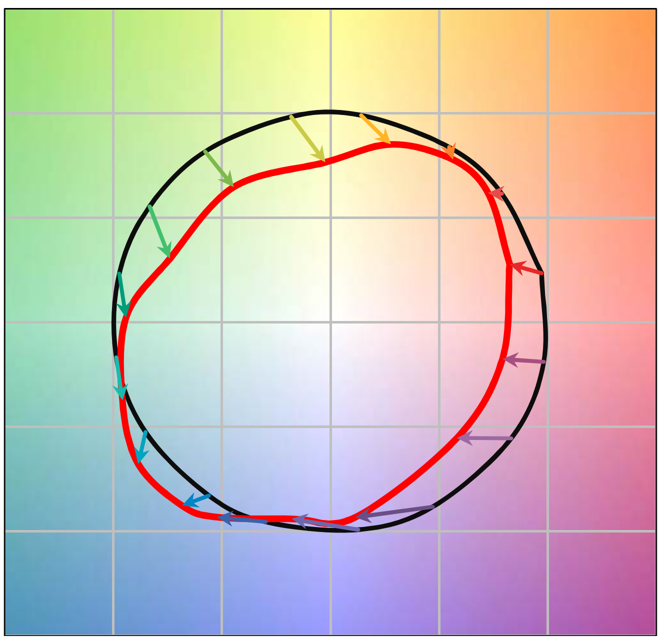
Source: Experimental Source 1

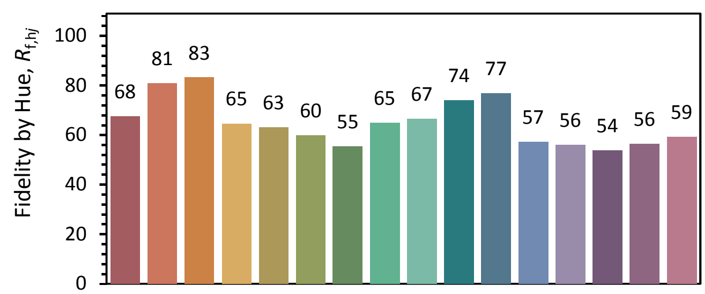
Date: 5-Aug-15

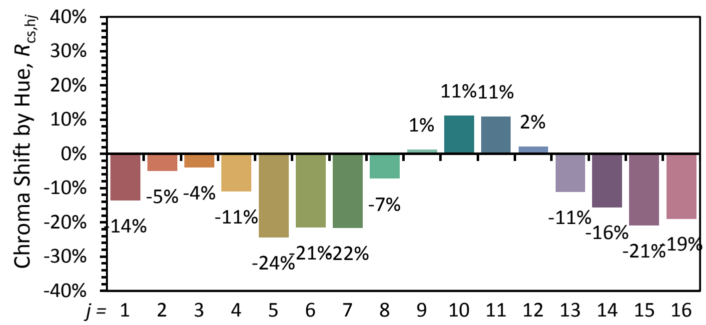
Notes:

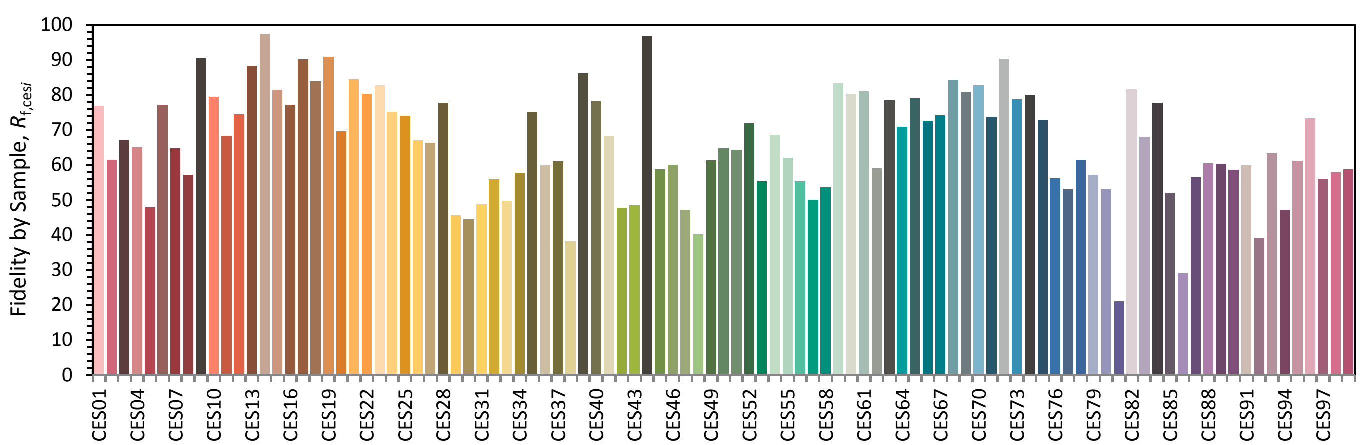


R_f	**66**	CCT	3514	x	0.4044	u'	0.2354	LER	322	CIE R_a	73
R_g	**79**	D_{uv}	-0.0001	y	0.3901	v'	0.5109			R_9	0
$R_{f,skin}$	83										









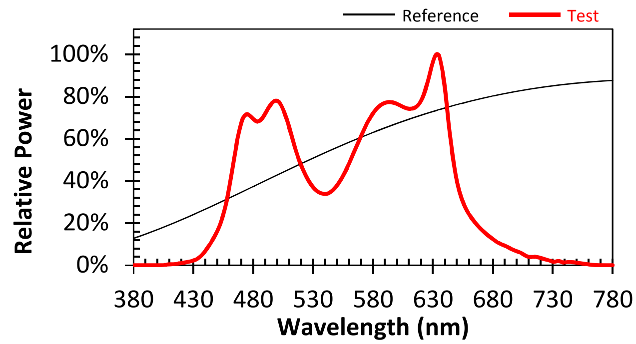
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

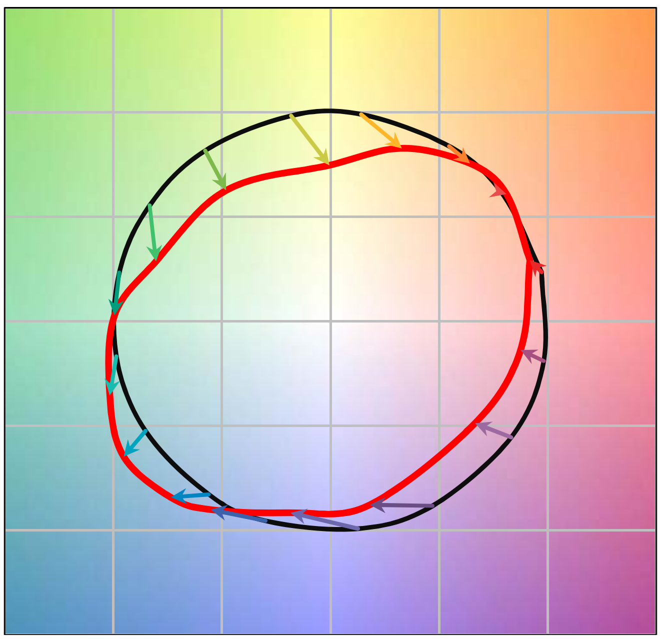
Source: Experimental Source 2

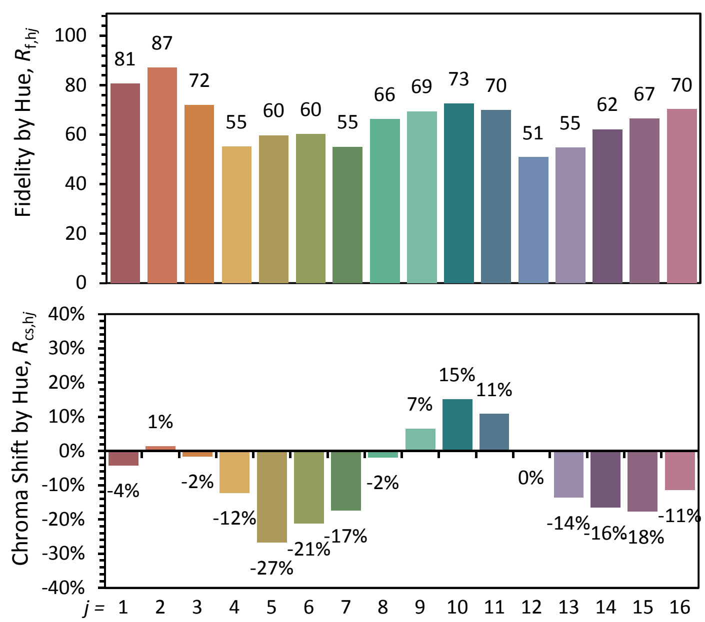
Date: 5-Aug-15

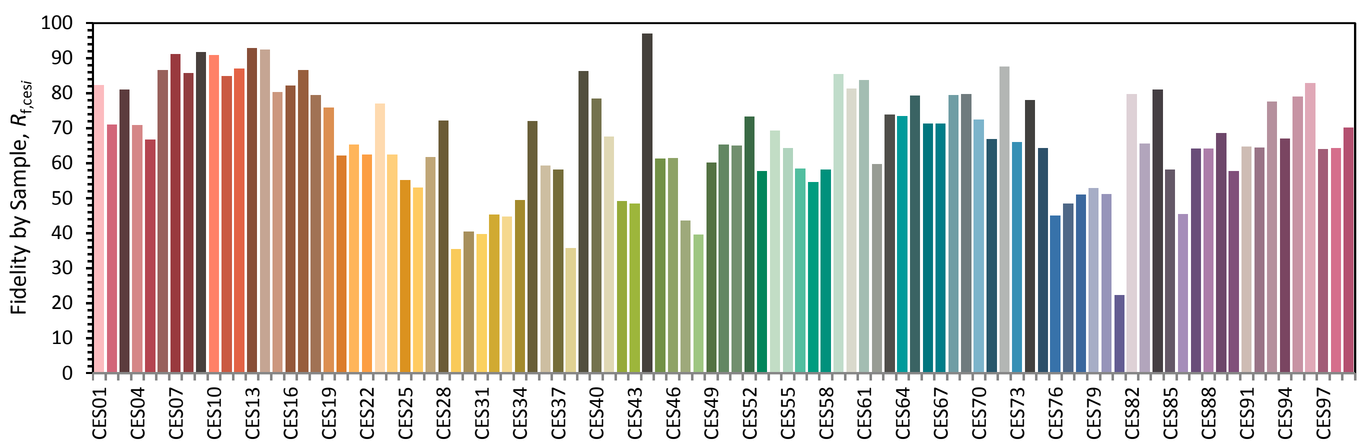
Notes:



R f **67**	**CCT** 3520	**x** 0.4045	**u'** 0.2351	**LER** 309	**CIE** R_a 77
R g **83**	D_{uv} 0.0003	**y** 0.3910	**v'** 0.5113		R_9 76
R f,skin 80					







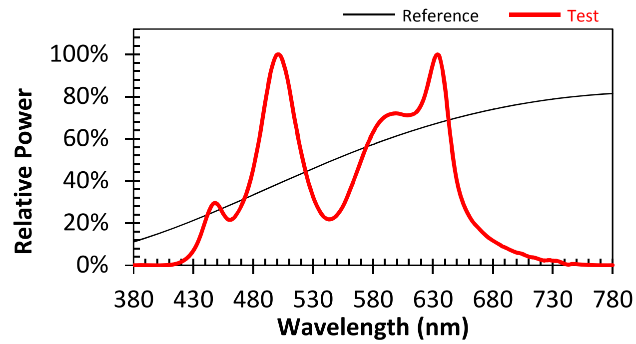
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

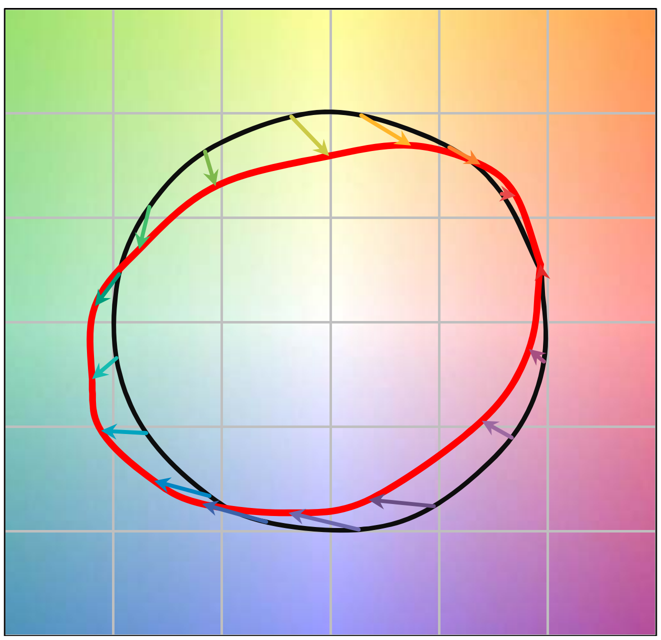
Source: Experimental Source 3

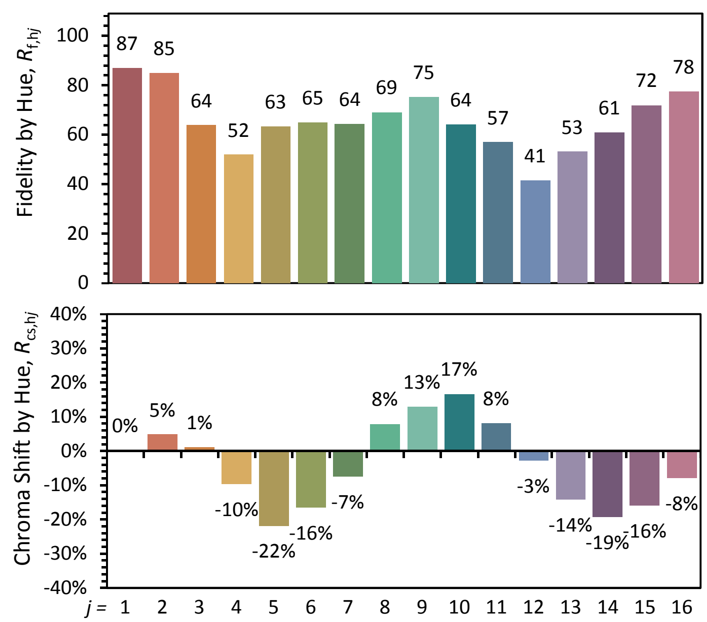
Date: 5-Aug-15

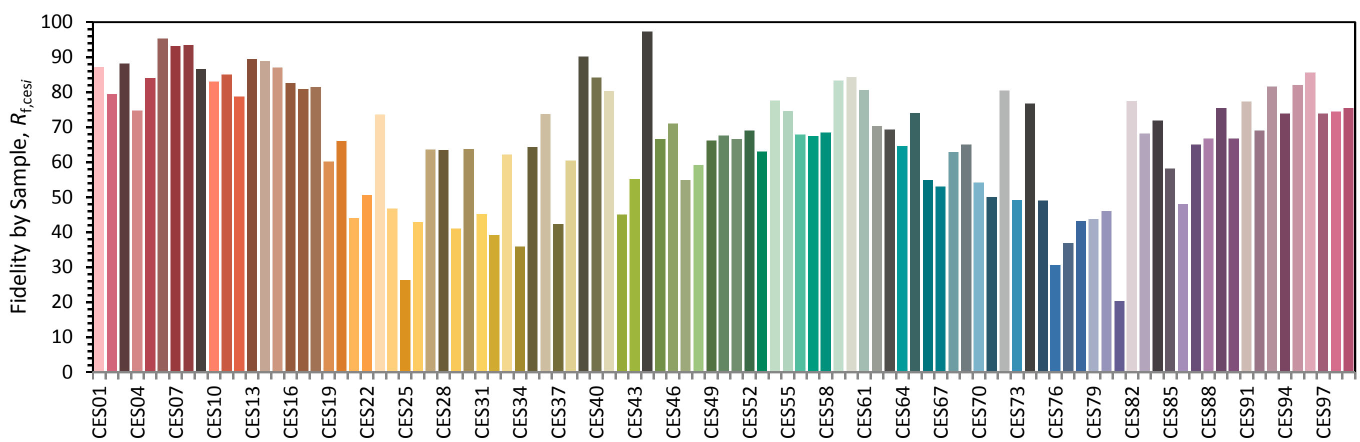
Notes:



R_f	67	CCT	3478	x	0.4062	u'	0.2364	LER	299	CIE R_a	72
R_g	89	D_{uv}	-0.0003	y	0.3905	v'	0.5113			R_9	94
$R_{f,skin}$	84										







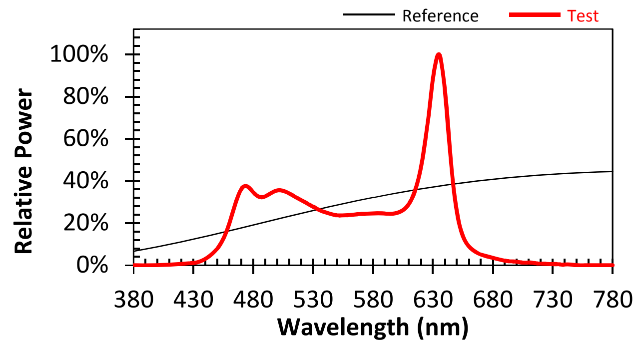
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

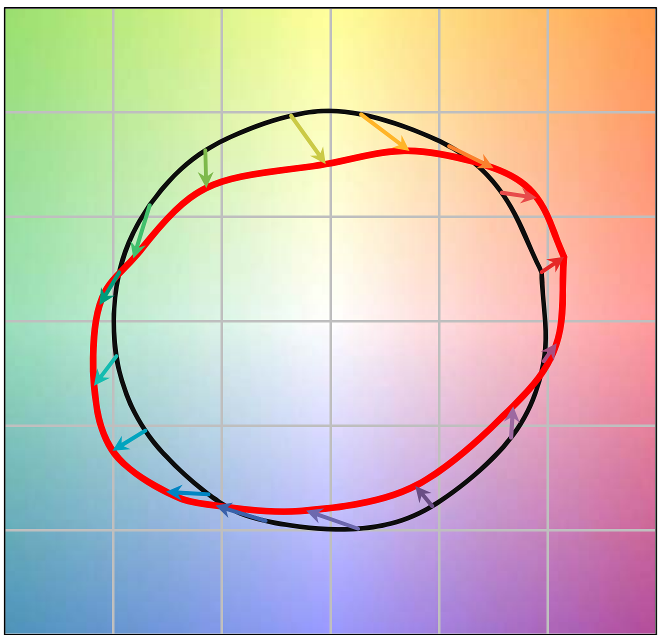
Source: Experimental Source 4

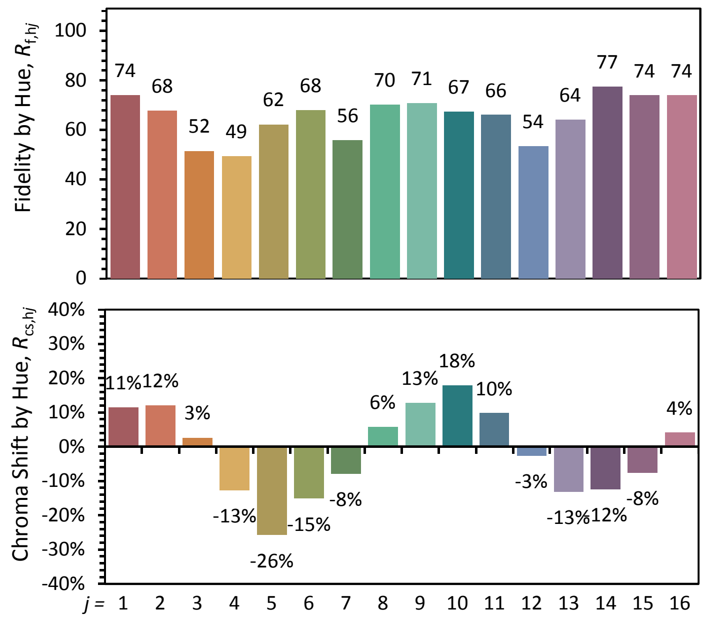
Date: 5-Aug-15

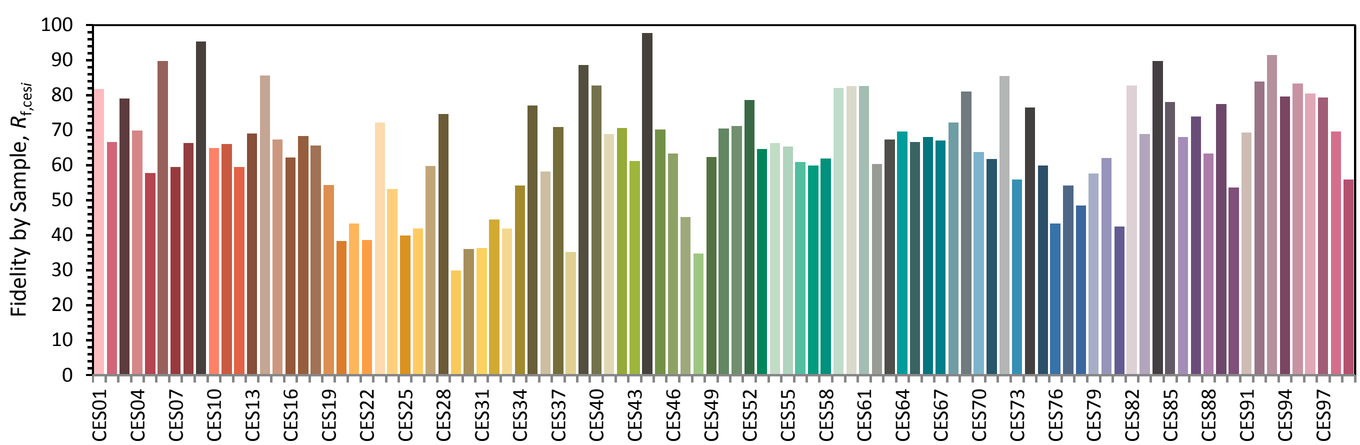
Notes:



R_f **65**	**CCT** 3531	**x** 0.4041	**u'** 0.2347	**LER** 294	**CIE R_a** 68
R_g **92**	D_{uv} 0.0005	**y** 0.3913	**v'** 0.5113		R_9 -10
$R_{f,skin}$ 67					







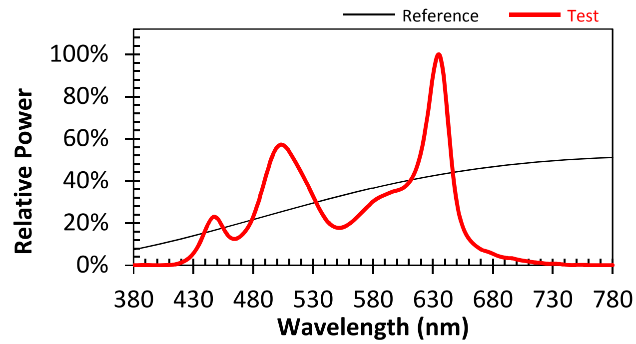
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

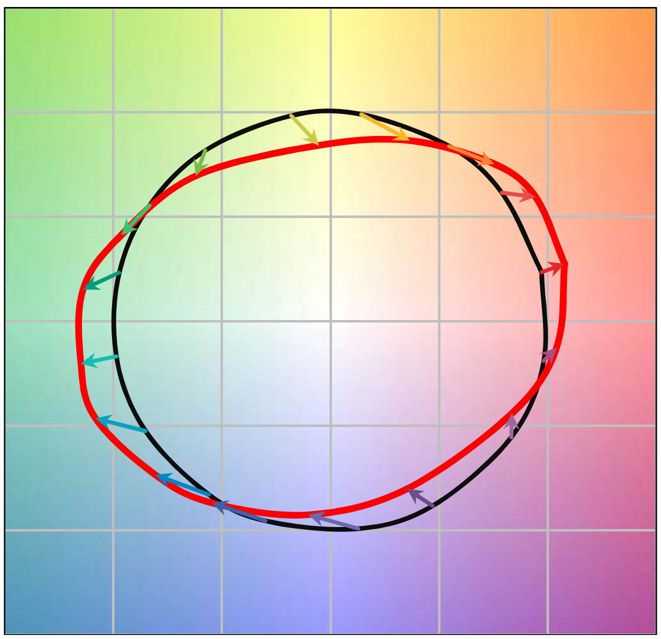
Source: Experimental Source 5

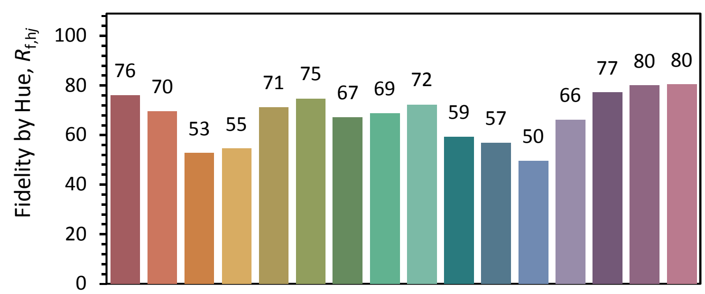
Date: 5-Aug-15

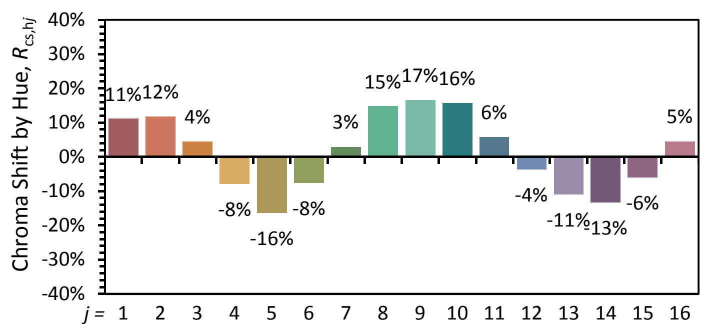
Notes:

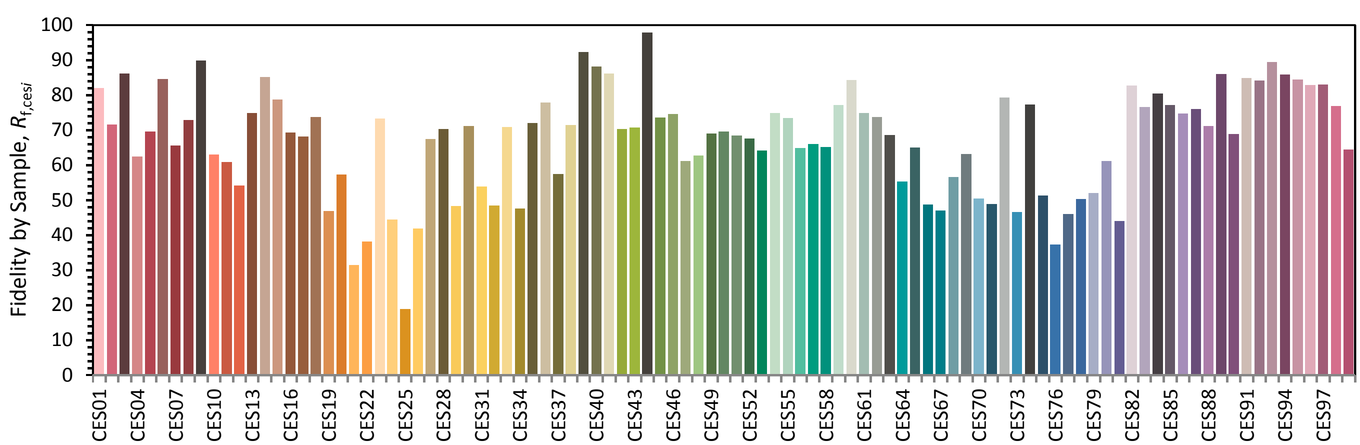


R_f 67	CCT 3515	x 0.4051	u' 0.2350	LER 292	CIE R_a 65
R_g 99	D_{uv} 0.0006	y 0.3921	v' 0.5118		R_9 9
$R_{f,skin}$ 76					









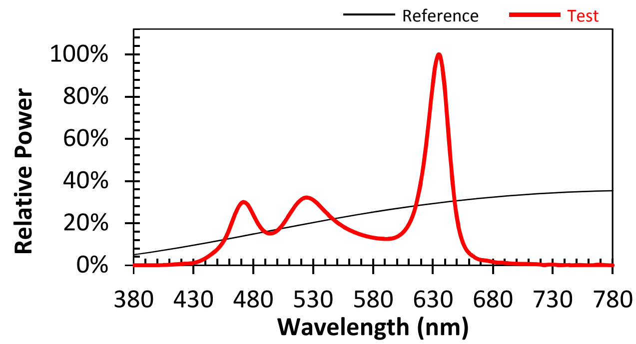
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

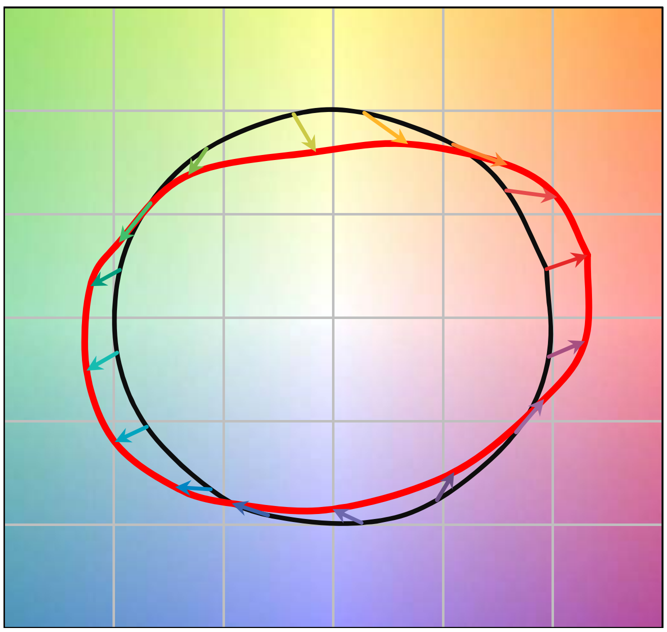
Source: Experimental Source 6

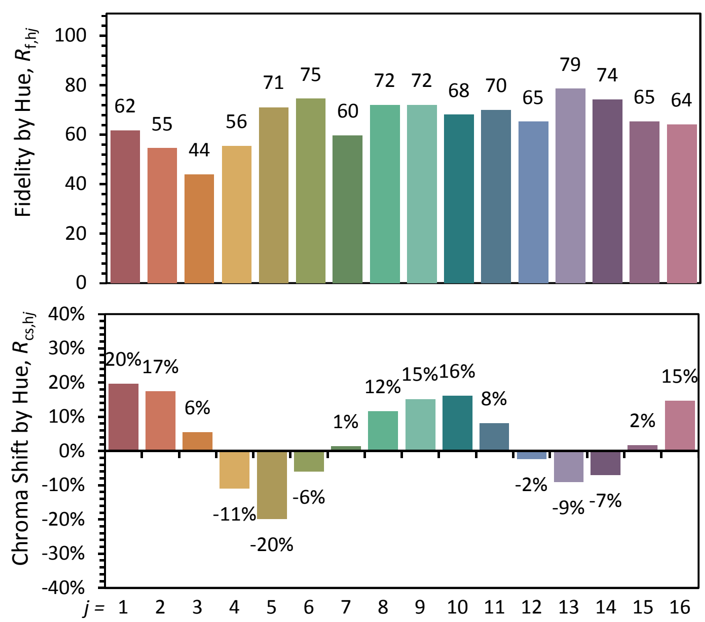
Date: 5-Aug-15

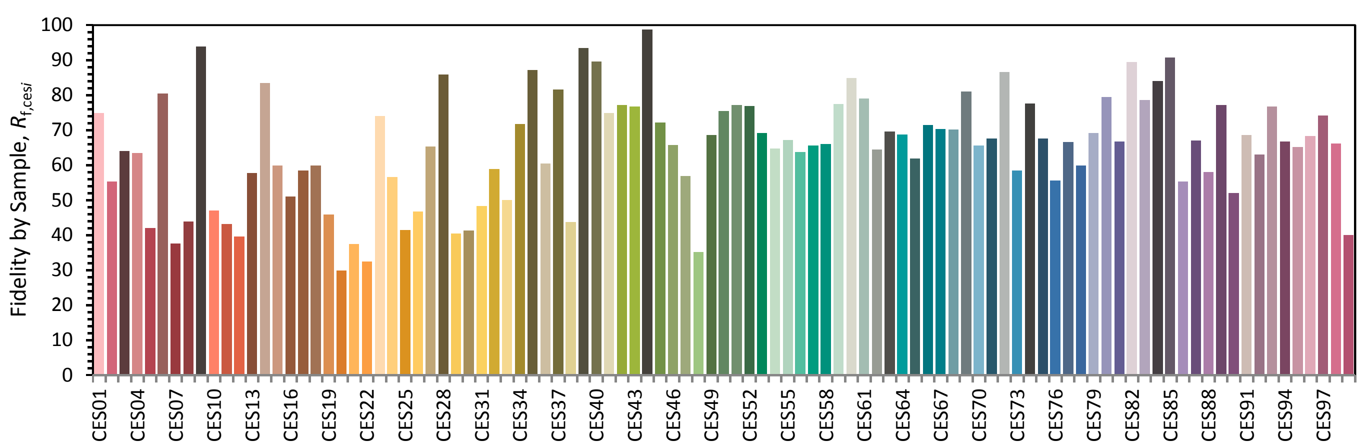
Notes:



R_f 65	CCT 3500	x 0.4056	u' 0.2356	LER 289	CIE R_a 56
R_g 102	D_{uv} 0.0003	y 0.3915	v' 0.5116		R_9 -76
$R_{f,skin}$ 60					







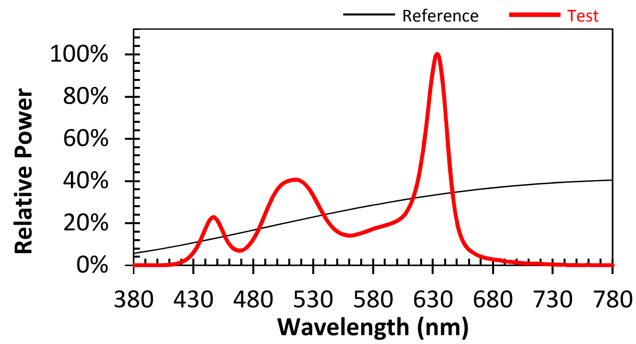
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

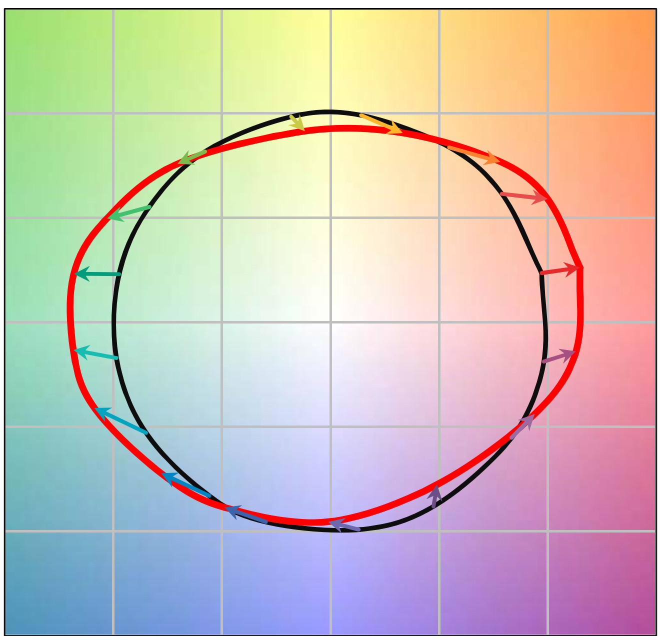
Source: Experimental Source 7

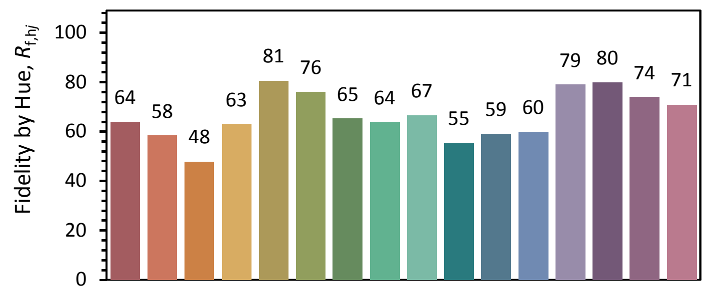
Date: 5-Aug-15

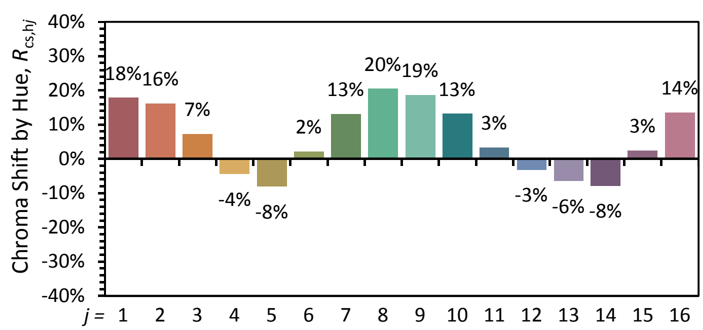
Notes:

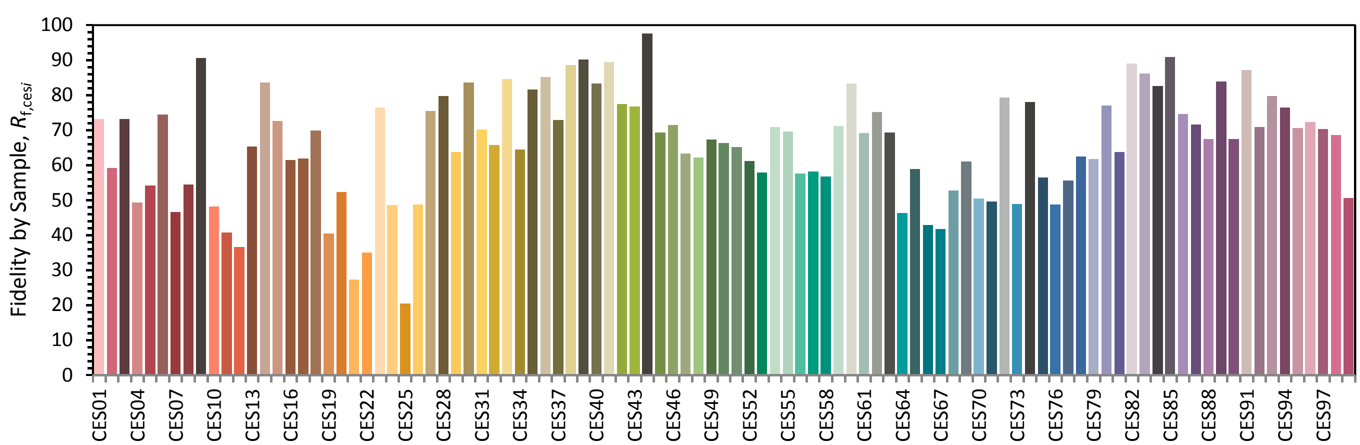


R_f	66	CCT	3489	x	0.4057	u'	0.2361	LER	290	CIE R_a	56
R_g	109	D_{uv}	-0.0002	y	0.3904	v'	0.5112			R_9	-45
$R_{f,skin}$	71										









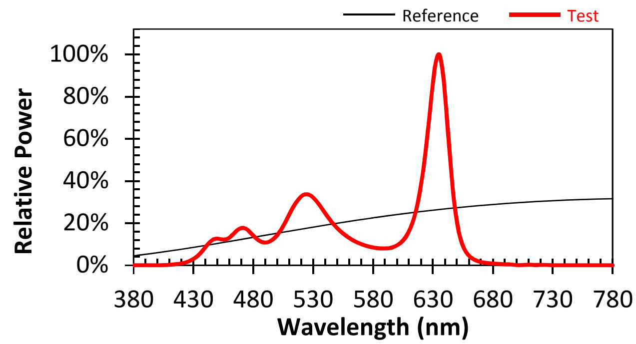
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

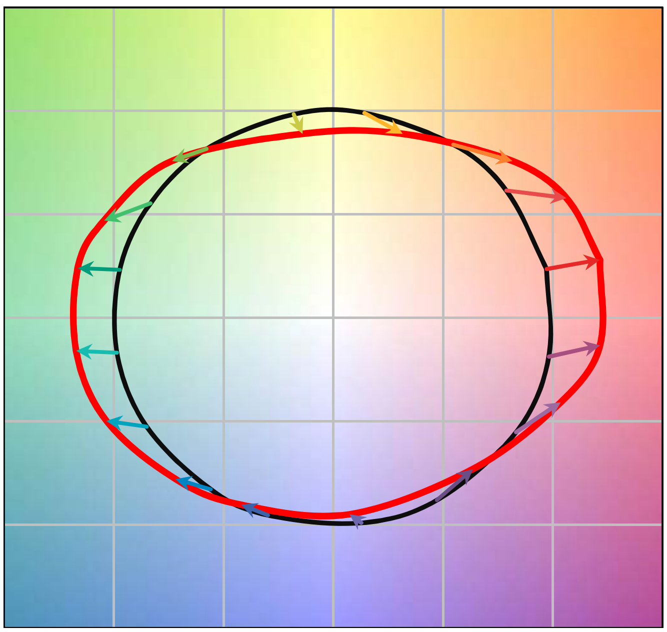
Source: Experimental Source 8

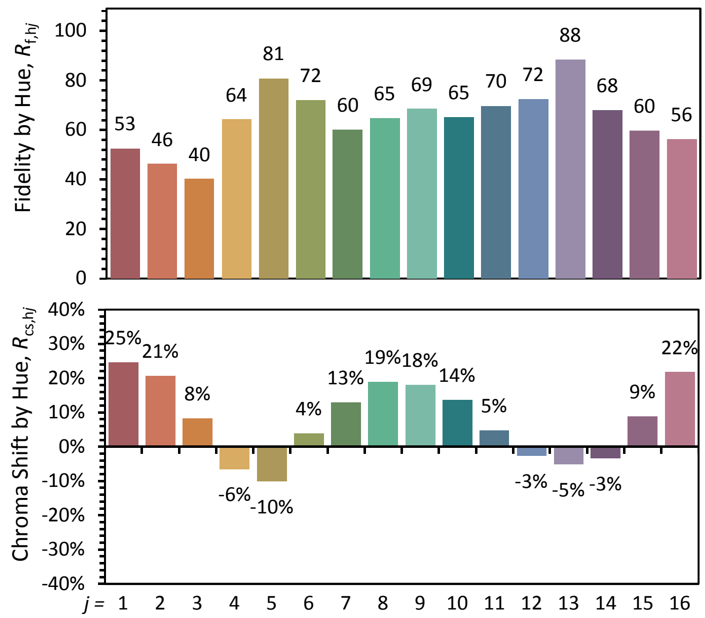
Date: 5-Aug-15

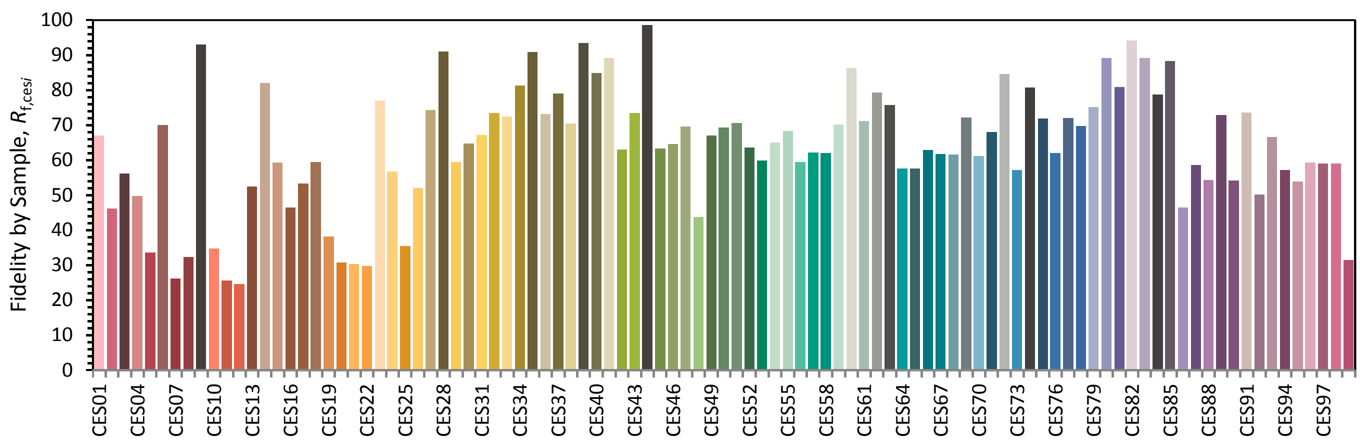
Notes:



R_f 64 R_g 112 $R_{f,skin}$ 59	CCT 3502 D_{uv} -0.0002	x 0.4049 y 0.3900	u' 0.2358 v' 0.5109	LER 286	CIE R_a 46 R_9 -112



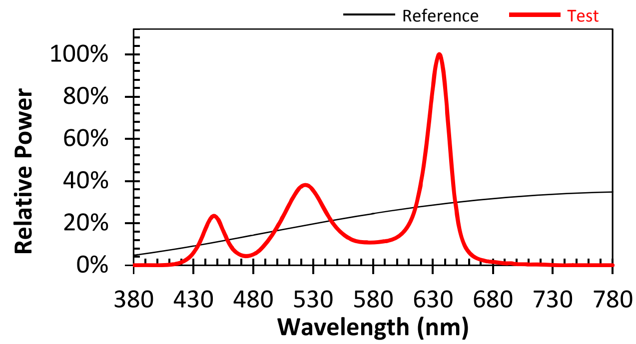




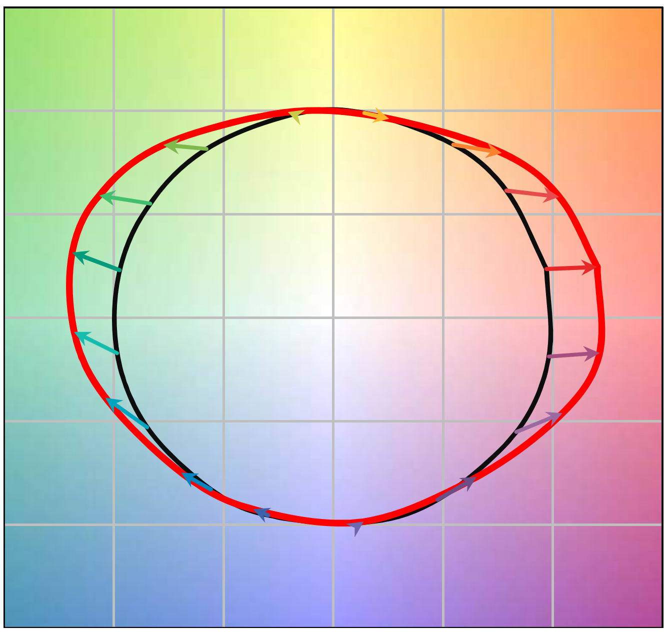
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

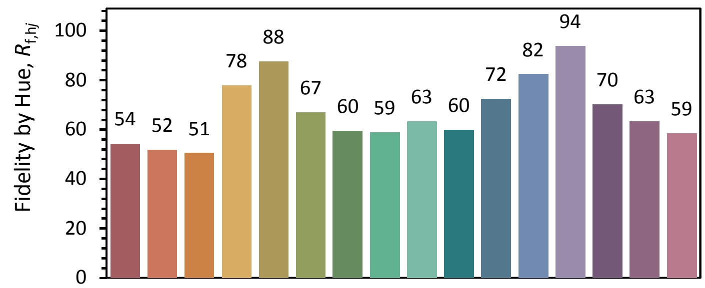
Color Rendition Report

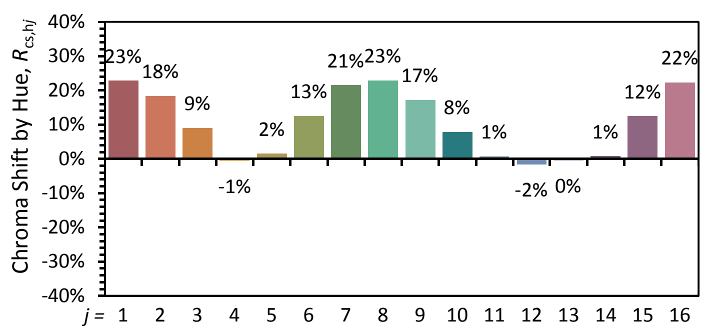
Source: Experimental Source 9
Date: 5-Aug-15
Notes:

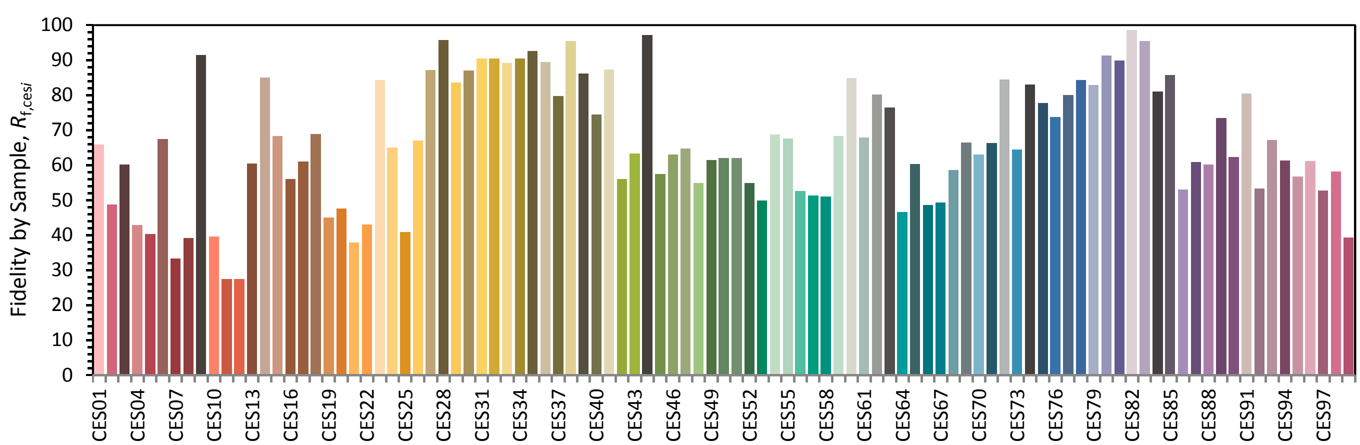


R_f **67**	CCT 3480	**x** 0.4060	**u'** 0.2364	**LER** 290	**CIE R_a** 50
R_g **119**	D_{uv} -0.0004	**y** 0.3901	**v'** 0.5111		R_9 -87
$R_{f,skin}$ 69					









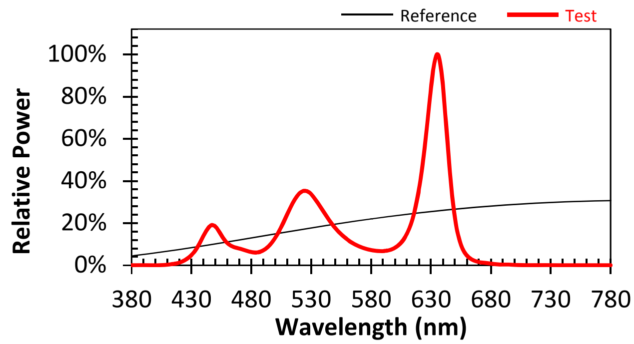
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

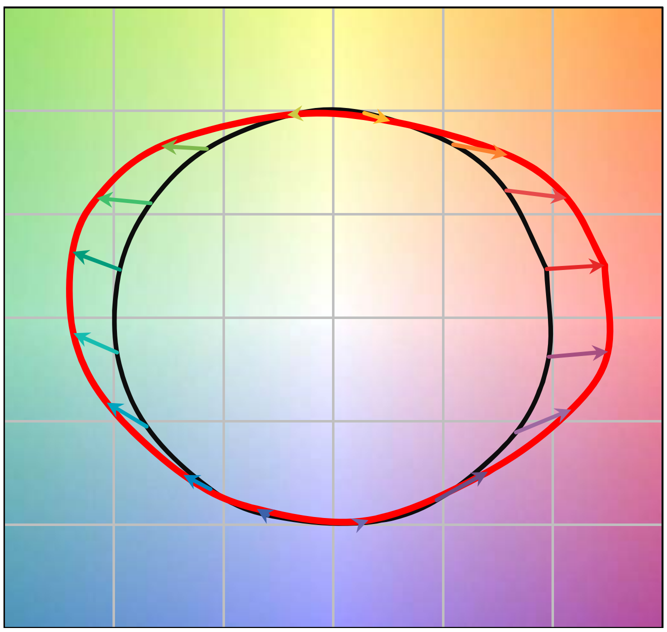
Source: Experimental Source 10

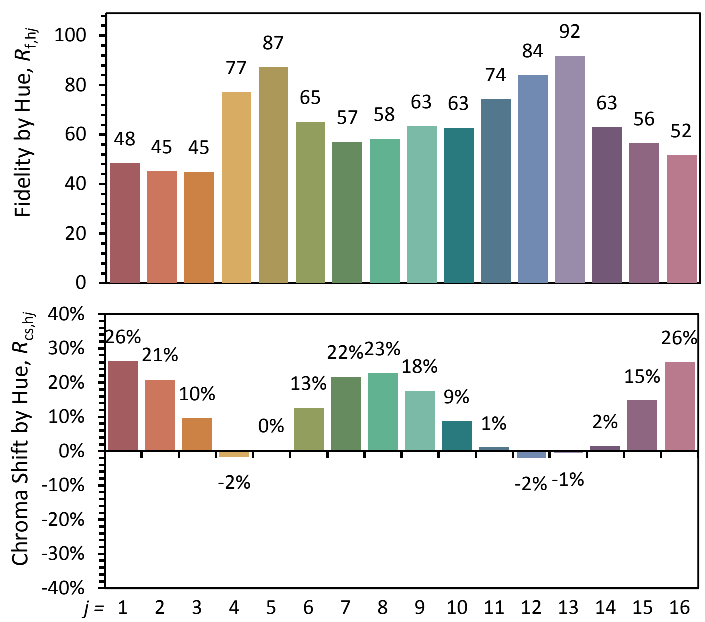
Date: 5-Aug-15

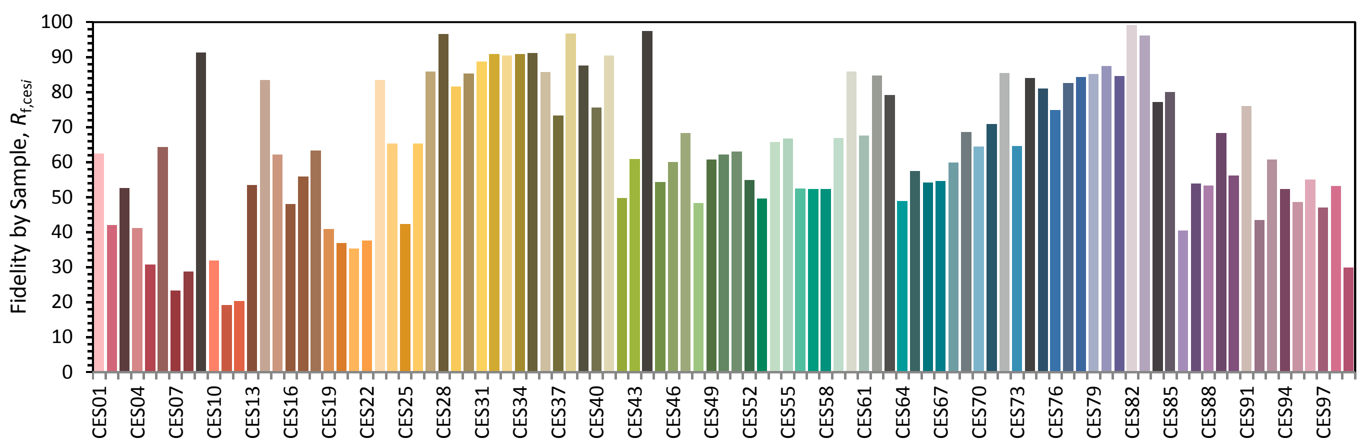
Notes:



R_f 64	CCT 3511	x 0.4047	u' 0.2354	LER 287	CIE R_a 43
R_g 120	D_{uv} 0.0000	y 0.3905	v' 0.5111		R_9 -120
$R_{f,skin}$ 63					







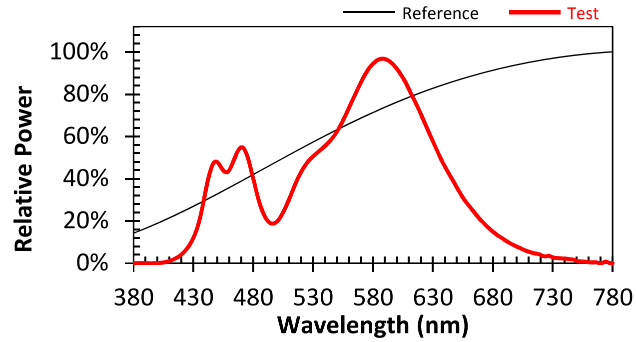
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

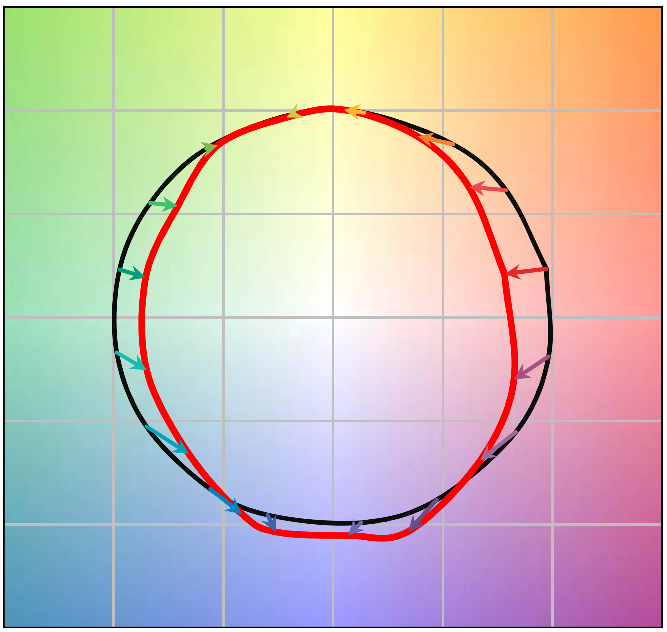
Source: Experimental Source 11

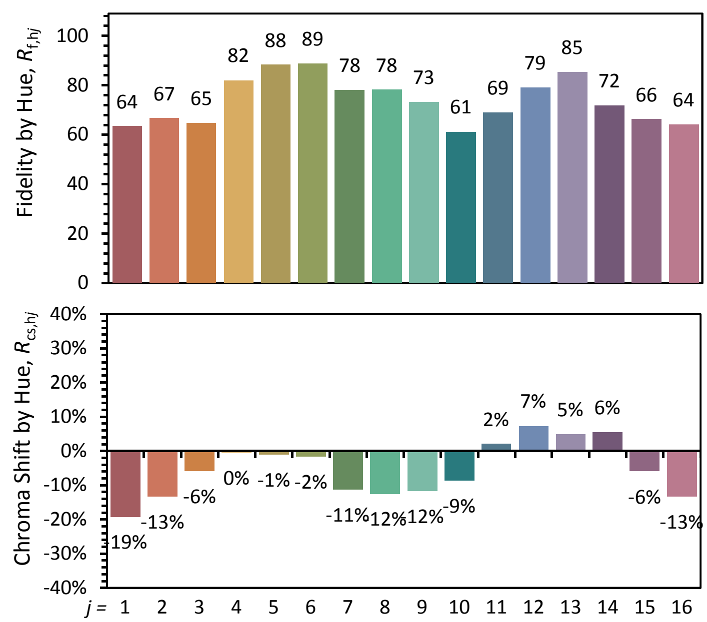
Date: 5-Aug-15

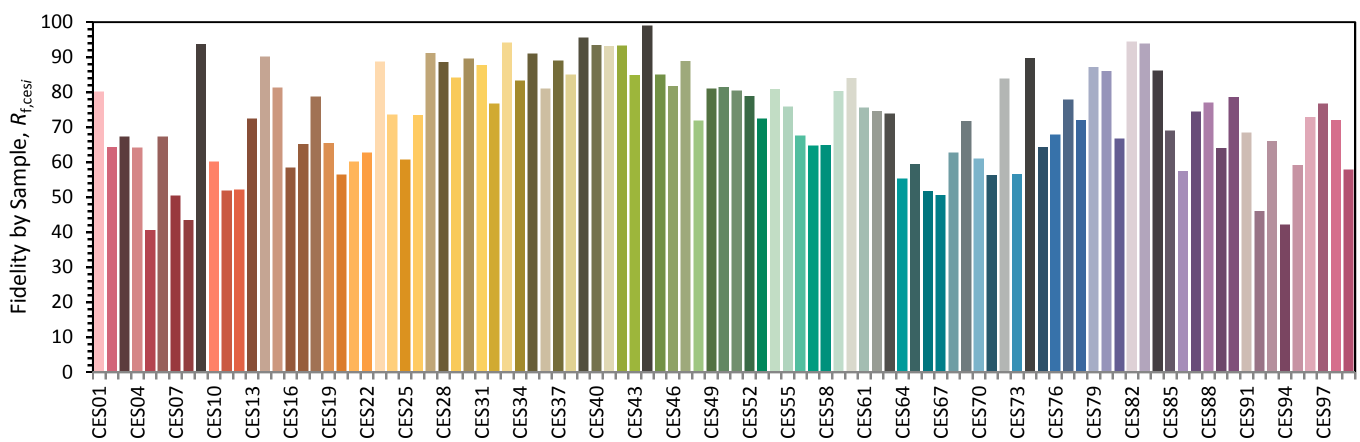
Notes:



R_f **73**	**CCT** 3504	**x** 0.4047	**u'** 0.2358	**LER** 352	**CIE R_a** 72
R_g **88**	D_{uv} -0.0003	**y** 0.3897	**v'** 0.5108		R_9 -41
$R_{f,skin}$ 80					



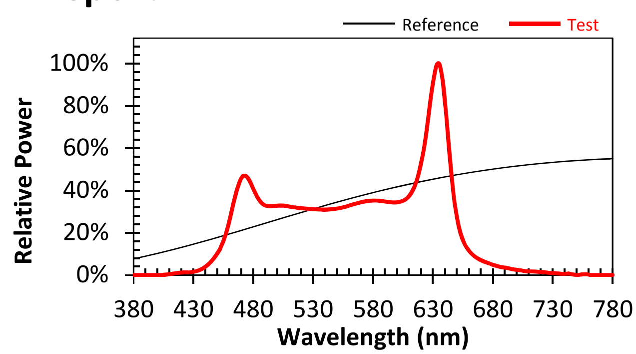




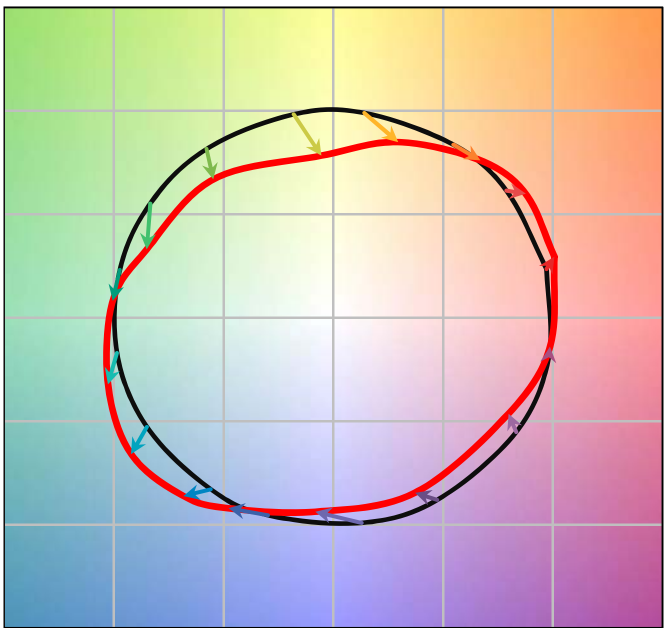
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

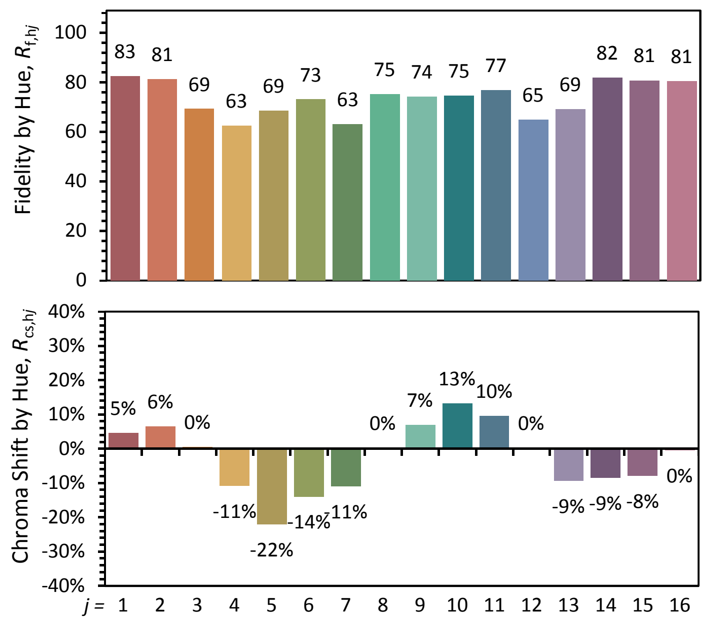
Color Rendition Report

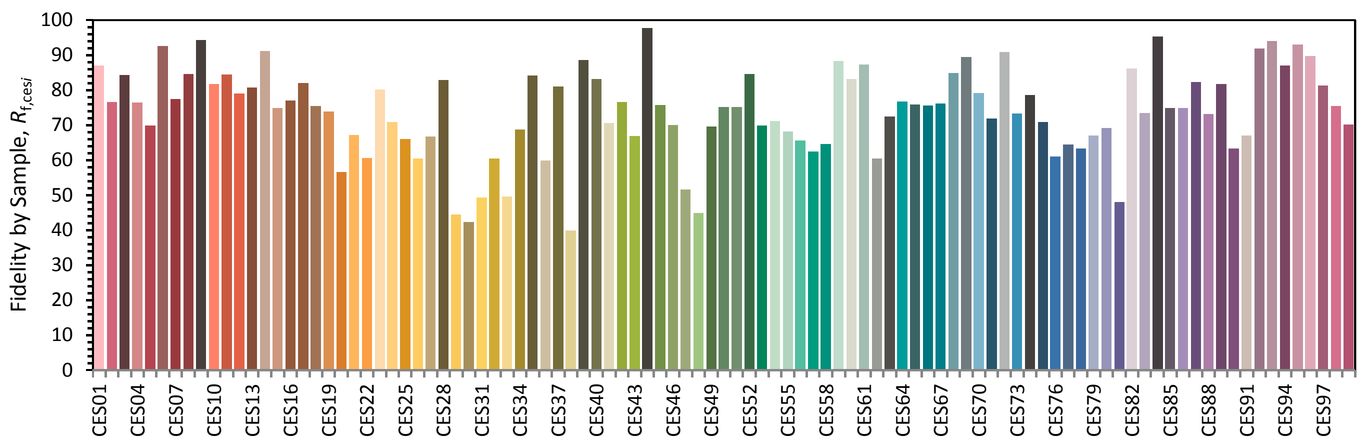
Source:	Experimental Source 12
Date:	5-Aug-15
Notes:	



R_f	**74**	CCT	3491	x	0.4059	u'	0.2359	LER	307	CIE R_a	81
R_g	**92**	D_{uv}	0.0001	y	0.3912	v'	0.5115			R_9	44
$R_{f,skin}$	75										







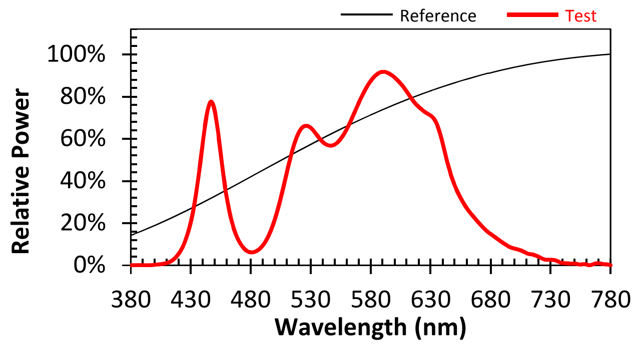
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

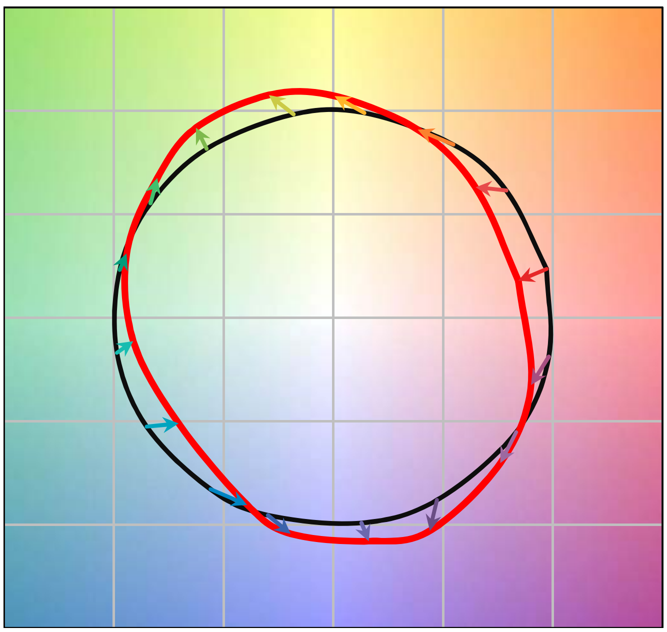
Source: Experimental Source 13

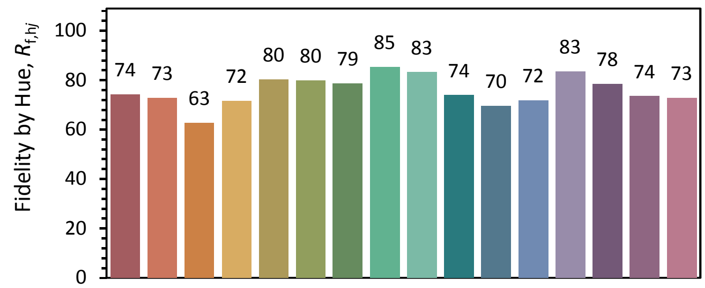
Date: 5-Aug-15

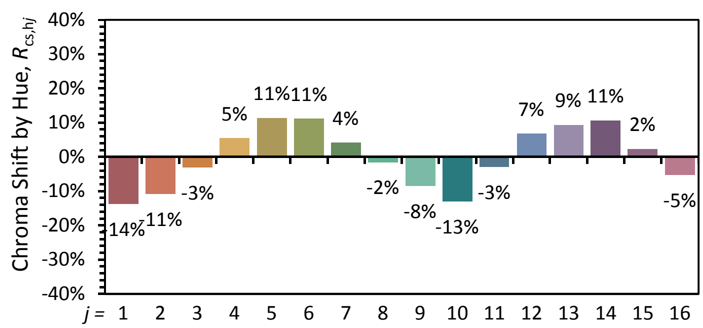
Notes:

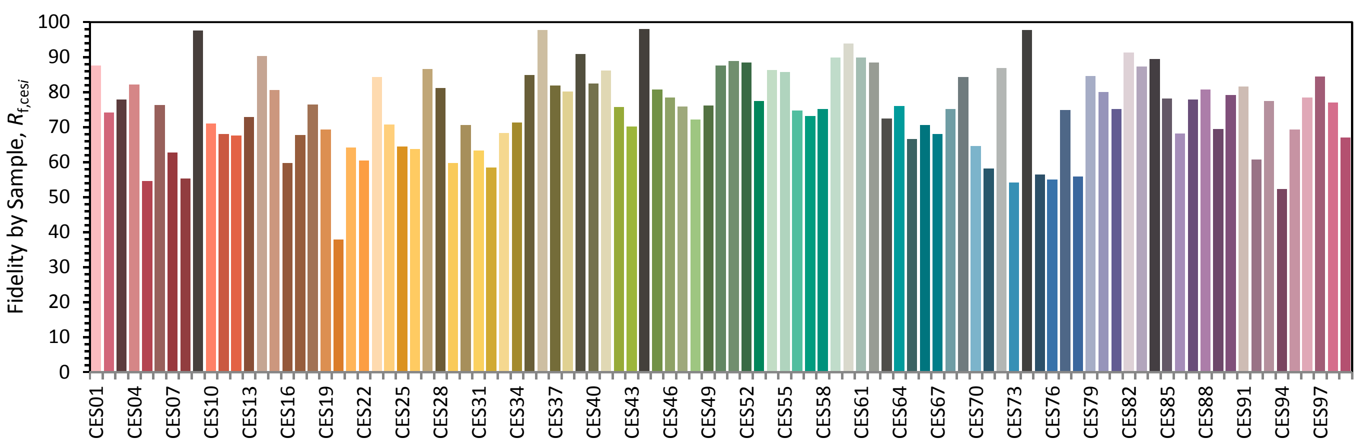


R_f	**75**	CCT	3502	x	0.4052	u'	0.2356	LER	351	CIE R_a	78
R_g	**99**	D_{uv}	0.0000	y	0.3908	v'	0.5113			R_9	-11
$R_{f,skin}$	79										





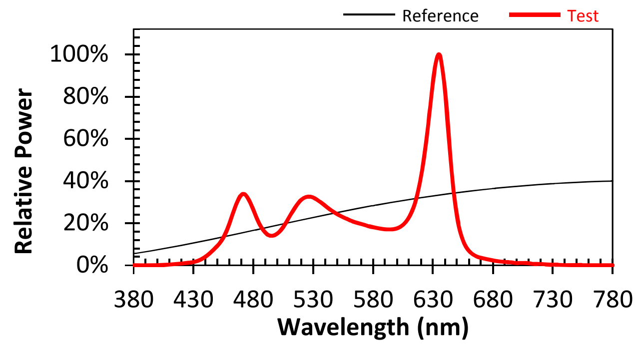




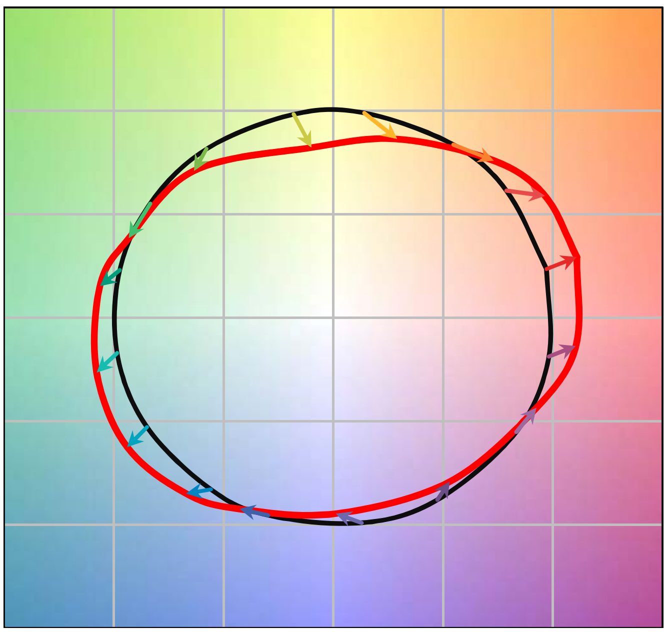
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

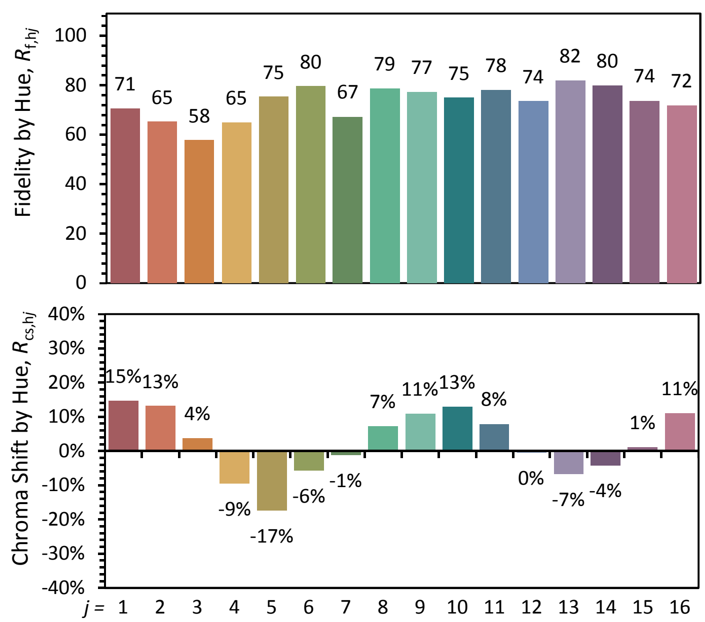
Color Rendition Report

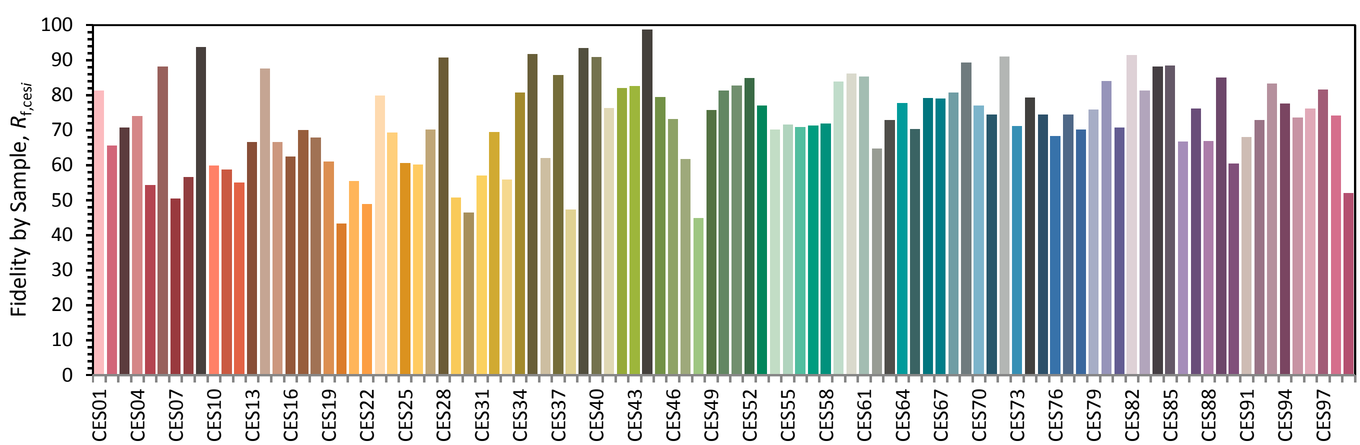
Source:	Experimental Source 14
Date:	5-Aug-15
Notes:	



R_f 73 R_g 102 $R_{f,skin}$ 67	CCT 3487 D_{uv} 0.0000	x 0.4060 y 0.3912	u' 0.2360 v' 0.5116	LER 298	CIE R_a 68 R_9 -37







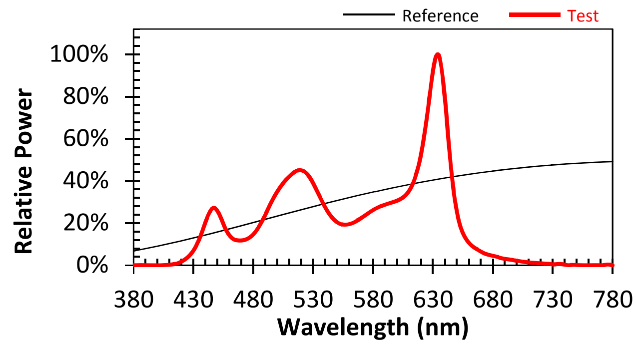
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

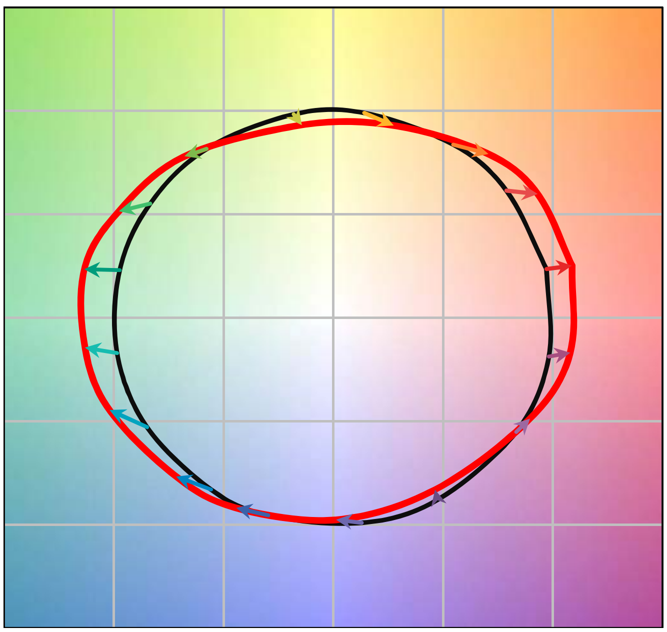
Source: Experimental Source 15

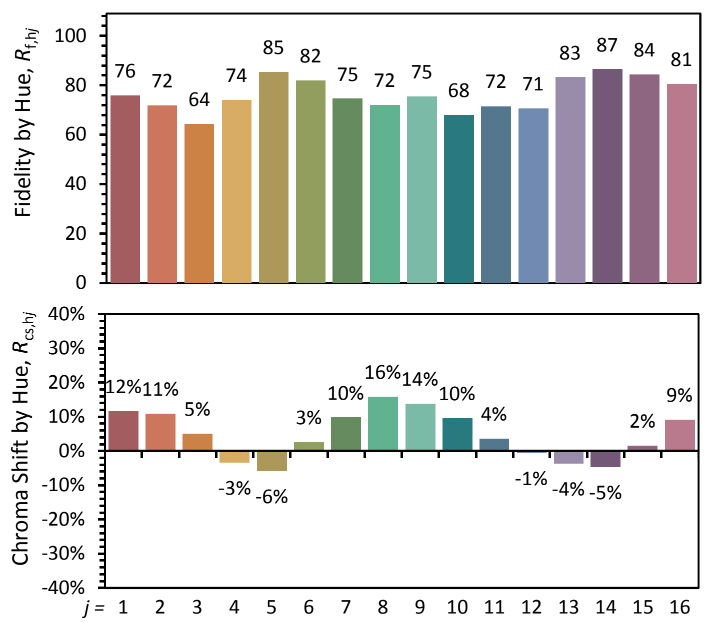
Date: 5-Aug-15

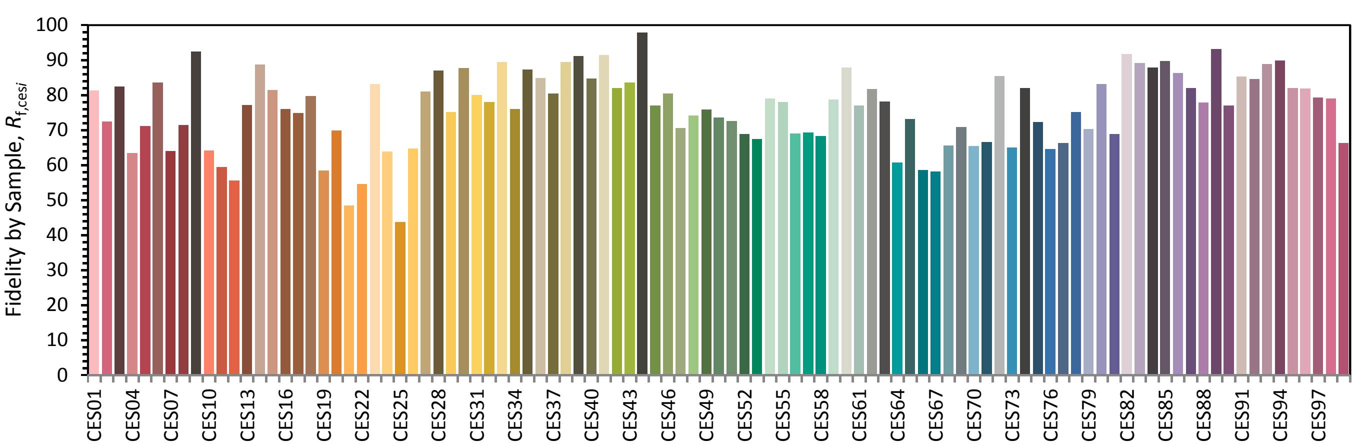
Notes:



R_f **76**	**CCT** 3484	**x** 0.4061	**u'** 0.2362	**LER** 301	**CIE R_a** 70
R_g **108**	D_{uv} -0.0002	**y** 0.3907	**v'** 0.5114		R_9 6
$R_{f,skin}$ 81					







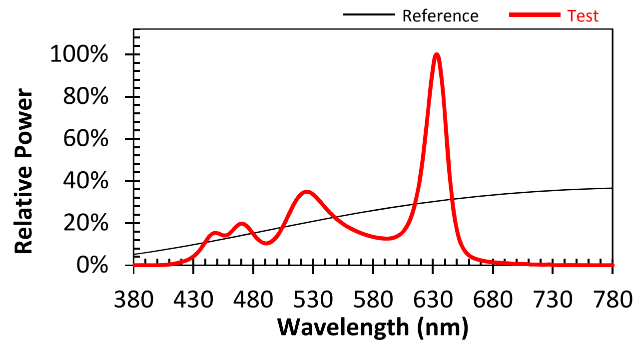
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

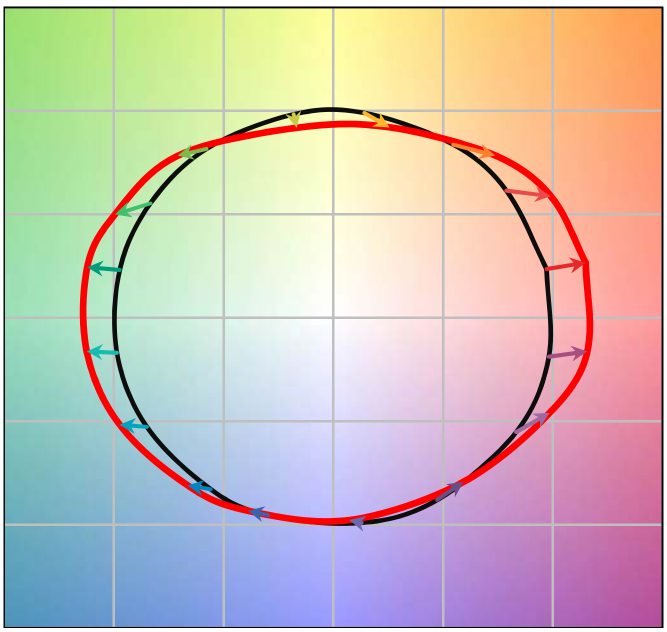
Source: Experimental Source 16

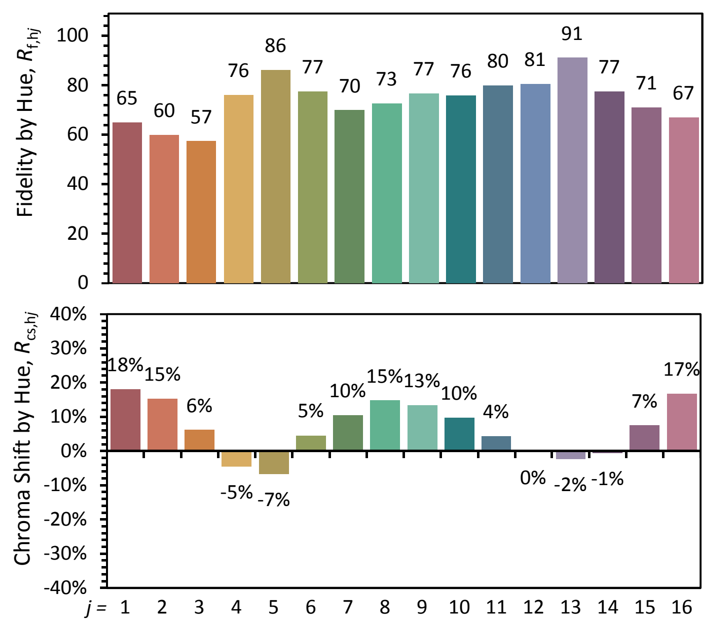
Date: 5-Aug-15

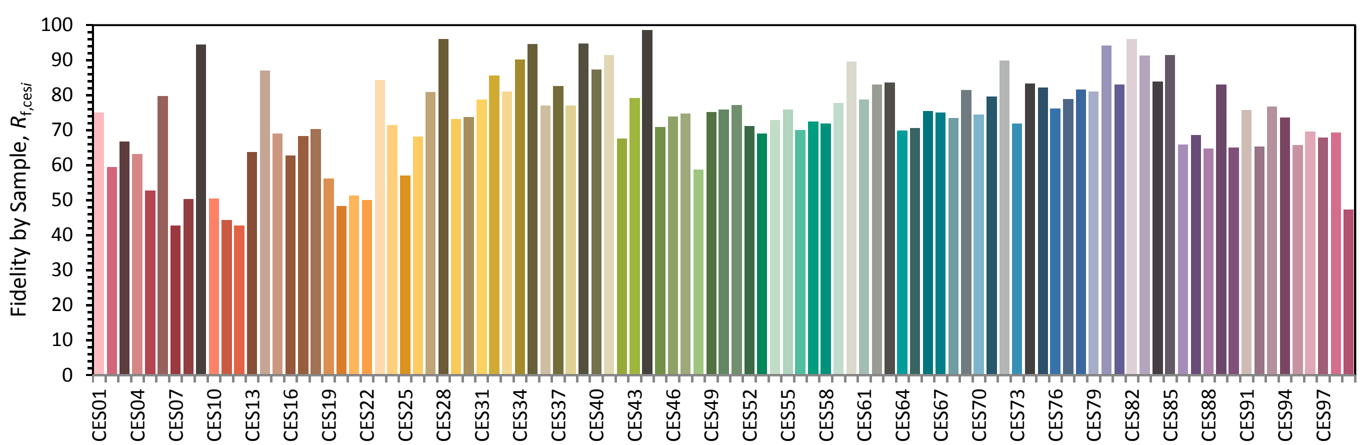
Notes:



R_f 74 R_g 111 $R_{f,skin}$ 70	CCT 3496 D_{uv} -0.0003	x 0.4052 y 0.3901	u' 0.2359 v' 0.5110	LER 301	CIE R_a 60 R_9 -57







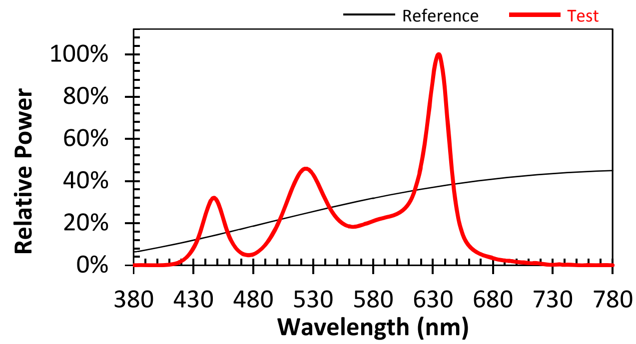
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

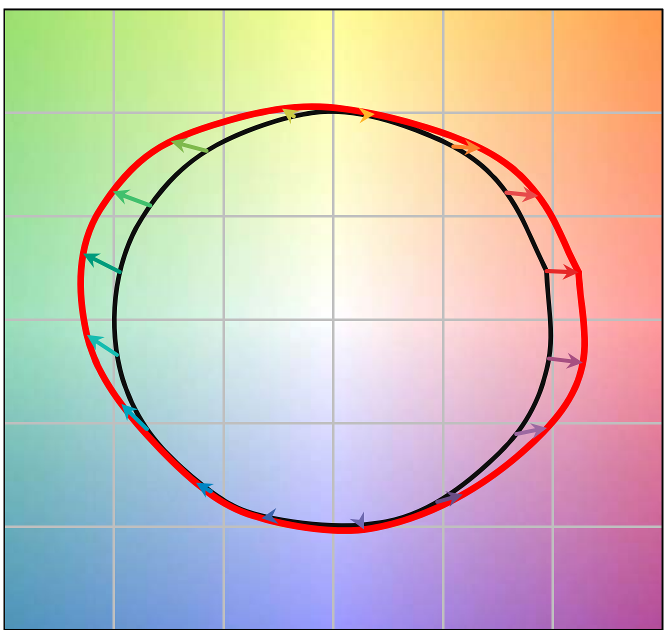
Source: Experimental Source 17

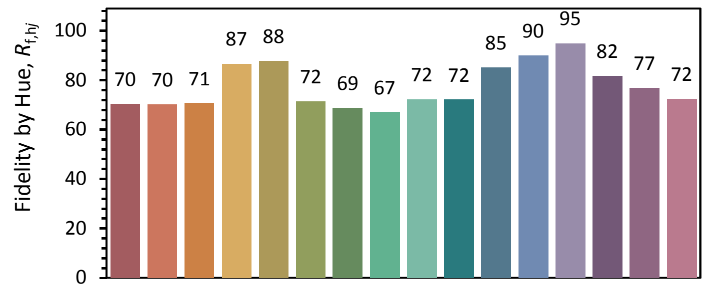
Date: 5-Aug-15

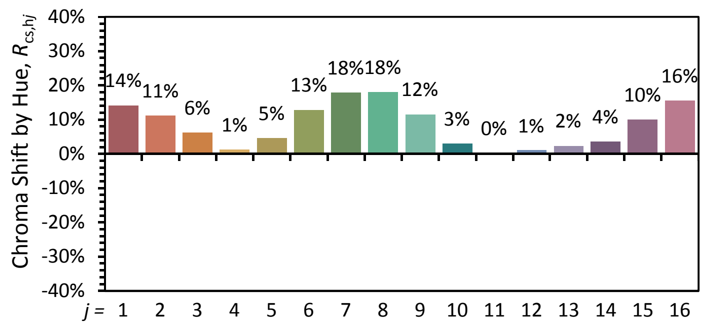
Notes:

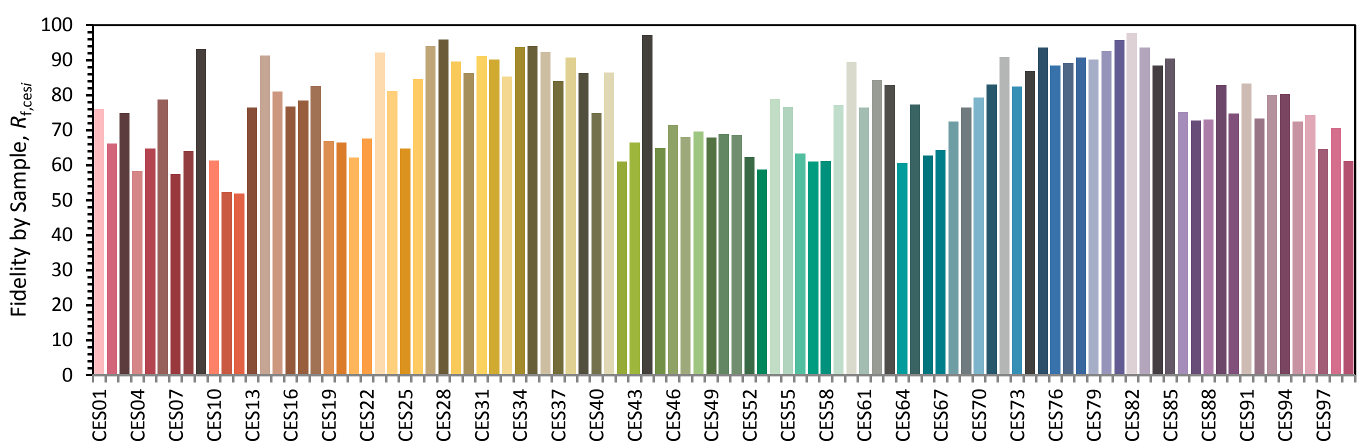


R_f 77	CCT 3489	x 0.4055	u' 0.2362	LER 305	CIE R_a 68
R_g 116	D_{uv} -0.0004	y 0.3898	v' 0.5109		R_9 -12
$R_{f,skin}$ 82					









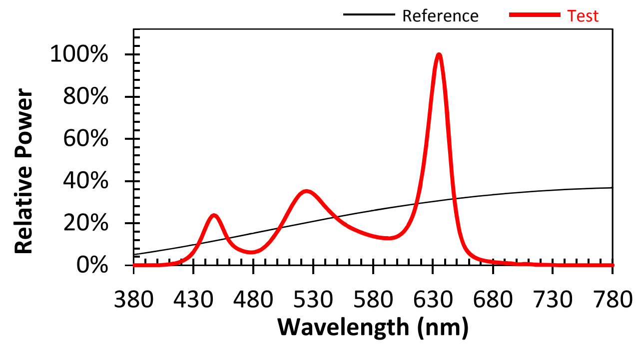
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

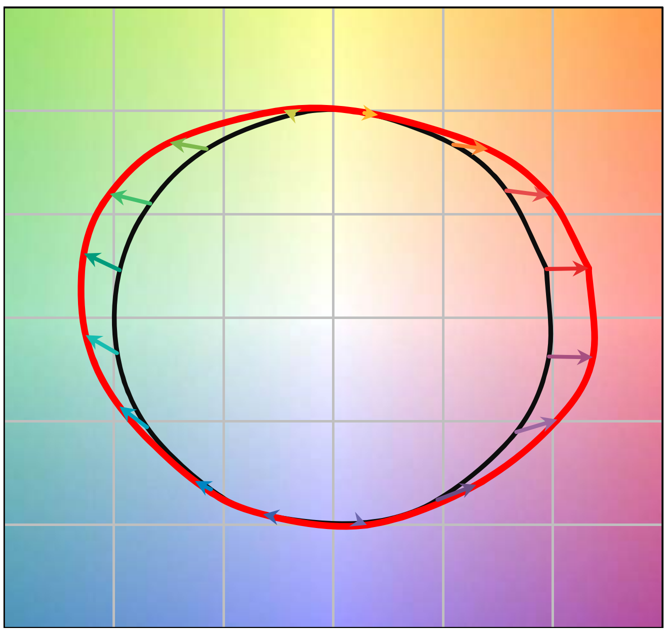
Source: Experimental Source 18

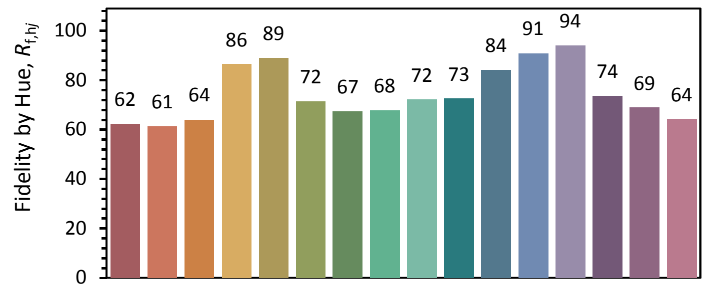
Date: 5-Aug-15

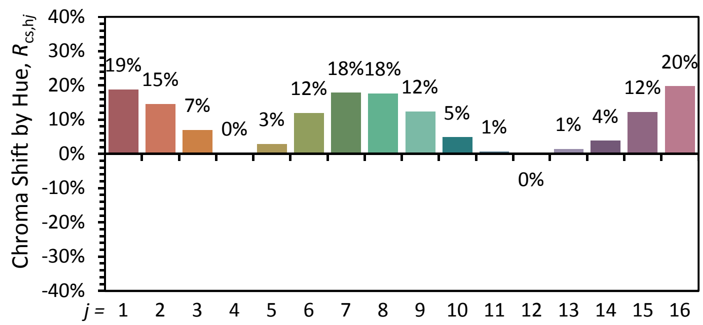
Notes:

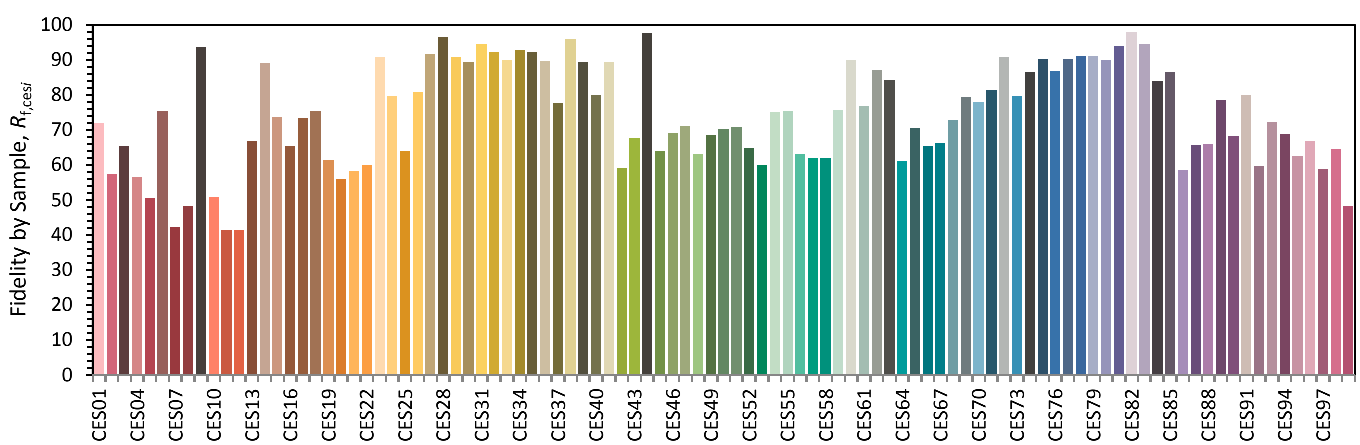


R_f 74	CCT 3485	x 0.4061	u' 0.2361	LER 299	CIE R_a 60
R_g 117	D_{uv} 0.0000	y 0.3912	v' 0.5116		R_9 -60
$R_{f,skin}$ 75					









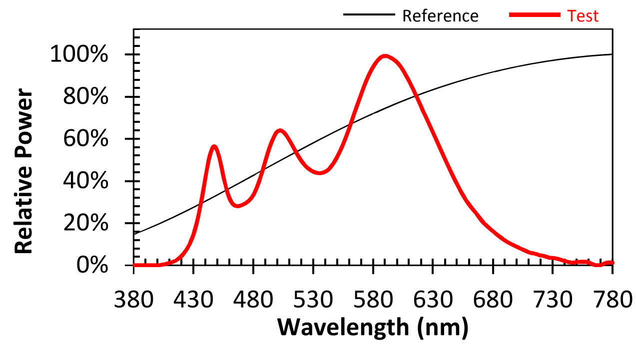
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

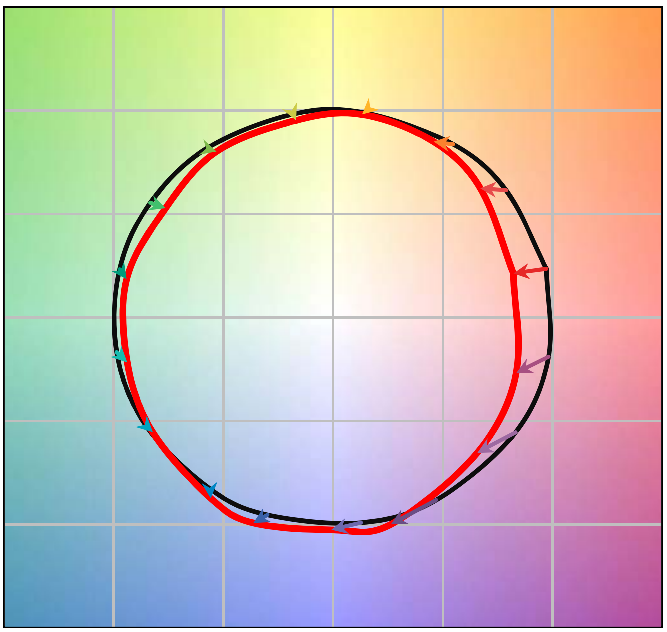
Source: Experimental Source 19

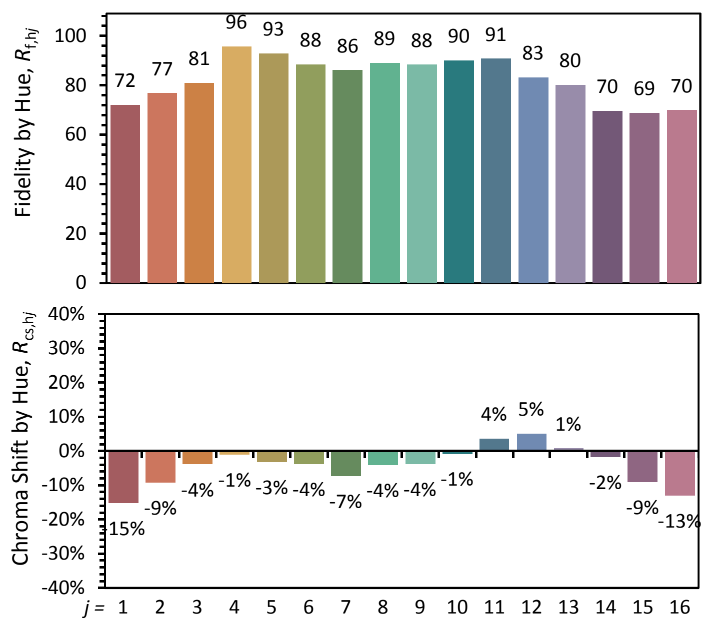
Date: 5-Aug-15

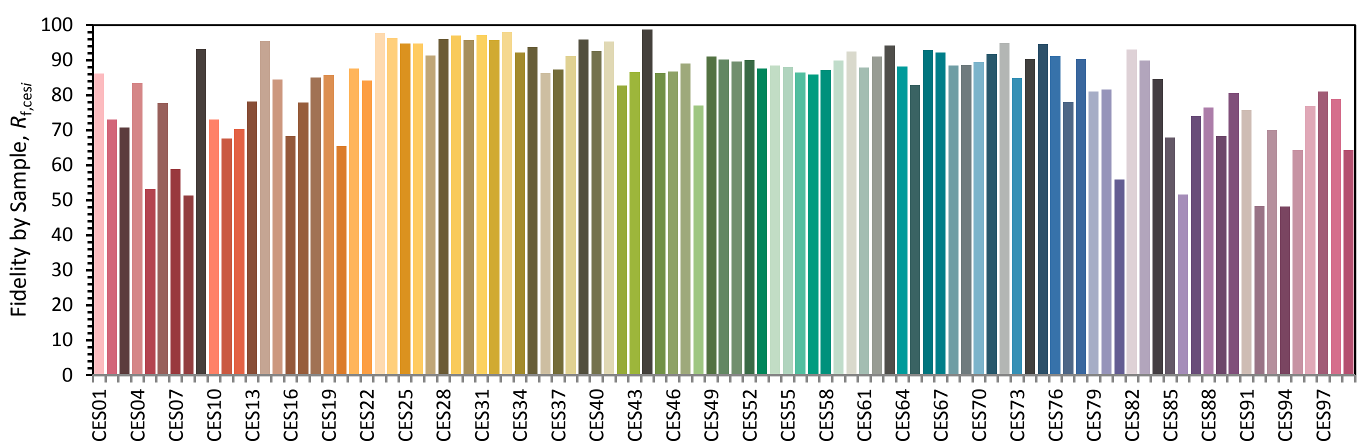
Notes:



R_f **83**	CCT 3520	**x** 0.4047	**u'** 0.2350	**LER** 337	**CIE** R_a 80
R_g **91**	D_{uv} 0.0005	**y** 0.3916	**v'** 0.5115		R_9 -19
$R_{f,skin}$ 85					





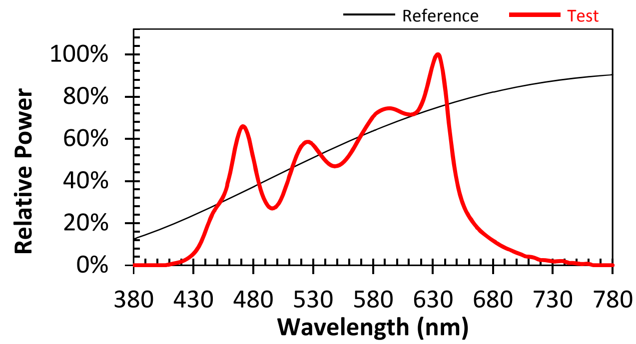


Color Rendition Report

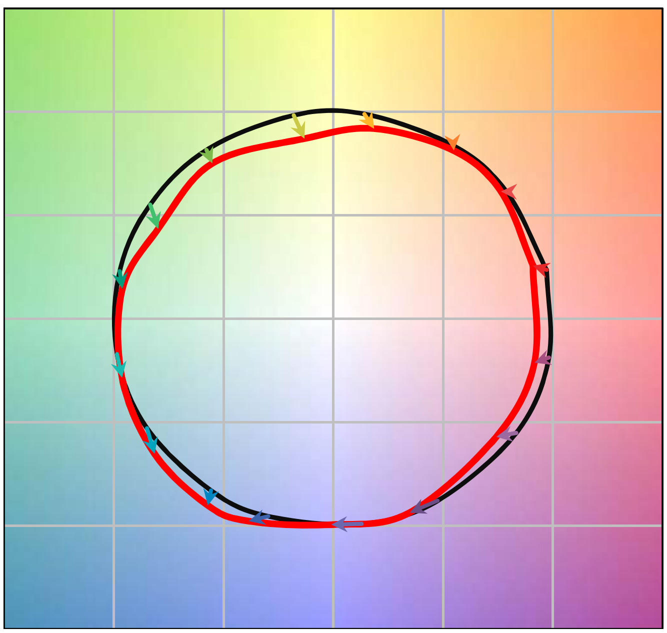
Source: Experimental Source 20

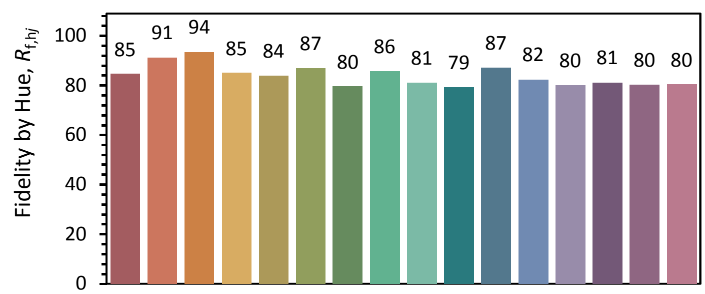
Date: 5-Aug-15

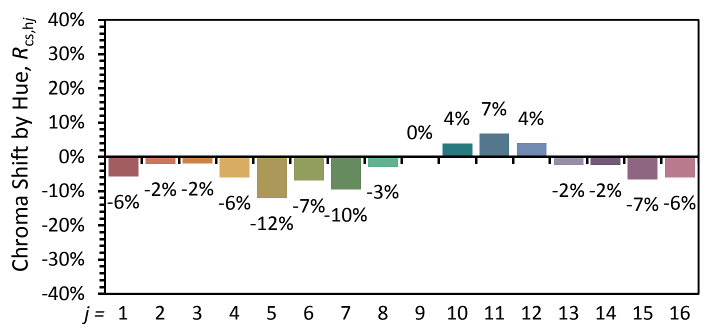
Notes:

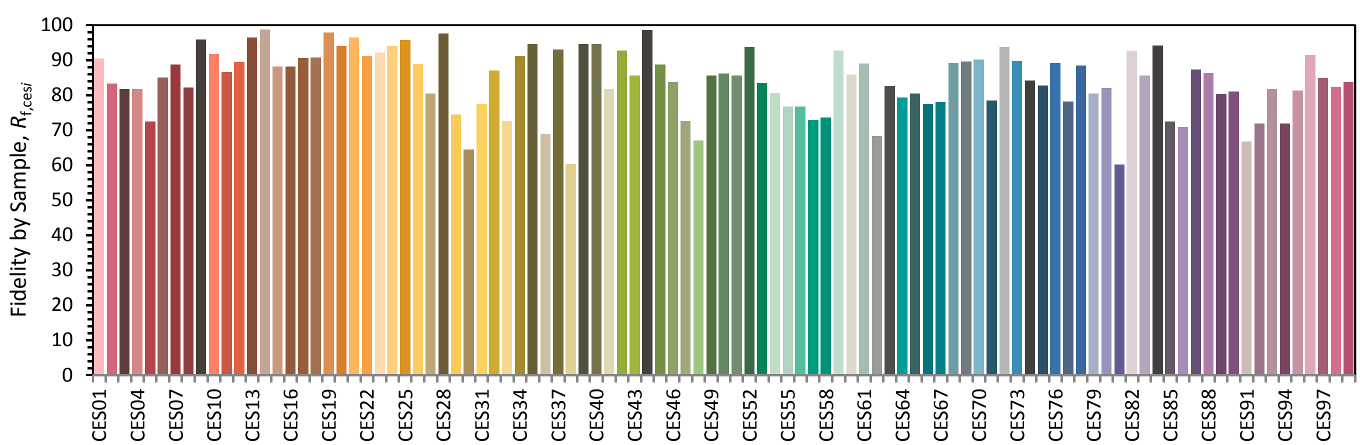


R_f **84**	CCT 3483	x 0.4065	u' 0.2360	LER 328	CIE R_a 91
R_g **93**	D_{uv} 0.0002	y 0.3919	v' 0.5119		R_9 63
$R_{f,skin}$ 89					









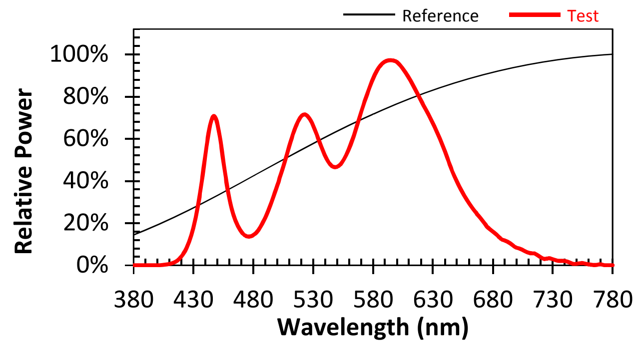
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

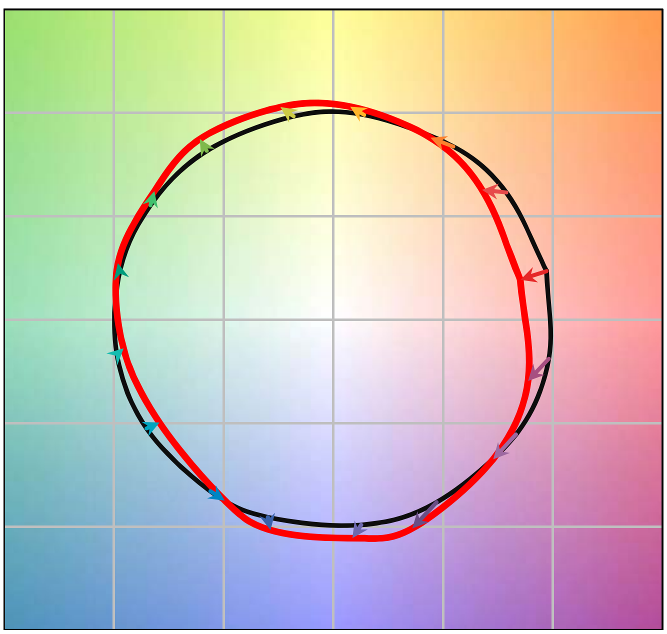
Source: Experimental Source 21

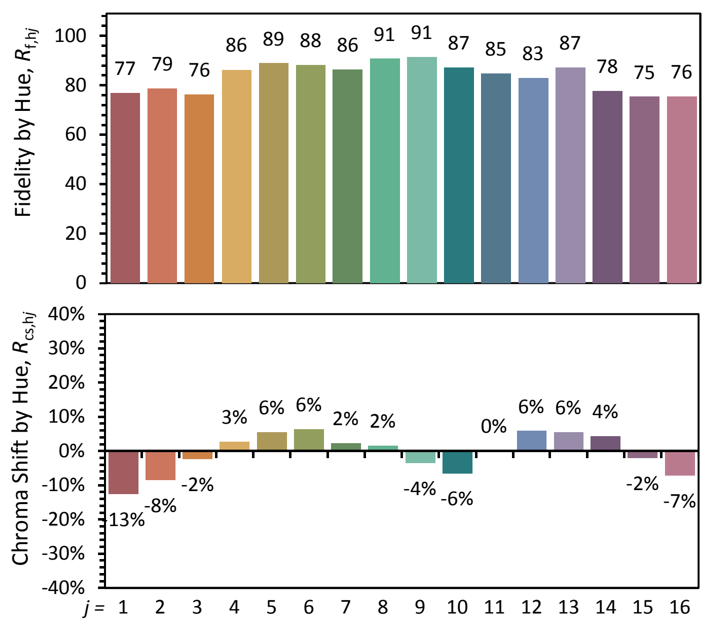
Date: 5-Aug-15

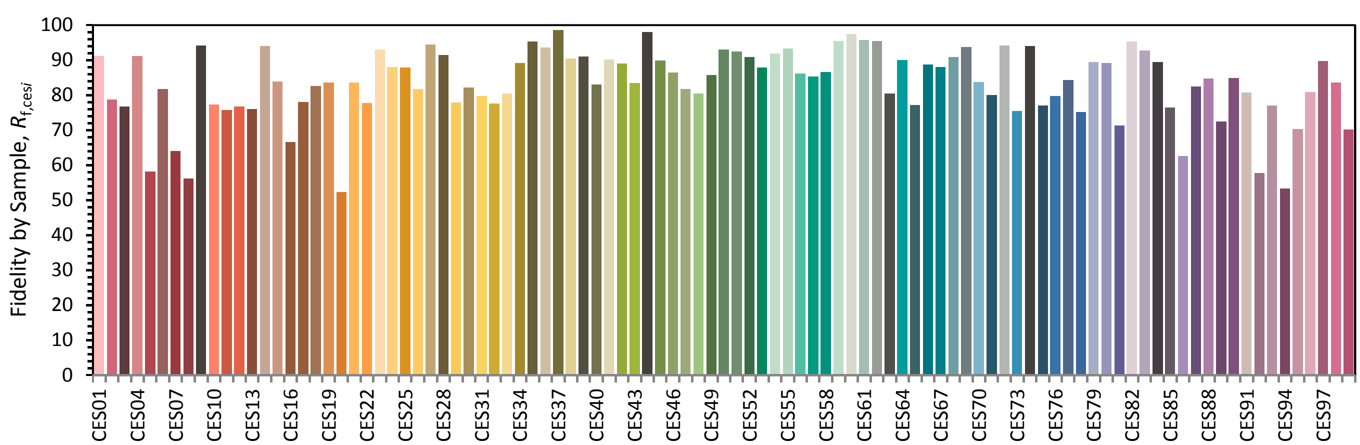
Notes:



R_f **83**	CCT 3513	x 0.4051	u' 0.2351	LER 343	CIE R_a 84
R_g **98**	D_{uv} 0.0005	y 0.3918	v' 0.5117		R_9 -7
$R_{f,skin}$ 83					





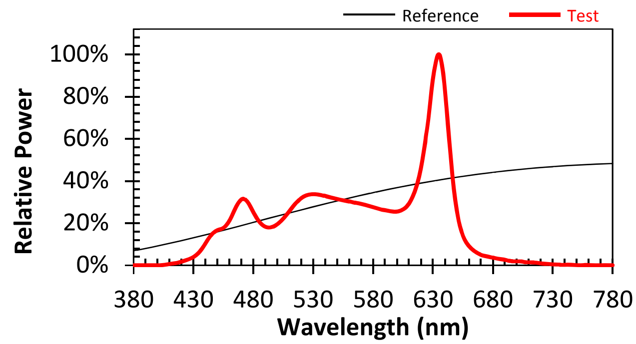


Color Rendition Report

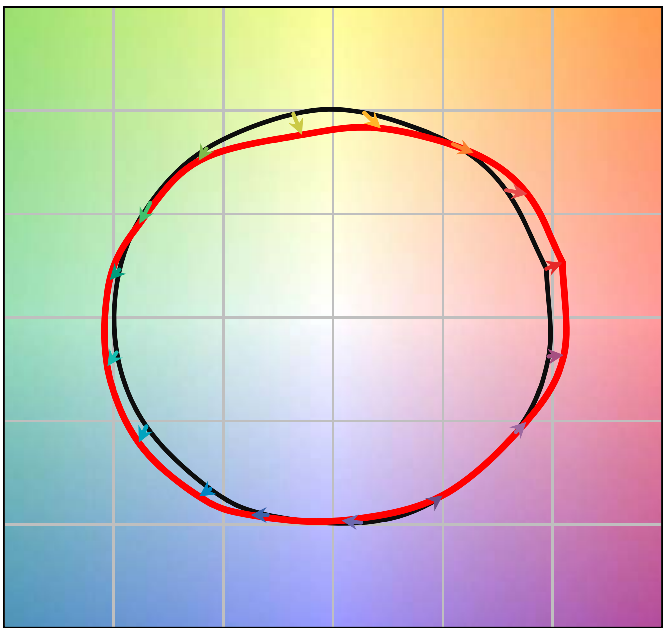
Source: Experimental Source 22

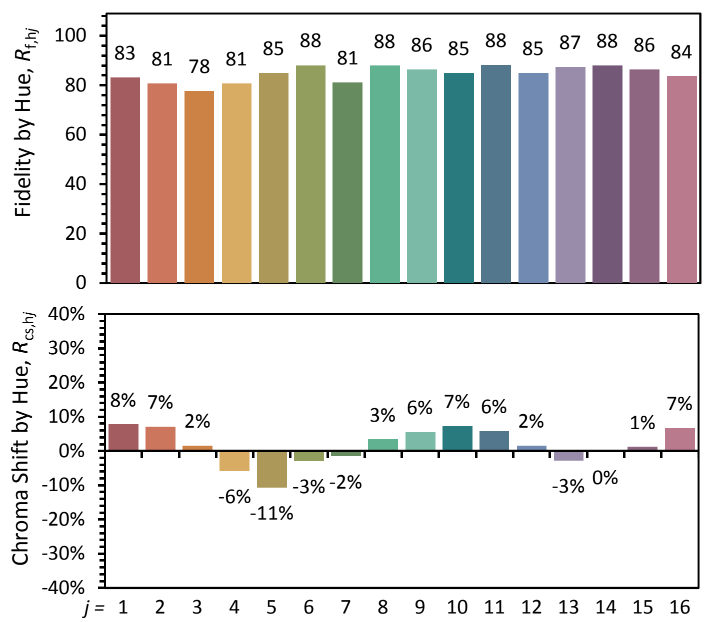
Date: 5-Aug-15

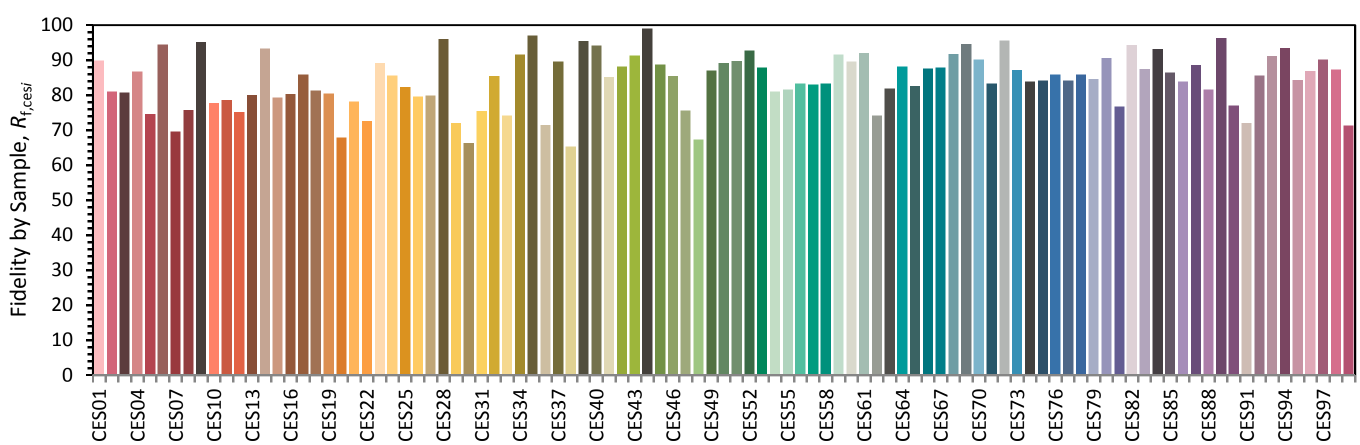
Notes:



R_f **84**	CCT 3506	**x** 0.4057	**u'** 0.2352	**LER** 311	**CIE R_a** 83
R_g **102**	D_{uv} 0.0007	**y** 0.3925	**v'** 0.5121		R_9 21
$R_{f,skin}$ 80					





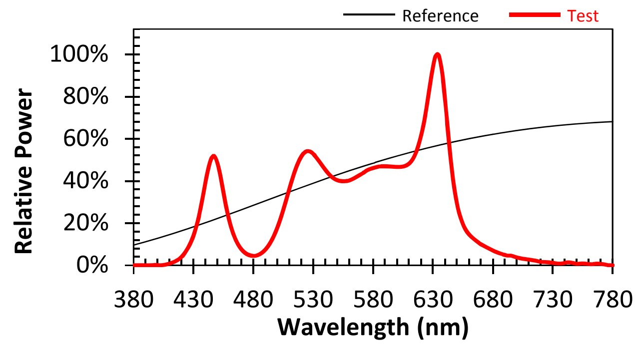


Color Rendition Report

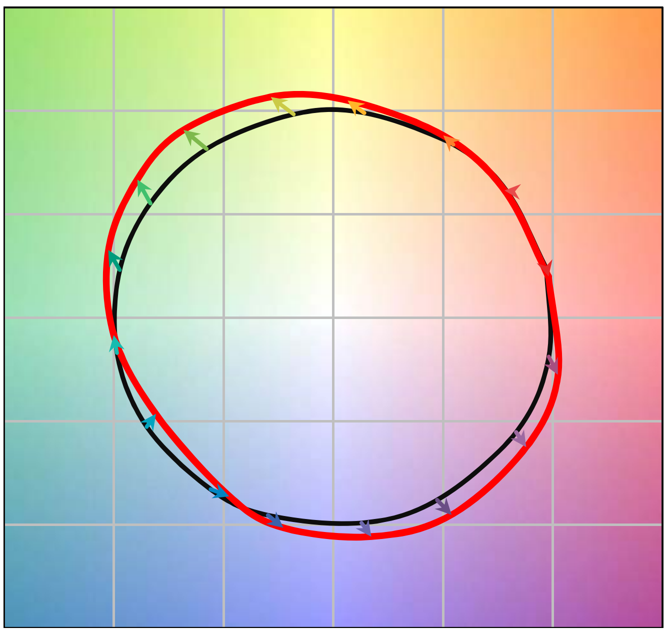
Source: Experimental Source 24

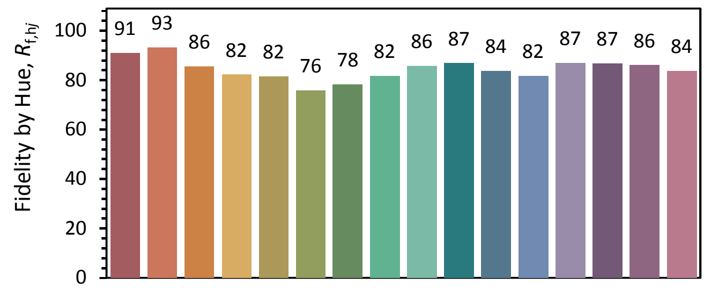
Date: 5-Aug-15

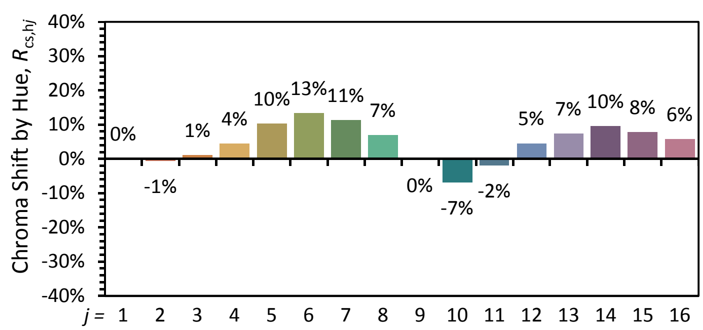
Notes:

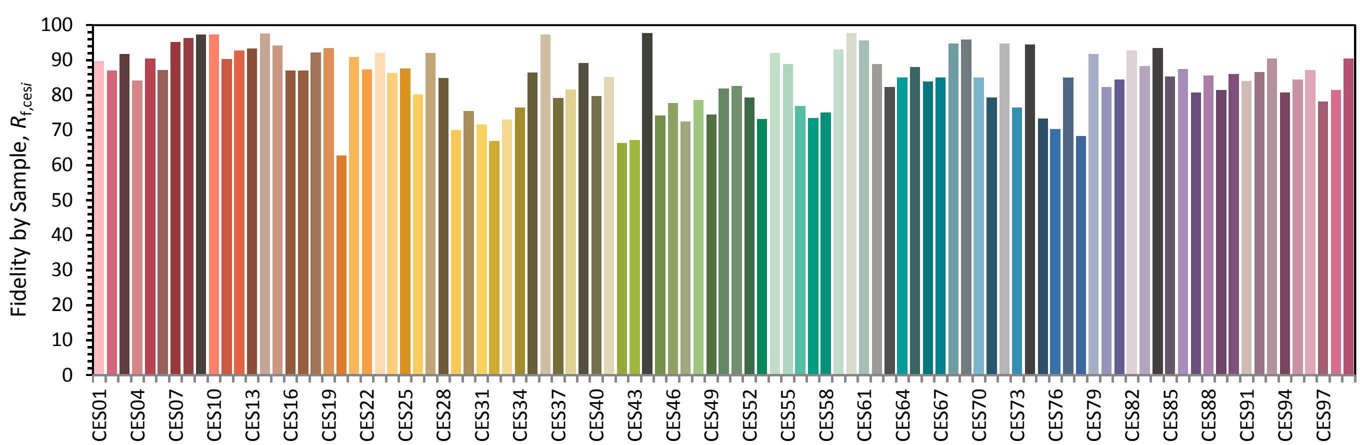


R_f 85	CCT 3498	x 0.4054	u' 0.2358	LER 332	CIE R_a 90
R_g 109	D_{uv} 0.0000	y 0.3907	v' 0.5113		R_9 98
$R_{f,skin}$ 93					









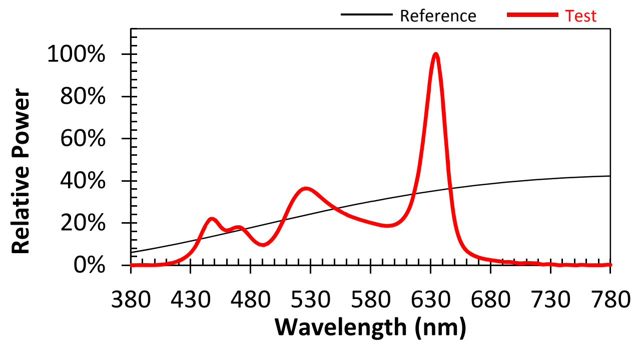
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

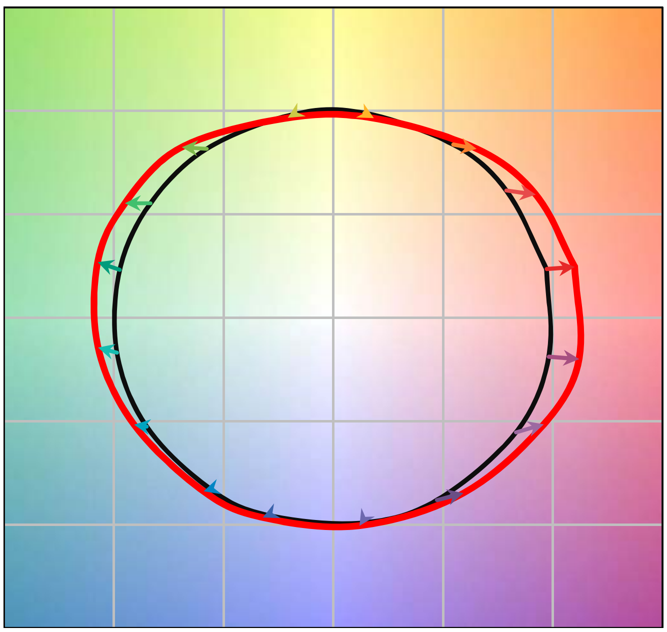
Source: Experimental Source 23

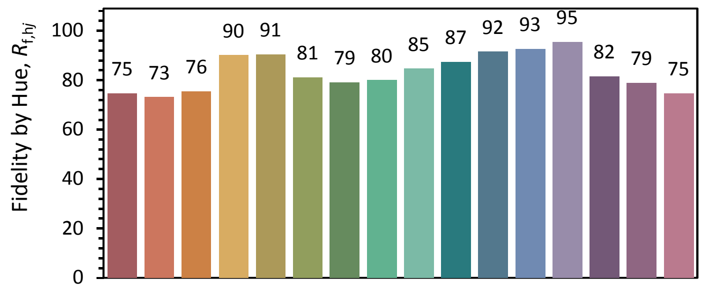
Date: 5-Aug-15

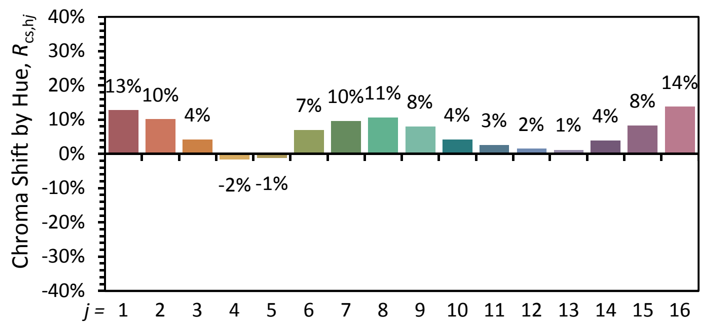
Notes:

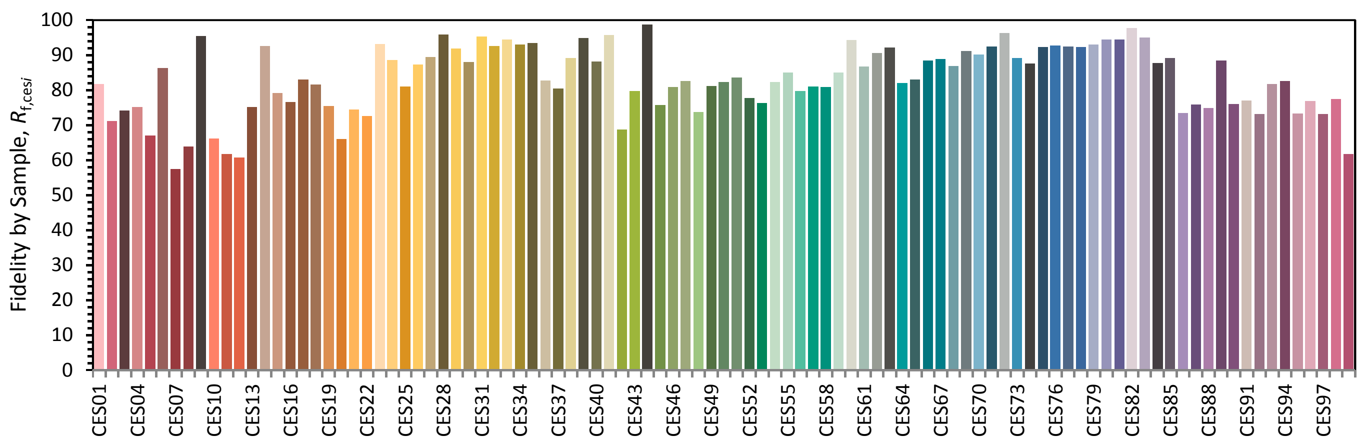


R_f 83	CCT 3504	x 0.4050	u' 0.2356	LER 309	CIE R_a 73
R_g 111	D_{uv} 0.0000	y 0.3905	v' 0.5111		R_9 -14
$R_{f,skin}$ 80					





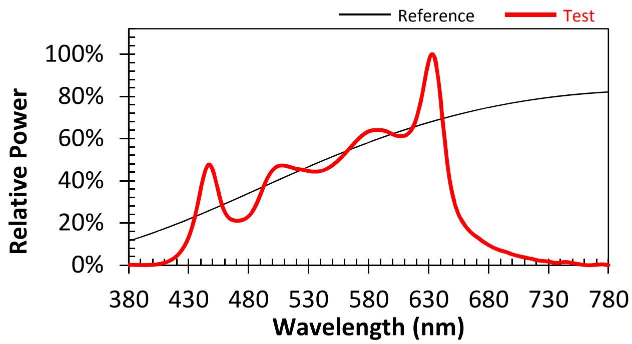




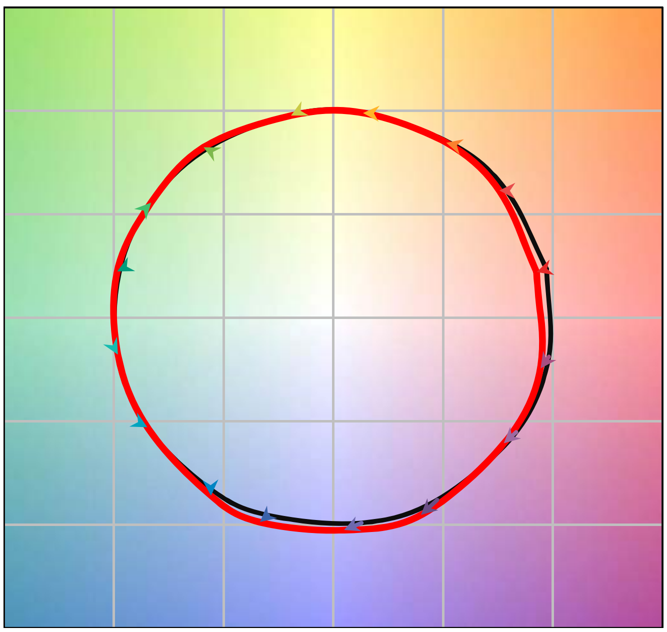
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

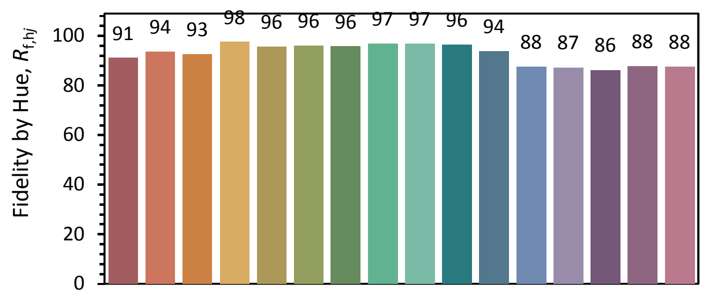
Color Rendition Report

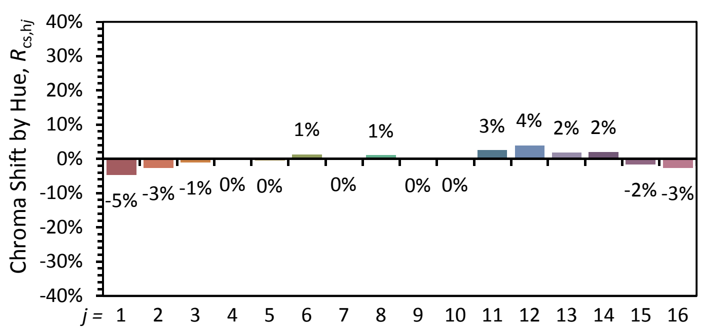
Source: Experimental Source 25
Date: 5-Aug-15
Notes:

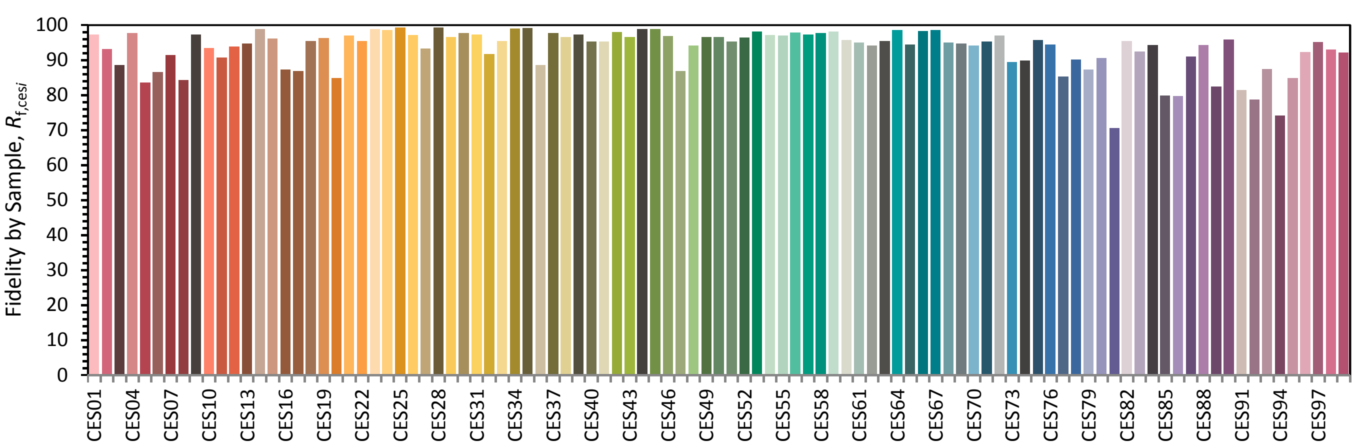


R_f 93	CCT 3491	x 0.4059	u' 0.2359	LER 328	CIE R_a 95
R_g 100	D_{uv} 0.0001	y 0.3912	v' 0.5115		R_9 68
$R_{f,skin}$ 96					









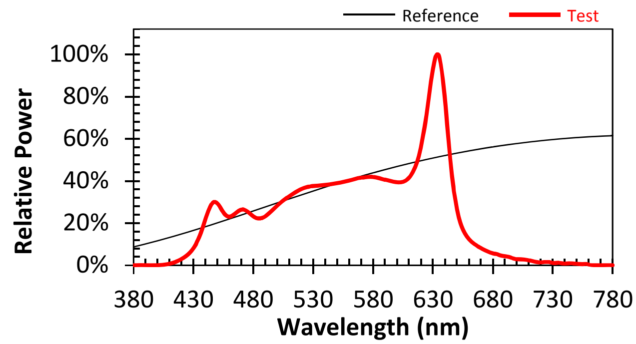
Calculated using IES TM-30-15 Advanced Calculator Version 1.01

Color Rendition Report

Source: Experimental Source 26

Date: 5-Aug-15

Notes:



R_f 93	CCT 3502	x 0.4051	u' 0.2357	LER 321	CIE R_a 95
R_g 101	D_{uv} -0.0001	y 0.3904	v' 0.5111		R_9 80
$R_{f,skin}$ 93