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Relative Contributions of sc-DER, mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception

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ABSTRACT

An experiment was conducted to examine spectrally based factors that contribute to the visual perception of interior environments, with a focus on brightness perception. Thirty-two participants evaluated 60 different lighting scenes in a mock office. The lighting spectral power distributions varied systematically in illuminance, chromaticity (CCT and Duv), s cone opic daylight efficacy ratio (sc-DER), melanopic daylight efficacy ratio (mel-DER), and color rendition (R_f, R_g, and $R_{cs,h1}$). At the operationalized levels of these variables, illuminance had the largest effect on brightness perception. Notably, the second largest effect was due to changes in red chroma ($R_{cs,h1}$). The effect of sc-DER was also statistically significant but was a tertiary effect. The effects of mel-DER, CCT, and Duv were not statistically significant. This large effect of red chroma is consistent with the existing understanding that changes in color perception are often perceived when illuminance changes. With appropriate changes in color rendition and other factors held constant, spatial brightness perception was preserved through a decrease from 500 lux to 250 lux.

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1. Introduction

Spatial brightness (SB), also known as scene brightness, is an attribute of a visual perception according to which a luminous environment appears to contain more or less light (CIE 2011). Many previous studies have shown that the photopic luminous efficiency function V_λ is insufficient to accurately characterize SB and that variations in spectral power distribution (SPD) lead to differences in SB (Fotios et al. 2015). One of the main objectives in SB research is to be able to optimize lighting spectra to create the desired visual environment while reducing lighting energy use. An electric lighting system associated with high SB could be dimmed – or designed to provide a lower average horizontal illuminance – and thereby save energy compared to another system delivering lower SB. Note that if two lighting systems provide equivalent SB, this cannot be taken to mean that they are necessarily equivalent in terms of other design criteria such as preference or visual performance.

Past studies have investigated the relationship between SB and many other measures, including correlated color temperature (CCT), gamut area, cone surface area, prime color theory, s-opic illuminance (e.g., scotopic/photopic ratio), and melanopic illuminance (e.g., melanopic/photopic ratio). While multi-metric models with high coefficients of determination (R^2) have been developed for specific datasets (e.g., Khanh et al. 2023; Rea et al. 2016), none has proven to have satisfactory external validity to enable widespread adoption in practice. For example, studies that varied lamp type or CCT tended to conclude that SB was affected by those factors (e.g., Flynn and Spencer 1977; Fotios and Gado 2005; Vrabel et al. 1998; Yu and Akita 2019), but these characterizations are only coarsely related to SPD at best. Because all measures proposed to predict SB are simplifications derived from a light source's SPD, there is substantial potential for confounded variables, leading to misappropriation of causal effects. Simple metrics cannot account for the complex differences in SPDs that may produce the same metric value.

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The following sections summarize recent research addressing the contribution of intrinsically photosensitive ganglion cells (ipRGCs), short-wavelength sensitive (s) cones, and color to SB. This work focuses on the effect of spectrum on SB perception under photopic lighting conditions typical of architectural interiors, excluding mesopic or scotopic conditions (e.g., exterior nighttime environments). The effect of luminance distribution on SB has also been widely studied but is outside the scope of this work.

1.1. Photoreceptor contributions: ipRGCs (melanopic)

ipRGCs have been found to contribute to brightness perception and reflexive visual responses (e.g., pupil constriction) at photopic light levels. Berman et al. (1990) initially proposed that brightness ratings depend on both illuminance and short-wavelength content, using rod sensitivity (i.e., scotopic/photopic ratio) as an initial predictor (Berman and Liebel 1996). As knowledge of ipRGCs emerged in the 2000s, this model was translated to use the melanopic/photopic ratio (Berman 2008). Since the publication of International Commission on Illumination (CIE) S026:2018 (CIE 2018a), updated quantities for addressing melanopic content, such as the melanopic daylight efficacy ratio (mel-DER) can be used. Likewise, there is increasing knowledge of the mechanisms that allow ipRGCs to contribute to brightness perception, as well as the size of the effect (Besenecker and Bullough 2017; Brown et al. 2012; DeLawyer et al. 2020; Spitschan et al. 2017; Yamakawa et al. 2019).

In the last decade, several researchers have proposed models of SB that include melanopic illuminance or related quantities, using coefficients and exponents to adjust the effect size of melanopic illuminance compared to photopic illuminance (Hu et al. 2022; Khanh et al. 2023; Rea et al. 2016; Zele et al. 2018). The degree to which these studies have controlled for other variables, including s cone opic daylight efficacy ration (sc-DER), chromaticity, color rendition, and the interaction of SPDs and spectral reflectance in a complex scene, has varied. These studies have included only a limited number of SPDs and/or SPDs created with only 4-primary LED systems, which offer limited flexibility for targeting different spectrally based quantities with metamers. This makes it difficult to operationalize SPD to identify causal effects, as well as the relative effect size of different factors that contribute to SB.

1.2. Photoreceptor contributions: S cones (cyanopic)

By the mid-1990s, models using the s cone response were proposed to address the apparent effects of short-wavelength content on SB. Fotios and Levermore (1997, 1998a, 1998b, 1998c) explored several alternative models, including one based on the ratio of s cone illuminance to photopic illuminance. Likewise, the more recent models of Rea et al. (2016), and Khanh et al. (2023) have included s cone contributions in addition to ipRGC contributions. Rea et al. proposed various levels of the coefficient for the s cone term based on vertical illuminance. Khanh et al., who examined more SPDs viewed in a chromatic environment, found s cone contributions to outweigh those of ipRGCs – as identified by the coefficients and exponents in their model. The s-cone-only model had an R^2 of 0.82, compared to the full model value of 0.95.

As with models including terms for ipRGC contributions, much of the experimental data is limited by the type and quantity of stimuli that could be created by the lighting technologies of the time. As Zele et al. (2018) noted, with limited spectral primaries to work with, cyanopic and melanopic responses can be difficult or impossible to differentiate (i.e., they become highly correlated) because the peak sensitivity varies by only about 45 nm. Effective separation of the effect requires at least two unique blue primaries, because one primary is not enough to vary the ratio of s-cone to ipRGC stimulation.

While the direct links between melanopsin and brightness perception have been elucidated, the case for s cones is not as clear. Bullough (2018) noted that "while there is little physiological evidence for an additive combination of photopic and s-cone signals to play a role in visual processing, the spectral sensitivity implied by such a combination can be matched [given that relative coefficients are appropriately adjusted] by an algebraic combination of the photopic luminance channel with the spectrally opponent blue – yellow [B-Y: S-cone/(L + M)-cone] color channel." The potential for chromatic contributions to SB have been studied since at least the 1970s, predating suggestions of s cone and ipRGC influence, although this explanation has been examined less in the last two decades, since the discovery of ipRGCs. As Bullough notes, however, the older explanation may be more physiologically plausible.

1.3. Chromatic contributions: CCT and chromaticity

There has been mixed evidence regarding the role of CCT (and chromaticity more broadly) on SB perception. While several studies have suggested that increasing CCT increases SB (Akashi and Boyce 2006; Baniya et al. 2015; Boyce and Cuttle 1990; Boyce et al. 2003; Jin et al. 2023; Ma et al. 2022; Van de Perre et al. 2023; Vienot et al. 2009), others have not (Houser et al. 2009; Hu et al. 2006; Ju et al. 2012; Kim et al. 2015; Manav 2007; Royer and Houser 2012; Tiller et al. 2005; Wei et al. 2014b; Yu and Akita 2023), and at least one study found the opposite (Hu et al. 2022). In several of these experiments, CCT was the only metric used to operationalize SPD; however, CCT is a coarse metric and other spectrally derived measures (e.g., color rendition, Duv) can vary substantially at constant CCT. Unless other factors are controlled for, the results from experiments where CCT was the primary independent variable likely have low external validity. Despite recommendations against this practice (CIE 2020; Durmus 2022; Royer et al. 2022), it continues. Further, given the important role of chromatic adaptation (Foster 2011; Fotios 2006; Rinner and Gegenfurtner 2000; Royer et al. 2022) in visual perception, at least some of the discrepancy may stem from differences in experimental adaptation conditions. That is, chromaticity may have an effect when adaptation is incomplete or mixed, but less or not at all when adaptation is complete.

Another important consideration is that CCT and other measures related to short-wavelength content, such as mel-DER and especially sc-DER, are correlated. For a set of 164,707 theoretical SPDs comprised of three to seven Gaussian primaries used in other recent research (Royer 2023), r was 0.49 between CCT and mel-DER, and 0.88 between CCT and sc-DER. When limited to a subset of the SPDs with $-0.0002 \leq \text{Duv} \leq 0.0002$, the latter increased to 0.96. Such a relationship means that varying CCT will often lead to changes in sc-DER, unless careful controls are implemented, and ultimately creates the potential to misattribute the cause of changes in SB. Nonetheless, CCT should not be used as a proxy for other more specific measures (Esposito and Houser 2022).

DeLawyer et al. (2020) varied melanopic stimulation while accounting for hue, finding the effect of melanopic activation on the perceived brightness of nonwhite stimuli on a projection screen was small but statistically significant, but it was larger when luminance and hue were held constant (i.e., there was a statistically significant interaction). While the perceived brightness of nonwhite light on a screen subtending a 20° visual field is a different phenomenon than SB perception of white light, it nonetheless provides important insight into the relative scale of melanopic effects, and how chromatic effects may diminish the size of the effect of melanopsin stimulation on brightness perception. The authors posited that the effect of melanopsin for different brightness tasks may vary.

1.4. Chromatic contributions: color rendition

The relationship between color rendition and perceived SB has been investigated in several previous studies using various gamut area measures, with generally positive findings (Boyce 1977; Fotios and Levermore 1997, 1998b; Fotios et al. 2015). However, gamut area is conceptually an average and increases or decreases can be achieved by changing the chroma of various hues in different ways (i.e., having different gamut shapes (Royer Michael et al. 2018)) – there are also functional differences between outdated metrics like the Color Discrimination Index (CDI) and modern measures of gamut area (Royer 2019a). Gamut shapes often have a nominally red-green or yellow-blue orientation, as can be quantified by examining rotation angles of ellipses fit to the shape or identifying the hue-angle bin with the greatest local chroma shift value (Esposito 2016; Royer et al. 2020). The prevalence of these orientations may be related to opponent channel signals. Furthermore, it can be demonstrated that at equal chromaticity, red-green gamut shapes almost exclusively have higher mel-DER values than yellow-blue gamut shapes. Figure 1 shows this phenomenon for a set of more than 970,000 SPDs with $R_f \geq 60$, all with 3500 K CCT and 0.000 Duv for a seven-channel LED system.

Related to this, at a given chromaticity, mel-DER is highly negatively correlated with $R_{cs,h13}$, the TM-30 measure for chroma shift of nominally purple-blue hues. For a set of metameric SPDs with $R_f \geq 60$ enumerated (Baxter et al. 2022) from a group of eight LED primaries (deep red, red, amber, lime, green, cyan, blue, indigo), r was – 0.98, with correlations only somewhat lower for several other hue-angle bins (e.g., $R_{cs,h10}$). A similar relationship was found for a different eight-channel LED system. Likewise, for the 60 SPDs examined in this experiment – which utilized up to 16 different channels – r was 0.91. The important takeaway is that gamut area is too coarse of a measure to capture the effects of color rendition on SB perception, and as a corollary, controlling for color fidelity (TM-30 R_f) – or even both color fidelity and gamut area (TM-30 R_g) – is unlikely to be sufficient for isolating other effects (e.g., of sc-DER or mel-DER), since it will not control for the effect of color rendition.

In at least two recent experiments focused on color rendition (Royer et al. 2018, 2020), participants indicated they thought the brightness of the space was changing; in the latter, 56% of participants indicated they thought the brightness of 90 lighting conditions with equal illuminance was not constant in a post-experiment questionnaire. However, SB was not included as a dependent measure, so it was not possible to correlate perceived SB with any spectrally derived quantities.

Understanding and quantification of color rendition has advanced substantially in the past decade. Modern methods, such as ANSI/IES TM-30 (Illuminating Engineering Society 2020; Royer 2022), allow for quantification of color rendition beyond average color fidelity and gamut area, including concepts such as gamut shape and chroma shift (Royer Michael et al. 2018) – a factor that has yet to be examined for its relevance to SB, despite strong importance to subjective evaluations of color (Esposito and Houser 2019; Royer et al. 2017; Zhang et al. 2017). Another important line of research has focused on color rendition and the Hunt effect (1952), showing how color rendition – specifically

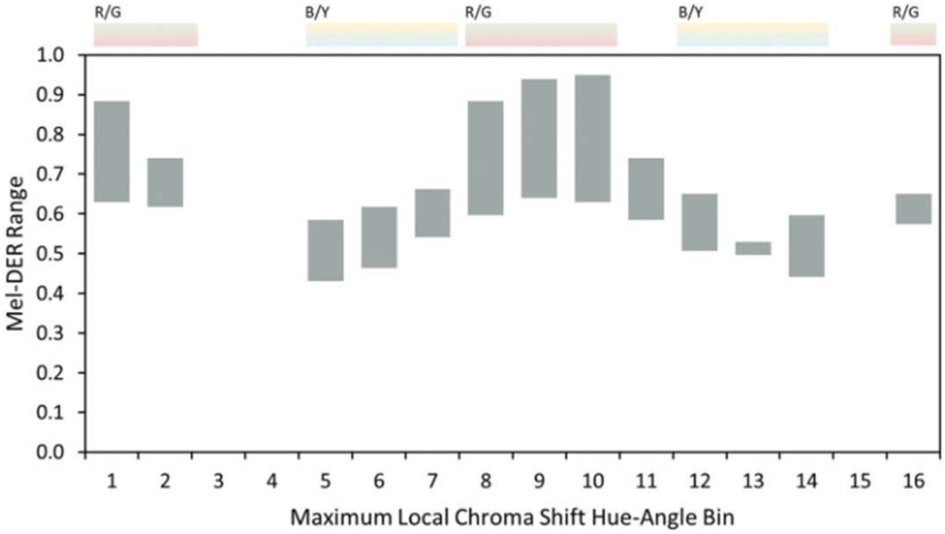


Fig. 1. Possible mel-DER values (shown with the shaded bar) for SPDs with the maximum local chroma shift value in each hue angle bin with a real seven channel LED system (red, amber, lime, green, cyan, blue, indigo) at constant chromaticity (3500 K, 0.000 duv). SPDs with a red-green oriented gamut shape (i.e., having maximum local chroma shift in hue angle bins 1, 2, 8, 9, 10, or 16) have little overlap in mel-DER values with SPDs having a blue-yellow oriented gamut shape.

increases in red chroma – can counteract the reduction in perceived colorfulness that arises from reduced light levels (Bao and Wei 2021; Kawashima and Ohno 2019; Wei et al. 2020). To date, no known research has connected these advancements to the study of SB.

1.5. Chromatic contributions: opponent channels

Predictions of a chromatic component, particularly the opponent channels, to brightness perception date to at least the late 1800s with the work of Hering, Hillerbrand, and others; Wasserman (1966) covers this early history. In modern times, contributions from opponent channels have received less attention than other potential factors. In the 1990s, Fotios and Levermore (1998c) examined SB models that included the opponent responses of the human visual system, utilizing earlier proposals by Thornton (1973, 1980) and Guth and Lodge (1973). In 2014, Wei et al. (2014a) considered opponent signal differences and their contribution to differences in perceived SB of two stimuli, but did not propose a broader model. Along with other studies that found CCT did not affect SB, Wei et al. investigated Thornton's prime color theory, which posits that the wavelength region between 570 nm and 580 nm may negatively affect SB (and color preference). This concept is congruous with opponent color theories.

As previously noted, Bullough (2018) described how s-cone-opic effects are likely to be acting through the blue-yellow opponent channel, rather than the s-cone itself providing direct input alongside the achromatic channel. The inclusion of s-opic quantities in brightness models may address the underlying physiological mechanism whereby the chromatic component affects SB.

1.6. Aims and hypotheses

A primary challenge in spectrum-focused SB research is operationalizing SPD as an independent variable so that effective inference can be made about different factors. All the metrics and concepts previously described as potentially influencing SB distill the complex information contained in a light source SPD to a single number; critically, these resulting values are not independent. These relationships are important because many past experiments have failed to control for them – oftentimes because more specific metrics did not yet exist. Even in well controlled experiments, it can be difficult to create variation in one quantity while holding another constant. For example, as subsequently discussed, when CCT, Duv, R_f, R_g, $R_{cs,h1}$, and mel-DER are held constant, the difference in minimum and maximum sc-DER may be very small.

The aim of this work was to examine the relative size of the effect of spectrally based chromatic and achromatic enhancements to SB perception, exploring the intersection of brightness and color perception. Specifically, the study examined perceived brightness, warmth, naturalness, vibrancy, and preference of 60 lighting conditions that systematically varied in color rendition (R_f, R_g, and $R_{cs,h1}$), CCT, Duv, mel-DER, sc-DER, and illuminance. The goal was *not* to develop a precise model of SB perception, which will require further examination of more widely varied SPDs in a variety of contexts.

Specifically, we hypothesized that at constant chromaticity, illuminance, mel-DER, and sc-DER, scene brightness would vary with color rendition characteristics, with SPDs inducing higher perception of vibrancy (i.e., increased $R_{cs,h1}$ and increased R_g) being perceived as brighter. Simultaneously, we hypothesized that with all other factors held constant, SPDs with higher mel-DER would be perceived as brighter. Finally, we hypothesized that increasing sc-DER would increase SB but that chromaticity would not.

2. Methods

2.1. Apparatus and test room

The experiment took place in two rooms. The primary experiment room, shown in Fig. 2, was 4.4 m by 6.7 m with a 2.6 m ceiling height. This room did not have any windows and was furnished to appear as an office space. It featured nominally 2×2 white acoustical ceiling tiles, walls painted with Munsell N8 gray paint, and gray

Fig. 2. Photograph of the experiment room from the participants' perspective.

carpet tiles on the floor. It had two solid doors, one on each of the shorter sides.

The experiment room was illuminated by 12 custom-built luminaires (Telelumen, LLC) each having 24 independently controlled LED channels, with each being a commercially available product. Sixteen of the channels were used in this experiment – those in the near UV, far red, and infrared were excluded.

An adjacent room was used for adaptation purposes. The dimensions of the room were approximately 4.4 m by 8.7 m with a ceiling height of 3.0 m, but only a portion of this room was used. This room was illuminated by 28 Ketra G2 linear tunable luminaires aimed downward to provide direct illumination. It included a table where participants submitted evaluation forms, chairs used during adaptation periods, and snacks and water.

2.2. Visual stimuli

Sixty experimental SPDs were created through an iterative process. They were grouped according to nominal values identified in Fig. 3. The measured characteristics of the final SPDs used in the experiment are provided in Table 1.

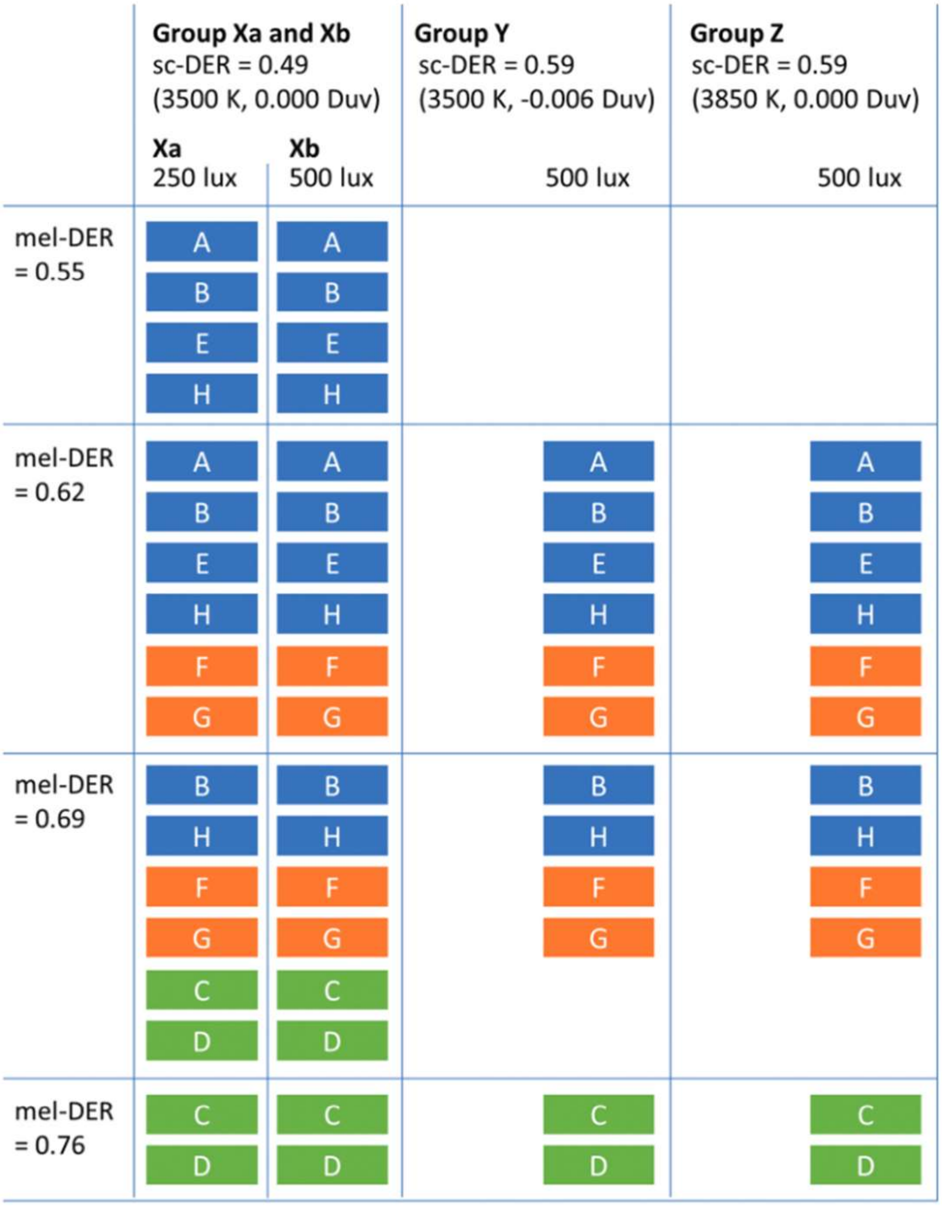
2.2.1. SPD target values

The process of generating SPDs began with measurements of the SPD for each channel of the lighting system made in the center of the luminaire array when the room was empty except for the meter and a black table to position it. The channel measurements were input to custom-developed software that computed an SPD given input parameters for CCT, Duv, R_f, R_g, $R_{cs,h1}$, mel-DER, and sc-DER, which were the parameters used to operationalize SPD for this experiment. If all criteria could be achieved in multiple ways (i.e., metamers), luminous efficacy of radiation was maximized for the optimization. The exact parameters for optimization target values were established after probing the limits of possible combinations of values. Figure 3 provides an overview of the partial factorial arrangement.

Eight unique color rendition conditions were chosen to cover a range of values that might be typical for an office. There were two nominal R_f values (80 or 90), three nominal R_g values (94, 100, 110), and four nominal $R_{cs,h1}$ values (−12%, −7%, 2%, and 10%). These are shown in Table 2. The eight nominal conditions were varied so that there were combinations that could be evaluated with only one of the three parameters changing. Furthermore, the color rendition specifications spanned the range of Preference priority levels documented in TM-30 Annex E (IES 2020). They were also created to have different gamut shapes, as defined by regions of chroma enhancement: red-green, yellow-blue, or neutral (i.e., approximately round) shape.

Four levels of mel-DER were established that spanned the range of what was possible given the desired variation in color rendition: 0.55, 0.62, 0.69, and 0.76. These were established at the target chromaticity of 3500 K with 0.000 Duv, which is common for offices in North America. This is referred to as chromaticity group X. For this group, target sc-DER was fixed at 0.49, although many of the conditions could not achieve that target exactly (error versus targets is subsequently described).

Importantly, given the relationship between color rendition and mel-DER, not every color rendition condition could be achieved at each target mel-DER value. However, each color rendition condition was represented in at least two mel-



	Group Xa and Xb sc-DER = 0.49 (3500 K, 0.000 Duv) Xa 250 lux	 Xb 500 lux	Group Y sc-DER = 0.59 (3500 K, -0.006 Duv) 500 lux	Group Z sc-DER = 0.59 (3850 K, 0.000 Duv) 500 lux
mel-DER = 0.55	A B E H	A B E H		
mel-DER = 0.62	A B E H F G	A B E H F G	A B E H F G	A B E H F G
mel-DER = 0.69	B H F G C D	B H F G C D	B H F G	B H F G
mel-DER = 0.76	C D	C D	C D	C D

Fig. 3. Illustration of the partial factorial design. Color rendition conditions A, B, E, and H have a blue-yellow gamut shape, F and G have a neutral gamut shape, and C and D have a red-green gamut shape.

DER levels. The highest mel-DER level had only color rendition conditions with a red-green orientation, and the lowest had only conditions with a blue-yellow orientation.

Once CCT, Duv, R_f, R_g, $R_{cs,h1}$ and mel-DER were established the variation in sc-DER was very restricted. For the 16 of the 18 SPD targets in chromaticity group X with variable sc-DER, the average possible range in sc-DER was 0.02, with a maximum of 0.05. This level of difference was deemed too small for multiple levels of sc-DER as a variable with all other factors fixed, given the achievability of the target values in the room and visual tolerances. Two of the eighteen stimuli in group X (color rendition conditions C and D) required minimizing mel-DER to approach the 0.69 target value, so no range in sc-DER was possible.

To vary sc-DER, two additional chromaticity groups were established: 3500 K with –0.006 Duv (group Y) and 3850 K with 0.000 Duv (group Z). One varied CCT in relation to chromaticity group X and the other varied Duv, with the level of perceptual variation chosen to remain within the overall

Table 1. Summary characteristics for the 60 SPDs.

Group	Condition	E_h (lux)	CCT (K)	Duv	sc-DER	mel-DER	LER	R_f	R_g	$R_{cs,h1}$
Xb (sc-DER = 0.49, 3500K, 0.000 Duv, 500 lux)	**1**	501	3492	0.0012	0.48	0.54	306	80	101	−11%
	2	500	3476	−0.0002	0.50	0.55	286	80	100	−7%
	3	498	3441	−0.0009	0.50	0.54	295	79	111	2%
	4	499	3483	−0.0006	0.52	0.55	267	79	95	−12%
	5	502	3503	0.0004	0.49	0.62	338	80	101	−10%
	6	501	3481	−0.0002	0.50	0.61	291	79	101	−7%
	7	500	3496	0.0008	0.48	0.61	321	81	110	2%
	8	500	3481	0.001	0.47	0.62	266	80	110	11%
	9	501	3448	−0.0007	0.49	0.62	249	90	100	2%
	10	497	3507	0.0004	0.51	0.62	276	80	94	−12%
	11	500	3513	0.0019	0.46	0.67	311	82	100	−7%
	12	501	3496	−0.0004	0.44	0.71	307	79	100	11%
	13	500	3458	−0.0005	0.43	0.72	321	80	94	2%
	14	500	3484	0.0003	0.47	0.68	276	80	110	10%
	15	499	3467	−0.0006	0.48	0.69	260	89	100	2%
	16	498	3454	−0.0004	0.49	0.68	294	80	95	−11%
	17	498	3459	0	0.47	0.76	214	78	100	10%
	18	501	3490	−0.0011	0.47	0.77	284	80	94	2%
Y (sc-DER = 0.59, 3500K, 0.006 Duv, 500 lux)	**19**	499	3508	−0.0057	0.59	0.62	288	80	100	−11%
	20	502	3447	−0.0069	0.60	0.62	255	79	101	−7%
	21	498	3497	−0.006	0.59	0.62	279	80	110	2%
	22	494	3452	−0.007	0.59	0.62	238	80	110	10%
	23	501	3442	−0.0067	0.53	0.64	278	90	100	2%
	24	499	3481	−0.007	0.61	0.62	250	80	95	−12%
	25	495	3477	−0.0061	0.59	0.69	261	79	101	−5%
	26	503	3446	−0.0064	0.58	0.68	223	79	110	10%
	27	501	3465	−0.0072	0.58	0.69	231	89	101	2%
	28	498	3527	−0.006	0.60	0.69	259	80	94	−12%
	29	500	3481	−0.0059	0.51	0.76	288	80	100	10%
	30	502	3467	−0.006	0.50	0.77	306	79	93	2%
Z (sc-DER = 0.59, 3850 K, 0.00 Duv, 500 lux)	**31**	499	3840	0	0.58	0.62	326	81	101	−11%
	32	499	3835	0.0001	0.59	0.62	286	80	100	−7%
	33	500	3862	0.0006	0.58	0.62	310	81	110	2%
	34	499	3798	−0.0005	0.58	0.62	265	80	111	10%
	35	500	3804	0.0001	0.53	0.64	286	90	99	2%
	36	501	3837	−0.0012	0.62	0.62	261	79	95	−12%
	37	499	3810	−0.0002	0.58	0.68	299	80	100	−7%
	38	500	3858	0.0004	0.59	0.69	256	79	110	11%
	39	498	3774	−0.0016	0.58	0.68	251	89	101	2%
	40	501	3864	0.0001	0.60	0.69	268	80	95	−12%
	41	500	3850	0.0013	0.50	0.78	295	80	99	10%
	42	500	3849	−0.0003	0.51	0.78	323	79	93	2%
Xa (sc-DER = 0.49, 3500 K, 0.000 Duv, 250 lux)	**43**	249	3441	0.0004	0.48	0.53	318	79	100	−12%
	44	250	3452	−0.0001	0.50	0.54	293	80	100	−7%
	45	249	3437	0.0008	0.47	0.52	293	80	110	1%
	46	253	3384	−0.0015	0.51	0.54	267	79	94	−12%
	47	249	3395	−0.0003	0.47	0.59	344	80	100	−13%
	48	251	3467	0	0.50	0.61	288	80	101	−7%
	49	252	3483	0.0011	0.47	0.60	329	81	110	1%
	50	251	3442	−0.0001	0.48	0.60	268	79	110	9%
	51	248	3480	−0.0001	0.49	0.62	257	90	100	1%
	52	253	3468	0.0002	0.50	0.61	268	79	95	−11%
	53	252	3457	0.0005	0.47	0.66	306	80	100	−8%
	54	248	3456	0.0002	0.43	0.70	299	80	99	10%
	55	250	3465	0.0006	0.42	0.71	322	80	93	1%
	56	249	3468	0	0.47	0.67	277	80	111	10%
	57	250	3470	0.0004	0.46	0.67	271	90	100	1%
	58	249	3468	−0.0002	0.49	0.67	294	80	95	−12%
	59	249	3484	0.0008	0.47	0.75	227	79	100	10%
	60	249	3464	−0.0003	0.46	0.75	280	81	95	2%

Table 2. Nominal targets for the eight different color rendition conditions.

Condition	R_f	R_g	$R_{cs,h1}$	Orientation
A	80	100	−12%	Blue-Yellow
B	80	100	−7%	Blue-Yellow
C	80	100	10%	Red-Green
D	80	94	2%	Red-Green
E	80	110	2%	Blue-Yellow
F	80	110	10%	Neutral
G	90	100	2%	Neutral
H	80	94	−12%	Blue-Yellow

range of nominally white light classified using ANSI C78.377 (NEMA 2017). These two chromaticity groups had matching target sc-DER values of 0.59, allowing the combination of the two groups to disambiguate the effects of CCT and sc-DER.

As shown in Fig. 3, the full range of mel-DER was not represented in chromaticity groups Y and Z, because the targets could not be achieved within a reasonable tolerance. However, three mel-DER levels were represented, and all color rendition conditions were represented.

The final variable was horizontal illuminance, which had two levels within chromaticity group X: 500 lux (Xb) and 250 lux (Xa). These cover the range of illuminance typically used for office lighting in the United States. Chromaticity groups Y and Z were presented at 500 lux. This variable was included to scale and interpret rating differences for the other variables.

It is important to note that the levels of variation were determined with the goal of maximizing variation in each variable without introducing confounded variables. For example, the range of mel-DER or sc-DER across all possible SPDs is considerably larger than the range exhibited in this experiment. However, to achieve this larger range, chromaticity has to be simultaneously varied, given the interrelationship of these spectrally-derived quantities.

2.2.2. Measured SPDs

The SPDs resulting from the optimization served as inputs to the Telelumen Dittosizer software. Each input SPD was calculated from two different sets of luminaire channel measurements, and then was recreated in the Dittosizer software using three different match modes (palette, spectrum, and color-corrected spectrum). This provided six prospective SPDs. The best solution was selected with an algorithm that weighted differences in the target characteristics, enabling the selection of a single version that provided the best overall match.

After fine tuning the illuminance, the settings of the chosen version were saved, and then final measurements were taken for each, as reported in Table 1, at the point at the center of the array of luminaires and 0.9 m above the floor. Full SPDs are available from (Royer 2023). The final measurements were taken with a recently calibrated Minolta CL-500A illuminance spectrometer (SN: 10003042). During these measurements the room was empty except for the table supporting the illuminance meter, which was covered in black paper.

2.2.3. Sources of error

As expected, the measurements reported in Table 1 do not precisely match the target nominal values. Table 3 summarizes the absolute value of the error relative to the nominal target across the 60 final measured SPDs. As previously noted, even the nominal targets for sc-DER were frequently not precisely achieved for the optimized SPDs due to the very small range possible given the other parameters, and a small number of mel-DER targets were also not achieved precisely in the optimization. Additional error arises from: 1) measurement error in the individual channel measurements; 2) translation of SPDs to different wavelength intervals for different equipment and software; 3) effects of the room surfaces on the measured values, 4) inability to exactly match the optimized SPDs given the three prior issues, despite the optimized SPDs using measurements

Table 3. Summary of the absolute value of the differences between the target values and measured performance.

	E_h (lux)	CCT (K)	Duv	sc-DER	mel-DER	R_f	R_g	$R_{cs,h1}$
Maximum	6	116	0.0019	0.09	0.03	2.0	1.0	1.7%
Mean	1	32	0.0005	0.02	0.01	0.5	0.5	0.4%
Median	1	31	0.0004	0.01	0.01	0.5	0.4	0.3%
St. Dev.	1	24	0.0004	0.02	0.01	0.4	0.3	0.3%

from the system; 5) variation in output of the luminaires due to varying thermal characteristics; and 6) differences between the expected system output and measurements taken in-situ in the room with some contributions of inter-reflected light.

Despite all the sources of error, the difference between measured and target characteristics was generally less than expected visual tolerances from past experience. It was also usually less than the number of significant digits to which the respective values are reported (e.g., R_f and R_g are typically reported as integers and the mean error was 0.5). The relative size of the errors also reflects the difficulty in achieving the target values given numerous other constraints. While the errors are small, they are not evenly distributed, so we decided it was more appropriate to analyze the data as continuous variables, rather than categorical. The only exception was illuminance, which had extremely small errors that could have been correlated inadvertently with some other aspect of spectrum.

2.2.4. Illuminance distribution

The target horizontal illuminance values were achieved at the measurement point below the center of the luminaire array, 0.9 m above the floor. Given the highly diffuse lenses on the luminaires that limited visual identification of the on or off state of each LED channel, the illuminance distribution across the room exhibited negligible variation across SPDs, as illustrated in Fig. 4. After normalizing to account for the small initial variation in illuminance, the mean variation in illuminance across five horizontal and four vertical measurement points distributed throughout the space was 2.6%. This is approximately 6 times smaller than the variation in luminance for a red jacket that was in the room due to changes in the SPD of the light. Because these measurements were taken with objects in the room, at least a portion of the variation is due to the interaction of each SPD and spectral reflectance characteristics of the objects in the room, rather than differences in the luminous intensity distribution of the luminaires, which would be minimal given the optical design of the system.

Spot illuminance measurements were made throughout the space to better characterize the illuminance distribution. This was done for one SPD when the nominal target illuminance was 500 lux. The horizontal illuminance at the center of the conference table was approximately 480 lux. The horizontal illuminance at the primary work areas of the desk was between 300 lux and 400 lux. Vertical illuminance at the artwork on three different walls of the room ranged from 220 lux to 260 lux.

2.2.5. SPD and room interaction

While characteristics of the SPD are what was operationalized, each visual stimulus was the interaction of the SPD and the objects and surfaces within the room. Objects in the experiment room were selected to provide a reasonable distribution within all three dimensions of the color volume (hue, chroma, and lightness). Spectral reflectance functions were measured for the objects and room surfaces (up to six measurements for polychromatic objects) using a Minolta CM-600d spectrophotometer (SN: 21011777). The objects were items commonly found in office spaces, including a desk, wood conference table, bookshelves, chairs, books, paper/notebooks, plants, fresh flowers, fresh food (strawberries, cantaloupe, and pineapple), packaged food, artwork, computer equipment, and jackets. An experimenter was always situated at the desk, dressed in dark blue jeans and a black shirt. The participants had a wide variety of answers when asked about what most influenced their choices. Some that were mentioned more frequently were the fresh fruit, jackets, and artwork.

2.2.6. Adaptation room conditions

Table 4 summarizes the conditions in the adaptation room, where the lighting always transitioned from matching the illuminance and chromaticity of the group of SPDs seen previously to that of the group of SPDs to be seen next. The measurements were taken after manual adjustment of the system using the Ketra app. With fewer channels of control, it was not possible to adjust the values for sc-DER or mel-DER.

When it was used to return response forms instead of adaptation, the room was illuminated to 1.5 lux, which combined with any spill light was sufficient for allowing the participants to return

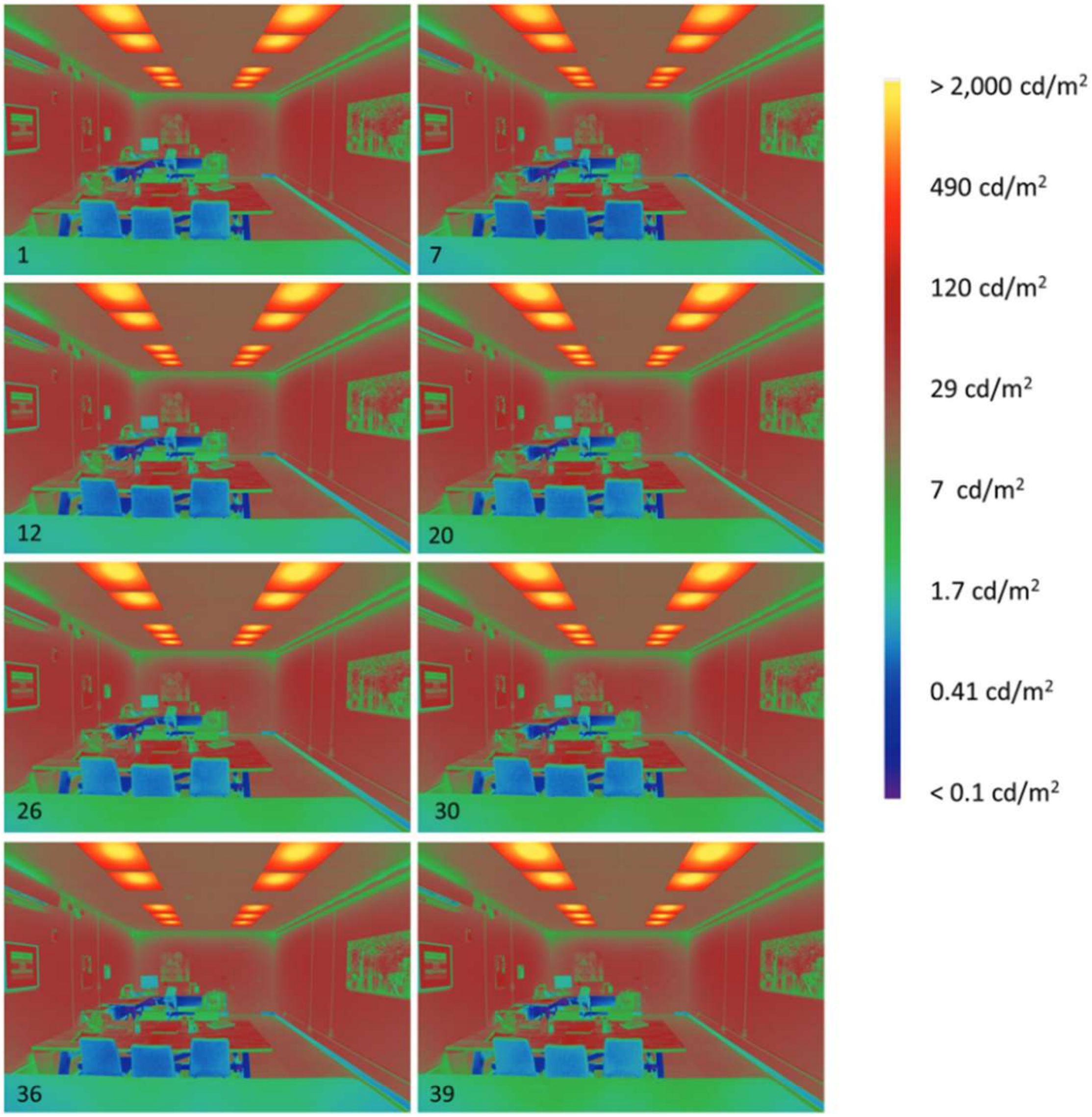


Fig. 4. Pseudocolor luminance maps generated from high dynamic range images for a selection of the stimuli. The condition number is noted in the lower left corner of each image. Perishable items were not present when these images were captured.

Table 4. Summary characteristics for the 4 SPDs used in the adaptation room. Note that conditions were routinely blended with a slow fade of the required adaptation time.

Group	E_h (lux)	CCT (K)	Duv	sc-DER	mel-DER	R_f	R_g	$R_{cs,h1}$
Xa	252	3507	0.000	0.47	0.52	85	101	−7%
Xb	497	3518	0.000	0.47	0.51	85	101	−7%
Y	502	3490	−0.006	0.54	0.54	85	103	−5%
Z	502	3852	0.000	0.55	0.56	83	100	−8%

their response forms, as well as creating a brief washout between evaluation of different stimuli.

2.3. Participants

Thirty-two people participated in the experiment, including 20 females and 12 males. This quantity was sufficient to address the central limit theorem and is approximately equal to or greater than the number for other similar studies. Participants were recruited from groups on social media and personal contacts. Five people identified that they had professional lighting experience. Ages of the participants ranged from 23 years to 69 years (one not provided), with a median of 38 years. During an adaptation period, each person completed a color vision test (Ishihara's Test for Color Deficiency, 24 plates). One participant demonstrated red-green color vision deficiency; their data were not excluded.

2.4. Participant ratings (dependent measures)

For each lighting scene, participants completed a paper response form that had five semantic differential rating questions, each with an eight-point scale (1 to 8) drawn with tick marks to reinforce its interval nature. The anchor words were bright-dim, warm-cool, natural-distorted, vibrant-dull, and like-dislike – the first word listed here was on the 1 end of the scale. During the instruction period, these terms were explained verbally, often using synonyms, as follows:

- *The first question asks about your impression of the space: is it brightly lit or dimly lit. If you think it's on the brighter side, you'd circle a number closer to 1, and if you think it's on the dimmer side, you'd circle a number closer to 8.*
- *The next question asks if the room looks more visually warm (that is, more yellow) or more visually cool (that is, more blue).*
- *The third question is a rating scale between natural and distorted. That is, does the lighting make the objects' colors look normal or as you would expect them to look, or does it make them look unusual or shifted in some way.*
- *After that you're being asked to rate whether the lighting makes the objects' colors look more vibrant or dull (you could also call this vivid or desaturated).*
- *Finally, the last question asks about your overall impression of the light: Is it something you like and would prefer to work under, or is it something you dislike and would prefer not to have in your workspace. The idea is to focus on how the light makes the space look, not the light fixtures themselves.*

To conclude the experiment, the participants completed a questionnaire to describe their experience, which provided insight into which objects were the most influential in determining their judgments. It also included a question regarding the difficulty of the experience, as well as general demographic questions.

2.5. Procedure

This experiment was approved by the Pacific Northwest National Laboratory Institutional Review Board.

Participants completed the experiment in groups of one to four people. Upon arrival, participants were escorted to the experiment room where they first provided consent to participate and were then read instructions. During the instructions, the lighting was set to SPD 15, 27, 39, or 57, depending on the first experimental group that would be presented. As part of the instructions, participants saw a demonstration of five additional SPDs to illustrate the approximate range of stimuli: 1, 25, 41, 51, and 53. Finally, before the experiment began, two practice trials – using SPDs randomly selected from the first upcoming block – were administered. This initial period lasted about 10 minutes, doubling as a period of chromatic and light-dark adaptation.

Twelve sequences of SPDs were generated prior to the experiment beginning. The experiment consisted of four blocks, corresponding to the four groups: Xa, Xb, Y, and Z. The low-illuminance group (Xa) was presented either first or last, thus requiring only one transition between illuminance levels and the longer 10-minute adaptation period. The order of the remaining three groups (equal illuminance but different chromaticity) was presented in a counterbalanced manner, with each appearing in each position and after each other stimulus in a balanced fashion. Within each group, the order of presentation for the individual SPDs was always randomized. Due to many registered participants not showing up, the number of participants experiencing each of the 12 sequences (4, 2, 5, 4, 3, 2, 2, 1, 1, 1, 4, and 3 people) was not balanced – a check found sequence was not a statistically significant predictor of the dependent measures.

Whenever they were in the experiment room, the participants were situated behind a standing table that was at one of the ends of the room. It had a black tablecloth covering it. For each stimulus, the participants were instructed to view the room for at least 20 seconds before providing a response on a paper form. After that, they were free to respond whenever they wished. After completing the response form, they took it through the small transition room (with safe movement provided by spill light from the experiment room), through another open door – which was offset from the door to the experiment room to limit line of sight – and handed in the form at a desk in the dimly lit adaptation room. While the participants were out of the room, the experimenter changed the light in the experiment room; the transition was not visible to participants.

Each of the four groups consisted of 12 or 18 SPDs, as identified in Fig. 3. After all were evaluated, participants were seated in the adaptation room, where the lights were turned on at a chromaticity matching the previous block. The light then transitioned over 5 seconds (for chromaticity changes only) or 10 minutes (for illuminance changes) to match the chromaticity and illuminance of the upcoming block. During this time, the door to the experiment room was completely closed. The combination of extended adaptation times, gradual transitions, relatively small changes in chromaticity both within and between blocks, and 20 second mandatory waiting periods were intended to provide for complete (short term) chromatic adaptation (Fairchild and Reniff 1995). Likewise, the 10-minute adaptation period was intended to provide for light-dark adaptation given the 250 lux change in illuminance.

After the final stimulus was evaluated, participants were given the final questionnaire to complete in the experiment room. Finally, they were compensated for their participation.

The total experiment took between 90 minutes and 120 minutes. All but one participant rated the experience as appropriately difficult; the other one rated it as easy.

All sessions were held within a six-day period. Fresh food was stored in a refrigerator when not in use and changed out every two days or more frequently if necessary.

3. Results

Table 5 provides summary results of all five dependent measures for all 60 lighting conditions; individual data is available from (Royer 2023).

The effect of predictor variables on brightness ratings was examined using a mixed linear model with the predictors as fixed effect variables and participants as a random effect variable to account for individual variability. The model was created using lmerTest R package and assumptions of linear mixed models were checked and met (Kuznetsova et al. 2017). Table 6 provides the results.

The statistical model used nine predictors: eight as continuous variables and illuminance using its nominal levels (500 lux or 250 lux). The interaction term $R_{cs,h1}$:illuminance was included to account for the known effects of illuminance level on perceived vividness (Bao and Wei 2021; Kawashima and Ohno 2019; Wei et al. 2020). This model used individual responses rather than the mean rating per condition. Significant effects on spatial brightness were found for illuminance level, sc-DER, $R_{cs,h1}$, and the interaction term $R_{cs,h1}$:illuminance.

The effect size was examined by calculating f^2, a standardized measure of effect size where the effect is small if $0.02 \leq f^2 < 0.15$, medium if $0.15 \leq f^2 < 0.35$, and large if f^2 is ≥ 0.35 (Cohen 1988). The largest effect size was for illuminance ($f^2 = 4.67$) followed by $R_{cs,h1}$ ($f^2 = 0.56$), the interaction term $R_{cs,h1}$:illuminance ($f^2 = 0.22$), and lastly sc-DER ($f^2 = 0.17$). This shows that the effect size of $R_{cs,h1}$ was about three times that of sc-DER. This ranking of effect sizes was confirmed by analysis of the variance explained by each fixed effect variable.

Figure 5 shows mean bright-dim ratings ordered by SPD from lowest to highest within each of the four chromaticity groups. This figure helps to visualize the relative effects of different metrics: the effect of illuminance was the largest: considering only the matched set of stimuli (i.e., group Xa vs. Xb) the mean rating was 1.1 points brighter for the 500 lux group. The effects of the difference in sc-DER and chromaticity were about five times smaller. Figure 5 demonstrates a clear gradient in brightness rating based on $R_{cs,h1}$, particularly for the three 500 lux groups. Some SPDs with low $R_{cs,h1}$ values at 500 lux had mean brightness ratings that were not significantly different from some SPDs at 250 lux. One SPD producing an illuminance of 500 lux had a mean brightness rating that was greater (i.e., rated as more dim) than the mean ratings for three SPDs producing an illuminance of 250 lux.

Table 5. Summary of rating data for each SPD.

	Bright-Dim		Warm-Cool		Natural-Distorted		Vibrant-Dull		Like-Dislike	
Condition	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	4.53	1.54	4.63	1.18	4.41	1.46	5.09	1.38	4.97	1.60
2	3.81	1.35	4.84	1.30	4.22	1.39	4.22	1.45	4.16	1.69
3	3.69	1.40	4.09	1.30	3.75	1.65	4.03	1.28	3.66	1.60
4	4.22	1.54	4.94	1.13	4.78	1.13	4.81	1.51	4.88	1.39
5	4.13	1.64	4.66	1.26	4.41	1.41	4.75	1.19	4.47	1.50
6	4.06	1.41	4.41	1.36	3.97	1.18	4.56	1.19	4.50	1.67
7	3.81	1.64	4.28	1.35	3.91	1.44	4.13	1.34	3.78	1.54
8	3.42	1.46	3.94	1.41	4.44	1.46	3.63	1.54	4.25	1.68
9	3.59	1.41	4.63	1.26	3.94	1.46	4.31	1.20	4.06	1.54
10	3.91	1.55	4.63	1.24	4.38	1.34	4.84	1.46	4.72	1.46
11	4.09	1.61	4.53	1.37	4.28	1.49	5.03	1.53	4.19	1.49
12	3.41	1.70	3.84	1.51	4.94	1.79	3.78	1.75	4.84	1.80
13	3.66	1.49	4.50	1.63	4.34	1.49	4.25	1.50	4.66	1.96
14	3.44	1.54	4.06	1.21	4.09	1.33	3.94	1.79	3.81	1.49
15	3.50	1.37	4.03	1.03	3.75	1.30	3.94	1.39	3.94	1.29
16	4.16	1.39	4.25	1.27	4.44	1.27	4.81	1.09	4.53	1.34
17	3.06	1.52	4.31	1.71	4.81	1.55	3.66	1.88	4.66	1.84
18	4.03	1.53	4.31	1.31	4.52	1.43	4.56	1.41	4.81	1.38
19	4.09	1.42	5.03	1.23	4.56	1.37	5.06	1.19	4.88	1.54
20	3.41	1.16	4.63	1.29	4.09	1.47	4.25	1.14	4.22	1.39
21	3.41	1.27	4.63	1.04	4.03	1.23	3.63	1.10	4.16	1.48
22	3.31	1.42	4.59	1.41	4.63	1.48	3.47	1.52	4.59	1.64
23	3.59	1.29	4.03	1.47	3.81	1.57	3.84	1.25	3.97	1.67
24	4.13	1.54	5.25	1.32	4.81	1.47	4.94	1.34	4.94	1.39
25	3.81	1.35	4.81	1.23	4.09	1.47	4.47	1.05	4.47	1.54
26	3.03	1.43	4.19	1.35	4.34	1.29	3.63	1.43	4.06	1.66
27	3.44	1.24	4.63	1.34	4.13	1.34	3.94	1.24	3.94	1.58
28	3.97	1.43	5.16	1.51	4.72	1.33	5.13	1.18	4.84	1.59
29	3.56	1.72	4.06	1.56	4.72	1.61	3.69	1.62	4.56	1.66
30	3.59	1.52	3.94	1.41	4.38	1.36	3.88	1.52	4.03	1.47
31	3.66	1.23	4.59	1.21	3.97	1.15	4.66	1.52	4.53	1.39
32	3.50	1.24	4.75	1.37	4	1.39	4.53	1.32	4.47	1.44
33	3.38	1.29	4.50	1.14	3.78	1.13	3.78	1.29	3.94	1.63
34	2.97	1.31	4.44	1.29	3.88	1.50	3.16	1.32	3.97	1.73
35	3.44	1.24	4.22	1.64	3.91	1.25	3.97	1.38	4.25	1.55
36	3.56	1.39	5.31	1.42	4.28	1.63	4.94	1.32	4.81	1.73
37	3.56	1.19	5.09	1.20	4.16	1.27	4.75	1.37	4.69	1.57
38	3.25	1.41	4.97	1.28	4.19	1.45	3.59	1.64	4.16	1.65
39	3.34	1.41	4.61	1.33	3.81	1.42	3.97	1.62	3.84	1.46
40	4.09	1.38	4.97	1.18	4.66	1.26	5.03	1.26	5.03	1.28
41	3.41	1.46	4.28	1.57	5.13	1.48	3.63	1.60	5.06	1.95
42	3.63	1.45	4.22	1.58	4.06	1.48	4.25	1.27	4.16	1.76
43	5.44	1.41	4.69	1.33	4.91	1.38	5.88	1.04	5.53	1.41
44	5.25	1.41	5.13	1.26	4.72	1.40	5.56	1.11	5.47	1.61
45	4.81	1	4.56	1.19	4.41	1.04	4.72	1.25	4.75	1.44
46	5.03	1.56	5.16	1.59	5.03	1.20	5.16	1.37	5.47	1.72
47	4.94	1.56	4.56	1.41	4.84	1.32	5.41	1.58	5.50	1.48
48	5.03	1.18	4.75	1.16	4.58	1.12	5.41	0.87	5.38	1.16
49	4.84	1.30	4.41	1.32	4.66	1.21	4.81	1.33	5	1.48
50	5.25	1.27	4.47	1.29	4.47	1.32	4.66	1.45	4.97	1.51
51	4.50	1.34	4.91	1.12	4.66	1.10	4.81	1.28	4.81	1.33
52	4.75	1.50	5	1.48	4.91	1.49	5.34	1.52	5.69	1.45
53	4.88	1.10	4.47	0.95	4.78	1.01	5.16	1.19	5.28	1.28
54	4.81	1.55	4	1.57	5.03	1.38	4.25	1.76	5.31	1.57
55	5.03	1.43	4.03	1.36	5.06	1.56	4.84	1.55	5.56	1.54
56	4.38	1.18	4.09	1.09	4.41	1.27	4.28	1.40	4.69	1.65
57	5.16	1.17	4.84	1.11	4.28	1.05	4.94	1.22	5	1.52
58	4.78	1.16	4.78	1.24	4.84	1.27	5.53	1.24	5.63	1.36
59	4.44	1.41	4.53	1.46	4.69	1.31	4.25	1.55	4.88	1.52
60	4.94	1.29	4.25	1.34	4.69	1.20	4.78	1.50	5.22	1.52

Table 6. Type III analysis of variance table with Satterthwaite's method. The dependent variable is spatial brightness ratings at the participant level (not averages per condition).

	Sum Sq	Mean Sq	Num DF	Den DF	F value	Pr(>F)
E_h(nom)	307.719	307.719	1	1878	268.2478	<0.001**
sc-DER	10.99	10.99	1	1878	9.5802	0.002**
mel-DER	2.208	2.208	1	1878	1.9244	0.166
R_f	1.6	1.6	1	1878	1.3952	0.238
R_g	0.123	0.123	1	1878	0.1074	0.743
$R_{cs,h1}$	31.675	31.675	1	1878	27.6119	<0.001**
CCT	1.371	1.371	1	1878	1.1955	0.274
Duv	3.485	3.485	1	1878	3.038	0.082
$R_{cs,h1}$:E_h(nom)	14.117	14.117	1	1878	12.3064	<0.001**

**denotes a significance level at α ≤ 0.01 level. (nom) denotes that a variable was modeled using its nominal values.

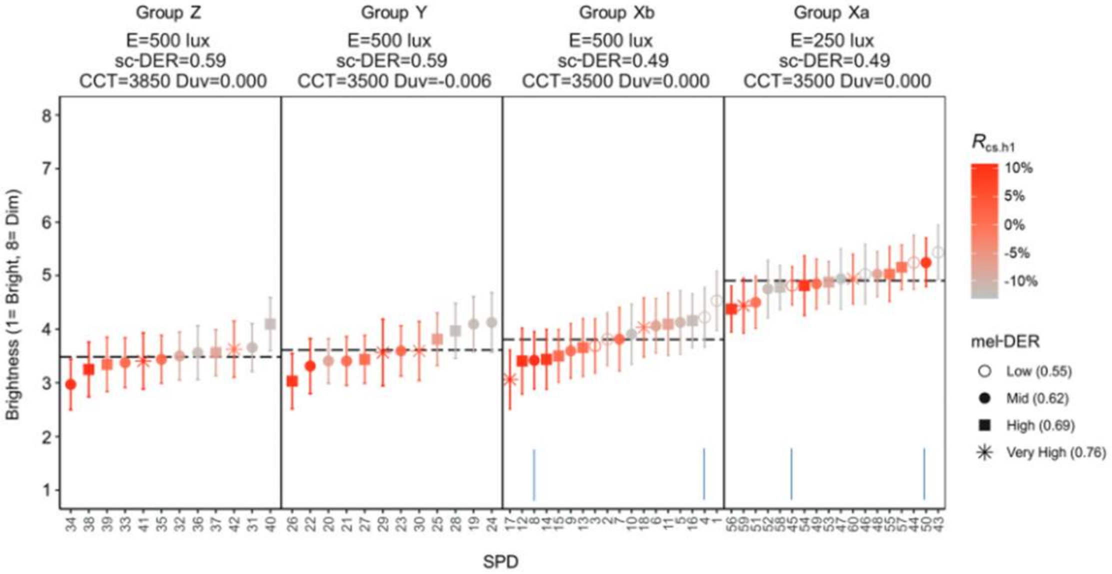


Fig. 5. Mean brightness ratings and 95% confidence intervals for all 60 evaluated conditions. The dashed lines represent the mean for the group.

Regarding the other dependent variables, illuminance level was found to significantly influence perceptions of warmth (Visually Warm-Visually Cool), naturalness (Natural – Distorted), vibrancy (Vibrant – Dull), and preference (Like – Dislike), as shown in Table 7. R_f and R_g significantly influenced rated naturalness and overall opinion of lighting, with the latter model also including the quadratic term for $R_{cs,h1}$. That is, increasing red chroma (and vibrancy) is only preferred up to a certain point. These findings are consistent with past research on perception of color rendition (Esposito and Houser 2019; Royer et al. 2017, 2018, 2020). sc-DER and mel-DER did not significantly affect these perceptions. In addition to illuminance, R_g, CCT, Duv, and sc-DER also were statistically significant predictors for rated warmth.

Comparing mean ratings for the different response variables, brightness and vividness were the most linearly correlated ($r = 0.81$), followed closely by brightness and preference ($r = 0.79$). The linear correlation between brightness and naturalness ($r = 0.56$) and brightness and warmth ($r = 0.23$) were lower. Given the limited illuminance range used in this experiment, it was not possible to detect non-linear effects involving brightness ratings; however, they would likely occur if the illuminance range was expanded. For example, preference would likely decrease if glare became present or visual performance became difficult.

Table 7. *P* value of predictors for the four remaining dependent variables (warm-cool, natural-distorted, vibrant-dull, and like-dislike). The $R_{cs,h1}$:Eh(nom) interaction was not significant for any dependent measure and thus was removed from the models.

	Warm–Cool	Natural–Distorted	Vibrant–Dull	Like – Dislike
E_h(nom)	0.005**	<0.001**	<0.001**	<0.001**
sc-DER	<0.001**	0.387	0.864	0.387
mel-DER	0.456	0.539	0.110	0.413
R_f	0.883	<0.001**	0.806	0.015*
R_g	0.002**	<0.001**	0.769	0.003**
$R_{cs,h1}$	0.763	0.023	<0.001**	0.602
CCT	0.001**	0.226	0.507	0.253
Duv	<0.001**	0.667	0.363	0.331
$R_{cs,h1}{}^2$	–	–	–	<0.001**
$R_{cs,h1}{}^2$:E_h(nom)	–	–	–	0.032*

* and ** denote significance at the $\alpha \le 0.05$ and $\alpha \le 0.01$ levels, respectively. Note: R_{csh1} squared is used to account for quadratic relationship.

4. Discussion

There is a large body of research on SB perception, and SPD has been operationalized in many ways. This is the first study to systematically vary illuminance, chromaticity (CCT and Duv), alpha-opic quantities (sc-DER and mel-DER), and color rendition (R_f, R_g, and $R_{cs,h1}$). Varying seven different factors leads to a highly constrained SPD, while also supporting study of the relative effect sizes of different factors. Even with a partial factorial design, this required evaluation of 60 different SPDs, which to our knowledge is the most presented in a study of SB.

4.1. Color-brightness interaction

The key result from this experiment was that color rendition – specifically $R_{cs,h1}$ – had the largest effect on SB beyond illuminance. While it does not contradict prior work, the use of measures beyond gamut area (and color fidelity) allowed for a more comprehensive evaluation that could also account for gamut shape, and the extensive range of SPDs evaluated allowed for understanding relative effect sizes. The unique finding is that *specific* increases in gamut (i.e., in the red direction) are more influential than others. It is possible that $R_{cs,h1}$ increases can serve as a proxy for opponent channel contributions to SB, as gamut shape is known to align with the red-green and blue-yellow axes of color space. However, it may be that increasing (red) chroma counteracts the Hunt effect, thereby leaving the impression that the illuminance is higher and the space is brighter, or activates the Helmholtz-Kohlrausch effect (Chapanis and Halsey 1955; Donofrio 2011), whereby color purity (saturation) influences brightness at equal luminance. The Hunt effect, Helmholtz-Kohlrausch effect and opponent channel effects may also be intertwined, which is a topic that deserves further investigation. The importance of red in particular is best explained by color psychology (Elliot and Maier 2014), even though the diversity of objects that participant's described as being influential to their decision-making was much greater than in prior studies on color rendition alone.

The experimental results reinforce recent finding on color rendition preference, vibrancy, and naturalness (Esposito and Houser 2019; Royer et al. 2017, 2018, 2020; Zhang et al. 2017): increasing $R_{cs,h1}$ increases preference up to a point where naturalness begins to decline, but increasing $R_{cs,h1}$ continues to increase perceived vibrancy even after rated naturalness declines. R_f and R_g have secondary roles for perceived naturalness and preference. The new element exposed by this research is that increasing preference and SB can be achieved simultaneously with the same spectral manipulations.

The interplay of color and illuminance has been recently explored by others. Bao and Wei (2021) found that preferred levels of $R_{cs,h1}$ and R_g decline with increasing illuminance. They reported maximum preference occurred at about $R_{cs,h1} = 8\%$ at 250 lux and 6% at 500 lux, in a region of relative plateau after sharper changes at lower illuminances. Our findings are consistent with this result. Substantially greater increases in $R_{cs,h1}$ may continue to increase SB, but are likely to negatively impact preference. That is, there is a limit to how much $R_{cs,h1}$ can be used to increase SB without degrading preference. The stimuli in our experiment did not allow for examining over-saturation effects.

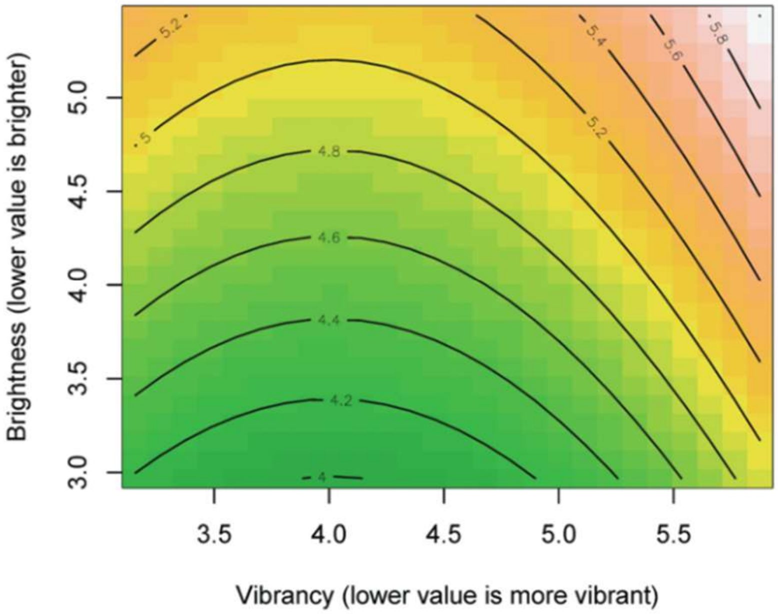


Fig. 6. Response surface contour lines of preference (like–dislike) by brightness and vibrancy. Note that lower values indicate higher brightness, vibrancy, or preference.

Figure 6 shows the response surface for mean preference based on mean brightness and mean vibrancy ratings. This is based on a regression model that includes first order and quadratic terms for vibrancy and brightness. In line with previous studies, preference is highest for mid vibrancy levels and drops at higher levels. In our study, we found higher preference at higher brightness levels; note that we did not test very high brightness levels. At high brightness levels, preference is expected to also drop.

The effects of CCT and Duv were statistically significant for ratings of warm-cool, but not any of the other dependent measures. While chromatic adaptation was carefully controlled, this suggest there was either a small degree of incompleteness, or the participants used other interactions between chromaticity and the room surfaces to determine warmth. For example, the luminance of the red jacket, which varied by about 15% across equal-illuminance stimuli) was correlated with CCT ($r = -0.65$) and to a lesser degree Duv ($r = -0.24$). Notably, luminance was not correlated with rated brightness ($r = 0.02$).

The lack of effect of CCT and Duv on preference is consistent with other findings where adaptation has been controlled (Royer et al. 2022), although it contradicts others where adaptation effects may have created a centering bias. It contradicts recent finding that suggested CCT can influence SB (Hu et al. 2022; Rea et al. 2016). It is possible that the effect is very small such that it can only be observed with very large changes in CCT, or when chromatic adaptation is not controlled. As Fotios (2006) elucidated in 2006, the control adaptation may influence the applicability of the findings in different scenarios, and in general complete adaptation can reduce effect sizes. We believe complete adaptation is the most relevant to office environments, and the most useful to specifiers because it is not depending on an (typically) unknown adjacent space.

It is also possible that the effect of CCT and Duv is minimized in typical chromatic environments (compared to achromatic test apparatuses), where color rendition may have a stronger effect on the chromatic aspect of the stimulus. It is also possible that the effect of chromaticity on SB does not exist when controlling for other measures that relate to the balance of spectral content, such as sc-DER.

4.2. Photoreceptor contributions

Most recent research on SB has focused on cyanopic and melanopic contributions to SB. In our experiment, sc-DER had a statistically significant effect on SB – although the effect size was less than one third the effect size of $R_{cs,h1}$, given the range of the variables studied as constrained by the correlation between spectrally-derived quantities and the need to avoid confounded variables. The significance of the effect is generally in agreement with other recently proposed models, such as those from Khanh et al. (2023), Hu et al. (2022), Rea et al. (2016), Fotios et al. (2015) and Fotios and Levermore (1998a). There is consistent evidence for this effect.

When other factors were controlled for, we found that mel-DER did not have a statistically significant effect on SB at the level of difference that could be evaluated. This does not agree with recent findings from Khanh et al. (2023), Hu et al. (2022), Besenecker and Bullough (2017), and Rea et al. (2016), although it is important to note that all of these studies also found melanopic content to have a smaller effect than cyanopic content. Hu et al. (2022) and Rea et al. (2016) utilized achromatic or minimally-chromatic environments and none of this work addressed color rendition beyond average fidelity (note that seven of the eight color rendition conditions in this work had equal color fidelity). It is possible an effect of mel-DER can be detected in more constrained environments or when the degree of variation in mel-DER is higher (although this is realistically possible only when CCT and Duv are also varied), but that the effect is negligible when color rendition and sc-DER are controlled for in realistic environments. This finding and concept is generally in agreement with the findings of DeLawyer et al. (2020) regarding the effect of mel-DER and hue on object brightness.

Brightness has been a research topic in the CIE for many decades, prior to the differentiation of spatial brightness (i.e., scene brightness) and photometric brightness. A post-hoc analysis examined the relationship between various spectral luminous efficiency functions, including $V_{b,2}(\lambda)$, $V_{b,10}(\lambda)$, $V_{10}(\lambda)$, $V_M(\lambda)$, $V_{2-2015}(\lambda)$, and $V_{10-2015}(\lambda)$ (CIE 1990, 2006, 2015, 2018b)and mean brightness ratings within the 500-lux group. With the exception of $V_{b,2}(\lambda)$, the correlation with mean brightness ratings was poor (R^2 <0.05). $V_{b,2}(\lambda)$ exhibited higher correlation with mean brightness ($R^2 = 0.38$), but this is because it is also highly correlated with $R_{cs,h1}$ ($R^2 = 0.85$). Adding $V_{b,2}$ and the interaction of $V_{b,2}(\lambda)$ and illuminance to the previously described linear mixed model for brightness indicated that neither of the additional terms were statistically significant. Likewise, L_{eq} from the CIE 200:2011 Supplementary System for Photometry, which utilizes scotopic luminance and chromaticity to attempt to correct for spectrum in converting luminance to brightness, was ineffective at predicting the mean experimental brightness ratings for the 500-lux group ($R^2 = 0.06$) – and in fact was negatively correlated.

4.3. Energy savings potential

As with many other studies investigating spectrally based effects on SB, this study found that adjusting the spectrum has the potential to deliver substantial energy savings. With the right changes, there was effectively no difference in SB between the 500 lux stimuli that were rated the dimmest and the 250 lux stimuli that were rated the brightest. Examples of these two types of SPDs are shown in Fig. 7. The chroma- and SB-reducing SPD on the left exhibits color rendition similar to ubiquitous "80 CRI" blue-pump phosphor converted LEDs, whereas the SPD represented on the right offers preferred color rendition and the mean brightness rating was higher than for the one on the left when illuminance was half. Of course, there are also differences in the luminous efficacy of radiation of these SPDs (306 lm/W_{opt} versus 277 lm/W_{opt} for left and right, respectively), but more spectrally efficient SPDs of similar performance can also be created. This experiment did not include the exercise of optimizing SPDs for maximum SB per watt. Conservatively, 30% energy savings are possible – in some applications – after accounting for differences in spectral efficiency (Royer 2019b) and electrical conversion efficiency – a more detailed accounting will be the subject of future work. This would apply in applications where visual performance is not a primary consideration, as in now the case in more situations were computer-based work is dominant compared to paper-based tasks. Enabling such energy savings will require adjustments to the typical means of establishing and implementing illuminance targets (e.g., IES illuminance selection procedure), which currently do not address SB.

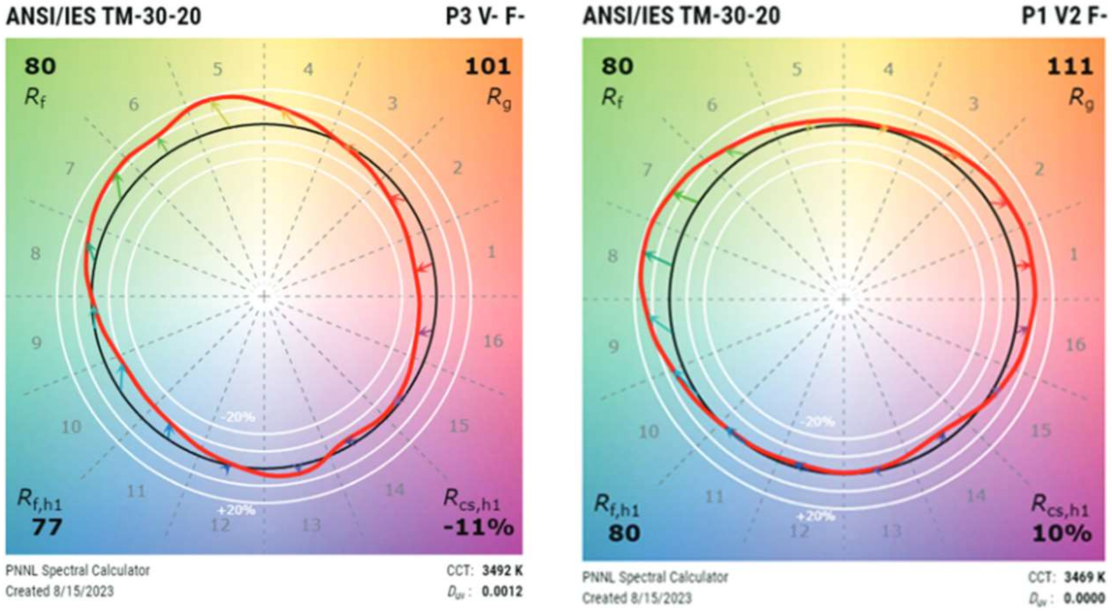


Fig. 7. Comparison of TM-30 color vector graphics and SPDs for stimuli with near equal rated brightness but substantially different illuminance. Left: SPD 2, mean brightness rating = 4.53, illuminance = 501 lux. Right: SPD 56, mean brightness rating 4.38 (lower is brighter), illuminance 249 lux.

4.4. Limitations and future work

This study evaluated spectrally based factors affecting SB. It did not address variations in luminance distribution in the space, mean room surface exitance, or other similar factors. It would be helpful to further understand the relative effect sizes of spectral changes and distribution of light changes. Likewise, this study did not address visual acuity or visual performance, which can be influenced by the spectrum and quantity of light. No visual tasks were performed other than observing the room, and the observation was only for a short duration (typically less than 60 s per stimulus). With prolonged exposure or more demanding tasks, the relative contributions of different photoreceptors may be different.

In this study, SPD was operationalized such that mel-DER varied from 0.53 to 0.77, or approximately 45%. The full range of variation for nominally white light is roughly 0.10 to 2.70. Likewise, sc-DER varied from 0.42 to 0.62, with the possible range for nominally white light of 0.15 to 1.60. While $R_{cs,h1}$ variation (–13% to 11%) was also a fraction of what is possible (–99% to 83%), it is possible that larger effect sizes and greater statistically significance could be found for mel-DER and sc-DER if they were varied over a wider range. However, this would require simultaneous variation in chromaticity and/or color rendition. Likewise, the variation in CCT was relatively small, and it is possible that larger differences could lead to a statistically significant effect.

The time of exposure to each stimulus was short (generally less than 1 minute), and the data generally represent an initial reaction to the stimulus. The time course of reaction for ipRGCs to a light stimulus can vary by subtype (Mure 2021). Not all ipRGCs would be expected to fully respond to each light stimulus – a similar limitation for other research on spatial brightness perception (e.g., 15 second (Zele et al. 2018), 90 second (Khanh et al. 2023), or 2 minute exposures (Hu et al. 2022; Khanh et al. 2023)). Longer duration validation of the experimental findings is warranted.

The effect of $R_{cs,h1}$ on SB was strongest and most consistent in the 500-lux group. Potential differences in the effect at different illuminance levels warrants further investigation.

5. Conclusion

An office-like room was illuminated with 60 different lighting conditions that systematically varied illuminance (nominally 250 lux and 500 lux), chromaticity (CCT [nominally 3500 K and 3850 K] and Duv [nominally –0.006 and 0.000]), sc-DER (nominally 0.49 and 0.59), mel-DER (nominally 0.55 to 0.76), and color rendition (R_f, [nominally 80 and 90] R_g [nominally 94 to 110], $R_{cs,h1}$ [nominally −12% to 10%]). The ranges for chromaticity, sc-DER, and mel-DER were limited to those that avoid introducing confounded variables, whereas the ranges for color rendition and illuminance represent typical conditions for architectural interiors. Using scales of 1 to 8, 32 participants evaluated each stimulus on scales of bright-dim, warm-cool, natural-distorted, vibrant-dull, like-dislike. Linear mixed models identified illuminance, $R_{cs,h1}$, the interaction of $R_{cs,h1}$ and illuminance, and sc-DER as statistically significant factors affecting rated brightness. The levels of variation presented for CCT, Duv, and mel-DER did not produce statistically significant differences in spatial brightness when accounting for variation in the other spectrally-derived quantities. When evaluated individually, mel-DER showed a small to medium effect on spatial brightness which may explain past findings of its effect when color rendition was not considered.

The results demonstrated that adjusting the light from a TM-30 P3 specification with $R_{cs,h1} < -7\%$ at 500 lux to a TM-30 P1 specification with $R_{cs,h1} > 2\%$ at 250 lux can provide equal spatial brightness perception. The latter was also found to appear warmer, more natural, more vibrant, and was more preferred. This presents a substantial opportunity for energy savings – while improving quality – in applications where performance of achromatic visual tasks is not a requirement or illuminance is already well above threshold conditions.

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CRediT authorship contribution statement

MR: conceptualization, funding acquisition, investigation, project administration, supervision, validation. BA: formal analysis, methodology, visualization, writing – original draft, writing – review and editing. ERFB: investigation, software, writing – review and editing.

Data availability statement

The authors are unable or have chosen not to specify which data has been used.

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