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The Paris effect: a tale of eccentricity

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Abstract

Differences in color perception as a function of eccentricity have been studied in the past, especially due to variations of macular pigment in the retina (e.g. [1,2]) and of cone pigment density [3]. However, such differences have been observed under laboratory conditions and this property of the human visual system is not pronounced under everyday conditions. This paper presents an example of a strong effect that was observed at the 31st Color Imaging Conference in Paris when viewing its stage layout and lighting under the overall environmental conditions of the conference hall. In particular, multiple chromatic purplish-violet focus lights were directed at the stage wall. When focusing on one of the lights' reflections on the stage wall, the other lights to the left or right appeared to have a significantly different, duller and cooler color appearance. The effect was immediate and robust to focusing on any one of the chromatic lights, with the others appearing different at the periphery of the field of view.

In order to understand the effect, an attempt was made first to reproduce it using common LED torches coupled with colored gel filters and a pilot psychophysical experiment was performed. The filtered LED light sources were then also measured for a variety of filter colors and simulations were performed, first with differences between 1931 and 1964 color matching functions and then using a cone sensitivity model that allows for predicting the effect of varying eccentricity. This led to the finding that the effect can be measured and expressed at least qualitatively using existing tools, with simulated colorimetries showing the correct direction of shift from warmer more vibrant to cooler, duller colors. We call this the "Paris effect" in honor of the location where we observed it and Paris being the "city of light".

Introduction

Color perception and the resulting color appearance of a scene are well known to depend on the conditions under which a scene is observed. Illumination spectral composition and intensity, scene composition, level of adaptation, viewing angle etc. all contribute to the colors perceived in a given scene. Most models, such as CIECAM02 [1] or CIECAM16 [2], aim to predict perceptual attributes throughout a scene for fixed viewing conditions. At the same time, it is also well documented that there is spatial variation when it comes to color perception – both due to local relational influences (like simultaneous contrast, crispening, etc.) as well as variations at the retinal level. For example, cone sensitivities vary as a function of eccentricity both due to the variation in macular pigment [3] and differences in cone density [3], [4], as is also represented by different standard colorimetric observers depending on angular subtense: the 2-degree and 10-degree observer.

What happens, then as a function of the human visual system's response across its field of view for a physically uniform color stimulus? Does the visual system compensate for its own inherent variations, as it does for variations in the environment (such as changes in illumination and the mechanism of color constancy)? Or does it benefit from such variation across the field of view, as postulated by some color constancy algorithms [5]? How much of these mechanisms are conditioned by the environment in which they evolved – i.e., daylight and natural surface spectral composition? More importantly, is this a phenomenon that can be observed in the real world and do we have the right data/tools to predict it?

In this paper a case is reported of a strong effect of spatially varying color appearance, as experienced at the 31st Color and Imaging Conference at the Sorbonne Université - Campus Pierre et Marie Curie in Paris, France [6]. Fig. 1 shows a photo of the stage layout where several purplish light sources can be seen. Note in particular two that are pointed at the background of the stage wall. What was observed was that when looking at one of the reflected light sources directly, the other one – seen at the periphery – looked noticeably duller and cooler. Switching the viewpoint and looking at the second light directly, the first one looked again noticeable duller and cooler. This was observed robustly over multiple days by two of the authors of this paper, and led to asking the aforementioned questions as well as the formulation of a hypothesis to test.

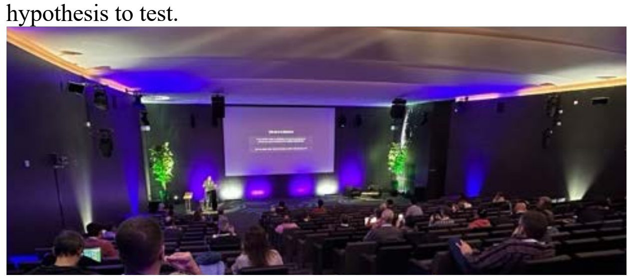

Figure 1: *Conference room showing blueish-purplish lighting on stage.*

A first hypothesis was that this may be an effect of macular pigment variation throughout the retina and when viewing the sample directly vs on the periphery, the density of macular pigment changes significantly enough for this to cause a difference in perceived color for a given stimulus. However, a key part of the observed phenomenon was the specific hue and spectral composition of the light sources. While the specifics remain unknown about the set-up at the Sorbonne, it was possible to successfully reproduce the phenomenon using LED lights with strong spectral peaks and, importantly, the effect was only perceived for a purplish color like that of the Paris stage and it was not reproducible using a display with spectrally smoother output.

This in turn led to refining the hypothesis with the additional constraint of peaks in the low wavelength range of the light source's output, amplified by a purple filter. A further important aspect was the ambient level of brightness where a darker environment (akin to that in the conference hall) was necessary for the effect.

The experiment and instructions on how to reproduce it will be reported first, followed by a theoretical exploration of measured data that confirms and predicts – at least qualitatively – the effect, by means of using the differences between the 1931 (2-degree) and 1964 (10-degree) standard colorimetric observers, first, and extensions with parametric macular pigment density next. These experiments also confirm that the effect is highly dependent on spectral composition of the stimuli, consistently showing the purples and blues result in highest predicted differences. This is not unexpected since the differences in the color matching functions shift in the bluish direction, however the magnitude is typically not substantial enough – for light sources with smooth spectra or with less energy in the blueish region.

This paper is admittedly a first, limited and in parts handwavy attempt at a qualitative analysis, focusing on some aspects of color perception, in particular the interplay between spectral composition and variations in retinal sensitivity. Further study is required to better characterize, quantify and understand the mechanisms that may give rise to such phenomena. However, sufficient evidence is shown to indicate that when non-smooth spectra, such as those of LED lights are at play, color appearance needs to be treated with additional care. What may not be objectionable or noticeable for daylights, tungstens or other spectrally smooth illuminants, may become a new challenge with spiky spectra.

A pilot psychophysical experiment

A key question in approaching this effect is whether it can be replicated. Following some initial attempts to do so unsuccessfully on computer displays led to the idea that the spectra of the Paris CIC lighting may have been LED-based and therefore "spiky". This led to the purchase of Blukar LED Torches using white LEDs and their combination with Decareta Correction Gel Light Filters from among which the purple one looked closest to the Paris CIC lighting when viewed at the center of the field of view.

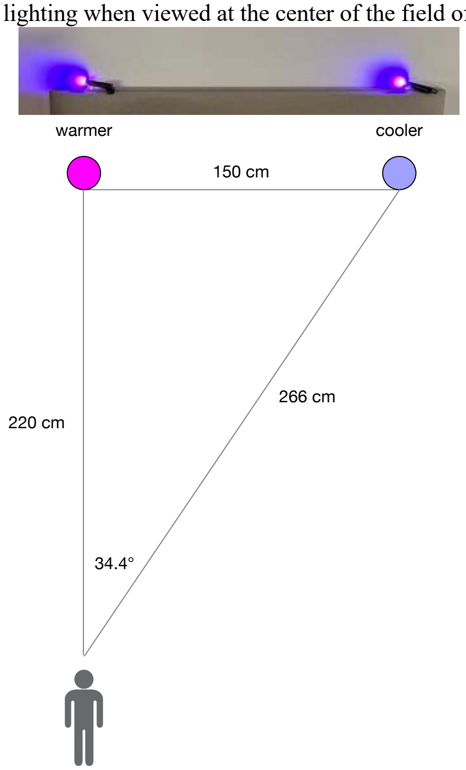

Figure 2. *Viewing setup of pilot psychophysical experiment, showing a case with Δα=34.4º.*

The viewing setup shown in Fig. 2 was used to evaluate the perceptibility of differences between filtered torch color at the center versus periphery. Viewers stood at a distance of 220 cm from a pair of filtered torches placed at an angle against a uniformly-colored wall.

Figure 3. *LED torch filtered by stack of five purple gels used in psychophysical experiment.*

To obtain a level of colorfulness like that at the Paris CIC, five layers of purple gel were stacked and attached in front of the torches (Fig. 3). Note that both choice of gel and gel stacking were made based on memory and likely resulted in significantly different stimuli from those during CIC '23. Nonetheless, they were broadly of a similar kind and the question of whether a similar effect can be observed for these related stimuli still speaks to the repeatability of the phenomenon.

Since it was noticed that both the extent of angular separation, and therefore eccentricity of the peripheral stimulus, and intensity of ambient illumination played a role, various choices were made for these. Angular separation ranged from 4° to 34° and ambient illumination from approximately 8 to 120 lux as measured with an Apple iPhone 14 Pro Max using the Lightaray Innovation GmbH Light Meter LM-3000 app.

Perceptibility of difference at periphery: 0% 50% 100%

JM

Δα \ lux	8.1	79
4	0	0
16	0	0
23	0	0
29	1	0
34	1	0

Δα \ lux	11	65	85	99
34	1	1	0	0

Δα \ lux	10	61
4	0	0
23	0	0
29	1	0
34	1	0

Δα \ lux	8.3	120
4	0	0
34	1	0

JFM

Δα \ lux	8.1	79
4	0	0
16	1	0
23	1	0
29	1	0
34	1	0

TM

Δα \ lux	8	54
34	0	0

Combined

Δα \ lux	8	80
4	0	0
16	0.3	0
28	0.7	0
40	0.7	0

Figure 4. *Per-observer and combined psychophysical data indicating whether stimulus at periphery has different color to stimulus at center of FOV showing results for three observers (JM, JFM, TM, with JM having repeated the experiment 4 times) under different viewing angles (Δα) and luminance level (lux).*

Three male observers with ages between 16 and 49 years took part in the experiment, where they were asked to look at one of the torch-lit regions on the wall in front of them and judge whether its color and the color of the other torch at the periphery of their field of view had the same color or not. If they reported seeing different colors, they were asked whether the peripheral color was warmer or cooler. In all cases where observers noted a difference, it was in a cooler direction.

Fig. 4 shows the results of the various observations recorded for the three observers, where TM and JFM participated in the experiment once and JM repeated in four times. In all cases, observers were asked to first view the stimulus straight in front of them at the center of their field of view and then to turn their head to the right and position the other stimulus at the center. In all cases observers reported the same response for the peripheral stimulus, regardless of which of the pair of stimuli was in the center of their field of view.

As can be seen, the very small-scale pilot experiment indicates that the phenomenon of color difference between the center and periphery of the field of view – the Paris effect – can be seen at low ambient illumination levels of around 8 lux and with angular separations exceeding around 28°.

Predicting the Effect

To build a better understanding of this psychovisual effect, a number of simulations were conducted, first with measurements of the torches/gels used for the psychophysical experiment and then also with synthetic data (CIE LED standards [7], the SOCS reflectance data set [8]). The key question asked here is whether current tools of color formation, color difference and knowledge of spectral sensitivities can reliably predict the observed effect or, conversely, whether predictions would be inconsistent with observations.

Measured filtered LED torches

To simulate the observed differences that were reproduced with off-the-shelf LED torches and colored gels, measurements were taken to compute predictions of color difference.

The torches and a series of filtered alternatives were measured in a viewing booth with all its lights turned off, using a white calibration tile that was spot-lit with the torch by itself as well as filtered versions through the color gels. Multiple measurements were taken using the PhotoReasech PR670 [9] telespectroradiomater for each case, with some repeated at different times (i.e., at the beginning and end of the experiment). The spectral representation provided by the PR670 is 380 to 780nm at 5nm intervals, resulting in 81 spectral samples. The measurement set-up is shown in Fig. 5.

Fig. 6 shows the spectral power distribution of the illuminant (torch) by itself – measured at the beginning and end of the experiment and repeated for two torches used. The LED torches were measured multiple times under the same geometry (45°/0°) and their maximum was used as the torch LED spectrum.

Fig. 7 shows the measurements of LED torch 1 with a sequence of 1 to 5 layers of colored gel filters, each measured twice, for the following color gel labels: violet, blue, green, yellow, red, with violet also measured with a second LED torch to check repeatability. The two measurements were performed to manage noise and averages were used in the experiments. The torch illuminant spectral power distribution by itself – as shown in Fig. 6 (showing both measurements), was used to divide the spectral power distributions measured through the colored gel filters to obtain transmittance spectra. Note how the extremes of the spectral range (380 to 400 nm and 700 to 780 nm) show large amounts of noise – this is due to there being little power in the illuminant (Fig. 6), resulting in divisions by small, noisy values. Since the color matching functions have little to no sensitivity in this area, it should have negligible impact on the simulations presented here.

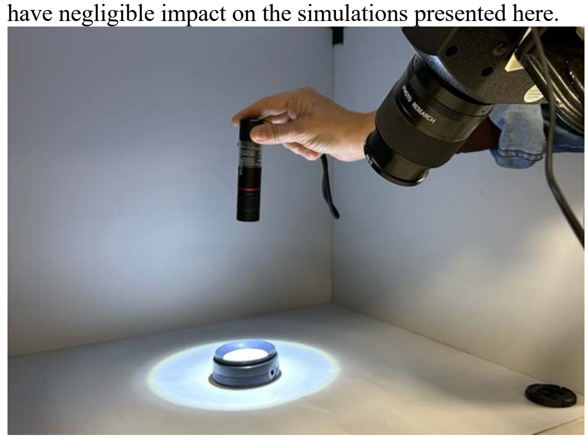

***Figure 5**: Measurement set-up in a VeriVide viewing booth (with all lights switched off), a calibration tile and the PhotoResearch PR670 telespectroradiometer.*

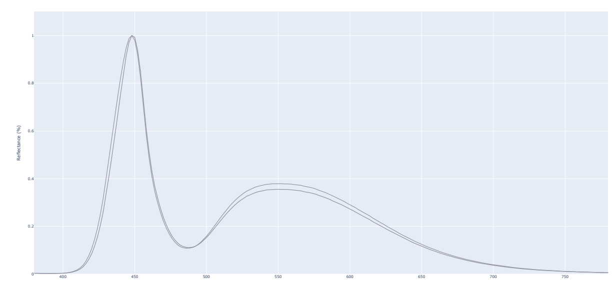

***Figure 6**: Torch LED white tile spectral power distribution average of multiple measurements for torch 1 and 2.*

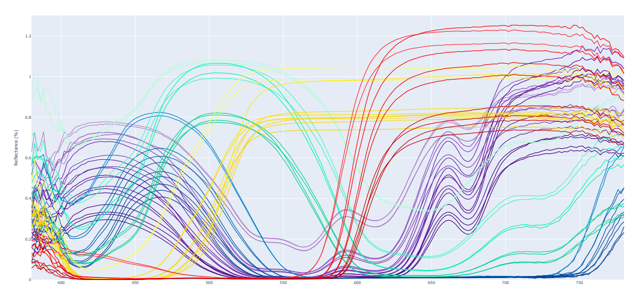

***Figure 7**: LED torch spectral reflectances filtered through all colored gels (violet, blue, green, yellow, red) with torch 1 and violet with torch 2 – showing in each case 1 to 5 layers of gel, measured twice each.*

The first set of experiments starts with the following assumption: if the observed effect is due to differences in retinal color sensitivity – such as cone density and macular pigment density – then it should also be present to some extent in the differences between CIE 1931 (2-degree) and CIE 1964 (10-degree) standard colorimetric observer color matching functions.

This hypothesis is tested by rendering measured transmittances under both 1931 and 1964 CIE color matching functions and the LED torch illuminant, such that:

$$XYZ_{CIE1931} = \boldsymbol{cmf}_{CIE1931} * D(\boldsymbol{l}) * \boldsymbol{r}^T \quad (1)$$

$$XYZ_{CIE1964} = \boldsymbol{cmf}_{CIE1964} * D(\boldsymbol{l}) * \boldsymbol{r}^T \quad (2)$$

where ***cmf*** are color matching functions (a 3xN matrix), ***l*** is the illuminant spectral power distribution (a 1xN vector) and ***r*** is the transmittance vector (1xN). In all following experiments, the maximum spectral resolution available was used and all other quantities at lower spectral samplings were up-sampled to the same resolution (following the ASTM standard for spectral interpolation and extrapolation [10]). The two standard colorimetric observer curves are shown in Fig. 8.

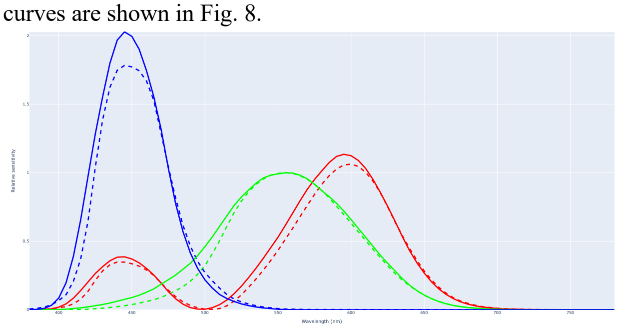

Figure 8 *CIE 1931 (dashed) and 1964 (solid) color matching functions.*

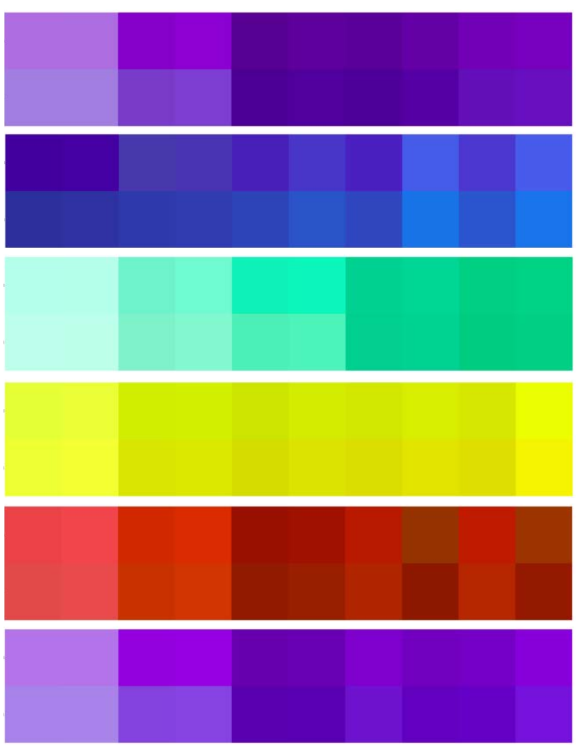

***Figure 9**: Illustration of color differences from CIE 1931 (top row) to CIE 1964 (bottom row) for all filtered versions, ordered by largest to smallest color difference in each row, with violet repeated with two LED torches.*

For both CIE XYZs, CIE LABs can be computed [7], resulting in $LAB_{CIE1931}$ and $LAB_{CIE1964}$, which in turn can be compared with the CIE ΔE2000 color difference metric [11].

Fig. 9 shows these LABs rendered as sRGB with the top row representing the 2-degree (1931) colorimetries and the bottom row representing the 10-degree (1964) case, ordered by largest to smallest DE2000 color differences.

Two observations can be made from the figures: First, the differences are bigger for the violet and blue gel as compared to green, yellow and red. Second, the shift is consistently towards less chromatic and cooler colorimetries. Both are to be expected, since the LED spectrum has a significant peak in the low wavelength range around 450nm, therefore impacting filters that transmit most energy in this wavelength range, while those that transmit more of the longer wavelength ranges are less affected. Tab. 1 summarizes the CIE DE2000 statistics for each of these gels and again, clearly shows that they are largest for the violet and blue cases (and consistent between the two repetitions using two LED torches).

Table 1: color differences of CIE 1931 vs CIE 1964 for measured filtered torch LED samples

Violet	95th %tile: 7.32 Maximum: 7.34
Blue	95th %tile: 10.05 Maximuim: 10.08
Green	95th %tile: 2.03 Maximum: 2.03
Yellow	95th %tile: 3.85 Maximum: 3.90
Red	95th %tile: 2.22 Maximum: 2.24
Violet (torch 2)	95th %tile: 6.94 Maximum: 7.02

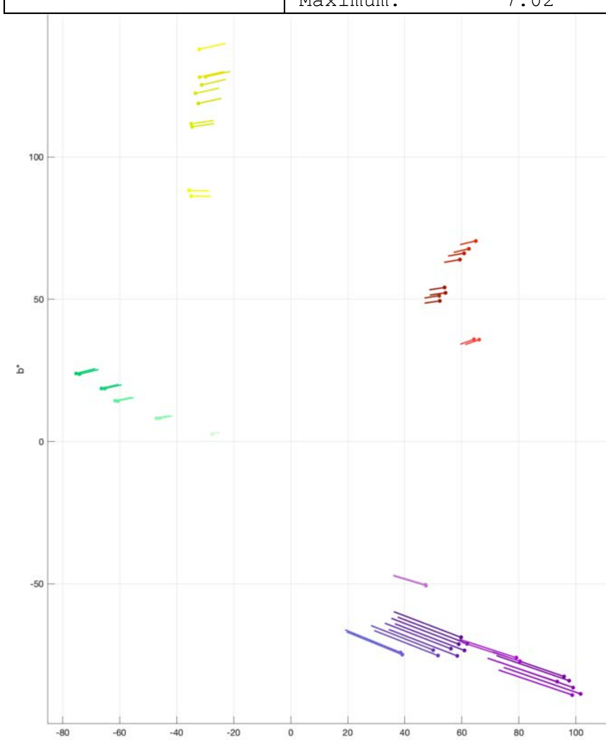

***Figure 10**: Direction of change between LABs from XYZ 1931 (circle) to XYZ 1964 (end of line) using the 5 gels (Violet, Blue, Green, Yellow, Red) with LED torch 1 at the 5 levels of density (numbers of gels stacked together) shown in CIE LAB a*b* view.*

Importantly, this shift in color is also approximately in the observed direction of the Paris Effect, i.e. shifting towards cooler and less chromatic appearances. Whether or not the magnitude correctly represents the observation is a matter of further study.

The table below also summarises the CIE ΔE2000 results for these measured samples and confirms that the largest differences can be seen for blueish-purplish samples, while for green, yellow and red the differences are significantly lower and – at this magnitude and given the viewing conditions (i.e., central versus peripheral vision) likely not observable.

Fig. 10 also shows these differences as directional changes between the 2-degree colorimetry and the 10-degree colorimetry, showing both the magnitude of the change (clearly largest for the violets and blues, as already shown in Table 1) as well as the direction, showing clearly the dulling (moving away from the more chromatic to the less chromatic) and cooling (moving towards blue, especially in the blue and violet samples).

Simulation with standards

The next level of analysis is done with a broader set of reflectances, the SOCS database [8], in order to further stress the areas of maximum possible signal. Additional LED illuminants, the CIE standard set, will also be examined.

Before evaluating the CIE LED set, a simulation with the measured LED torch and the SOCS database is also performed, showing the 10 colors with largest color differences between CIE 1931 and CIE 1964 observers (Fig 11).

***Figure 11**: CIE 1931 vs CIE 1964 maximum color difference patches for the measured LED torch illuminant over the SOCS reflectance set.*

Again blues/purples are the colors with highest color differences, consistent with the original Paris Effect.

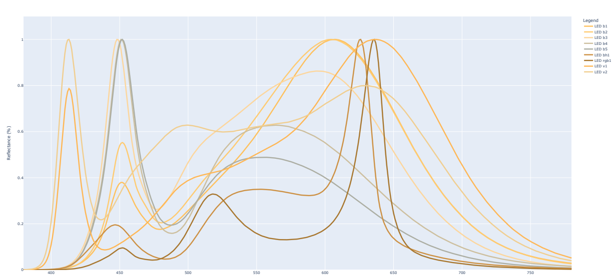

***Figure 12:** Spectral power distributions of CIE LED standard illuminants.*

Turning to the CIE LED standards, these are plotted in Fig. 12, sampled from 380 to 780 nm at 1 nm intervals (401 spectral samples) to show a variety of spectral compositions. As can be seen, several of the CIE standard LEDs also have characteristic peaks in the 400-450 nm range, although some also have additional peaks elsewhere (e.g., around 650nm). Of all the illuminants in this set, LED b5 has the most similar spectral composition to that of the measured LED torch shown earlier.

Fig. 13 shows the top 10 patches from the SOCS dataset for which a change of observer from CIE 1931 to CIE 1964, under the 9 CIE LED standard illuminants causes maximum color difference.

Tab. 2 then summarizes the 95th percentile and maximum color differences for each case (the maxima corresponding to the first pairs of patches in the previous Figure):

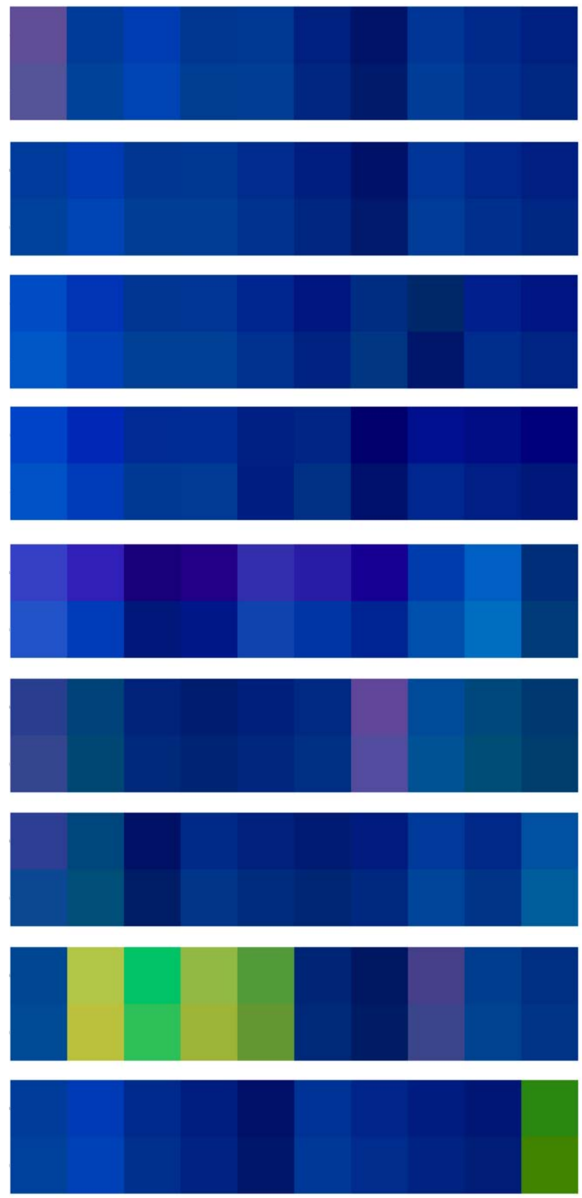

***Figure 13**: Top 10 color differences for the CIE LED standard illuminants (top to bottom) LED b1, b2, b3, b4, b5, v1, v2, rgb1, bh1, showing a simulated colorimetry for CIE 1931 (top row) and CIE 1964 (bottom row) as rendered for sRGB.*

What is clear from these results is that the change of observer from 1931 to 1964 can result in substantially different tristimulus values, depending on the illuminant, with maxima ranging from 4 to over 10 ΔE2000. Also of interest is that in most cases the highest color differences occur for blueish or purplish colors. Since many of the CIE LED standards have a characteristic peak in the lower wavelengths – between 400 and 460 nm – and since a substantial difference between 1931 and 1964 is in the Z function, this is consistent and expected. Also, the highest colorimetric errors are in CIE LED b5, which is the one closest to the LED torch measured in the earlier experiment – the result of pure coincidence.

Table 2: color differences of CIE 1931 vs CIE 1964

CIE LED b1	95th %tile: 2.46 Maximum: 5.74
CIE LED b2	95th %tile: 2.56 Maximum: 6.50
CIE LED b3	95th %tile: 3.02 Maximum: 7.73
CIE LED b4	95th %tile: 3.24 Maximum: 8.44
CIE LED b5	95th %tile: 4.02 Maximum: 10.03
CIE LED v1	95th %tile: 2.70 Maximum: 4.85
CIE LED v2	95th %tile: 3.37 Maximum: 7.43
CIE LED rgb1	95th %tile: 2.52 Maximum: 4.65
CIE LED bh1	95th %tile: 2.40 Maximum: 4.72

Simulation with parametric cone sensitivities

A final level of simulation is performed using formulae for generating standard and individual human cone spectral sensitivities in function of eccentricity [3], [12]. The starting point here is to re-generate the equivalents for the 2-degree and 10-degree case, as well as two additional versions simulating further eccentricity of the visual field with parameters chosen to be progressively more extreme. The resulting curves are shown in Fig. 14 as RGB color matching functions based on the 2016 cone fundamentals [13].

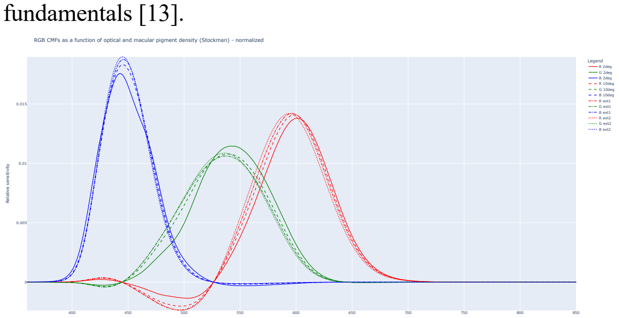

Figure 14: Stockman and Rider RGB spectral sensitivities for 2 degree, 10 degree and two further (more eccentric) alternatives – parameters are provided in Table 3.

Table 3: Human cone spectral sensitivity parameters.

	2-deg	10-deg	Ext1	Ext2
L cone	0.5 OD	0.38 OD	0.3 OD	0.2 OD
M cone	0.5 OD	0.38 OD	0.3 OD	0.2 OD
S cone	0.4 OD	0.3 OD	0.2 OD	0.1 OD
Lens pigment density	1.7649	1.7649	1.7649	1.7649
Macular pigment at 460nm	0.35	0.095	0.0095	0.0

These RGB color matching function can be normalized to have unit area and converted to pseudo-XYZ to remove negative lobes using the CIE process (Fig. 15). As can be seen, these functions differ from those in Fig. 8 that shows the CIE 2-degree and 10-degree standard colorimetric observers, as expected, since the source cone fundamentals are also different.

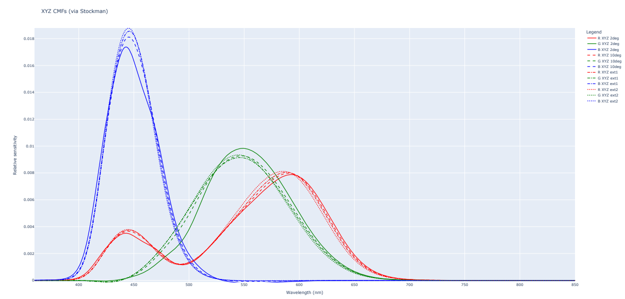

Figure 15: Stockman and Rider RGB spectral sensitivities for 2 degree, 10 degree and two further (more eccentric) alternatives – parameters are provided in Table 2.

In order to determine the relative relationship between the CIE curves and Stockman et al.'s curves for nominally the same angular subtense of 2-degree and 10-degreee, Fig. 16 plots the correlation between each of X/Y/Z functions for the two versions (from Fig. 15 and Fig. 8) based on tristimulus values for all SOCS reflectances, showing very high correlation, with R^2 values of [0.992, 0.999, 0.999] for the 2-degree X, Y, Z functions respectively and [0.994, 0.998, 0.999] for the 10-degree cases.

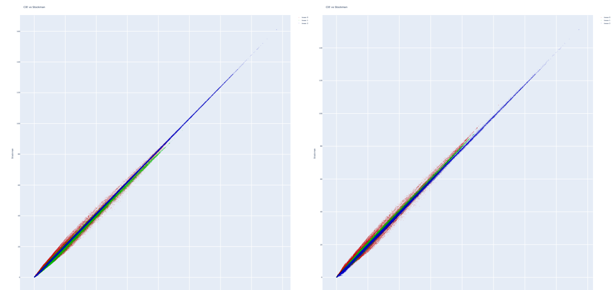

Figure 16: Stockman and Rider RGB spectral sensitivities for 2 degree, 10 degree and two further (more eccentric) alternatives – parameters are provided in Table 2

Given this level of correlation, a qualitative comparison can be made for the change from Stockman's 2-degree to, e.g., the most eccentric parametrized cone sensitivities (denoted "ext2" in Tab. 3) and the relative shift for the LED torch gels looked at, shown in Fig. 17. Here the colorimetry is pseudo-LAB – i.e. applying the RGB → XYZ → LAB conversions to the Stockman cone sensitivities and what is of interest is the qualitative shift in hue which – as before – is towards duller and cooler colors, consistent with the previous experiments shown in Fig. 9 (top sample – corresponding to the same illuminant and same transmittances).

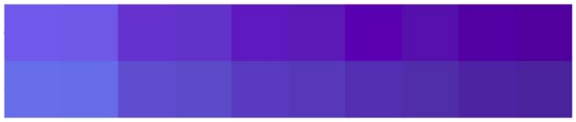

***Figure 17**: Pseudo-LAB colored samples showing Stockman 2-degree (top) vs Stockman ext2 (most eccentric) tristimulus values (bottom) – top 10 samples with largest error from all LED1 filtered gel samples (over all colors).*

Several important caveats apply here: the conversion from RGB to XYZ color matching functions is not derived from this data, affecting the XYZ computation. Likewise, the conversion from pseudo-XYZ to pseudo-LAB is not intended or derived from this data and finally the prediction of color difference using a color difference formula such as ΔE2000 has unknown validity for this data. Nevertheless, as mentioned already, a qualitative evaluation can be done.

Conclusions

In this paper we explored a case where within a static scene, differences in color appearance can be appreciated as a function of central vs eccentric color vision. The effect was observed in the wild but was also successfully reproduced under controlled conditions that approximated them. An analysis of measurements of the spectral composition, coupled with simulations, correctly predicts the nature of this effect, which can be summarized as follows: if there are two identical stimuli which arise from a light source with significant peak energy in the low wavelength ranges, when viewing one of the stimuli directly, the second one on the periphery will appear duller and cooler. Specifically, for blues or purples that have a sharp peak in the 400 to 500 nm range, the color appearance shifts towards cooler, less saturated (duller) bluish hues. From measurement and computational simulation it is shown that this effect is significantly stronger for such samples as opposed to other spectral compositions that don't have pronounced spectral peaks. The ambient luminance level also appears to play a role here, where the effect is more pronounced at lower levels of luminance.

These findings are of a primarily qualitative nature with the quantitative analysis being a first, limited investigation. More work is needed to fully characterize the luminance levels, angular dependency and spectral dependencies of the Paris effect. Furthermore, identifying whether this effect results in challenges e.g. for newer display, projection (such as laser projectors) or AR/VR technology remains to be seen.

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