



International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

OP69

**VISUAL EVALUATION OF CIE 2015 CONE FUNDAMENTAL-
BASED 10° COLOUR MATCHING FUNCTIONS FOR
LIGHTING APPLICATIONS**

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DOI 10.25039/x46.2019.OP69

from

CIE x046:2019

**Proceedings
of the**

29th CIE SESSION

Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

The paper has been presented at the 29th CIE Session, Washington D.C., USA, June 14-22, 2019. It has not been peer-reviewed by CIE.

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VISUAL EVALUATION OF CIE 2015 CONE FUNDAMENTAL-BASED 10° COLOUR MATCHING FUNCTIONS FOR LIGHTING APPLICATIONS

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DOI 10.25039/x46.2019.OP69

Abstract

The CIE 2015 cone fundamental-based colour-matching functions (CMFs), especially the 10° CMFs, are expected to improve visual colour matching in lighting applications. The chromaticity specifications for lighting products are based on the CIE 1931 CMFs (2° observer) and are given by correlated colour temperature (CCT) and the distance from Planckian locus (Duv). To study the impact of introducing the CIE 2015 CMFs, computational analyses were first made to determine the magnitude of changes in CCT and Duv values for various lighting sources. The results showed significant changes in both CCT and Duv. Then vision experiments were conducted to compare the CIE 2015 CMFs and the CIE 1931 CMFs for visual colour matching of lights with various spectral distributions. The results showed that CIE 2015 10° CMFs performed better overall but also that there is a strong dependence on the age of subjects and the spectral distribution of light sources.

Keywords: colour matching function, cone-fundamental-based CMF, colour appearance, correlated colour temperature, Duv, lighting applications

1 Introduction

In the current International Commission on Illumination (CIE) colourimetry system, the CIE 1931 colour matching functions (CMFs) (2° observer) and the CIE 1964 CMFs (10° observer) are standardized (CIE/ISO, 2007). The CIE 1931 CMFs are dominantly used in lighting applications, and in particular, the colour specifications of all lighting products are based on the CIE 1931 CMFs. The CIE 2015 cone-fundamental-based CMFs (CIE, 2015) were recently developed from the latest research on human vision. CIE encourages field research to compare the new and existing CMFs in light-emitting diode (LED) lighting applications to support future standardization of the new CMFs (CIE, 2016). The 10° CMFs, especially, are considered to better represent visual experience in daily lighting environments. Thus, there is a strong interest in introducing the CIE 2015 10° CMFs (abbreviated "CIE F,10" in this paper) to replace the CIE 1931 CMFs (abbreviated "CIE 1931" in this paper) for colour specifications in lighting.

The chromaticity of lighting products is specified or designed by correlated colour temperature (CCT) and, often, also by Duv (distance from Planckian locus) (e.g., ANSI, 2017). CCT and Duv are currently based on CIE 1931. The details of the calculation procedures for Duv are available (Ohno, 2014). To evaluate the impact of introducing CIE F,10 into lighting applications, therefore, the differences in CCT and Duv values between CIE 1931 and CIE F,10 for various light sources need to be evaluated. When different CMFs are adopted for chromaticity diagrams, the chromaticity coordinates of all light sources will change significantly. However, by definition, the CCT and Duv values of Planckian radiation do not change regardless of CMF, while these values for non-Planckian sources can change significantly if CMFs are changed, depending on their spectral power distributions (SPDs). Then, the question is: which CMFs, CIE F,10 or CIE 1931, correlates better with perception of the CCT and Duv of real light sources?

First, a computational analysis was performed to quantify the magnitude and direction of changes of CCT and Duv of various light sources when CMFs are changed from CIE 1931 to CIE-F,10. Based on this computational analysis, a vision experiment was designed and conducted to test whether CIE F,10 better correlates with perception, by comparing perceived

colours of pairs of lights matched under CIE 1931 and CIE F,10. The experiment was carried out using a spectrally-tuneable LED lighting double booth at National Institute of Standards and Technology (NIST) at two CCTs, 3000 K and 5000 K, which are typical CCTs in general lighting.

2 Computational analysis

For the analyses, the (u', v') chromaticity diagram using CIE F,10 was created for computation of CCT and D_{uv} under CIE F,10. The chromaticity coordinates on this chromaticity diagram are denoted $(u'_{F,10}, v'_{F,10})$. The CCT and D_{uv} calculated on this diagram based on CIE F,10 are denoted $T_{cp,F,10}$ and $D_{uv,F,10}$. **Figure 1** shows the (u, v) and $(u'_{F,10}, v'_{F,10})$ chromaticity diagrams comparing CIE 1931 and CIE F,10. **Figure 2** shows the comparison of the Planckian locus on (u, v) and $(u'_{F,10}, v'_{F,10})$ diagrams.

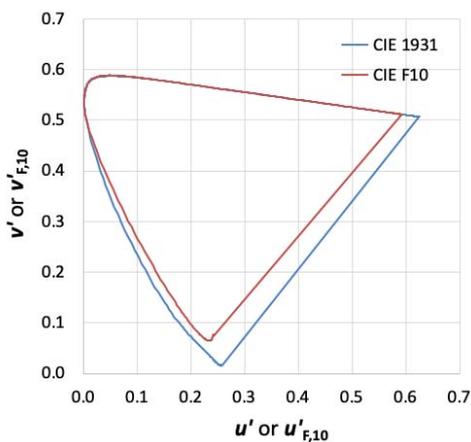


Figure 1 – (u, v) and $(u'_{F,10}, v'_{F,10})$ chromaticity diagrams

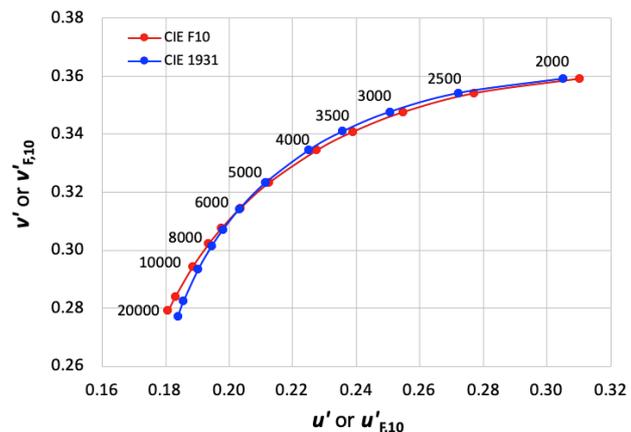


Figure 2 – Planckian locus on (u, v) and $(u'_{F,10}, v'_{F,10})$ diagrams

The values of T_{cp} and D_{uv} (in CIE 1931) and $T_{cp,F,10}$ and $D_{uv,F,10}$ (in CIE F,10) were computed for various light source SPD data. **Figure 3** shows the results for a set of SPD data from the SPD Library in the TM-30-15 (IES, 2015) calculation tool. Among the 318 lamps' data in the Library, only the data of commercial lamp products (except incandescent lamps) with $R_a \geq 60$ were selected, comprising a total of 187 lamp spectra, including 36 fluorescent lamps, 14 high-intensity discharge (HID) lamps, 129 LED phosphor-type lamps, and 8 LED hybrid lamps. Note that there are no data for red-green-blue (RGB) or red-green-blue-amber (RGBA) type products in this data set.

The figure shows that the changes in CCT and D_{uv} (from CIE 1931 to CIE F,10) are mostly in the same direction, and are larger for higher CCT sources. The average change of D_{uv} for sources ≥ 4000 K is around -0.004 and maximum change of D_{uv} is about -0.009. This means that a light with a certain value of D_{uv} under CIE F,10 is more yellowish or greenish than a light with the same D_{uv} value under CIE 1931. The CCT values also change significantly for some sources. Therefore, introducing CIE F,10 to lighting applications would make a significant impact, especially for chromaticity specifications of light sources (e.g. ANSI C78.377) that define tolerance ranges by CCT and D_{uv} .

A comparison was also made for the 2° CMFs of CIE 2015 (CIE F,2) and CIE 1931 for the same set of SPD data, the result of which is shown in **Figure 4**. It is clear from this result that the changes are insignificant in most cases. The maximum difference in D_{uv} is 0.002. Note that CCT is given in a linear scale in this graph, so that the same CCT difference value (the horizontal lengths of two points) for higher CCTs corresponds to a much smaller perceived colour difference than for lower CCTs. From this result, it is considered that there would be little benefit to introducing the cone fundamental-based 2° CMFs in lighting applications.

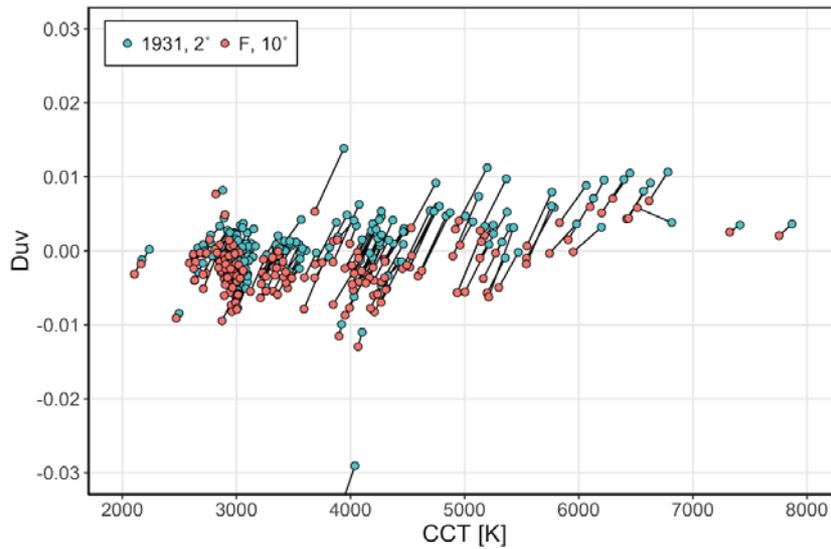


Figure 3 – Comparison of CIE 2015 10° CMFs and CIE 1931 for calculated CCT and Duv values of 187 SPDs’ data from the TM-30 SPD data library

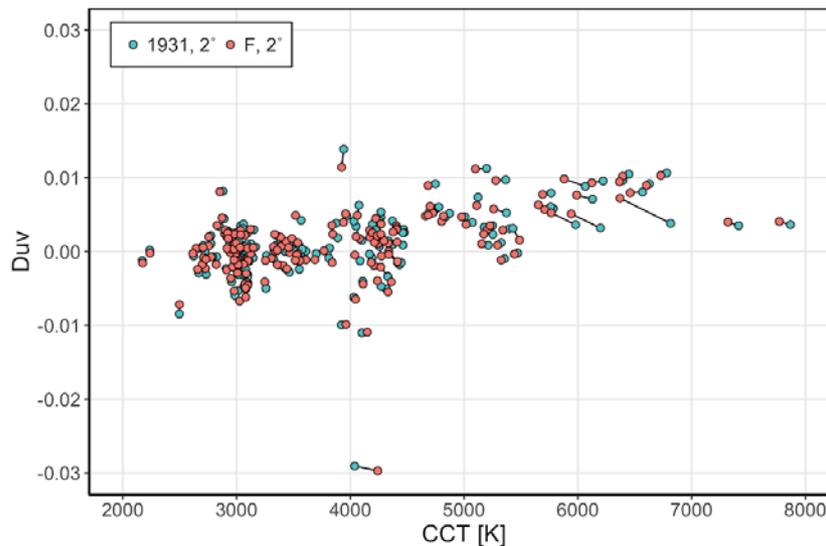


Figure 4 – Comparison of CIE 2015 2° CMFs and CIE 1931 for calculated CCT and Duv values of 187 SPDs’ data from the TM-30 SPD data library

Since the TM-30 SPD Library does not include RGB and RGBA type sources, the same analysis was made for the collection of SPD data in the author’s calculation tool (CQS 9.0) associated with the publication (Davis and Ohno, 2010). **Figure 5** shows the results for 47 SPDs’ data for real and simulated RGB(A) type LED spectra.

Some points in this figure show that the CCT and Duv values change in the opposite direction as shown in **Figure 3**, and that the changes can be larger than those for phosphor LEDs ($\Delta Duv > 0.01$). For such large differences and opposing directions of Duv shifts, the question arose regarding which Duv values, from CIE F,10 or CIE 1931, better reflect visual perception.

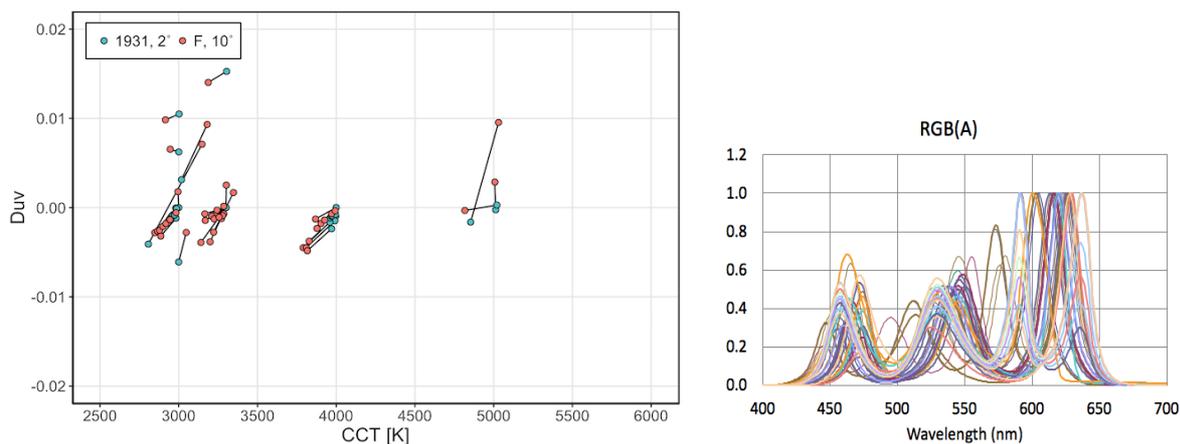


Figure 5 – CCT and Duv values of 47 RGB(A) type LED spectra calculated under CIE 1931 and CIE F,10 (left) and their SPDs (right)

3 Vision experiment

3.1 Experimental setting

Figure 6 shows the experimental set-up. The experiment was carried out using a spectrally-tuneable double booth in a dark room. Each booth is equipped with 16 different LED channels, and the inside walls are painted a neutral grey ($\approx 50\%$ reflectance). A polymer-based white sheet (30 cm x 30 cm) was placed in the middle of each booth.



Figure 6 – Spectrally-Tuneable Double Booth used for the experiment

The left side of the booth was used to present a reference source, which is a broadband spectrum as close as possible to Planckian radiation (so, $Duv = 0$) at a CCT of 3000 K or 5000 K. The right side of the booth was used to present test lights having different SPDs. The test lights were always presented as a pair, one having the same chromaticity (CCT and Duv) as the reference (left side) under CIE 1931, and the other light having the same chromaticity as the reference under the CIE F,10. The former light was called “A” and the latter was called “B” in the experiment (but the subject was not informed of what these were). The illuminance of all test light was fixed at 250 lx on the white sheet.

3.2 Experimental methods

The subject was seated in front of the booth. After adapting for 2 min to the light at a given CCT, light A and light B were presented alternately on the right side in 2 s to 3 s intervals (the experimenter says “this is A, B, A, B, ...”) until the subject responded. The subject was asked to compare the colour appearance of the white sheets on the left side and right side, and judge which light, A or B (on the right side), showed the colour closer to the colour of the left side (reference). The task was a forced choice, but the subject was instructed to say “difficult” if the judgement was difficult, and such comments were also recorded with the answer. The

left side (reference) was a broadband light set to Duv = 0, calculated under either CIE 1931 or CIE F,10. Light A on the right side was set to the same CCT and Duv as the reference under CIE 1931. Light B was set to the same CCT and Duv as the reference under CIE F,10. When A was selected, CIE 1931 provided closer matching. When B was chosen, CIE F,10 provided closer matching, for the particular light and subject. These comparisons were repeated for different light pairs (see 3.4) and for the two CCT conditions, 3000 K and 5000 K.

3.3 Subjects

A total of 22 volunteers were recruited from NIST employees and the students participating in NIST Summer Undergraduate Research Fellowship (SURF) program. The age of subjects ranged from 18 years old to 63 years old, and they consisted of nine males and 13 females. Fifteen were white, five were Asians, and two were African-American. All subjects were tested for normal colour vision for each of their eyes using the Ishihara Test under 5000 K broadband illumination.

3.4 Test lights

In the experiment, a total of six different pairs of test lights and a reference light per CCT were used to compare colour matching with CIE 1931 and CIE F,10. **Figure 7** shows the SPDs of the reference light at 3000 K and 5000 K. These reference lights were set to have a broadband spectrum as close as possible to Planckian radiation, using the available channels of the spectrally tuneable sources of the booth.

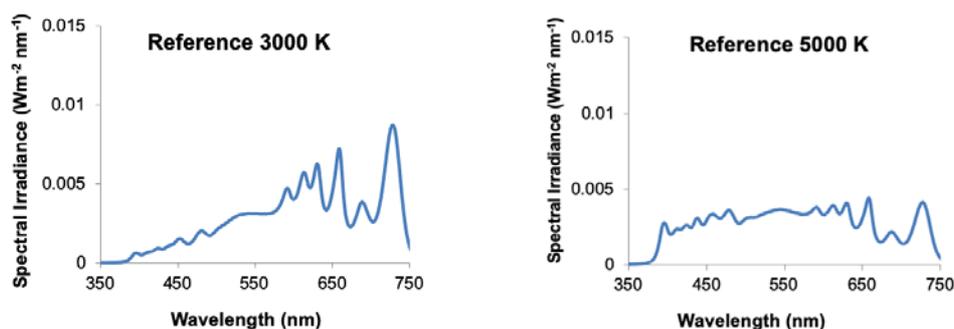


Figure 7 – The SPDs of the reference lights at 3000 K (left) and 5000 K (right) presented to the left side of the booth

Figures 8 and **9** show the SPDs of the six pairs of test lights (Test 1 through Test 6) at 3000 K and 5000 K, respectively. In each graph, two light spectra are shown, one matched under CIE 1931 and the other matched under CIE F,10, to have the same chromaticity (CCT and Duv) as the reference light. Note that the two curves are mostly overlapping in these graphs. The test light, Test 1, was intended to simulate a phosphor-converted white LED light but including a red peak, which was needed to achieve the required chromaticity. Other test lights are RGB white lights with different peak wavelengths of R, G, and B components, which were chosen to produce Duv shifts in different directions.

Figure 10 shows the chromaticity coordinates expressed in CCT and Duv for the reference lights shown in **Figure 7**, calculated under CIE 1931 and CIE F,10, so two points are plotted in each graph. Note that the two points are overlapping in the figure for 3000 K (left).

Figures 11 and **12** show the CCT and Duv values of the six pairs of test lights shown in **Figures 8** and **9**. In each graph, light A (shown by circles) was matched with the reference light under CIE 1931, B (shown by diamonds) was matched under CIE F,10. Their CCT and Duv values were calculated under CIE 1931 (red filled marks) and under CIE F,10 (white filled marks). Note that the two points in the centre of each graph were intended to be completely overlapped. Small deviations were due to experimental limitation. Note also that test lights 1, 3, and 6 have Duv shifts in the same direction, and test lights 2, 4, and 5 have Duv shifts in the opposite direction when the CMFs are changed in the calculation.

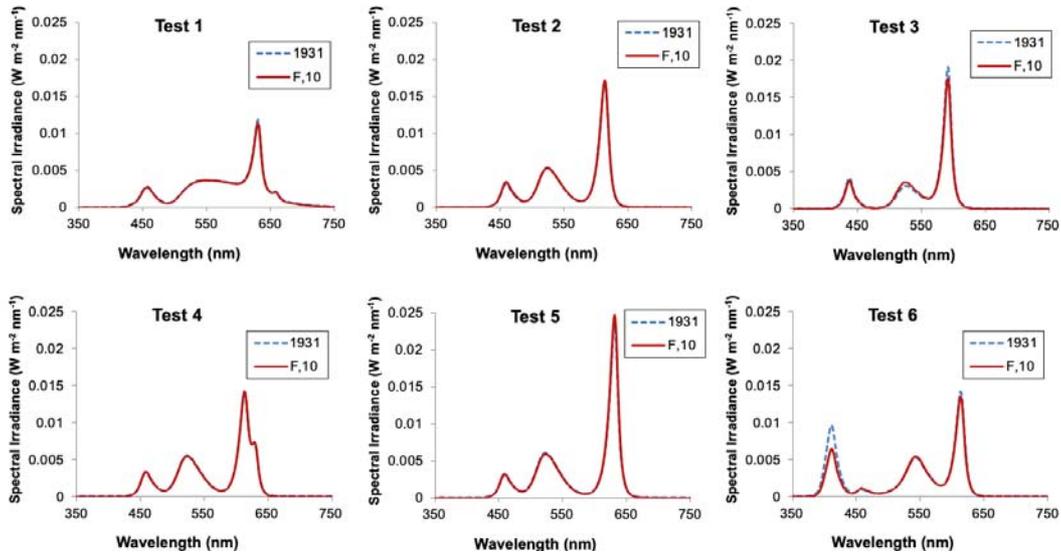


Figure 8 – The SPDs of the test lights at 3000 K presented to the right side of the booth

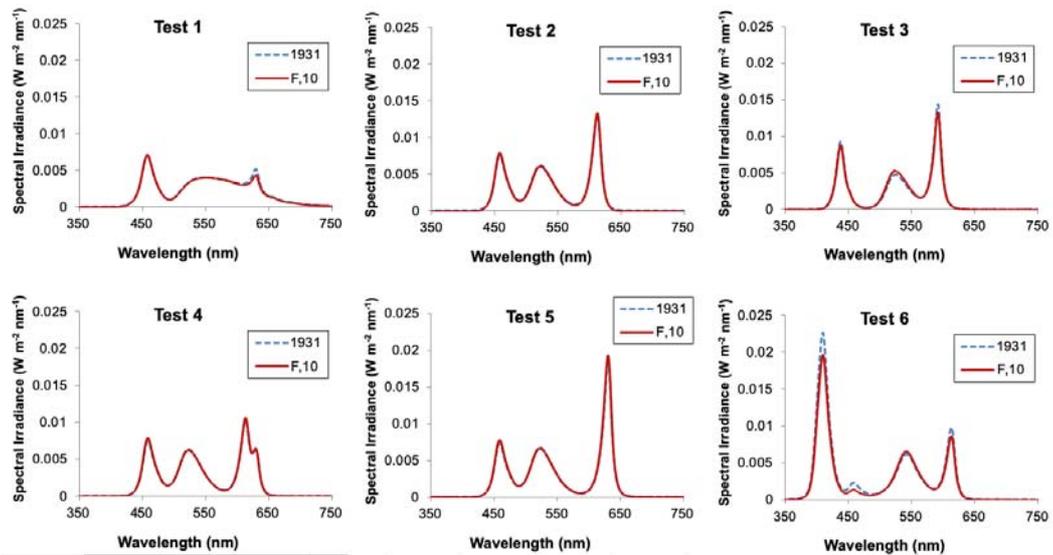


Figure 9 – The SPDs of the test lights at 5000 K presented to the right side of the booth

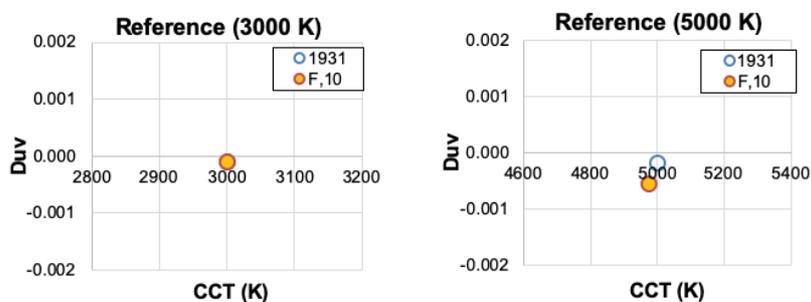


Figure 10 – The chromaticity coordinates expressed in CCT and Duv, for the reference lights shown in Figure 7, calculated under CIE 1931 and CIE F,10

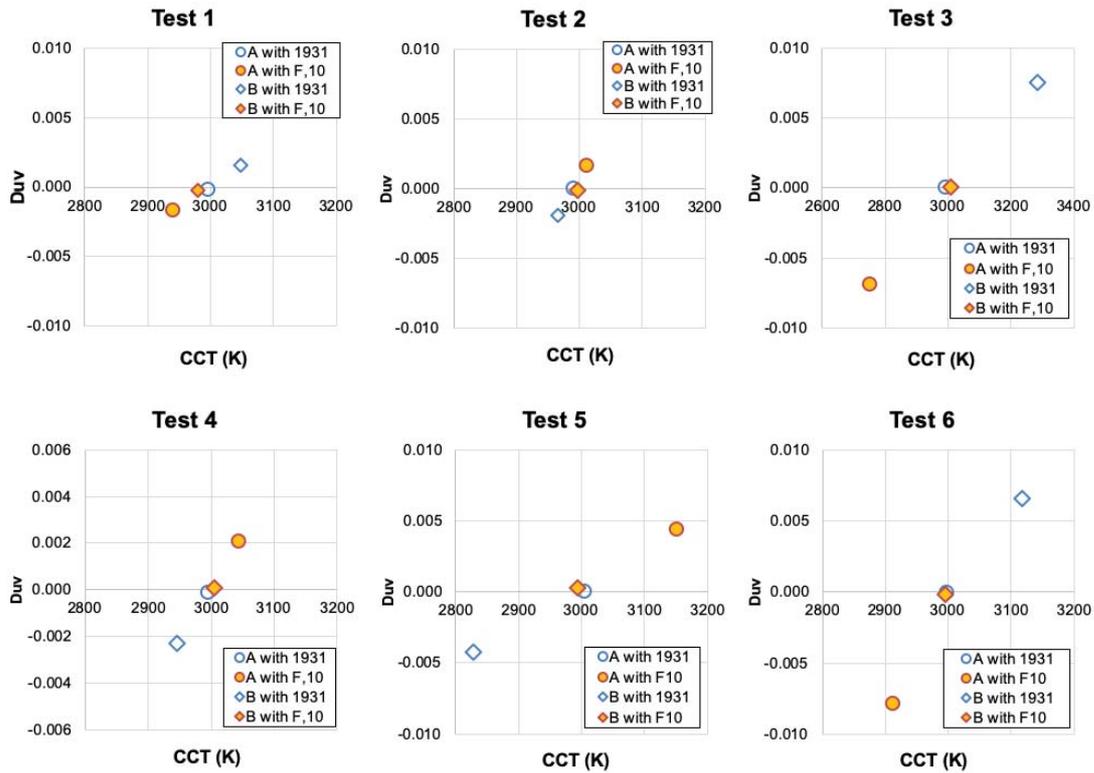


Figure 11 – The chromaticity coordinates expressed in CCT and Duv, for each set of test lights at 3000 K shown in Figure 8, calculated under CIE 1931 and CIE F,10

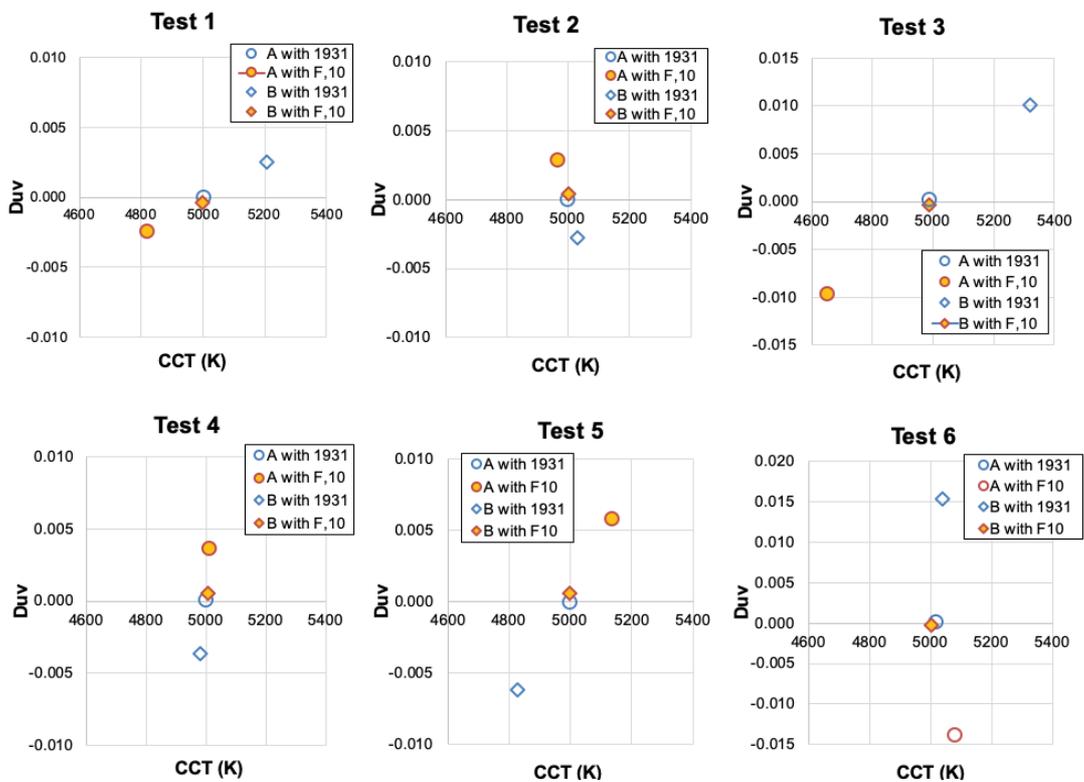


Figure 12 – The chromaticity coordinates expressed in CCT and Duv, for each set of test lights at 5000 K shown in Figure 9, calculated under CIE 1931 and CIE F,10

3.5 Experimental procedure

Each subject was first tested with the Ishihara Test to check that he/she had a normal colour vision. This test was conducted for each of their eyes, under the broadband illumination of 5000 K, $Duv \approx 0$ inside the lighting booth.

Prior to starting the main experiment, each subject was adapted to the 5000K reference condition (both sides of the booth) for two minutes. During the adaptation time, experimental instructions were given and a training session was conducted for the subjects to get familiarized with the experimental procedures. Then, the test light pairs were presented to the right side of the booth, from Test 1 to Test 6. For each pair of light, light “A” and light “B” were presented sequentially for about three seconds each. This was repeated until the subject was able to answer. The subject compared the colour appearances of the white sheets on the left and right side of the booth and answered which light, A or B, was closer in colour appearance to the left side of the booth (reference). This was a forced choice, but if the choice was difficult, the subject could report “difficult” after choosing A or B.

When all comparisons were done at 5000 K, both sides of the booths were changed to the reference condition at 3000 K, and the subject was adapted for two minutes. Then the experiment was conducted in the same way. For each CCT condition, the experiment with six pairs of light was repeated, thus there were a total of four runs involving comparison of six light pairs. All experiments for each subject took about 30 min. including preparation time.

3.6 Data analysis

For data analysis, the response “A” (for CIE 1931) was converted to a score value of 1 and response “B” (for CIE F,10) to a score value of -1. If the subject also reported “difficult” also, the choice was considered to be 20 % of the full score. For example, if a subject answered “A” and “difficult”, the response was converted to 0.2. After conversion, all the scores from the two runs for each CCT were averaged for each test light.

4 Results and discussion

Figure 13 shows the average scores for each test light of 3000 K and 5000 K. A score value of 1.0 would mean that 100 % of subjects chose CIE 1931, a value of -1.0 would mean that 100 % of subjects chose CIE F,10, and a value 0 would mean that the choice was even.



Figure 13 – The results of the experiment for each test light of 3000 K and 5000 K

As shown in the Figure, the scores in most cases are negative values for both CCTs, which means that, overall, CIE F,10 had a better correlation with visual evaluation for these test lights than CIE 1931. However, there were some variations in score values depending on the test light. Test lights 1 and 3 show scores closest to -1.0, meaning that CIE F,10 performed well for these lights. Test lights 1, 3, and 6 had Duv shifts in the same direction (see **Figures 11** and **12**). The results for test lights 2 and 4 show scores closer to zero. Test lights 2, 4, and

5 had Duv shifts in the opposite direction (see **Figures 11, 12**). There seems to be some correlation with the direction of Duv shift.

Figure 14 shows the experimental results divided into two groups according to the subject's age – “younger” (under 40 years) and “older” (40 years and above). Among the 22 subjects, 14 were in younger group and eight were in the older group.

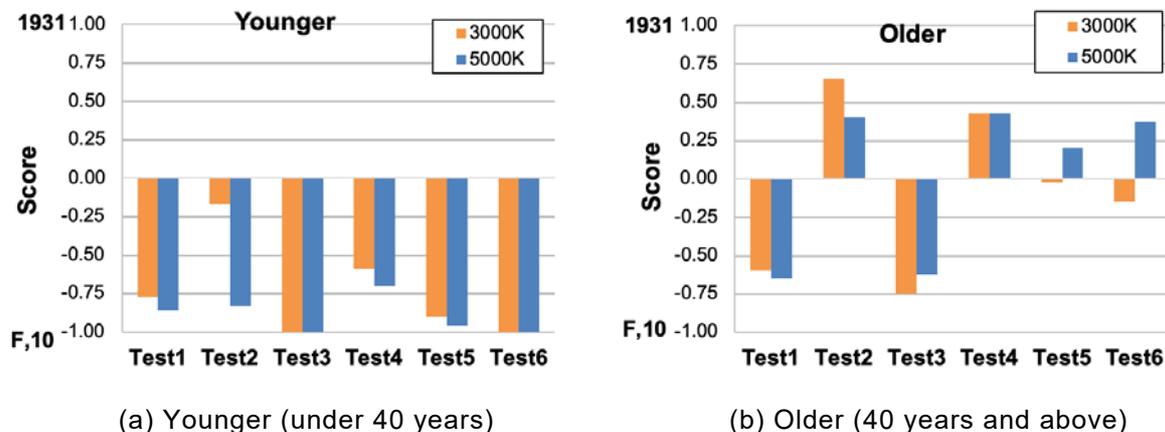


Figure 14 – The experimental results for the age groups of the subjects

The results clearly show meaningful differences between the age groups. The younger group shows strong support for the use of CIE F,10. The results of the older subjects, however, are not conclusive, being dependent on the SPD of light. In particular, test lights 2 and 4 showed positive score values for both CCTs, meaning that the CIE 1931 performed better. It is reported in the reference (CIE, 2006) that there are effects of age on visual sensitivity due to the change of optical density of the lens and other factors. It has not been investigated whether these effects can explain the results of this experiment. Further study on this aspect is needed. The strong dependence of the experimental results on the spectrum of light also needs to be studied further.

5 Conclusion

The computational analysis showed that CIE F,10, if changed from CIE 1931, would cause significant changes in CCT and Duv values for typical lighting sources including phosphor-converted white LEDs. To determine whether these significant changes in CCT and Duv values would better predict visual perception in lighting applications, a vision experiment was conducted using a large field of view setting, with 22 subjects of a wide range of age, using various light source spectra. The results, showed that, overall, CIE F,10 gives better correlation with visual evaluation. However, the results showed strong dependence on the age of subjects and the spectrum of light. These variations need to be further studied, as the colourimetry system should work for all types of light sources and all ages of people. Due to these large variations identified, and the lack of more substantial experimental validation, it is premature to introduce CIE F,10 for lighting applications.

Acknowledgement

The experiment using human subjects in this study was conducted under NIST Institutional Review Board approval PML-16-0001.

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