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THE IMPACT OF MATCHING PRIMARY PEAK WAVELENGTH ON COLOR MATCHING ACCURACY AND OBSERVER VARIABILITY

Li, J.[1]*, Hanselaer, P. [1], Smet, K.A.G.[1]
[1]KU Leuven, ESAT/Light&Lighting Laboratory, Ghent, BELGIUM
jiaye.li@kuleuven.be

Abstract

Over time, much work has been carried out to ascertain the accuracy of the CIE standard color-matching functions, but no definitive answer has been given. Recent work indicates an undeniable discrepancy between visual and computed metamers calculated using the existing CIE (the International Commission on Illumination) standard observer CMFs, especially when matching with narrowband sources. With a spectrally tunable solid-state light source, a series of pilot matching experiments have been done using primaries with different peak wavelengths. The results indicate which regions in wavelength space are most sensitive to generating matching inaccuracies for a given CMF set and which primary combinations have the most stable matching performance.

1. Introduction

Color matching functions (CMFs) or cone fundamentals (CF) are one of the most fundamental aspects of color science and color perception. However, studies have shown that undeniable discrepancies exist between visual matches and those predicted by existing CMFs, especially for matches made using narrow-band primaries generated by solid-state sources or laser based sources [1-4].

For color perception and applied color science, it is of interest to investigate which primaries and CMF set(s)result in the most stable (independent of CMF set) and accurate match predictions. These issues have been explored in a series of color matching experiments with a spectrally tunable multi-channel LED source and an analysis of the results in terms of matching accuracy and variability.

2. Methods

2.1 Experimental setup

Matching experiments were performed using a specially designed viewing booth that allows to present spectrally tunable stimuli in reflective / object appearance mode and immersive or non-immersive viewing conditions. A schematic of the viewing booth is shown in Figure 1.

The background is covered with a neutral (spectrally flat) grey material and illuminated by a 50W halogen lamp. To obtain a neutral reference illumination, the halogen light was filtered by a uniform and flexible blue filter (CCT conversion filter: LEE filter 201). The filtered halogen light has a chromaticity slightly above the blackbody locus at around 5000 K. The luminance of the background was set at a level representative of building interiors (~40 cd/m²) [5].

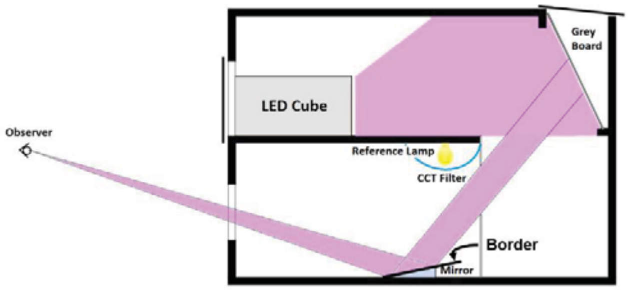

Figure 1. Experimental Setup: Overall configuration of viewing box.

The matching field was provided by the specular image, in a tilted mirror (3° field of view), of a grey diffusive plate illuminated by a spectrally tunable light source. The latter was a calibrated Thouslite LED cube with 15 10-bit channels providing the different matching primaries (see Figure 2). The mirror was surrounded by a frame (5° field of view) of spectrally neutral (grey) material. As the mirror was tilted, an observer, seated at a fixed position using a chin rest, could not see the halogen reference lamp, but only the reflected image of the diffuse plate (see Figure 1). This mirror set-up has been shown in a pilot study that, it can provide an indistinguishable stimulus with the same luminance and color as an opaque, reflective card covered by a glass plate illuminated by the filtered halogen.

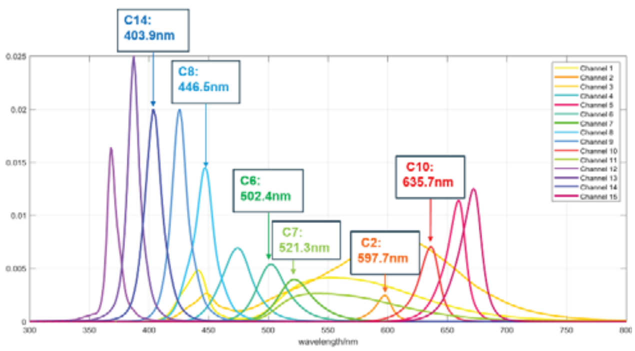

Figure 2. Spectral radiance of the channels of the LED cube as measured in the mirror from the observer position. The channels selected as matching primaries are also indicated.

The viewing box was separated in a top and bottom section by a black painted wooden plate. The setup as shown in Figure 1, with the neutral grey plate and LED cube located in the upper chamber of the viewing box and with a small aperture to the front bottom chamber, was designed to minimize biasing the adaptation and reference fields provided by the filtered halogen lamp. To provide optimal mixing, the upper chamber was covered by spectrally flat, non-UV-enhanced, white material.

A calibrated Ocean-optics tele-radio spectrometer was used to measure the spectral radiance of each match made by the observers.

2.2 Matching primaries

Matching stimuli were generated by the reflected light of a calibrated spectrally tunable LED cube. Six channels were chosen as primaries: two long wavelength (red), two medium wavelength (green) and two short wavelength (blue). The primaries were chosen to provide a large gamut size at 40 cd/m² (see Figure 3) and to have a substantial gap in wavelength space between their peaks. The selected primary and their peak wavelengths are shown in Figure 2. These primaries were combined in 6 different primary sets, each composed of a long, medium and short wavelength primary (See Table 1 for an overview of their peak wavelengths, full-width-half-maxima and maximum radiance (LED channel supplied by maximum current) as measured in the mirror from the observer's position).

Table 1: Overview of primaries

Primary	Peak wavelength (nm)	Full-width-half-maxima (nm)	Maximum radiance (W/m².sr)
Red 1	635.7nm	19	31.42
Red 2	597.7nm	16	24.05
Green 1	521.3nm	34	88.80
Green 2	502.4nm	29	75.17
Blue 1	446.5nm	18	22.97
Blue 2	403.9nm	15	3.72

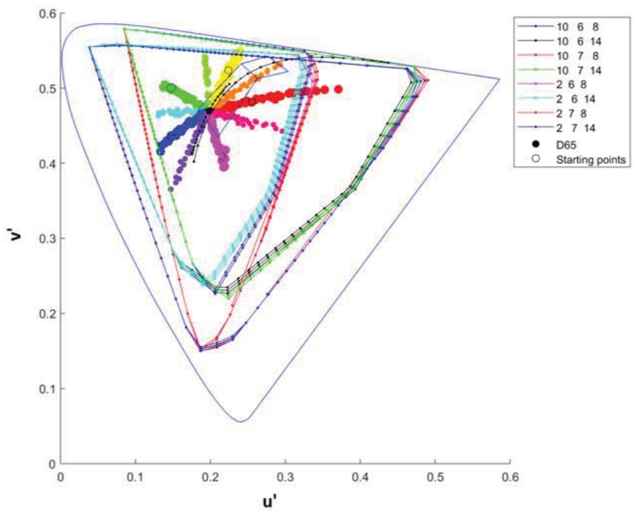

Figure 3. Color gamuts of primary sets at 40 cd/m² in the CIE 1976 u'v' chromaticity space diagram. Starting points (open circles) distributed evenly on the Munsell hue lines (indicated by the red, yellow, green, blue and violet solid circles) and having the same distance to the D65 reference white point are also shown.

2.3 Experiment sessions

Matching experiments were made under immersive and non-immersive conditions and with observers making achromatic matches from memory (memory achromatic matching) and with the grey mirror frame, illuminated by the filtered halogen, as reference color. Note that the latter has a smooth broad-band reflection spectrum and had the same luminance as the match field (40 cd/m²). For both memory achromatic matching and reference color matching, the halogen illumination was turned on.

In the non-immersive condition, observers were positioned 125 cm away from the mirror (matching field), the open window of viewing box was 25 cm wide, 15 cm high, which provided an adapting field size around 18°. In the immersive environment, observers' eyes were positioned 45 cm away from the mirror, just inside the viewing window of the viewing box. The adapting field size for the immersive environment was above 150°. To ensure a fixed position, observers used a chin-rest. In the immersive case, the size of mirror and frame were proportionally decreased to give the same matching field as in non-immersive case. A photo taken from the observer's point of view is shown in Figure 4.

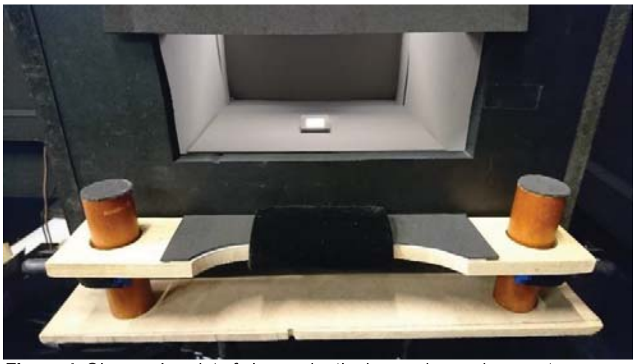

Figure 4. Observer's point of view under the immersive environment condition: A chin rest was installed on the viewing box; a smaller mirror than in the non-immersive conditions was used to maintain the same field of view.

2.4 Experimental procedure

The experiments were split in 4 sessions (2 environment conditions: immersive and non-immersive; 2 matching paradigms: memory color matching or simultaneous matching).

At the start of each session, observers were briefed on the goal of the study and given verbal instructions on the experiment procedure, during which time they could adapt to the background and surround conditions. During the experiment, observers were asked to make several achromatic matches by adjusting the color of the LED cube illumination. Observers could navigate in the CIE 1976 u'v' chromaticity diagram by using the arrow keys on a regular keyboard.

After finishing their color match, observers were asked to rate how satisfied they were with the final match on a scale of 0-10 (0 means not satisfied at all, 10 means very satisfied).

In each of the four sessions, observers made 30 matches (6 primary sets x 5 starting points). Each observer made a total of 120 matches. Each primary set was matched 5 times starting from different initial chromaticities, evenly distributed along the hue circle centered on the D65 chromaticity (see Figure 3), to avoid starting bias.

The luminance of matching field, the matching primary-sets, starting stimuli, and field of view of matching field (mirror and mirror frame) were kept the same across all four sessions. The order of the primary sets and starting points was randomized for each observer in each session.

2.5 Observers

9 observers (6 females, 3 males, average age: 24± 4 years) with normal color vision, as tested by the Ishihara 24 plate test, participated in the experiments. The same observers participated in all four experiment sessions.

3. Results and discussion

Nine observers made a total of 1080 matches spread over 4 sessions. Results were analyzed per environment condition (immersive (I) vs non-immersive (NI)) and match condition (memory matching (MM) vs reference matching(RM)). In each session, ninety matches were made for each primary set. The chromaticity of the mean match and the standard error (SE) ellipses around the matches are plotted in the CIE 1976 u'v' diagram in Figs. 5 (NI-MM), 6 (NI-RM), 7 (I-MM) and 8 (I-RM). Chromaticity was calculated using the CIE 1931 2°, CIE 1964 10° and CIEOP06 2° and 10° CMFs (each indicated by different colors in the figures).

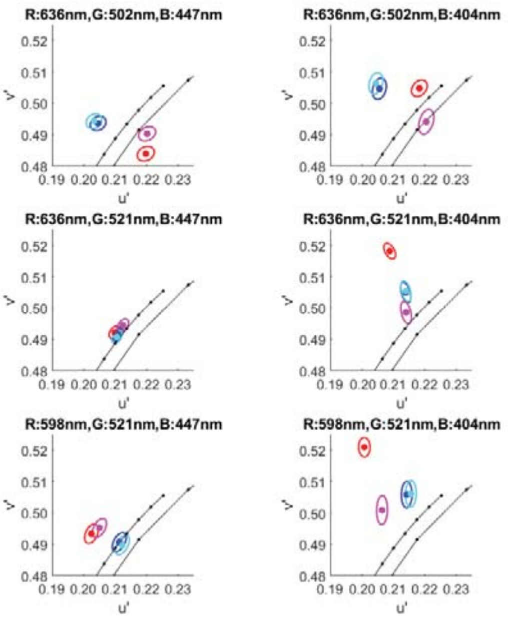

__Figure 5.__ NI-MM condition: mean CIE 1976 u'v' chromaticity of the memory matches (color dots) made in the non-immersive condition and their SE ellipses for different primary sets (subplots a-f) and different CMF sets (Red: CIE 1931 2° CMFs, Blue: CIE 1964 10° CMFs, Magenta: CIE 2006 2° CMFs, Cyan: CIE 2006 10° CMFs).

From Figure 5 several observations can be made for the non-immersive memory matching condition (NI-MM). First, different primary sets result in different distributions of the mean match. The mean matches calculated using some CMF are substantially different (non-overlapping SE ellipses). Second, while most primary sets lead to approximately equal sized SE ellipses, the primary-set with peak wavelengths at 636 nm, 521 nm, and 447 nm (channel: 10, 7, 8), are slightly smaller than the others. In addition, for this primary set the matches predicted by the different CMF sets are much more similar, suggesting that these primaries are less sensitive to generating metameric differences. Other primary sets show spreads in the average matches that differ over different directions depending on which primary is switched in a set.

For example, switching the 521 nm green primary to the 502 nm primary mainly causes a split between the 2° and 10° CMFs along the u'-direction, with the 10° and 2° matches moving to the lower and higher u' values, respectively (compare the middle column graphs in Figure 5 with the left column). On the other hand, switching the 635 nm red primary with the 598 nm primary, does not substantially affect the 10° matches, but causes a shift of the 2° matches to lower u' values (compare the middle column graphs in Figure 5 with the right column). Furthermore, a switch of the 447 nm blue primary with a 404 nm primary causes a shift of the match chromaticity towards higher v' values for all CMFs, except for those of the CIEOP06 2°, which remain quite stable. The CIE 1931 2° show the largest upward shift. Finally, the CIE 1964 and CIE0P06 show very similar predicted matches, both in the position of the mean, as the size, shape and orientation of the SE ellipses. The CIE 1931 and CIEOP06 2° CMFs result in very different matches for many primary sets, especially for the primary sets containing the 404 nm primary. This is consistent with the reported underestimation of the sensitivities of this CMF set at lower wavelengths.

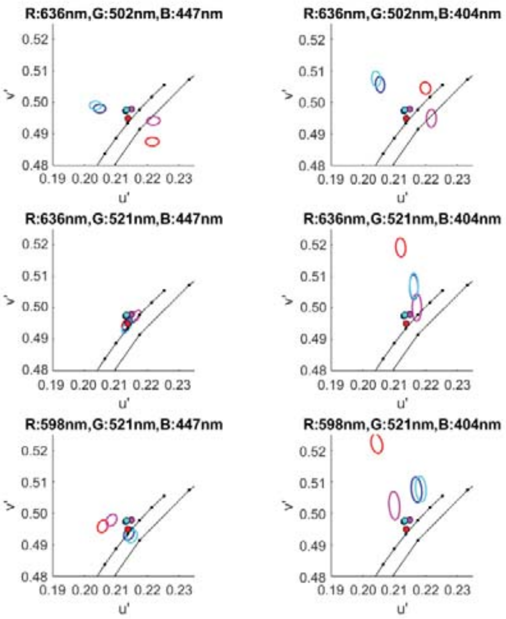

__Figure 6.__ NI-RM condition: SE ellipses in the CIE 1976 u'v' chromaticity diagram of the matches made to a reference for the non-immersive condition for different primary sets (subplots a-f) and different CMF sets (Red: CIE 1931 2° CMFs, Blue: CIE 1964 10° CMFs, Magenta: CIE 2006 2° CMFs, Cyan: CIE 2006 10° CMFs). The color dots represent the reference chromaticity generated by the grey frame of the mirror illuminated by the filtered halogen.

The results for the matches made to a reference grey in the non-immersive condition (NI-RM) show very similar results, as can be seen from Figure 6. In addition, it can be observed that the ellipses are smaller when matching to a reference color compared to memory color matching (each observer has his own idea about what constitutes neutral grey, regardless of any differences in their visual perception). It can also be seen that the reference grey, generated by the spectrally neutral frame of the mirror illuminated by the filtered halogen, with its smooth broadband spectrum, results in similar chromaticity values for all CMF sets.

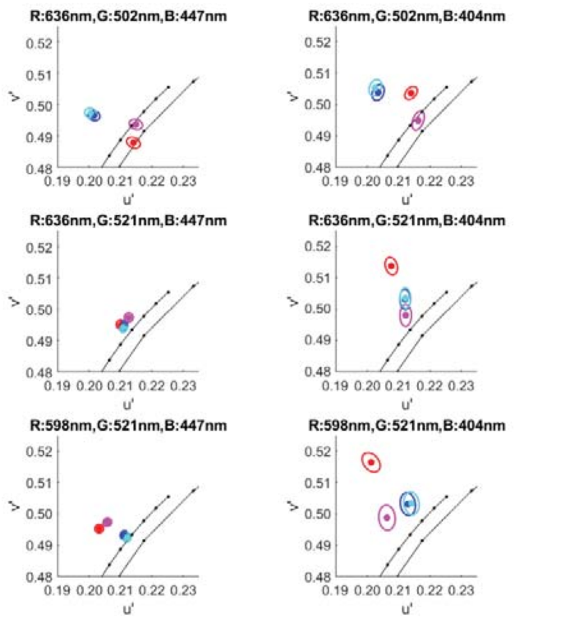

Figure 7. I-MM condition: mean CIE 1976 u'v' chromaticity of the memory matches (color dots) made in the non-immersive condition and their SE ellipses for different primary sets (subplots a-f) and different CMF sets (Red: CIE 1931 2° CMFs, Blue: CIE 1964 10° CMFs, Magenta: CIE 2006 2° CMFs, Cyan: CIE 2006 10° CMFs).

For the immersive memory matching condition, it can be observed from Figure 7 that the ellipse sizes are slightly smaller than for the non-immersive memory matching situation. It can also be seen that there is a shift towards higher v' values. In fact, the matches moved closer to the chromaticity of the reference grey, presumably, because observers used the grey background as reference despite being instructed to ignore this and just match based on memory. For the reference match condition in the immersive environment, again the results are quite similar to before, as can be seen from Figure 8. The same distributions of the ellipses and shifts in their positions upon switching the different primaries can be observed.

The results from all four experiments indicate that the primary set with the 636 nm, 521 nm and 447 nm peak wavelengths is the most stable across changes in CMF set. These wavelengths are typical LED RGB-primaries [2] and are widely used both in research and industry [12]. Of all tested wavelengths, they are also closest to the monochromatic red (650 nm), green (530 nm), blue (460 nm) used by Wright [6] in his 2° matching experiments and to the peak wavelengths (645.2nm, 526.3nm, and 444.4nm) of the primaries in the Stiles & Burch [7-8] experiments. These experiments generated data used in the derivation of the CIE 1931 2° and 1964 10° CMFs. The Stiles & Burges data was also used by Stockman in the development of a cone fundamental model [9-10], on which the later CIEOP06 CMFs are based [11]. It is therefore understandable that this particular primary set is stable across changes in CMFs set. Finally, it is important to mention that recent work on color matching [13-16], also adopted primaries with peak wavelengths close to the ones of the stable set, thereby potentially underestimating the discrepancies between visual and calculated matches.

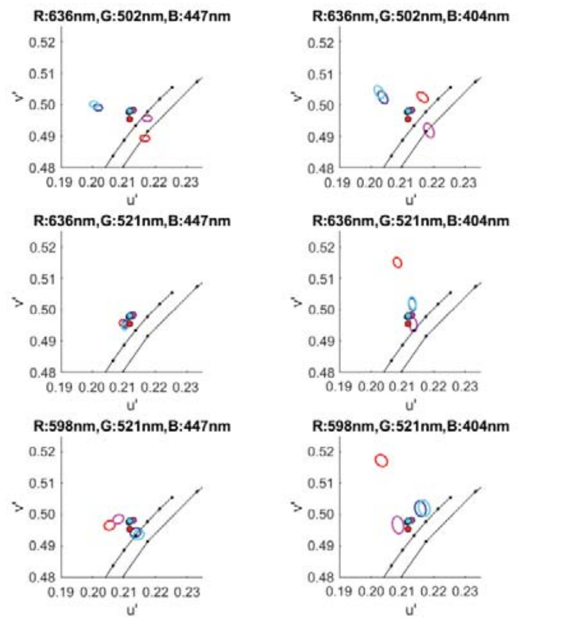

Figure 8. I-RM condition: SE ellipses in the CIE 1976 u'v' chromaticity diagram of the matches made to a reference for the non-immersive condition for different primary sets (subplots a-f) and different CMF sets (Red: CIE 1931 2° CMFs, Blue: CIE 1964 10° CMFs, Magenta: CIE 2006 2° CMFs, Cyan: CIE 2006 10° CMFs). The color dots represent the reference chromaticity generated by the grey frame of the mirror illuminated by the filtered halogen.

4. Conclusion

According to the experiment results, the choice of spectrally narrowband primary set has a clear impact on the chromaticity of the color match calculated using different CMF sets. Switching one of the primaries resulted in different shifts in the chromaticity calculated by the different CMFs. The same relative trends were observed for all experiment conditions. The 10° CIE 1964 and CIEOP06 CMF produced very similar match chromaticities, while those of the 2° CIE 1931 and CIEOP06 differed much more. The former was found to the most different when a very short wavelength primary (404 nm) was used, confirming earlier reports on the problems of this CMF set. While there were substantial differences in the calculated match chromaticities depending on the adopted (spectrally narrowband) matching primaries, the chromaticities calculated using the different CMF sets were very similar for the spectrally smooth and broadband reference grey. Calculated chromaticities for matches made by mixing the light of the 636 nm, 521 nm and 447 nm primaries which are typical LED RGB-primaries [2], were found also found to be stable across changes in the CMF set used to calculate them. From all the test primary sets, this set has peak wavelengths closest to those adopted in the Wright [6] and Stiles&Burges [7-8] matching experiments which generated data that was used in the development of the CIE 1931 2° and the CIE 1964 10° CMFs. The data from Stiles&Burges was also used in the development of Stockman's cone fundamental model [9-10] on which the CIEOP06 CMFs are based [11]. It is therefore reasonable that this particular primary set can obtain the least discrepancy between visual and computed metamers. Furthermore, as recent work on color matching accuracy also adopted primary sets with wavelengths close to those of this stable set, the reported accuracy and variability of calculated matches could be severely underestimated. In future work, we will look collect a large scale color matching data set for different primary sets to more accurately characterize color matching accuracy and variability and to provide an improved set of CMFs.

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Author Biography

Jiaye Li received her MS in optical electronics from the University of Xiamen, China (2016) and her ME from ENSEA, France (2017). She is currently working as a PhD student in Light & Lighting Laboratory in KU Leuven University. Her research has focused on color matching and observer variability.