# Human Perceptions of Color Rendition at Different Chromaticities

Michael P Royer[1]
Andrea Wilkerson[1]
Minchen Wei[2]

[1]Pacific Northwest National Laboratory
620 SW 5th Avenue, Suite 810
Portland, OR 97204
michael.royer@pnnl.gov

[2]Hong Kong Polytechnic University

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## Abstract

An experiment was conducted to evaluate how perceptions of a light source's color quality depend upon color rendition and chromaticity. Thirty-four participants each evaluated 50 lighting scenes in a 3.7 m by 5.5 m room filled with objects. The lighting scenes included five chromaticity groups, with 10 systematically-varied color rendition conditions repeated in each group. Participants, who chromatically adapted to each chromaticity group, were asked to rate each scene on eight point scales for saturated-dull, normal-shifted, and like-dislike (preference), as well as choosing whether they found the scenes to be acceptable or unacceptable.

The findings suggest that color rendition perceptions can vary with chromaticity, with an interactive effect of CCT and $D_{uv}$. The same IES TM-30-15 measures—$R_f$, $R_{cs,h16}$, and $R_g$—could be used to effectively model perceptions within each chromaticity group, and provided suitable performance for the overall set of 50 conditions. The differences in ratings between the chromaticity groups were substantially smaller than the range in ratings for the 10 color rendition conditions within each group, allowing the same acceptability-based criteria of IES $R_f \geq 75$, IES $R_g \geq 98$, and $-7\% \leq$ IES $R_{cs,h16} \leq 15\%$ to be applied to all chromaticity groups.

# 1 Introduction

In 2015, the Illuminating Engineering Society (IES) published TM-30-15, *IES Method for Evaluating Light Source Color Rendition*.[1, 2] IES TM-30-15 is an objective characterization of differences between colors as rendered by a test source and reference illuminant, going beyond the average magnitude of the difference (average color fidelity) and average saturation level (gamut area). It was specifically developed without assigning merit to any types of color differences, also referred to as color shifts or distortions. In the ensuing year, several research efforts attempted to assign perceptual meaning to various color rendition characteristics, including hue-specific patterns of shifts (gamut shape), based on characterizations provided by TM-30.[3-8] This is an important process, because a principal goal in lighting is to engineer or specify a light source that will make objects' colors appear pleasing—or another given perception, such as normal, natural, dull, or vivid, for example.

Research investigating the link between human perceptions and color rendition has been ongoing for more than 50 years, with some of the earliest work identifying that high average color fidelity—in these cases, light sources with high Commision Internationale de L'Eclairage (CIE) General Color Rendering Index, $R_a$ (often called CRI) values—were not always the most preferred.[9-12] With the advent of commercially-viable solid-state lighting for architectural interiors in the mid-2000s, there has been renewed interest in this topic, with more than 20 published studies on color rendition perception.[3-7, 13-38] This is due to both questions about lighting quality for LED products and the ease of using LEDs to create a variety of color rendition conditions. Collectively, these many studies have driven the understanding that average color fidelity is a limited characterization, that color saturation is an important consideration, and that certain hues may be more influential than others when humans judge normalness (naturalness), saturation (vividness), preference, or acceptability.

In the past decade, research has also emerged on the perception of nominally white light of different chromaticities. Specifically, several investigations have sought to understand perception of light sources with chromaticities "above" and "below" the blackbody locus,[24, 39-45] which is characterized with $D_{uv}$.[46] One question that has been raised is what role color rendition might play in judgements of chromaticity, because a relationship between chromaticity and color rendition has been identified.[39] This relationship exists primarily because of the reference-based methodology used in most methods for evaluating color rendition. A recent pilot study found that when color rendition was held constant, preference for negative $D_{uv}$ values varied with correlated color temperature (CCT).[45] At least one proposal has been made to include $D_{uv}$ with average color fidelity and average saturation level in a composite measure for color quality;[47] however, few studies have rigorously investigated the interaction of chromaticity and color rendition on judgements of color quality.

This work follows a recently published study by Royer and colleagues[3]—heretofore referred to as color rendition experiment one (CREX1)—which examined perceptions of normalness, saturation, and preference for 26 lighting scenes. All of the scenes had the same chromaticity (3500 K on the Planckian locus), with a range in IES TM-30-15 Fidelity Index ($R_f$) values of 63 to 93, IES TM-30-15 Gamut Index ($R_g$) values of 79 to 120, and IES TM-30-15 hue-angle bin 1 (Red) Local Chroma Shift values ($R_{cs,h1}$) of -19% to 26%. The findings suggested that gamut shape was more important than gamut area for human preference, with red playing a more important role than other hues. While the IES TM-30-15 measures, used in combination, were excellent in characterizing mean ratings for the three perceptual attributes, the present study examines if the models developed can be applied to other spectral power distributions (SPDs) with different chromaticities. The basic structure included five chromaticity groups, with 10 color rendition conditions in each group (see Table 1). Across the five chromaticity groups, each color rendition condition had the same nominal IES $R_f$ and IES $R_g$ targets, with IES $R_{cs,h1}$ either maximized or minimized to produce variations in gamut shape.

## 1.1. Past Experiments

A small number of studies have been identified that have investigated the interaction of chromaticity and color rendition on human perceptions of object color quality. That is, they systematically varied both chromaticity and color rendition—not haphazardly varying both simultaneously. These studies still have the major limitation of not considering or not systematically varying gamut shape simultaneously with chromaticity. Many also specified only CCT, ignoring the major role that $D_{uv}$ can play in color perception.

- Zukauskas and colleagues had participants mix desaturating and saturating color-mixed LED combinations at 3000 K, 4500 K, and 6500 K ($D_{uv}$ or chromaticity not reported) to maximize a number of perceptions, such as naturalness and preference.[34] The viewed scene was a booth containing fruits and soda cans. One suggested result was that preference for higher saturation lighting conditions increased with CCT, although there was no statistical analysis comparing the CCT groups. Rating scales were not used, so absolute preference differences between CCTs cannot be evaluated.
- Szabo and colleagues examined color perception using two different CCTs, but each was shown in one environment (home or kitchen) so no conclusions about the effect of CCT on color rendition perception can be drawn.[22]
- Islam and colleagues examined the perception of 24 lighting conditions (21 LED conditions), with eight in each of three CCT groups (2700 K, 4000 K, 6500 K).[21] Chromaticity was not held constant, with substantial differences within and between each group. The reported $D_{uv}$ values were between -0.0050 and 0.0058. Between groups, the conditions were designed to have comparable average color fidelity and gamut area values, but gamut shape was not considered. The authors concluded that conditions with higher CCTs led to more pleasing color appearance.
- Ohno, Fein, and Miller had 20 participants view fruits, vegetables and skin tones under four lighting conditions: 2700 K, 3500 K, and 5000 K on the Planckian locus, as well as 3500 K with a $D_{uv}$ of -0.015.[18] Nine different levels of red-green chroma shift were presented; in this case, gamut shape was held constant but average color fidelity and gamut area varied. The authors concluded that the preferred chroma enhancement ($\Delta C^*_{ab} = 5$) did not vary with chromaticity (or object set).
- Jost-Boissard and colleagues conducted two separate experiments, using two CCTs (3000 K and 4000 K), but variable $D_{uv}$ values (-0.023 to 0.0058).[23] The lighting conditions had a range of average color fidelity values, but gamut area and gamut shape were not investigated systematically between CCTs. The participants viewed a plate of fruits and vegetables and an X-rite Color Checker chart. No statements were made regarding the relative perceptions of the different CCT groups.
- In a series of experiments, Khanh, Bodrogi and colleagues examined color perceptions of groups of seven, five, seven, and seven SPDs in four different but related experiments.[48-51] One experiment found that for high average color fidelity conditions, there was a preference for conditions between 3985 K and 6428 K (out of a full range of 2719 to 6428 K). Another found color preference for high average color fidelity conditions with CCTs of 3221 K did not vary with distance from the Planckian locus. General conclusions from this collection of experiments suggested color preference to be a function of average color fidelity and chroma shift. None of the individual experiments, which featured different applications, systematically varied gamut shape.

Combined, these results offer mixed evidence for the interactive effect of chromaticity and color rendition on human psychophysical responses to lighting. None of the studies systematically varied the combination of chromaticity (for example, CCT and $D_{uv}$), average color fidelity, gamut area, and gamut shape. Doing so requires a large number of different scenes, which is challenging for experimental design.

## 1.2. Hypotheses and Goals

The null hypotheses for this experiment were that human perceptions related to color rendition—preference, saturation, normalness, acceptability—do not vary with chromaticity. Additionally, a goal was to examine the performance of a provisional model for color preference developed in CREX1, which combines average color fidelity (IES $R_f$) and red chroma shift (IES $R_{cs,h16}$). As an extension of the prior work, individual best-fit models for each chromaticity were developed and compared, again in an attempt to examine the generalizability of the findings.

Fundamentally, the goal of this work is to continue investigating the meaning of the objective data provided by IES TM-30-15. Because the breadth and depth of information provided by IES TM-30-15 is much greater than past color rendition metrics have provided, there is a need for information pertaining to the meaning of specific values. Developing models and threshold values helps manufacturers and specifiers to create and use the best light sources for a given application.

# 2 Methodology

## 2.1 Apparatus and Test Room

### 2.1.1 Experimental rooms

Aside from a room with large windows that was used for welcoming and completing informed consent, the participants spent the majority of their time in two distinct rooms, separated by a dark corridor. These are referred to as the experiment room and the adaptation room in this article. Both are shown in **Figure 1**.

**Figure 1. Photographs of the inside of the experiment room (top) and adaptation room (bottom).**

The experiment room was a recreation of that used in CREX1, with some notable differences. The room was created within a high-bay space, using a moveable grid ceiling bounded by heavyweight white curtains that hung flat to resemble walls. The room was approximately 3.7 m by 5.5 m, with a 3 m ceiling height. Entry points, formed with arrangement of staggered curtains, were provided along either end of one of the 5.5 m sides. This is the biggest contrast with the CREX1 experiment room, which featured only one entry in the middle of one of the sides, because the room was smaller.

The adaptation room featured neutral gray walls, floor, and ceiling, with black curtains on two sides. A wood door led into the space, but was always at the participants' backs when they were in the room. A table covered by a black tablecloth and two gray chairs were the only objects in the room, which was approximately 2 m by 3.5 m by 2.5 m.

#### 2.1.2 Lighting Equipment

In the experiment room, a group of seven spectrally tunable theatrical luminaires, the Electronic Theater Controls (ETC) Source Four Series 2 Lustr, was used to create 50 different lighting scenes, with 10 at each of five chromaticities. The luminaire had seven independently controlled LED channels (red, amber, lime, green, cyan, blue, indigo), as detailed in CREX1. 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. This computer was outside the experiment room.

Five of the luminaires were mounted to provide directional lighting of the object displays, similar to the typical use of theatrical luminaires to light a scene. In an atypical manner, two of the luminaires were mounted above the grid ceiling, with the luminaire shutters adjusted to project the light onto a 2'x2' piece of acrylic which was mounted in the ceiling grid and covered by a sheet of Lee 252 theatrical gel that provided extra diffusion and gave the appearance of a typical troffer luminaire. This configuration gave the appearance of a recessed troffer, making the room seem more familiar and helping to reduce strong shadows.

Three ETC D22 Lustr luminaires were used in the adaptation room. The D22 is also a seven-channel color-tunable luminaire that is similar to the Source Four Series 2 Lustr, but a phosphor-coated white emitter is included instead of a lime emitter.

#### 2.1.3 Objects for Evaluation

Objects for the experiment room 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. A mirror was also provided to allow participants to assess the color appearance of their own faces. Spectral reflectance functions (available as a supplementary file) were measured for the room surfaces and 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 nine of the most prominent colors, at the discretion of the experimenters.

The objects were ostensibly the same as used in CREX1. The fresh foods and flowers were replaced with as similar of objects as possible. The only other substantial changes was the addition of a polychromatic wall hanging with a red-dominant color scheme, which replaced a red blouse.

Objects were placed in specific areas of the room according to their category**.** Central to the field of view when entering the room was either the artwork or clothing, although most objects would have been seen simultaneously.

## 2.2 Lighting Scenes

For the primary experiment room, 50 SPDs were first calculated using measurements of each channel of the luminaire to achieve the 10 systematically-varied color rendition conditions for each of the chromaticity groups. Final refinements of each SPD were made in-situ using a calibrated Minolta CL-500A illuminance spectrophotometer (SN: 100020008). All objects were removed from the room for the final measurement to ensure that the characterization was of the SPD itself, as is the intended use of TM-30.

The SPDs were divided into five chromaticity groups (A through E), delineated based on CCT and $D_{uv}$. Group C was at the same chromaticity as the scenes from CREX1 (3500 K, 0.000 $D_{uv}$). Groups A and D were chosen to be equal CCT-steps from the original data (2700 K and 4300 K with 0.000 $D_{uv}$), with groups B and E being their equal-CCT counterparts having $D_{uv}$ values of -0.007 (or an approximate $\Delta u'v'$ from the on-Planckian chromaticity of 0.01). This $D_{uv}$ value was chosen because it falls just outside the nominal bins specified in ANSI C78.377-2015,[52] but is a reasonable chromaticity that could be used in architectural lighting. It is closer to zero than the ranges examined in recent chromaticity perception studies,[40-45] which were considered too impractical. Other values will be examined in subsequent work.

Ten of the original 26 color rendition conditions from CREX1 were created at each of the 5 chromaticities, with the chosen subset representing a range in preference rating from the past experiment. **Table 1** provides characteristics comparing the five sets of ten SPDs having the same nominal color rendition targets. **Figure 2** shows the 10 IES TM-30-15 Color Vector Graphics (CVG) for the Group B conditions, illustrating the typical variation between the 10 conditions in each chromaticity group. **Figure 3** shows the CVGs for color rendition condition 7 across the five chromaticity groups, illustrating the stability of the CVGs across the groups. More data for each SPD can be found in the supplemental files. Included in the 10 conditions were three specific pairs, each having the same $R_f$ and $R_g$ target, but a different gamut shape that either minimized or maximized IES $R_{cs,h1}$. These pairs were conditions 2/7, 3/5 and 6/8.

Given the priority of matching chromaticity, DMX signal discretization of only 255, the lack of a specific criterion for red chroma shift, and limitations of the luminaire channels, among other factors, there was some variation in attributes for the same color rendition condition across the five chromaticity groups. The most notable attribute difference was for red chroma shift, particularly for conditions that increased red chroma. In those cases, the conditions in Groups A and B (2700 K) increased red chroma somewhat less than the Groups C, D, and E (3500 K or 4300 K). Importantly, these differences are not accounted for if color rendition condition (1-10) is simplified to a categorical variable in an analysis of variance (ANOVA) procedure.

All photometric and colorimetric data in this report is based on measurements taken prior to the start of subjective data collection. A second set of color measurements was taken immediately after the final participant completed the experiment. The difference between the pre- and post-experiment measurements were minimal, with a maximum difference in $R_f$ of 0.73 points and a maximum difference in $R_g$ of 0.56 points. All Local Chroma Shift values differed by less than 0.9%. The maximum difference

**Table 1. Characteristics of the 50 lighting scenes.** Luminous efficacy of radiation (LER) describes the lumens per watt of optical radiation.

| Chromaticity Group | CCT (K) | $D_{uv}$ | Color Rend. Cond. | IES TM-30-15 $R_f$ | $R_g$ | $R_{cs,h1}$ | $R_{cs,h15}$ | $R_{cs,h16}$ | $R_a$ | LER | $E_{ver}$ (lux) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A (2700 K, 0.000) | 2704 | 0.0002 | 1 | 82 | 89 | -12% | -11% | -17% | 80 | 337 | 207 |
| A (2700 K, 0.000) | 2704 | -0.0001 | 2 | 86 | 100 | -6% | 1% | -4% | 89 | 342 | 208 |
| A (2700 K, 0.000) | 2702 | 0.0002 | 3 | 94 | 100 | -3% | -2% | -4% | 97 | 332 | 207 |
| A (2700 K, 0.000) | 2708 | -0.0001 | 4 | 73 | 88 | 0% | -14% | -8% | 83 | 316 | 206 |
| A (2700 K, 0.000) | 2703 | 0.0002 | 5 | 93 | 102 | -1% | -1% | -1% | 96 | 330 | 208 |
| A (2700 K, 0.000) | 2696 | 0.0001 | 6 | 85 | 110 | 2% | 6% | 3% | 89 | 329 | 208 |
| A (2700 K, 0.000) | 2700 | -0.0001 | 7 | 83 | 101 | 6% | -3% | 3% | 81 | 314 | 208 |
| A (2700 K, 0.000) | 2702 | -0.0002 | 8 | 82 | 110 | 9% | 4% | 9% | 74 | 313 | 207 |
| A (2700 K, 0.000) | 2698 | -0.0001 | 9 | 74 | 116 | 15% | 9% | 16% | 60 | 305 | 207 |
| A (2700 K, 0.000) | 2697 | -0.0001 | 10 | 60 | 119 | 23% | 11% | 23% | 38 | 290 | 207 |
| B (2700 K, -0.007) | 2693 | -0.0069 | 1 | 81 | 91 | -14% | -10% | -18% | 77 | 328 | 208 |
| B (2700 K, -0.007) | 2699 | -0.0070 | 2 | 86 | 100 | -8% | -1% | -6% | 89 | 329 | 207 |
| B (2700 K, -0.007) | 2702 | -0.0071 | 3 | 90 | 100 | -5% | -3% | -6% | 92 | 321 | 208 |
| B (2700 K, -0.007) | 2697 | -0.0072 | 4 | 72 | 88 | -3% | -16% | -12% | 79 | 304 | 208 |
| B (2700 K, -0.007) | 2699 | -0.0068 | 5 | 91 | 102 | -1% | -3% | -2% | 91 | 315 | 208 |
| B (2700 K, -0.007) | 2707 | -0.0068 | 6 | 85 | 110 | -2% | 5% | 1% | 93 | 323 | 207 |
| B (2700 K, -0.007) | 2703 | -0.0069 | 7 | 82 | 100 | 4% | -6% | 0% | 82 | 306 | 207 |
| B (2700 K, -0.007) | 2707 | -0.0068 | 8 | 83 | 110 | 10% | 3% | 10% | 73 | 302 | 207 |
| B (2700 K, -0.007) | 2704 | -0.0069 | 9 | 74 | 116 | 15% | 6% | 14% | 60 | 294 | 206 |
| B (2700 K, -0.007) | 2699 | -0.0070 | 10 | 64 | 122 | 21% | 11% | 22% | 43 | 285 | 205 |
| C (3500 K, 0.000) | 3495 | -0.0002 | 1 | 83 | 91 | -15% | -11% | -14% | 80 | 334 | 207 |
| C (3500 K, 0.000) | 3512 | -0.0002 | 2 | 84 | 99 | -10% | 0% | -5% | 85 | 340 | 207 |
| C (3500 K, 0.000) | 3510 | -0.0001 | 3 | 92 | 100 | -5% | -3% | -3% | 95 | 327 | 206 |
| C (3500 K, 0.000) | 3511 | -0.0001 | 4 | 73 | 90 | 3% | -10% | -3% | 80 | 309 | 208 |
| C (3500 K, 0.000) | 3492 | -0.0003 | 5 | 92 | 102 | 1% | 0% | 2% | 94 | 325 | 206 |
| C (3500 K, 0.000) | 3509 | -0.0001 | 6 | 85 | 111 | 3% | 9% | 8% | 87 | 329 | 206 |
| C (3500 K, 0.000) | 3504 | -0.0001 | 7 | 84 | 101 | 7% | 0% | 5% | 83 | 314 | 205 |
| C (3500 K, 0.000) | 3511 | -0.0002 | 8 | 83 | 111 | 12% | 7% | 13% | 74 | 311 | 205 |
| C (3500 K, 0.000) | 3514 | 0.0000 | 9 | 74 | 117 | 17% | 10% | 17% | 62 | 303 | 206 |
| C (3500 K, 0.000) | 3508 | 0.0002 | 10 | 62 | 124 | 27% | 17% | 28% | 40 | 292 | 208 |
| D (4300 K, 0.000) | 4316 | 0.0001 | 1 | 82 | 90 | -14% | -10% | -12% | 82 | 325 | 207 |
| D (4300 K, 0.000) | 4286 | 0.0000 | 2 | 85 | 100 | -9% | 2% | -2% | 87 | 333 | 207 |
| D (4300 K, 0.000) | 4308 | 0.0000 | 3 | 90 | 99 | -7% | -2% | -4% | 92 | 325 | 207 |
| D (4300 K, 0.000) | 4287 | 0.0001 | 4 | 75 | 92 | 3% | -8% | -3% | 81 | 301 | 208 |
| D (4300 K, 0.000) | 4301 | 0.0000 | 5 | 92 | 101 | 0% | -1% | 0% | 94 | 312 | 208 |
| D (4300 K, 0.000) | 4298 | 0.0001 | 6 | 85 | 110 | 2% | 9% | 8% | 87 | 323 | 208 |
| D (4300 K, 0.000) | 4326 | 0.0003 | 7 | 82 | 100 | 7% | -1% | 5% | 83 | 302 | 207 |
| D (4300 K, 0.000) | 4317 | -0.0001 | 8 | 82 | 111 | 13% | 9% | 14% | 74 | 301 | 206 |
| D (4300 K, 0.000) | 4299 | 0.0000 | 9 | 75 | 116 | 18% | 11% | 18% | 63 | 294 | 207 |
| D (4300 K, 0.000) | 4298 | -0.0003 | 10 | 63 | 123 | 28% | 18% | 28% | 43 | 283 | 206 |
| E (4300 K, -0.007) | 4313 | -0.0071 | 1 | 82 | 91 | -12% | -9% | -12% | 82 | 312 | 208 |
| E (4300 K, -0.007) | 4300 | -0.0067 | 2 | 84 | 99 | -10% | 0% | -4% | 87 | 321 | 207 |
| E (4300 K, -0.007) | 4306 | -0.0070 | 3 | 92 | 101 | -6% | -2% | -3% | 93 | 309 | 208 |
| E (4300 K, -0.007) | 4311 | -0.0069 | 4 | 72 | 90 | 2% | -11% | -5% | 77 | 291 | 206 |
| E (4300 K, -0.007) | 4319 | -0.0070 | 5 | 92 | 101 | 0% | -1% | 0% | 92 | 302 | 207 |
| E (4300 K, -0.007) | 4277 | -0.0071 | 6 | 84 | 112 | 3% | 11% | 9% | 87 | 312 | 206 |
| E (4300 K, -0.007) | 4293 | -0.0074 | 7 | 83 | 101 | 6% | -2% | 3% | 81 | 292 | 208 |
| E (4300 K, -0.007) | 4324 | -0.0067 | 8 | 83 | 110 | 12% | 7% | 12% | 75 | 293 | 207 |
| E (4300 K, -0.007) | 4319 | -0.0070 | 9 | 75 | 116 | 18% | 10% | 17% | 63 | 285 | 207 |
| E (4300 K, -0.007) | 4281 | -0.0074 | 10 | 63 | 122 | 28% | 16% | 27% | 42 | 274 | 208 |

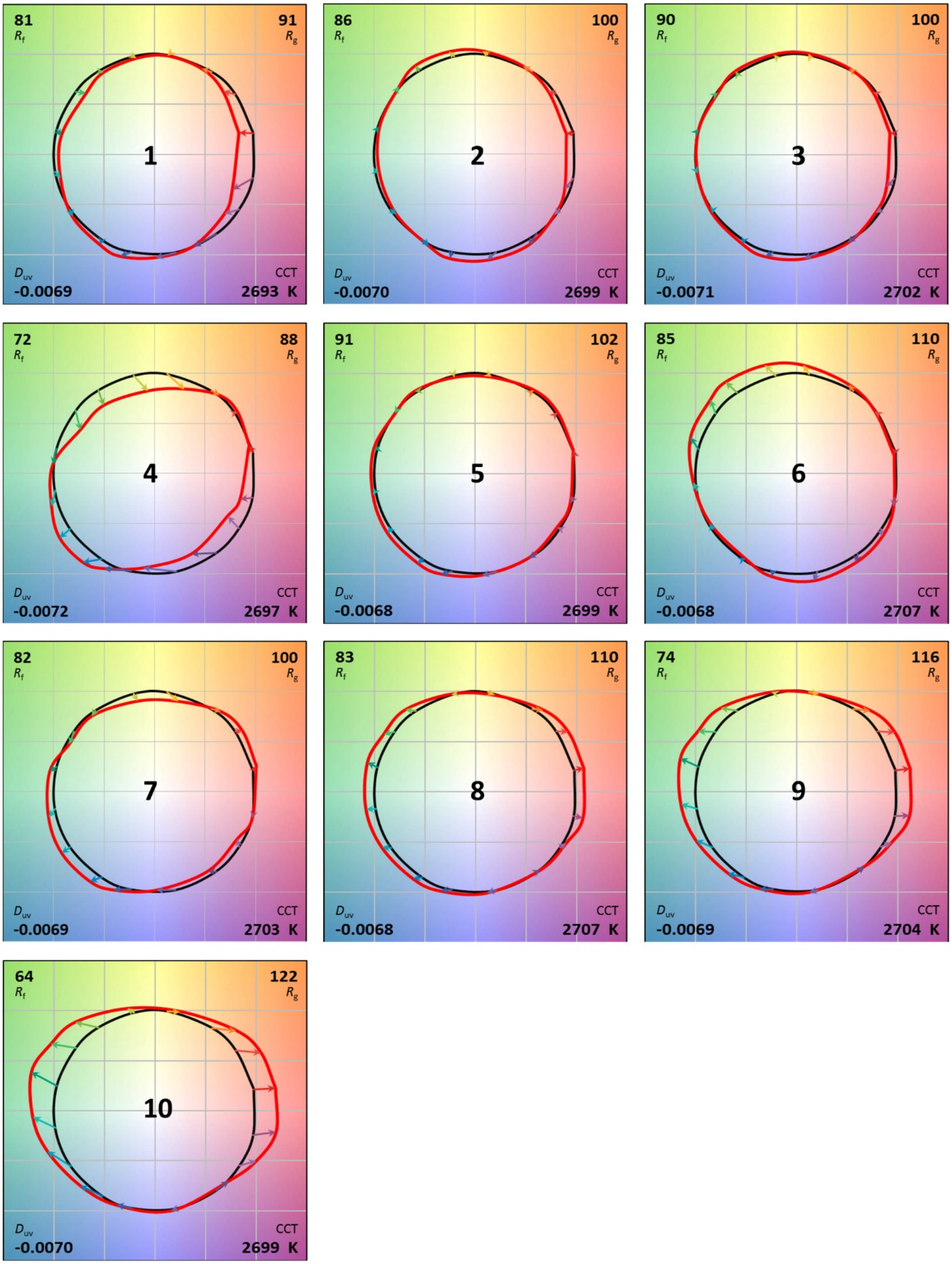


**Figure 2. IES TM-30-15 Color Vector Graphics for the 10 color rendition conditions in Group B.**

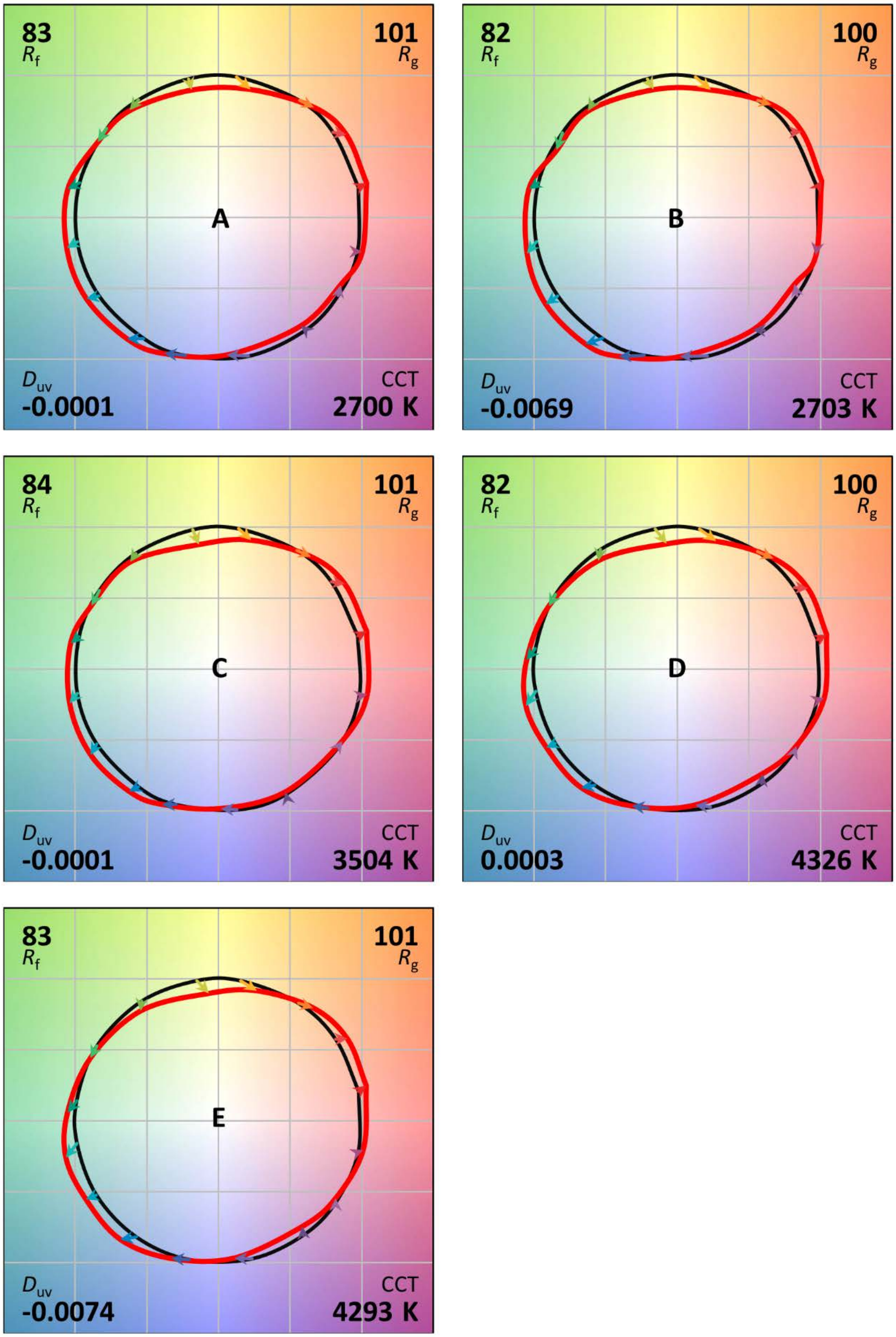


**Figure 3. IES TM-30-15 Color Vector Graphics for color rendition condition seven in each of the five chromaticity groups.**

in CCT was 87 K, and the maximum difference in $D_{uv}$ was 0.001. Note that some of the differences, particularly for chromaticity, may be due to slightly different positioning of the meter.

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 207 lux ± 2 lux across all 50 lighting scenes. The illuminance distribution throughout the room was consistent between lighting scenes, but was not perfectly uniform. Spot measurements revealed a vertical illuminance range from as low as 100 lux to as high as 400 lux, with a horizontal illuminance on the table of approximately 280 lux. Because the objects always remained in the same location, the illuminance on each object was nominally the same for each scene.

Although the 50 scenes represent a wide range of color rendition conditions, neither the IES TM-30-15 values nor the SPDs themselves are the true experimental independent variables, because the participants were viewing the interaction of the SPDs and the objects.[53] To ensure the appropriateness of the conclusions, custom average color fidelity and gamut area measures were calculated, based on the reflectance measurements of the experimental objects, and compared to standard IES TM-30-15 calculations. Due to the careful selection of the objects, the match was sufficient to justify using the IES TM-30-15 measures as a characterization of the visual stimulus. In other words, there was little difference between the custom and standard calculations, and no meaningful difference between subsequently developed regression models.

## 2.3 Participants

Thirty-four people participated in the experiment, 16 males and 18 females. None of their professions was related to lighting. Ages ranged from 20 to 69 years, with a mean of 35 years (32 years for men and 37 years for women). Before participating, each person completed a color vision test (Ishihara's Test for Colour Deficiency, 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, which is consistent with past findings.

## 2.4 Participant Ratings (Dependent measures)

For each lighting scene, participants completed a paper response form that had three semantic differential rating questions, each with an eight-point scale, and one choice question. The first two semantic differential questions requested 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, constituting a rating of preference. The multiple choice question required participants to choose whether they found the scene to be acceptable or unacceptable.

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 the same as CREX1, and similar to other studies on color preference,[3-5, 13, 19] in order to allow for comparisons based on the different methodologies.

## 2.5 Procedure

Upon arrival, participants sat in a daylit space with a researcher to review and sign the informed consent form and complete the Ishihara's Test for Colour Deficiency. Participants were provided with a white lab coat to wear during the experiment in order to minimize any effect of the color of the participants' clothing on their assessments. A general information questionnaire was also issued in order to collect demographic and lighting-knowledge information.

The participants were then led down a corridor and into a high-bay space housing the experiment room. The high-bay space was dark, except for spill light from the experiment room. The researcher and participants entered the experiment room, which was preset to scene C5. While the participants were seated at the table facing the long table of objects, the researcher provided instructions for several minutes, then showed the participants four scenes that demonstrated the range of color rendition conditions that would be experienced (scenes C1, C10, C7 and C5). A minimum of three minutes elapsed while the participants were in the room, allowing for sufficient chromatic adaptation,[54-57] although long-term color contrast adaptation artifacts cannot be completely accounted for in a short-term laboratory experiment. After concluding the instructions, the participants completed two practice trials, scenes C2 and C8. These trials were used to ensure comprehension of the task. The researcher answered any questions and ensured proper completion of the response forms.

Next, the participants were escorted through a vestibule and into the adaptation room. Doors on either side of the vestibule prevented the participants from ever being able to simultaneously view the lighting in the experimental and adaptation rooms. The lighting in the adaptation room was always set to the highest average color fidelity (IES $R_f$) possible at the chromaticity for the group to be subsequently viewed in the experimental room. For the initial period, the lighting in the adaptation space was always set to 3500 K with a 0.000 $D_{uv}$, since Group C was always viewed first in the experiment room.

After brief instructions, the participants completed a numerical verification task while sitting at the table. They had to find as many mismatched numbers as possible in three minutes on a white sheet of paper with black text. The primary purpose of the task was to direct participants' gaze to the same area of the adaptation room, and provide an activity during the adaptation period. The data were not tabulated or analyzed. There were no colored objects in the room. The horizontal illuminance on the table was approximately 230 lux.

After completing the numerical verification task, the participants were escorted back to the experimental room, where the lighting was set to the first scene. The first set of scenes to be viewed was always Group C, because it was a repeat of CREX1. It was also the neutral point among the three CCTs. The order of the other four chromaticity groups was randomized. The first trial, randomly chosen from the 10 color rendition conditions, was treated as a practice trial, and was intended to provide further chromatic adaptation and be a randomized precursor to the first recorded response. The subsequent 10 conditions were presented in random order. The light from the researcher's computer monitor was altered using the F.lux program to approximate the color appearance of the subsequently viewed scene, in order to prevent it from acting as a clue to the chromaticity of the experimental lighting—even though it was outside the experiment room, it was visible to the participants along with spill light from the room when they returned from the adaptation space. No other light sources were visible to the participants at any time.

For each lighting scene, participants were instructed to enter the experiment 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 into the dark high-bay space and handed their forms to the researcher. After the researcher changed the lighting condition to the next setting, participants re-entered the room and repeated the process. The total time outside the room was typically less than 10 seconds. After viewing all 10 conditions in a given chromaticity group, the participants were escorted back to the adaptation room, which was set to match the chromaticity of the upcoming chromaticity group viewed in the experiment room. That is, participants always performed the adaptation procedure prior to the experimental procedure for a given chromaticity group, thus alternating rooms throughout the experiment. After first viewing Group C, the order of presentation for the remaining four chromaticity groups was randomized.

After the final experimental trial, the researcher set the lighting scene back to color rendition condition 5 of the last chromaticity group, and the participants entered the room to complete the concluding summary questionnaire. Each experimental session required a total of about 90 minutes. All except one session included two participants who made evaluations simultaneously. Participants were instructed not to communicate with each other while in the experiment and adaptation rooms.

# 3 Results

For each of the four perceptions evaluated (normalness, saturation, preference, acceptability), hypothesis testing was carried out in multiple stages. First, ANOVA was conducted using chromaticity group (five levels), color rendition condition (ten levels), and participant (34 levels). For each of the four perceptions, all three variables reached statistical significance ($\alpha < 0.05$), with $p < 0.001$ for all cases except chromaticity group for acceptability ($p = 0.011$). Thus, it can be concluded that color quality perceptions vary with chromaticity, rejecting the null hypotheses. Additional comparisons revealed that specific differences in the chromaticity groups led to the significant effects for the four studied perceptions. This more nuanced analysis is the focus of this article, with emphasis (for brevity) on preference ratings.

More detailed models comprising only the data for Groups A, B, D, and E were created based on mean responses for each color rendition condition (ten levels), and using nominal CCT (2 levels) and $D_{uv}$ (2 levels) as factors instead of chromaticity group. The mean data is useful because it eliminates individual differences and further counterbalances short-term memory effects arising from the order of presentation. This subset of data enabled investigation of the interaction of CCT and $D_{uv}$—Group C was excluded because only one $D_{uv}$ level was presented. The results revealed that the significant differences in chromaticity groups for the four perceptual attributes stemmed from different characteristics. For normalness, preference, and acceptability, $D_{uv}$ ($p = 0.008$, $p = 0.004$, and $p = 0.033$, respectively) and the interaction of $D_{uv}$ and CCT ($p = 0.003$, $p = 0.004$, and $p = 0.045$, respectively) were significant factors. In contrast, CCT was a significant factor ($p < 0.001$) for perceived saturation, while $D_{uv}$ and the interaction of CCT and $D_{uv}$ were not. Notably, the 2700 K conditions were rated as more saturated, on average, despite having lower average values for red chroma shift (IES $R_{cs,h1}$ IES $R_{cs,h16}$, or IES $R_{cs,h15}$). It is worth noting that in all cases, color rendition condition had a stronger effect on the perceived color quality than either CCT or $D_{uv}$; it was always significant with $p < 0.001$.

The simple interpretation from a visual examination of **Figures 4 through 7**, which show mean data for each color rendition condition and for each chromaticity group, is that $D_{uv}$ has an effect on perceived normalness and preference at lower CCTs (2700 K), with negative $D_{uv}$ values being perceived as more normal and more preferred. The effect of $D_{uv}$ is negligible at 4300 K. The exact transition between 2700 K and 4300 K is unclear; further experimentation at intermediate chromaticities is planned. In addition, 2700 K was perceived as more saturated than 3500 K or 4300 K, with little difference due to $D_{uv}$; the differences in rating were remarkably consistent across all 10 color rendition conditions **(Figure 8)**. Visual analysis also shows that the patterns for color rendition condition were fairly consistent across the five chromaticity groups. While chromaticity played a role, color rendition played a much stronger role in this experiment, where participants were chromatically adapted to each chromaticity prior to judging multiple color rendition conditions.

With the more extensive set of color rendition conditions in CREX1, red chroma shift (specifically IES $R_{cs,h16}$) was the best single-measure predictor of preference ($r^2 = 0.81$), saturation ($r^2 = 0.95$), and normalness ($r^2 = 0.53$), performing better than IES $R_f$, IES $R_g$, CIE $R_a$, Gamut Area Index (GAI),[26] Color Quality Scale (CQS),[37] Memory Color Rendering Index (MCRI),[31, 32, 58] or Feelings of Contrast Index (FCI).[59, 60] Similar levels of fit were found for this experiment when considering the five chromaticity groups independently; the coefficient of determination ($r^2$) for preference versus IES $R_{cs,h16}$ ranged from 0.65 to 0.86 (**Figure 9**). On average, slightly better correlation was found with IES $R_{cs,h15}$ for this experiment—mean $r^2$ values across groups of 0.81 versus 0.75 (Note that the range of IES $R_{cs,h15}$ values was smaller than that for IES $R_{cs,h16}$.) **Figure 9** also illustrates key differences in preferences across the chromaticity groups, with the 2700 K conditions being rated less preferred with large increases in red chroma. In part due to this difference and in

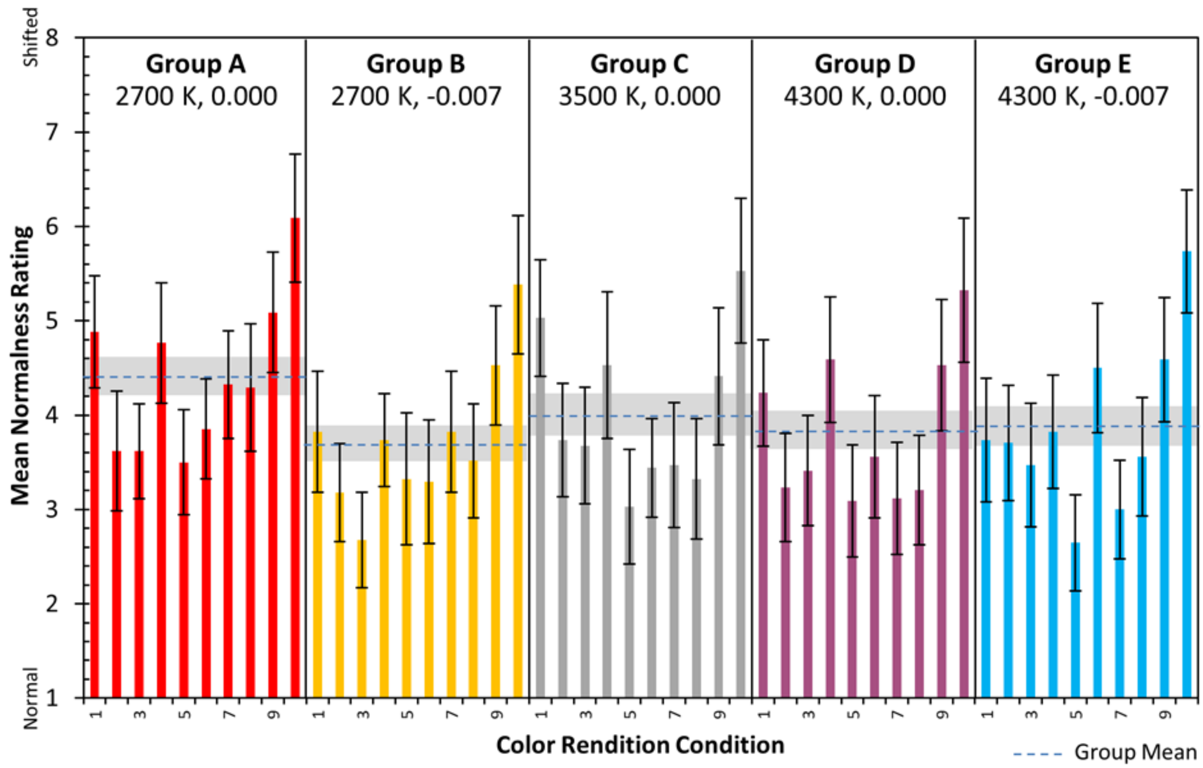


**Figure 4.** **Mean normalness ratings for each of the color rendition conditions, and the mean normalness ratings for all conditions in each chromaticity group. Error bars and gray shaded areas show 95% confidence intervals for the individual condition means and group means, respectively. Lower values indicate higher rated normalness.**

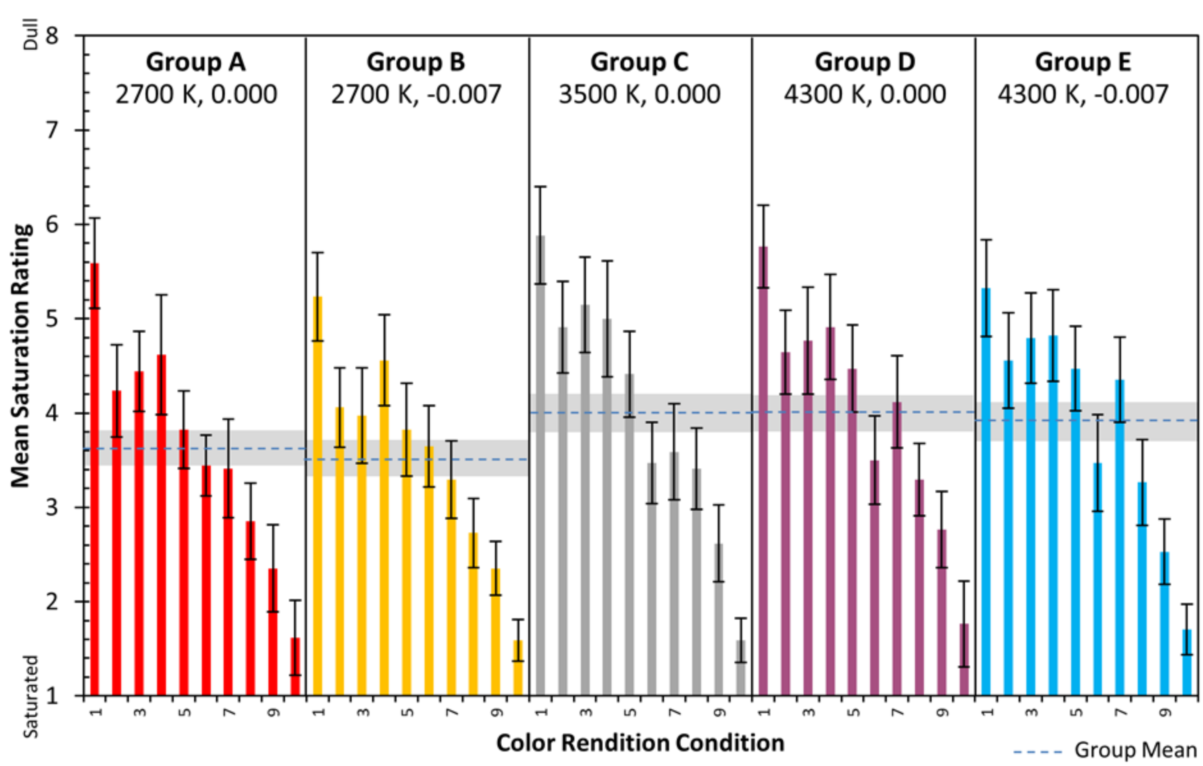


**Figure 5.** **Mean saturation ratings for each of the color rendition conditions, and the mean saturation ratings for all conditions in each chromaticity group. Error bars and gray shaded areas show 95% confidence intervals for the individual condition means and group means, respectively. Lower values indicate higher rated saturation.**

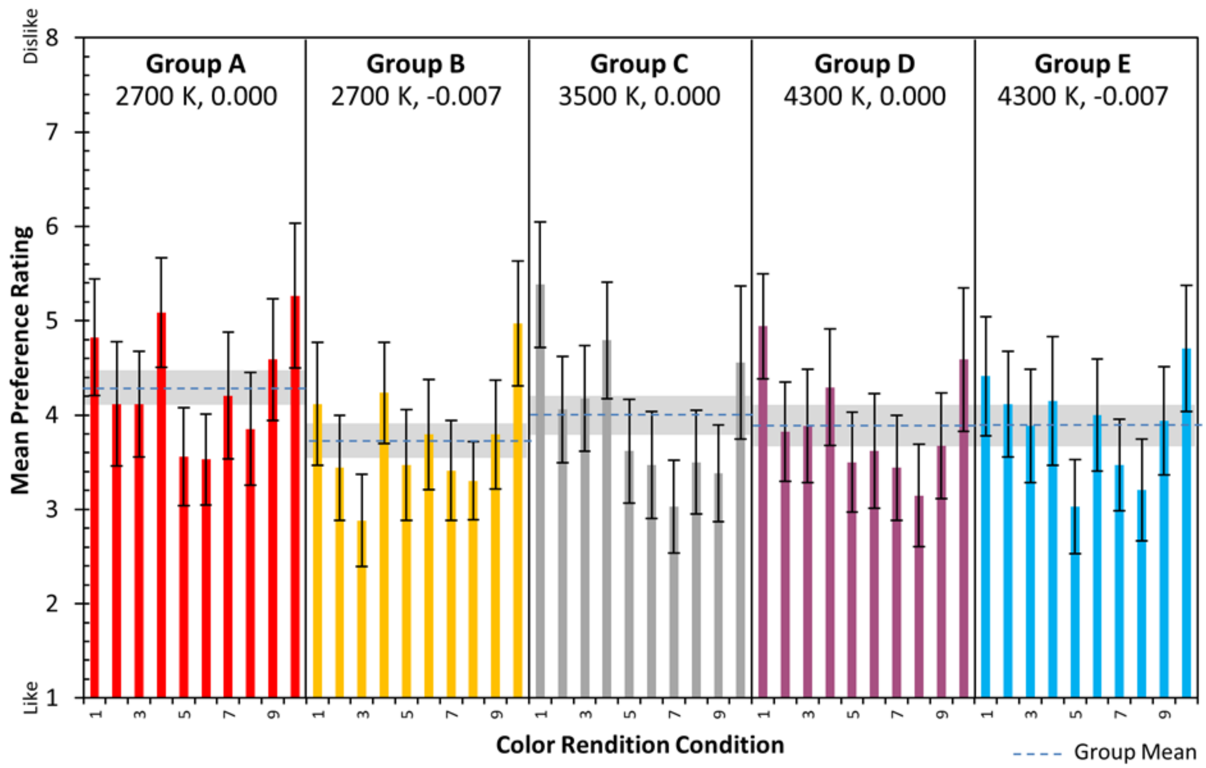


**Figure 6.** Mean preference ratings for each of the color rendition conditions, and the mean preference ratings for all conditions in each chromaticity group. Error bars and gray shaded areas show 95% confidence intervals for the individual condition means and group means, respectively. Lower values indicate higher rated preference.

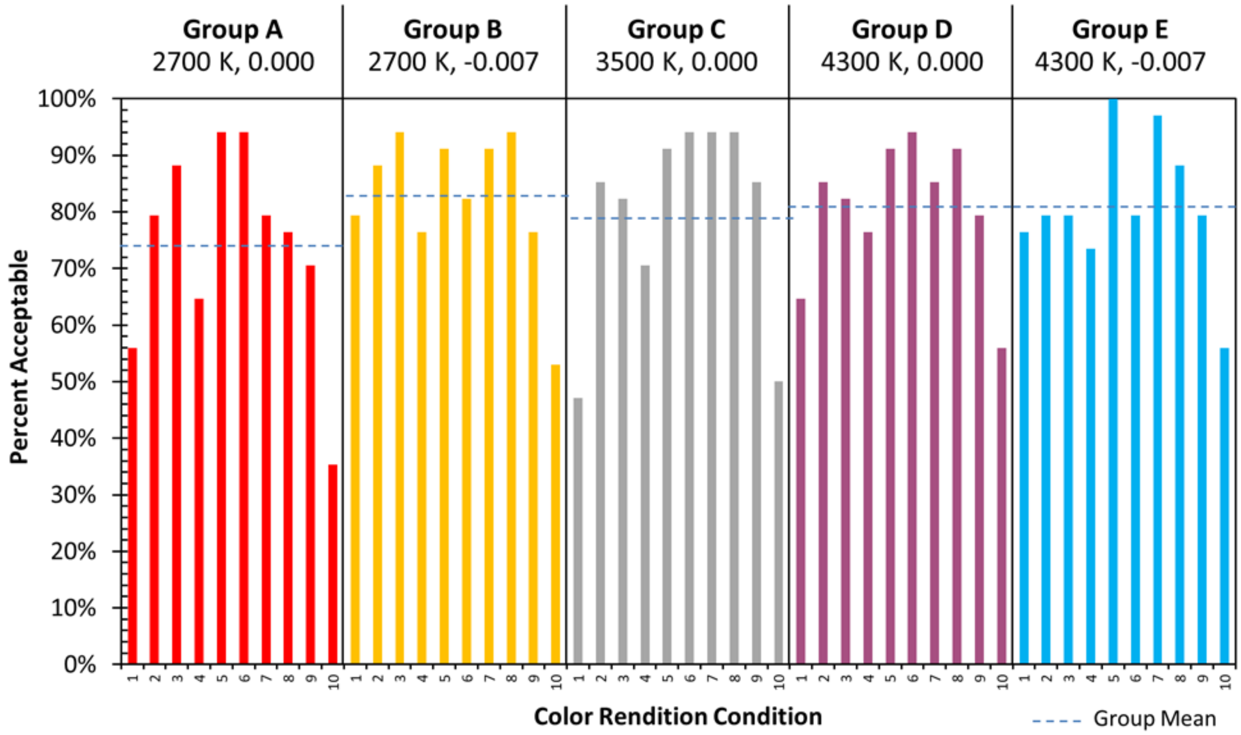


**Figure 7.** Percent acceptable for each of the color rendition conditions, and mean percent acceptable for all conditions in each chromaticity group.

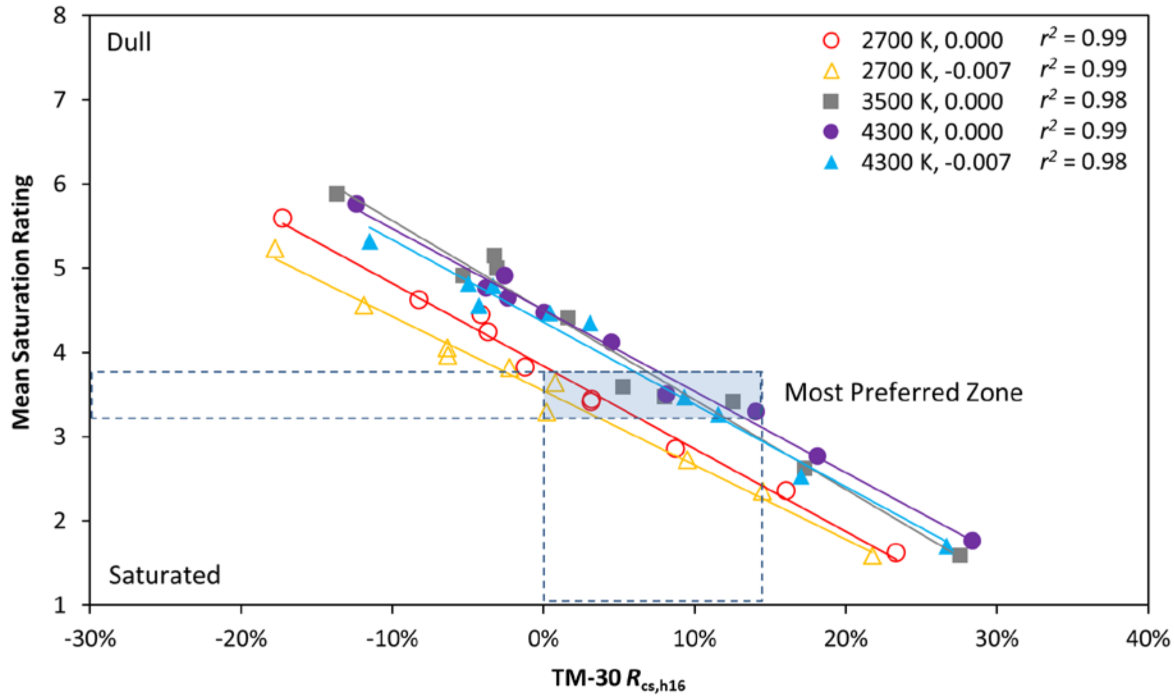


**Figure 8. Mean saturation rating versus IES $R_{cs,h16}$. The same offset for the 2700 K conditions occurs with IES $R_g$ as the independent variable, although the correlations are weaker. The most preferred zone is derived from Figure 10.**

part due to less exhaustive sampling of the combinations of average color fidelity, gamut area, and gamut shape, the correlation between preference and $R_{cs,h16}$ for the overall dataset ($r^2$ =0.43) was not as high as for CREX1.

The fits and factors were also similar to CREX1 for saturation and normalness. IES $R_{cs,h16}$ was a very strong predictor of saturation ($r^2 \geq 0.98$ for all five groups individually, $r^2 = 0.87$ overall). Normalness was reasonably correlated with red chroma shift (IES $R_{cs,h16}$) or average color fidelity (IES $R_f$), with the most normal ratings occurring when reds are neither over- or under-saturated compared to the reference. The fit for average color fidelity (IES $R_f$) was best for normalness of Group A ($r^2 = 0.90$), and the worst for normalness of Group C ($r^2 = 0.64$). This may suggest a potential memory or nostalgia effect related to incandescent lighting, which is similar to the chromaticity of Group A. In all cases, the fits for average color fidelity (IES $R_f$) versus normalness (and preference) were higher than for CREX1, which included a greater variety of distortions at any given average color fidelity level. This illustrates how evaluating a small number of SPDs can potentially lead to misleading correlations between average measures and perceptual attributes.

Understanding the evidence in **Figure 8** that the 2700 K groups were perceived as more saturated at the same IES $R_{cs,h16}$ (and IES $R_g$, not shown) values, it is also understandable that preference is a slightly better and more consistent fit with *rated* saturation (**Figure 10**) than with characterized saturation (IES $R_{cs,h16}$, IES $R_{cs,h1}$, or IES $R_g$). Likewise, **Figure 10** shows the relationship between saturation and normalness, with maximum normalness at slightly less saturated ratings than maximum preference. Thus, the data supports a preferred level of perceived saturation and a level of saturation perceived as normal, but also suggests a possible limitation in the CAM02-UCS model that underlies IES TM-30-15, because equal characterizations of saturation (relative to a reference at the same CCT) lead to different perceptions of saturation.

Following with the results shown in **Figures 8-10**, **Figure 11** illustrates that the preference model developed in CREX1 has varying levels of fit with the different chromaticity groups. It has excellent fits for Group C (a

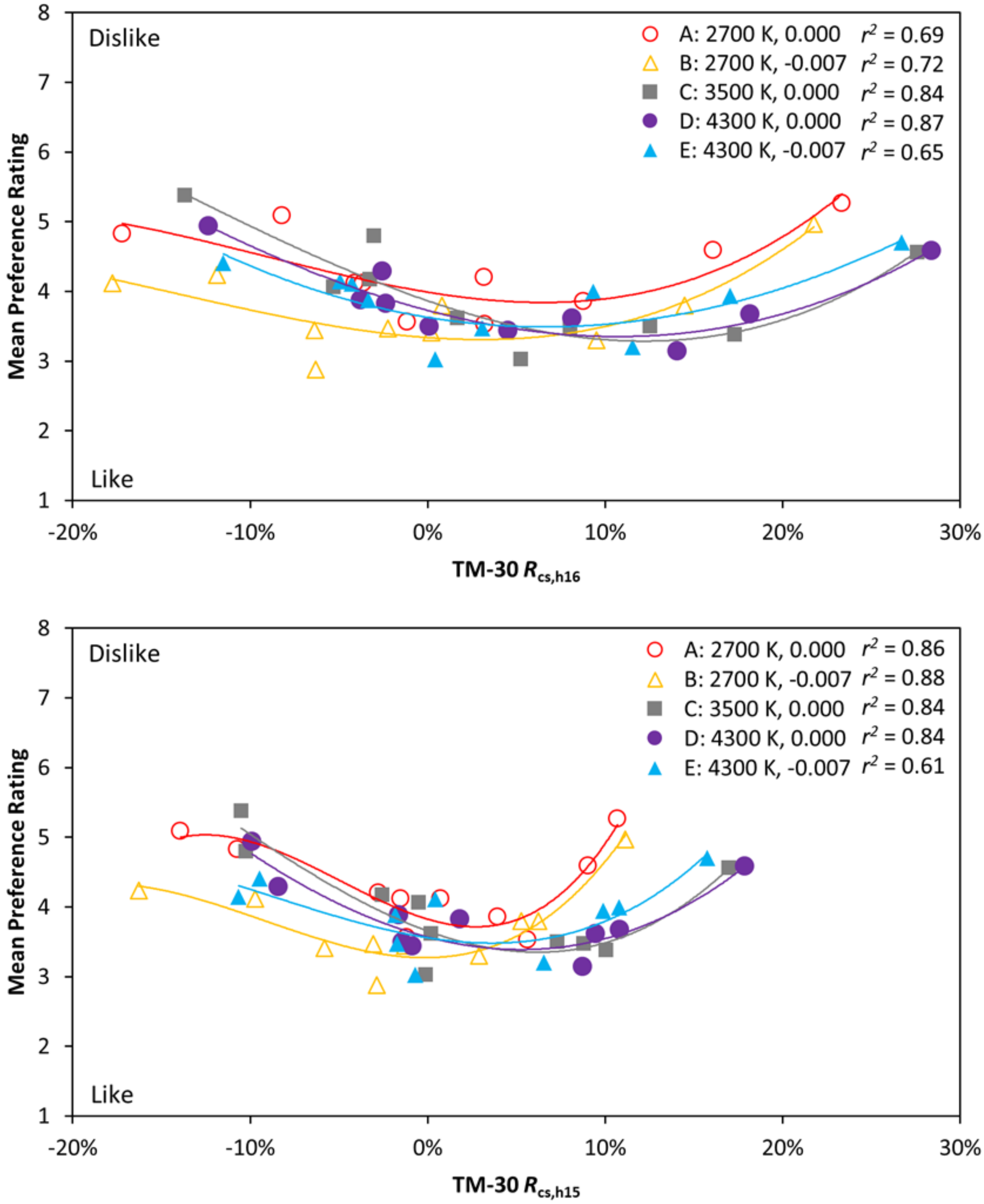


**Figure 9. Mean preference rating for each condition versus IES $R_{cs,h16}$ (top) and IES $R_{cs,h15}$ (bottom).**

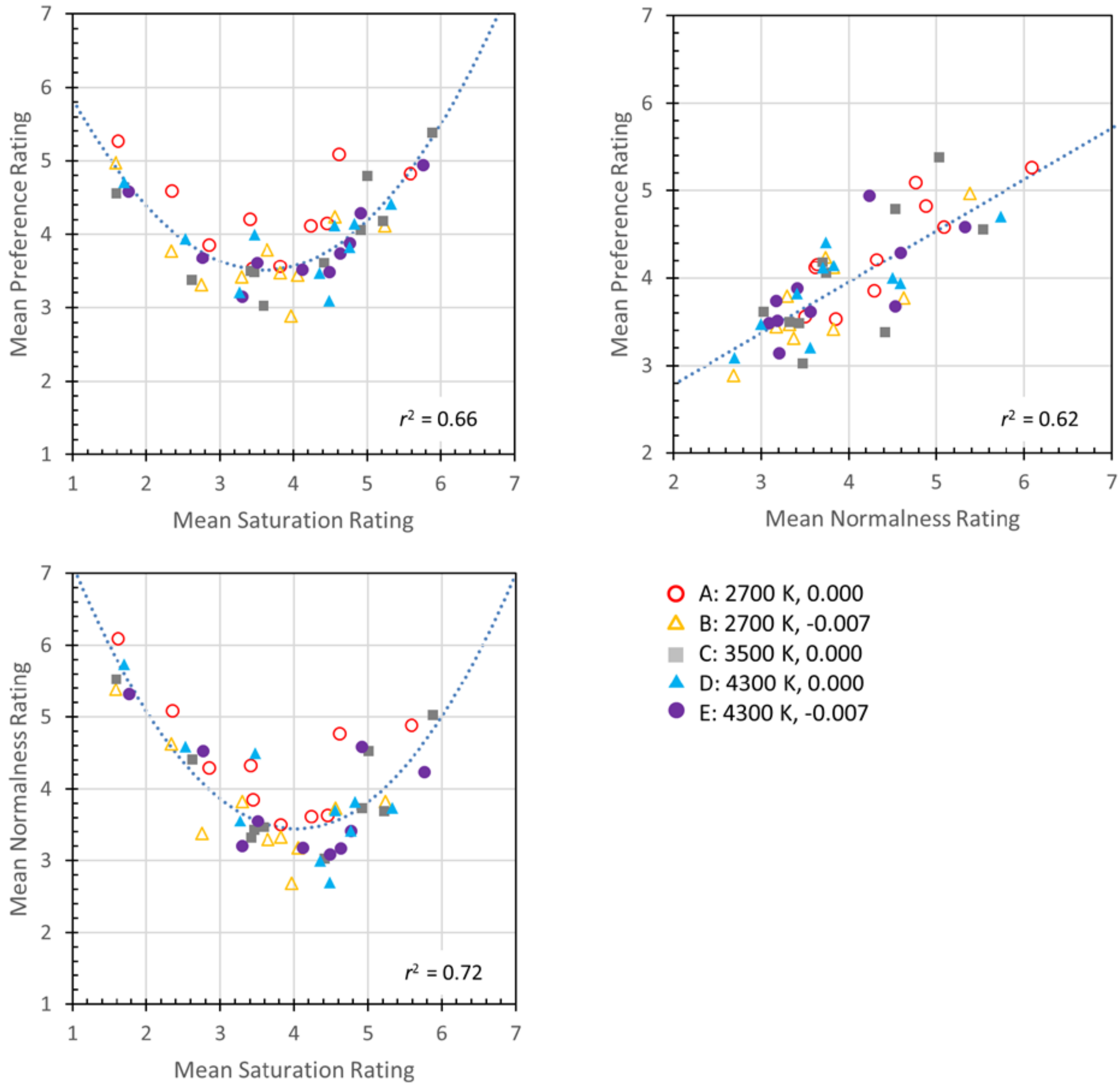


**Figure 10. Relationships between mean rated perceptions, with coefficients of determination for the entire dataset.**

subset of the conditions under which it was developed) and Group D. It has much poorer fits for Groups A, B, and E. It is important to note, however, that the weakness does not necessarily stem from other measures of color rendition being more important at these different chromaticities. Rather, it is the preferred levels of each factor that change. Simply, less increase in red chroma is preferred at 2700 K.

**Figure 12** illustrates the average $r^2$ value across the five chromaticity groups for 36 different regression models. The best models, in terms of $r^2$, remain IES $R_f$ paired with a measure of red chroma shift (e.g., IES $R_{cs,h16}$). An excellent model of preference for each group (average $r^2$ = 0.95, range 0.89 to 0.99) can be created by including all three of TM-30's key measure types (IES $R_f$, IES $R_g$, and IES $R_{cs,h16}$). Note that all factors in this regression model are not statistically significant; it might be considered over-fit, but including all key measures could help prevent inappropriate optimizations in the future. If the entire dataset is modelled together, $r^2$ for this set of factors is 0.61, implying moderate correlation. Only small gains can be made by adding CCT and $D_{uv}$ to this model, increasing $r^2$ to 0.67. No other set of measures were found to be better, including measures outside IES TM-30-15.

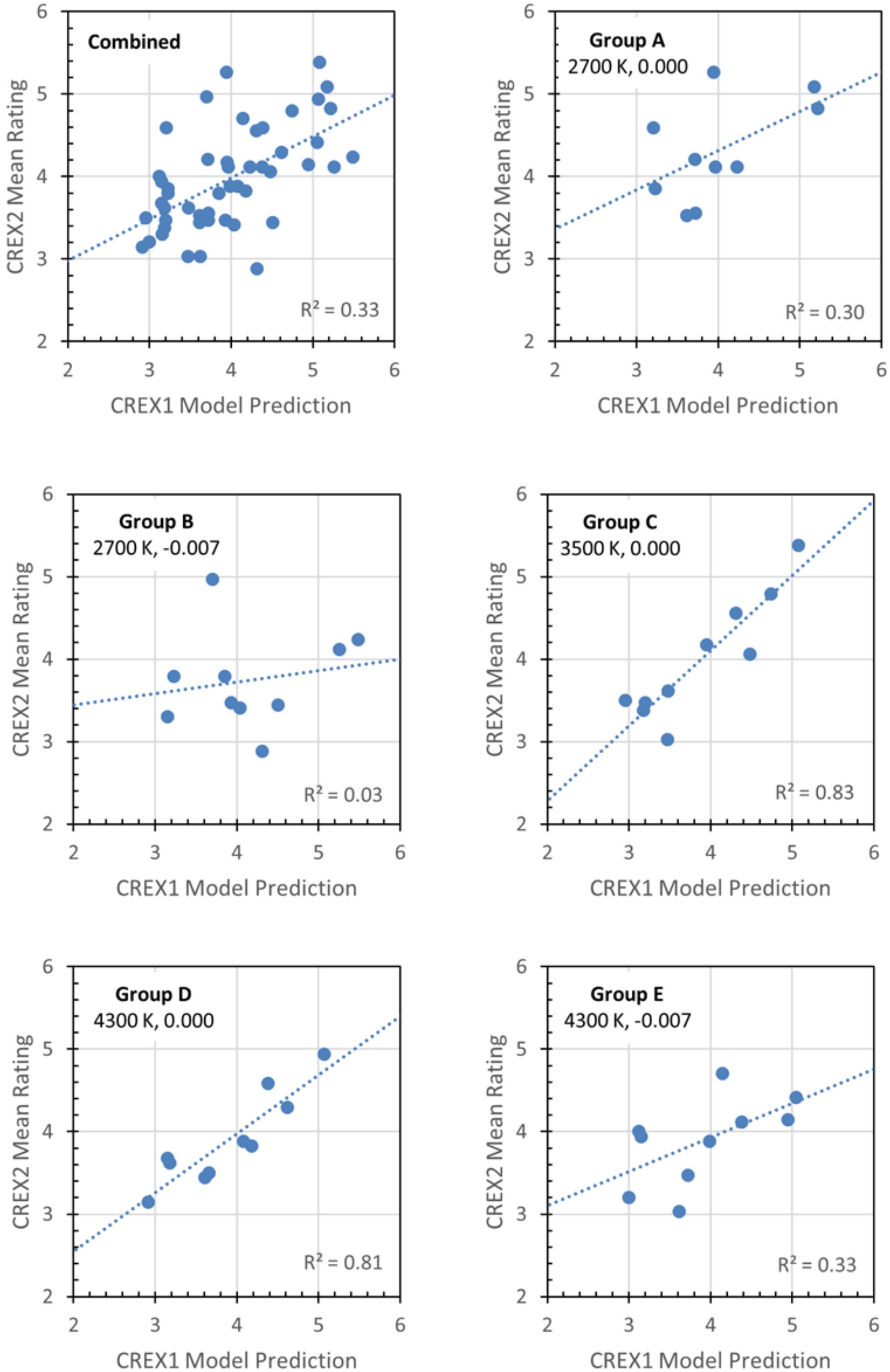


**Figure 11. Mean preference ratings versus predicted preference rating using the CREX1 model.**

**Order Effects and Individual Data**

Analysis of individual data shows that the ratings for almost every condition varied across the entire scale for all questions. This is due to individual differences, but the viewing order—specifically the immediately preceding condition—may also have contributed. The difference in IES $R_{cs,h16}$ between the current and previous condition was divided into four groups with boundaries at -10%, 0% and 10%. When analyzed as a factor in an ANOVA that also included participant (34 levels), color rendition condition (10 levels), and chromaticity group (5 levels), the p-value was 0.119, which is outside the a priori significance level.

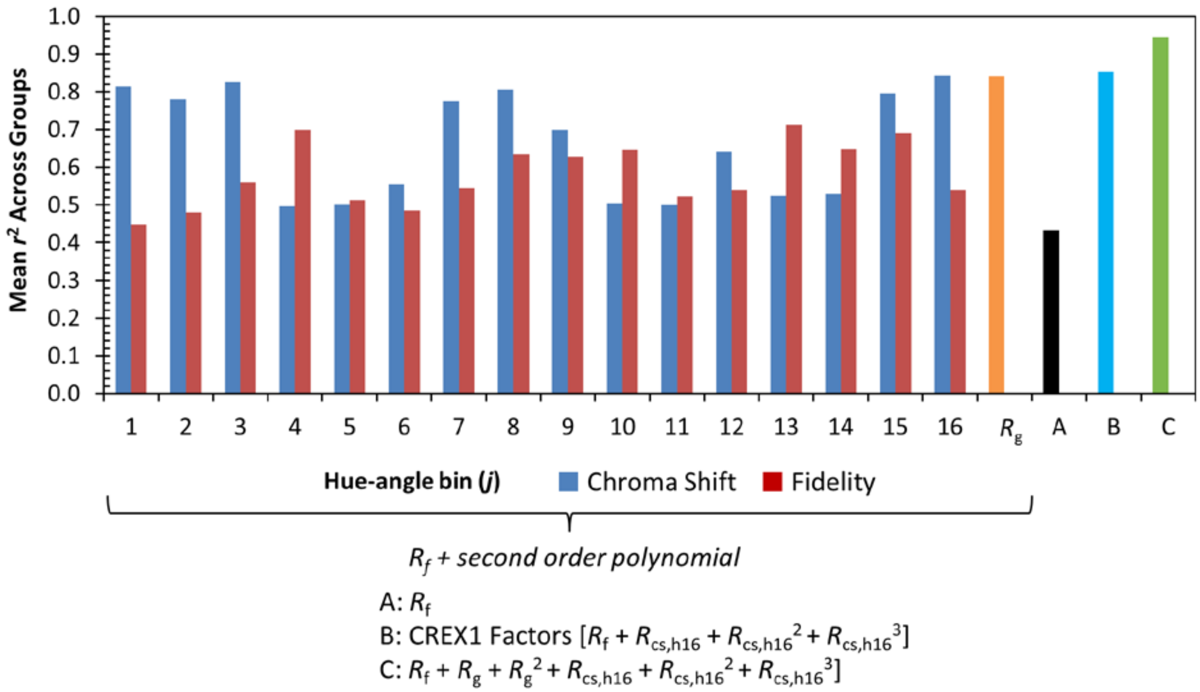


**Figure 12. Mean coefficient of determination for 36 different regression models over the five chromaticity groups.**

# 4 Discussion

## 4.1 Influential Objects and Hues

Some data from the final questionnaire are presented in **Figures 13 and 14**. The same questionnaire was used with CREX1, and the trends are similar, but with some important differences. Most notably, consumer goods became the clear choice as the most influential object group, changing from 29% to 53% of responses. At the same time, the natural objects went from the most influential to the third most influential object group. Although most of the objects were the same (with new fresh food and flowers), the presentation was slightly different. The consumer goods were displayed on one shelf instead of two, with a black tablecloth instead of wire shelves.

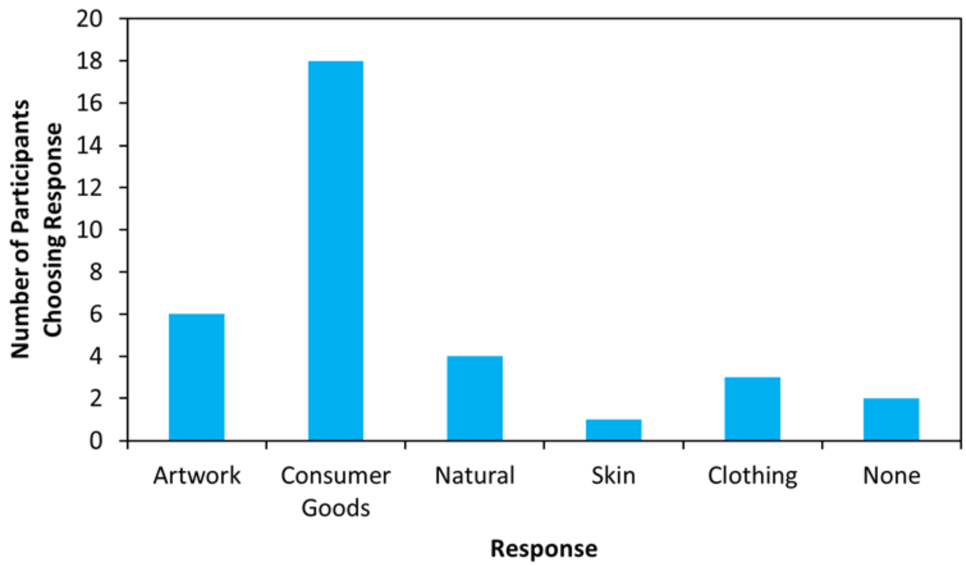


**Figure 14. Responses to the post-experiment question:** ***Which group of objects, if any, influenced your overall opinion of each condition the most?***

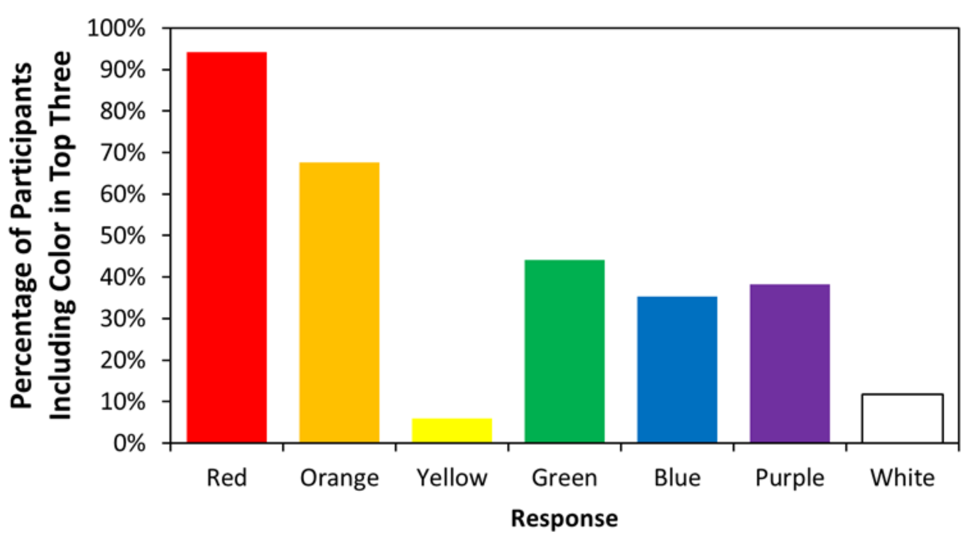


**Figure 13. Percentage of participants for which a color was ranked in the top three based on having the most influence on the participant's judgements.**

This may have contributed to 27 of 34 observers mentioning the box of Coke as one of the top three most influential objects, which in turn may have contributed to the fact that 32 of 34 participants ranked red as one of the three most influential colors. For CREX1, the consumer goods and natural objects were directly in front of the participants when entering the room, whereas for this experiment the participants entered at the corners of the room. Red and the Coke box were still very influential in CREX1, however.

Because of its notability, the chroma of the Coke was investigated as a potential explanatory factor in the preference ratings, with the hypothesis that there may be an ideal level of saturation for the Coke that is related to memory of the familiar color. The chroma of the Coke box had lower correlation with rated preference than IES $R_{cs,h16}$, however, which indicates broader consideration of the objects in the room.

## 4.2 Average Color Fidelity, Gamut Area, and Gamut Shape

Confirming earlier findings, this study further documents that average color fidelity alone is insufficient for identifying acceptable or preferred light sources, which tend to reduce average color fidelity by increasing red chroma. The average rank of the two color rendition conditions with $R_f > 90$ was second for condition 5 and fifth for condition 3 (out of ten)—condition 5 slightly increased red chroma, whereas condition 3 slightly decreased red chroma. The lack of correlation between IES $R_f$ (alone) and preference is not a limitation of IES $R_f$, but is inherent to any measure of average color fidelity. CIE $R_a$, used alone or in combination with other measures, performed substantially worse than IES $R_f$, as it also did in CREX1, due to its specific faults as a measure of average color fidelity.

While supplementing average color fidelity with gamut area offers some improvement in the fit of predictive models or criteria, it was shown to be insufficient for differentiating between lighting conditions that were found to have statistically different mean ratings for preference in CREX1. In this experiment, the equal-fidelity (IES $R_f$), equal-gamut area (IES $R_g$) pairs had different values than in CREX1—most notably higher IES $R_f$ values—which results in less difference in gamut shape. Differences in ratings of preference for any of the three such pairs included in this study did not reach statistical significance—collectively or for any individual group. When analyzed collectively, the SPD in the pair with greater red saturation was always preferred. At the same time, there were some statistically significant differences for saturation ratings. In general, the variance was lower for saturation ratings than preference ratings.

Gamut shape proved to be an important characteristic, which is consistent with CREX1 and other recent findings.[3, 5, 6, 8] Taken as individual groups or as a combined set, the best-fit models revealed that the combination of IES $R_f$ and IES $R_{cs,h16}$ (a proxy for gamut shape) provided a very good model of average preference. IES $R_g$ can be added to further constrain the solution and slightly improve the model fit. Similar results can be found for normalness, with a greater contribution from IES $R_f$. IES $R_{cs,h16}$ alone was the best predictor of perceived saturation. In all cases, the influence of chromaticity on perceptions weakens the models' fit to the whole 50-scene dataset, compared to models for any of the five chromaticity groups, because the optimum level for each variable changes with chromaticity.

**Other Measures of Preference**

A few other measures still receive some attention as possible correlates for preference, either alone or in combination, often despite substantial evidence that they are sometimes or always ineffective. These include the Memory Color Rendering Index ($R_m$), GAI, and FCI. As shown in **Figure 15**, $R_m$ and GAI have very poor correlation with the combined dataset. GAI is a reasonable predictor for each individual chromaticity group, performing similarly to IES $R_g$ on a per-group basis, but falls short overall because it has a strong dependence on CCT due to the use of a fixed reference illuminant and non-uniform color space. $R_m$ also has some inherent CCT-dependence that is unsupported by this data, and is not a good fit for the data even

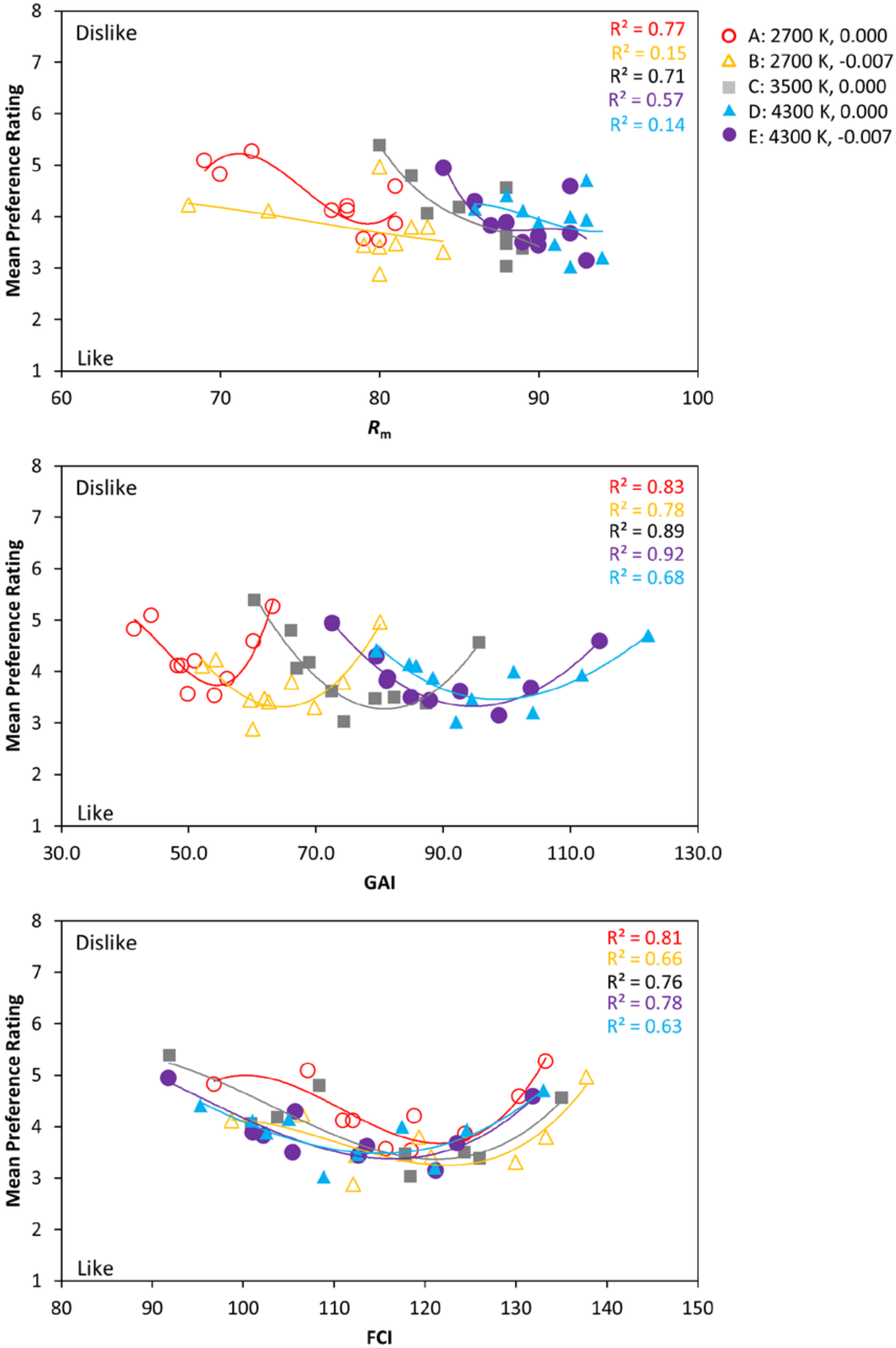


**Figure 15. Mean preference rating versus three previously-developed preference measures.**

when specific groups are isolated. Of the three measures considered, FCI is the best, performing similarly to IES $R_g$. What is not captured with this dataset—which was specifically designed to stress IES $R_f$ and IES $R_g$—is that average values (or pairs of average values) cannot capture gamut shape, which is a key determinant of perceptions.

## 4.3 The Role of Chromaticity

When contemplating the role of chromaticity in color rendition, two key concepts must be understood: reference illuminants and chromatic adaptation. First, most measures of color rendition are based on a relative reference illuminant, including TM-30.[61] That is, every test source is compared to a continuous-spectrum reference illuminant at the same CCT—but not necessarily at the same $D_{uv}$. In this experiment—and any other exploring multiple color rendition conditions at the same CCT—all light sources with the same CCT are compared against a common reference illuminant, regardless of $D_{uv}$. Yet there are observable differences in the SPDs of the on-Planckian and off-Planckian light sources.

As illustrated in **Figure 16,** SPDs from this experiment with a negative $D_{uv}$ at 2700 K have proportionally more blue energy (provided by the LEDs with 447 nm and/or 470 nm peak wavelengths). Adding red energy (provided by the LED with a 633 nm peak), may also help move the chromaticity toward a negative $D_{uv}$, to a lesser extent. At the same time, adding these proportionally greater very short and very long wavelength components tends to increase chroma, particularly for reds. Because IES $R_f$ and IES $R_g$ were set equally for both the on-Planckian scenes and off-Planckian scenes, other tradeoffs were necessary. One possibility is

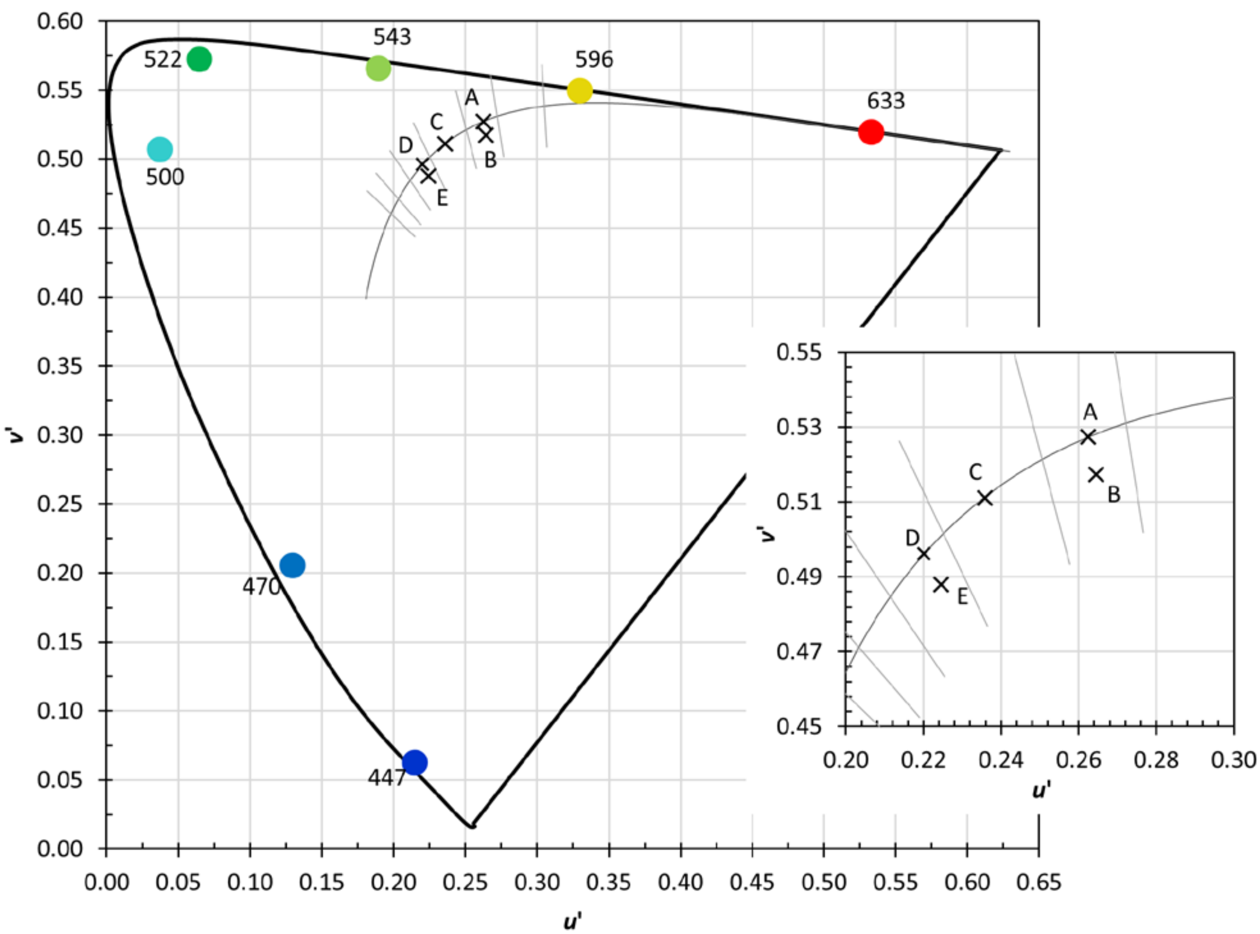


**Figure 16. Chromaticity targets and chromaticity of each primary in the ETC Source 4 Series 2 Lustr.**

trading off green and red for more amber. Trying to evaluate SPDs directly makes it clear why color rendition measures are necessary, as there are many combinations of the seven LED channels that can create the same chromaticity.

Importantly, for the 4300 K conditions, the iso-CCT line is oriented somewhat differently due to the curve of the Planckian locus, and lowering the $D_{uv}$ requires proportionally different additions of the nominally blue and red LEDs than at 2700 K. It is possible that this contributed to the differences in perception attributed to negative $D_{uv}$ conditions at 4300 K and 2700 K. Both CCT and $D_{uv}$ are numerical constructs that are not derived from perceptual experiments.

This leads directly to the second consideration, chromatic adaptation. The human eye-brain system is able to adapt to a wide range of lighting conditions, enabling a degree of color constancy by detecting the color of the illumination. Sophisticated models of chromatic adaptation[62] have been developed and are employed in the colorimetric calculations that underlie IES TM-30-15. Limitations in our adaptation ability are what enables color rendition to be varied; that is, our broadband photoreceptor system can adapt to gross differences in the balance of energy across the visible spectrum, but cannot adjust sensitivity on a wavelength-by-wavelength basis.

Great effort was made to ensure chromatic adaptation of the observers to each chromaticity group for this experiment. Nonetheless, the 2700 K lighting conditions were rated as producing more saturated object colors, despite having approximately the same IES TM-30-15 ratings. The resulting preference ratings were also different. This may imply a weakness in the CIECAM02 color appearance model that is part of IES TM-30-15, in which the model predicts an ability to chromatically adapt over a wider range of conditions than was possible for the participants in this experiment. Given the analysis finding the correlation between the real objects and the 99 IES TM-30-15 color evaluation samples (CES), as well as the investigation of chroma for the Coke box, there is no evidence that the IES TM-30-15 CES or calculations themselves contribute to this discrepancy.

Another related set of considerations is the roles of color memory, nostalgia, and long-term adaptation. 2700 K is the predominant color temperature for residential lighting in the United States. The participants likely had incandescent, compact fluorescent, or phosphor-coated white LEDs in their homes, none of which increase red chroma—the latter two typically decrease red chroma and increase yellow-green chroma. This may contribute to the reduced preference for increased red chroma at that CCT, but does not explain the greater preference for negative $D_{uv}$ lighting conditions at that CCT.

A key takeaway from this experiment is that using current models of human vision, specific models for color preference can vary with chromaticity. Neither CCT nor $D_{uv}$ alone are significant factors in the difference; rather, there was an interactive effect, where $D_{uv}$ had a significant effect on mean preference rating at 2700 K, but no effect at 4300 K. Thus, including $D_{uv}$ (regardless of CCT) in a composite measure of color quality, as has been proposed by Vick and Allen,[47] is not advisable. This effect is consistent with some previous research findings. For example, Rea and Freyssinier found that $D_{uv}$-based perceptions of neutral white varied with CCT,[43] and Wang and Wei found the same for color preference of illuminated objects.[45] It's possible that a significant effect from $D_{uv}$ only arises at lower CCTs (e.g., 2700 K), where it is possible that the limits of human chromatic adaptation are being approached. Additional research will be needed to refine the relationship at other CCTs. Still, adding both CCT and $D_{uv}$ to models of color preference offered little improvement in the predictive power of those models, because differences in perception were most strongly influenced by color rendition.

## 4.4 Specification Criteria

The lighting industry has typically relied upon specification criteria to identify preferable (or acceptable) products. This approach has notable advantages over trying to identify an exact preference (or other perception) model; it provides more flexibility over different applications and does not imply an optimum, which is generally irrelevant given the consistent need to trade off color quality with other characteristics, such as energy efficiency. Set appropriately, specification criteria can ensure acceptability while promoting innovation.

The inclusion of a question on acceptability in this study helped to facilitate development of specification criteria. A criteria set of IES $R_f \geq 75$, IES $R_g \geq 100$, and $-1\% \leq$ IES $R_{cs,h1} \leq 15\%$ is successful in isolating the four color rendition conditions that had the highest acceptability ratings (≥ 89%), as well as the best preference ratings. This is illustrated in **Figure 17**. These criteria are very similar to criteria that were suggested following CREX1. By relaxing the criteria to IES $R_f \geq 75$, IES $R_g \geq 98$, and $-7\% \leq$ IES $R_{cs,h1} \leq 15\%$, two additional color rendition conditions (2 and 3) with acceptability ratings of 84% and 85% can be included. The next highest rated color rendition condition (9) for acceptability was at 79%—although it had higher mean preference rating than condition 2. It fails based on the IES $R_f$ criterion in all chromaticity groups, and the IES $R_{cs,h1}$ condition in four of the five groups.

## 4.5 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. Only one illuminance level was used; due to the Hunt effect,[62, 63] it is possible that preferred saturation levels may change with illuminance. None of the current results should be applied to light sources with IES $R_f < 60$, 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.

A continuation of this line of inquiry is planned. It will focus on more precisely defining the transition where $D_{uv}$ begins to have an effect on object color perceptions. This next experiment will focus on chromaticity groups between 2700 K and 3500 K.

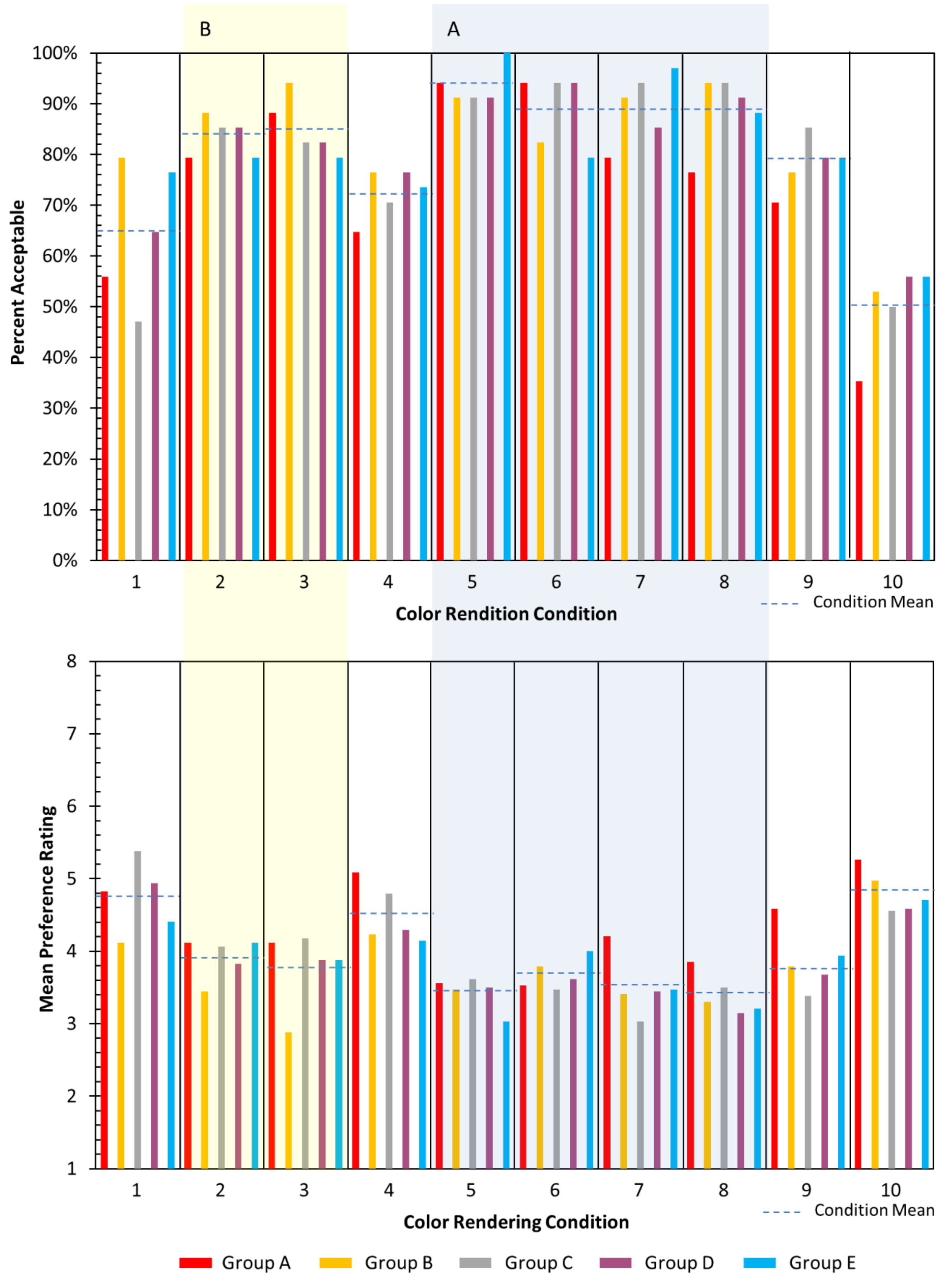


**Figure 17. Mean percent acceptability and preference rating for each condition. Conditions in shaded area A meet the most stringent criteria: IES $R_f \geq 75$, IES $R_g \geq 100$, $-1\% \leq$ IES $R_{cs,h16} \leq 15\%$. Conditions in shaded area B would meet a more relaxed set of criteria: IES $R_f \geq 75$, IES $R_g \geq 98$, $-7\% \leq$ IES $R_{cs,h16} \leq 15\%$.**

# 5 Conclusions

Augmenting the results of a prior experiment at a single chromaticity, color preference and normalness were strongly correlated with a combination of average color fidelity (IES $R_f$) and red chroma shift (IES $R_{cs,h16}$) across five chromaticity conditions. Some additional predictive benefit can be gained by adding gamut area (IES $R_g$) to the models. These models performed substantially better than CIE $R_a$, GAI, $R_m$, or FCI or select combinations thereof.

Although perceived saturation was extremely well correlated with IES $R_{cs,h16}$ for all five chromaticity groups, there was a significant difference in perceived saturation based on CCT. The chromaticity groups at 2700 K were perceived as more saturated for the same level of IES $R_{cs,h16}$. This affected the preference and normalness ratings, which were universally correlated with perceived saturation across all groups and conditions.

Chromaticity group was a statistically significant factor for rated preference, although there were similar trends across all five groups, with preference for 0% to 15% increase in IES $R_{cs,h16}$. The exact amount of increase was dependent on CCT; at 2700 K, a smaller increase (or no increase) in red chroma was preferred, but there was no difference between 3500 K and 4300 K. While there was a statistically significant improvement in preference with a negative $D_{uv}$ value at 2700 K, there was no difference in preference due to $D_{uv}$ at 4300 K. CCT and $D_{uv}$ should not be used alone as factors in a model of color preference; adding both offers a small increase in predictive value for IES TM-30-15-based models of color preference.

The perception of normalness was related to the same factors as preference—average color fidelity (IES $R_f$) and red chroma shift (IES $R_{cs,h16}$)—with less desire for increased saturation. This indicates that the participants knew that what they preferred was different than what they considered normal, and perhaps what would be called natural.

Percent acceptability was well correlated with rated preference. In lieu of a single numerical model of preference, it was possible to develop a set of specification criteria that were effective across all chromaticities tested. The most stringent criteria (IES $R_f \geq 75$, IES $R_g \geq 100$, $-1\% \leq$ IES $R_{cs,h1} \leq 15\%$) were able to isolate the color rendition conditions with mean acceptability ratings of 89% or greater. A less stringent set of criteria (IES $R_f \geq 75$, IES $R_g \geq 98$, $-7\% \leq$ IES $R_{cs,h1} \leq 15\%$) was able to isolate the color rendition conditions with mean acceptability ratings of 84% or greater.

Overall, the results show that IES TM-30-15 measures can be used to effectively predict perceptions of normalness, saturation, preference, and acceptability in a generic polychromatic architectural environment. This holds true across chromaticities, with minor differences in the models at different CCT and $D_{uv}$ combinations. The model parameter coefficients may vary with contextual factors, which should be the subject of future work. Refinement of the understanding of the CCTs where $D_{uv}$ may affect perceptions is also needed.

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