OP02

VISION EXPERIMENT II ON PERCEPTION OF CORRELATED COLOUR TEMPERATURE

Semin Oh et al.

DOI 10.25039/x47.2020.OP02

Paper accepted for the 5th CIE Symposium on Colour and Visual Appearance

The paper was selected by the International Scientific Committee (ISC) for presentation at the 5th CIE Symposium on Colour and Visual Appearance, Hong Kong, CN, April 21–22, 2020, which, due to the corona pandemic, could not take place. The paper has not been peer-reviewed by CIE.

CIE Central Bureau
Babenbergerstrasse 9
A-1010 Vienna
Austria
Tel.: +43 1 714 3187
e-mail: ciecb@cie.co.at
www.cie.co.at

OP02

VISION EXPERIMENT II ON PERCEPTION OF CORRELATED COLOUR TEMPERATURE

Oh, S.[1], Kwak, Y.[1], Ohno, Y.[2*]
[1] Ulsan National Institute of Science and Technology, Ulsan, SOUTH KOREA
[2] National Institute of Standards and Technology, Gaithersburg, Maryland, USA
ohno@nist.gov

Abstract

This study investigates which chromaticity space, (*u, v*) or (*u', v'*), has a better correlation with human perception when correlated colour temperature is calculated. The vision experiment was conducted using the NIST Spectrally Tuneable Lighting Facility simulating a real-size interior room. A total of 22 subjects evaluated eight different test lighting settings at 2 700 K, 3 500 K, 4 500 K, and 6 500 K with D_{uv} shifts of +0.015 or –0.015. The results showed that the (*u', v'*) chromaticity space was better at a low CCT, 2 700 K, but the results were neutral or (*u, v*) slightly better at high CCTs. The difference depending on CCT can be explained from MacAdam ellipses, i.e., the shape of the ellipses is circular at lower CCTs on the *(u', v')* diagram and deviates from circle as CCT goes higher. There were also differences with subjects' age observed.

Keywords: correlated colour temperature, chromaticity coordinates, visual perception, LED, MacAdam ellipses

1 Introduction

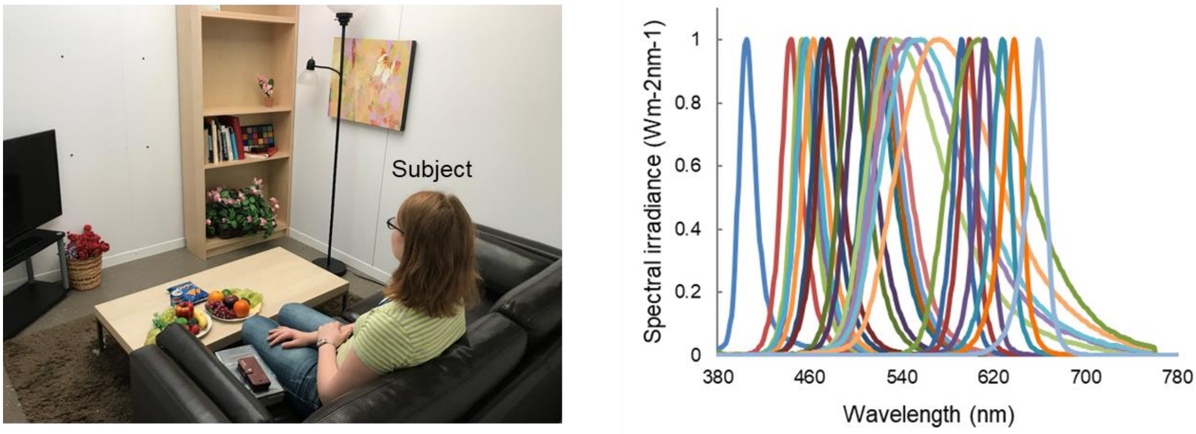
Correlated colour temperature (CCT) is defined by Commission Internationale de l'Eclairage (CIE, 2019), and according to the definition, CCT is calculated as the nearest point to the Planckian locus on the CIE 1960 (*u, v*) chromaticity diagram, which is obsolete. It is questioned in the lighting community why this obsolete chromaticity space is still used and whether the (*u', v'*) chromaticity space would provide better correlation for CCT with human perception. CIE Division 1 established a reportership DR1-67 (Revisiting correlated colour temperature) to investigate this question.

In 2017, our previous study showed that using the *(u', v')* chromaticity space provided overall better correlation with human perception (Kwak et al., 2017), however, futher experimental data were desired to make conclusive recommendations. This previous study used a double-booth with subjects comparing the perceived colours of white sheets. The present study is to provide additional visual data on which chromaticity space, *(u, v)* or *(u', v')*, has better correlation in the perception of CCT. The experiment was conducted using the National Institute of Standards and Technology (NIST) Spectral Tuneable Lighting Facility (STLF) (Miller et al., 2010) simulating an interior room with some furniture and ornaments, for the conditions closer to real lighting applications, at different CCT conditions, 2 700 K, 3 500 K, 4 500 K and 6 500 K.

2 Vision experiment

2.1 Experimental facility

The vision experiment was conducted in a room cubicle (2.4 m × 2.4 m × 2.4 m) of the NIST STLF simulating an interior room with the LED light sources installed at the ceiling of the space. Figure 1 (a) shows a photo of an experiment scene and Figure 1 (b) shows the spectral power distributions (SPDs) of 25 LED channels installed in the NIST STLF. The room cubicle was decorated with some furniture and objects to make the place feel natural. Subjects sat on the couch during the experiment sessions and were asked to look around the entire room space when comparing the lighting colours.



a) Experimental settings   b) The SPDs of 25 LED channels in the NIST STLF

Figure 1 – Experimental settings (left) and the SPDs of 25 LED channels in the NIST STLF (right)

2.2 Reproducibility of STLF

The reproducibility of the chromaticity settings on the NIST STLF at four CCT conditions (the reference spectra described in 2.3) were measured 40 times on different dates over the course of the experiment, thus, a total of 160 measurements were made. The chromaticity and illuminance (set to 300 lx) of the lighting settings were measured on the centre of the table in the room cubicle.

Table 1 summarizes the STLF reproducibility measurement results. Each value shows the average of 40 measurements and its standard deviation. The facility had been very reproducible that its deviation was far less than 1% in all measurement quantities.

Table 1 – The NIST STLF reproducibility test results

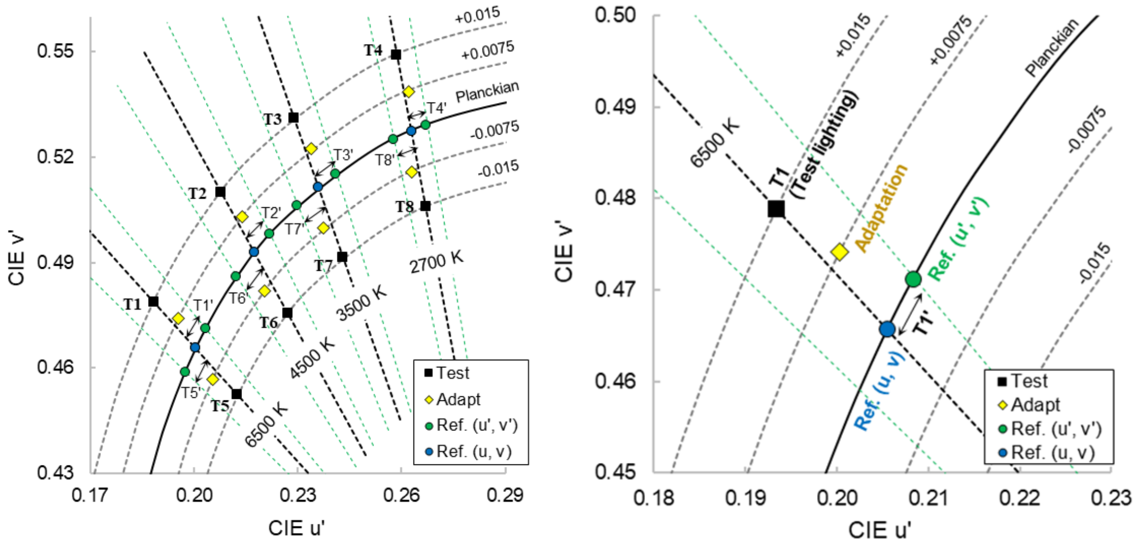
Target value		Mean measurement value (±SD)		
CCT (K)	Illuminance (lx)	CCT (K)	Illuminance (lx)	D_{uv}
2 700	300	2704 ± 4	299.5 ± 1.61	-0.0001 ± 0.0001
3 500	300	3487 ± 26	300.9 ± 1.64	0.0001 ± 0.0001
4 500	300	4499 ± 8	299.2 ± 1.53	0.0004 ± 0.0001
6 500	300	6485 ± 16	302.3 ± 1.55	0.0003 ± 0.0001

The colour quantities and illuminance of the lights were measured on the centre of the table in the cubicle. The measurements were made using an array type spectroradiometer with a small integrating sphere input for cosine response, calibrated with a NIST spectral irradiance standard (NIST, 2011). The spectroradiometer measured spectra and illuminance on the table from the 2π solid angle including light from the entire room including reflections from the walls and other objects as well as from the light source itself. The estimated expanded uncertainties (k=2) of measurements varied depending on the spectra, but in all cases, they were within 0.0012 in u', 0.0011 in v', 0.0009 in D_{uv}, 22 K in CCT at 2 700 K, 34 K at 3 500 K, 50 K at 4 500 K, and 92 K at 6 500 K. The expanded uncertainty of illuminance of the spectroradiometer is estimated to be 3 % (k=2) for directional incident light, and its uncertainty for relative measurement was 0.1 %, which is the typical repeatability of the instrument. Also, when the spectrum is changed on STLF, the spectrum and colour are switched instantly and stable immediately so that sequential comparison of lights was possible.

2.3 Experimental lighting settings

The experiments were conducted for four CCT conditions; 2 700 K, 3 500 K, 4 500 K, and 6 500 K with shifts from the Planckian locus, expressed by D_{uv}. D_{uv} is defined as “the closest distance of the chromaticity coordinates of a light source from the Planckian locus on the (*u’*, 2/3 *v’*) chromaticity diagram and is positive if the chromaticity coordinate of the light source is above the Planckian locus or negative if it is below the Planckian locus” (CIE, 2018).

Figure 2 (a) shows all the lighting settings used in the experiment presented on the *(u’, v’)* chromaticity diagram, and Figure 2 (b) is a magnified figure for only 6 500 K positive D_{uv} condition. In each CCT condition, two test lights were set for D_{uv} shifts of either +0.015 or –0.015 (black squares in Figure 2). Therefore, the test lights were the off-Planckian points, and each was compared to two reference lights, one being the point on the Planckian locus that had the same CCT calculated under the (*u, v*) diagram (blue circles in Figure 2), and the other being the point on the Planckian locus that had the same CCT calculated under the (*u’, v’*) diagram (green circles in Figure 2). Before comparing each pair of lights, subjects were adapted to the midpoint of chromaticities among the test light and two reference lights (so the points at D_{uv}= +0.0075 or -0.0075, yellow diamonds in Figure 2). The illuminance of all lights (test and reference) was set to 300 lx measured at the centre of the table placed at the STLF cubicle.



(a) Showing all four CCTs

(b) 6500 K, D_{uv} +0.015 condition magnified

Figure 2 – Test lights, reference lights, and adaptation lights used in the experiment, (a) plotted on the (*u’, v’*) chromaticity diagram, and (b) 6 500 K D_{uv} +0.015 condition magnified

As shown in Figure 2 (b), the test light at 6 500 K with D_{uv} shift of +0.015 (T1) is compared to two points on the Planckian locus (T1’ pair), one is the point of 6 500 K calculated under the current CCT definition based on (*u, v*) diagram (blue circle), and the other point (green circle) is the point of 6 500 K calculated based on the (*u’, v’*) chromaticity diagram. Therefore, it directly compares which chromaticity space, either (*u, v*) or (*u’, v’*), resembles the test light better in the perception of CCT.

Figure 3 shows the SPDs of all lighting settings used in this study. To minimize the effects of colour rendition properties in the experiment, broadband spectra were used though there were some peaks in the spectrum due to limitation of the available LED channels of STLF.

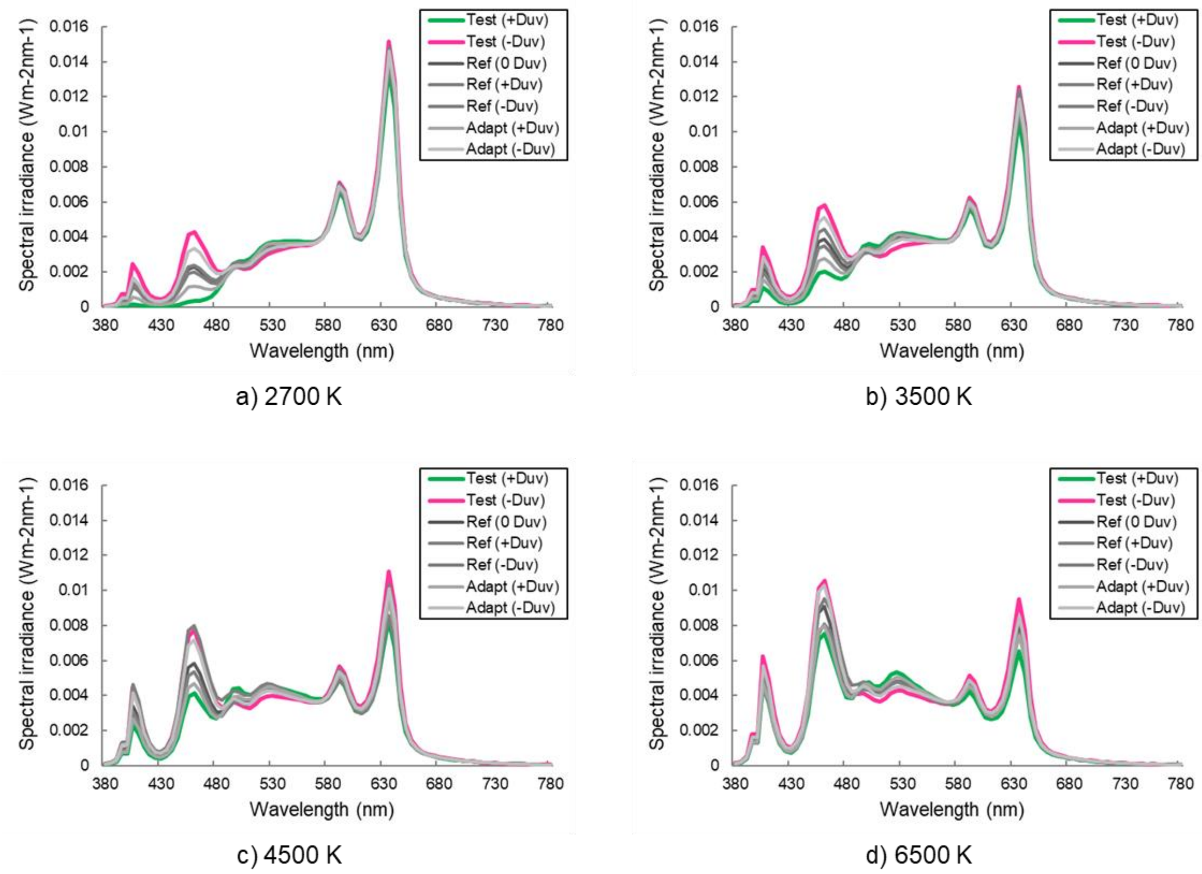


Figure 3 – The SPDs of all lighting settings used in the experiment

2.4 Experimental procedures

Figure 4 summarizes the experimental procedure.

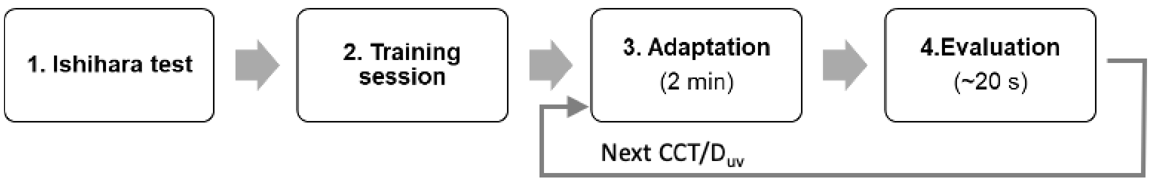


Figure 4 – The flow chart of the experimental procedure

First, all subjects, upon their arrival, had the Ishihara colour vision test under the 4 500 K reference light condition, then introduction was given for the experimental procedures. Prior to the experiment, there was a training session using one or two test light conditions for the subjects to get used to the experimental task. Then, the subject was adapted to the adaptation light for the first test condition for 2 min. After the adaptation, the test light and two reference lights were compared. Test light was called ‘Test’, the reference light having the same CCT on *(u, v)* was called ‘A’ and the reference light having the same CCT on *(u’, v’)* was called ‘B’. The lights were presented sequentially in the order, Test-A-B for about 3 seconds each and repeated for Test-B-A. Each subject assessed which of reference light, ‘A’ or ‘B’, appeared closer to the test light. It was a forced choice, but subjects were also asked to add ‘difficult’ if judgement was difficult. The viewing time (3 s each light) was kept short so that the chromatic adaptation condition (to the adaptation point) was maintained during the comparison. Then, the experiment was repeated for other CCT/D_{uv} conditions. The orders of the CCT conditions and D_{uv} (positive or negative) in each CCT were randomly chosen for each subject. An example of the experimental scenes is shown in Figure 1 (a).

2.5 Subjects

For the experiment, a total of 22 subjects were recruited from among NIST employees (having no expert knowledge on lighting) and summer internship students. There were 11 males and 11 females, the age of the group being from 18 to 64 years, and most were Caucasian except three. All subjects had a normal colour vision.

3 Results and discussion

3.1 Data analysis method

To analyse the data, the answer 'A' *(u, v)* was converted to a value of 1 and 'B' *(u', v')* to -1. In case of the 'difficult' answer, it was considered half of the full evaluation. For example, 0.5 point was given when subject chose 'A' but said it was difficult. After the conversion, all subjects' responses were averaged.

3.2 CCT perception experiment results

Figure 5 shows the averaged CCT perception experiment results according to eight different test lighting settings. If the CCT perception score is close to 1, the *(u, v)* chromaticity space works better, otherwise if the value is close to -1, the *(u', v')* is better.

As shown in the figure, it was clear that the *(u', v')* chromaticity space performed better for lower CCT, 2 700 K, especially on the positive D_{uv} test light For the other CCT conditions, there were no significant differences in scores except at 4 500 K positive D_{uv} where *(u, v)* was slightly higher. The result was still not conclusive, except 2 700 K, as the scores were low (absolute values less than 0.3.

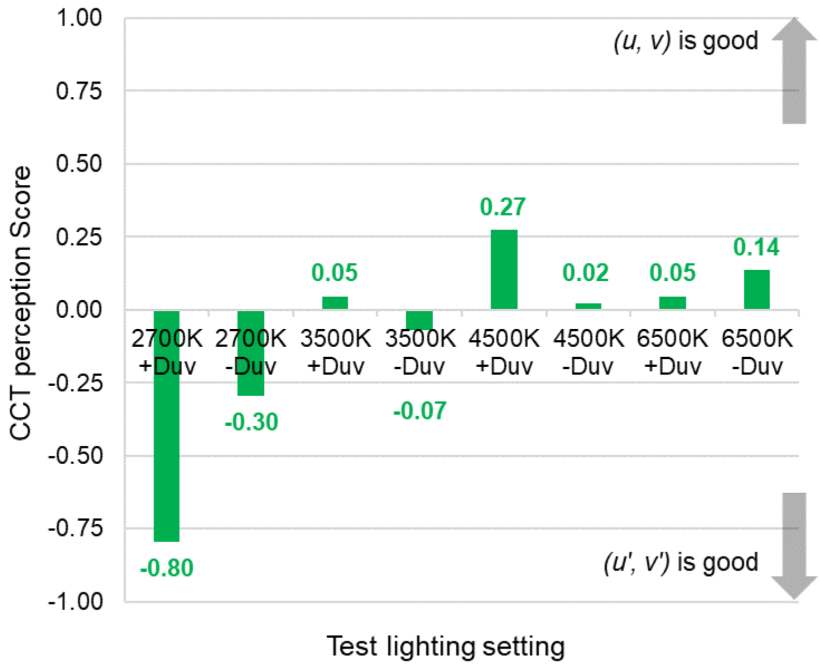


Figure 5 – The averaged CCT perception experiment results

3.3 Results over subject's age

The results were also compared for two different age groups – the older (age 40 or higher, N=7) and the younger (below age 40, N=15). The age 40 was chosen because the aging in the eye is known to begin from the early to mid-40s (American Optometric Association, n.d.).

Figure 6 shows the results of the CCT perception experiment comparing the younger and the older groups.

In 2 700 K, both age groups evaluated the *(u', v')* was better. In the other CCTs, results were different for different age groups. The older group chose *(u', v')* better except the 4 500 K condition, regardless of the D_{uv} direction. However, the younger group evaluated the *(u, v)* better at 3 500 K and 6 500 K, which was the opposite from the older group's result. In case of 4 500 K condition, it was dependent on the D_{uv} direction, i.e., the *(u, v)* was better at +0.015 D_{uv} and the *(u', v')* was better at –0.015 D_{uv}.

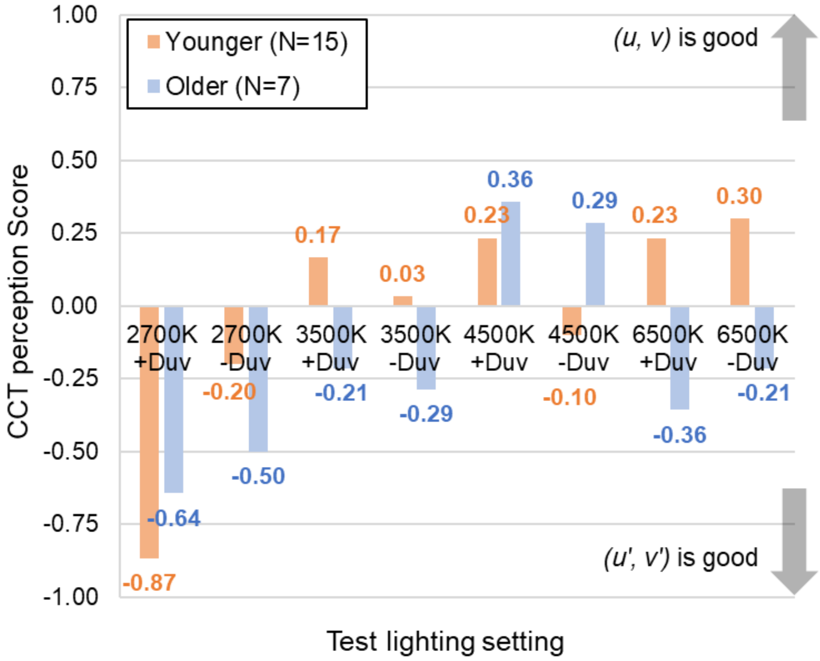


Figure 6 – The experimental results according to subject's age

3.4 Comparison to the results of the previous (2017) experiment

The results of our experiment in 2017 (Kwak et al, 2017) were re-analysed to be compared with the results of the current study in the same format. In the 2017 results, a value of 1 or -1 was given to each subject when his/her response supported (*u, v*) or (*u', v'*), respectively, in the haploscopic and non-haploscopic experiments, and the average values of all subjects for each CCT/D_{uv} condition were calculated. Figure 7 shows the summary results presented in the same format as in Figure 5. Although this experiment was conducted only at two CCTs (3 000 K and 5 500 K) and the number of subjects were limited (12 for haploscopic, 6 for non-haploscopic), the results showed a similar trend that (*u', v'*) was strongly supported at lower CCT (3 000 K) and not consistent or conclusive at higher CCT (5 500 K). The results especially with the non-haploscopic experiment, which was a similar viewing condition to the current study, agreed well with the results of the current study.

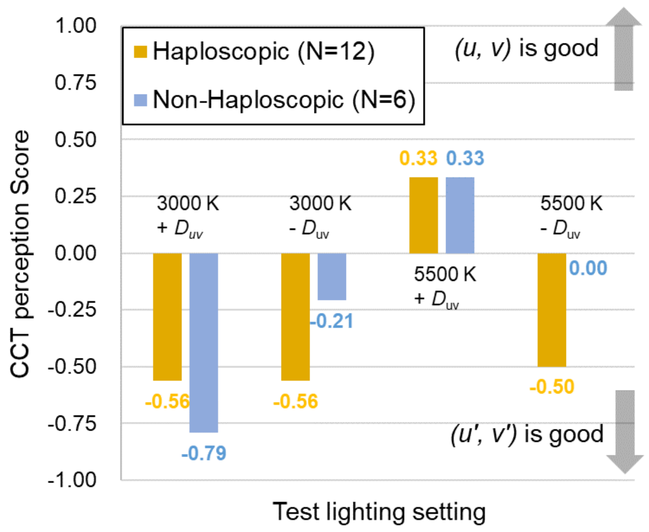


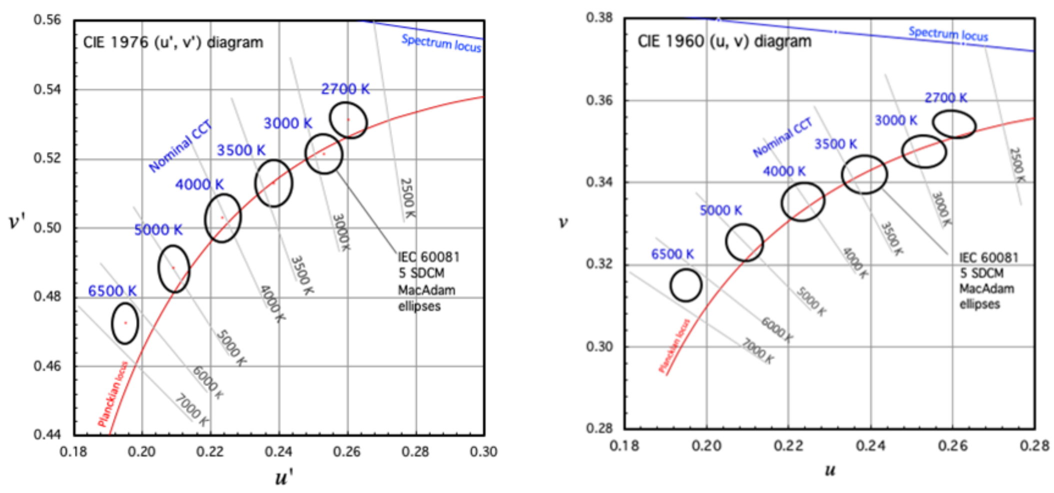
Figure 7 – The results of NIST 2017 experiment analysed in the format of Figure 5.

3.5 Discussion: CCT perception vs. MacAdam ellipses

The experiment results showed that, lower CCT correlates better with the (*u', v'*) chromaticity space, and the results were not conclusive at higher CCTs and (*u, v*) tends to be slightly better at higher CCTs. This trend can be related to MacAdam ellipses (MacAdam, 1942).

Figure 8 shows the 5-step MacAdam ellipses for the range of 2 700 K–6 500 K (IEC 1997) plotted on (*u', v'*) diagram (a) and on (*u, v*) diagram (b). Note that the form of the ellipse (grey circle) is five times the size of just noticeable colour differences from the centre of the ellipse. See also (CIE, 2014) on a similar graphic presentation of MacAdam ellipses.

Figure 8 (a) shows that the shape of the ellipses is almost circular at 2 700 K and 3 000 K on (u', v') diagram, and its shape becomes more oval at higher CCTs. On the other hand, Figure 8 (b) shows the opposite; the shape of the ellipses is near circular at 6 500 K and 5 000 K, and its shape becomes more oval at lower CCTs. This indicates that the *(u', v')* diagram is more uniform at low CCTs with respect to perceived colour differences and the (*u, v*) is more uniform at high CCTs. Although the results of the experiment did not show that (*u, v*) is definitely better at 6 500 K, the overall trend of the results with different CCTs agrees with what MacAdam ellipses indicate.



(a) Plotted on *(u', v')* diagram (b) Plotted on *(u, v)* diagram

Figure 8 – The 5-step MacAdam ellipses on (*u', v'*) diagram (a) and on (*u, v*) diagram (b)

4 Conclusion

The vision experiment showed that the (*u', v'*) chromaticity space has better visual correlation with perception of CCT at 2 700 K, while the results at higher CCTs were rather neutral or not conclusive. The results also depended on the age of subjects. Older subjects tend to support *(u', v')* more than younger subjects. The experiment results generally agreed with the results obtained by our previous study (Kwak et al, 2017). With the results for lower CCTs (2 700 K and 3 000 K in the current and previous studies) strongly supporting the *(u', v')* chromaticity space, and also considering the importance of warmer colours of lamps common for indoor lighting, we judge that a CCT definition based on the (*u', v'*) will serve better for the users of lighting. This study performed the experiment in a room-like space, so the situation was more likely to be the scenario of a real-life experience, adding to the more fundamental results obtained from our previous study. Further studies by other institutions are desired to provide more conclusive recommendation. Also, CCT is used not only for lighting but also other applications such as displays. It is hoped that similar studies will be done for such different applications.

References

American Optometric Association (AOA). Adult Vision: 41 to 60 Years of Age. www.aoa.org/patients-and-public/good-vision-throughout-life/adult-vision-19-to-40-years-of-age/adult-vision-41-to-60-years-of-age#1

CIE, 2014. CIE TN 001:2014. Chromaticity Difference Specification for Light Sources

CIE, 2018. CIE 15:2018. Colorimetry, 4th ed.

CIE, 2019. CIE FDIS 017:2019. ILV: International Lighting Vocabulary, 2nd ed.

IEC. 1997. IEC 60081. Double-capped fluorescent lamps – Performance specifications, Annex D.

MacAdam, D. L. 1942. Visual sensitivities to colour differences in daylight. J. Opt. Soc. Am. 32, 32(5), 247-274. DOI:10.1364/JOSA.32.000247.

Kwak, Y., Ha, H., Ohno, Y. 2017. VISION EXPERIMENT ON PERCEPTIN OF CORRELATED COLOUR TEMPERATURE. CIE x044:2017 Proc. of the Conference at the CIE Midterm Meeting 2017, CIE, 512-521. DOI:10.25039 x44.2017. PP06.

Miller, C., Ohno, Y., Davis, W., Zong, Y., and Dowling, K. 2010. NIST spectrally tunable lighting facility for lighting related to vision science experiments, CIE x034 Selected Papers of the Light and Lighting Conference with Special Emphasis on LEDs and Solid State Lighting, May 2009, pp.89-93.

Yoon, H. W. and Gibson, C. E. 2011. NIST Special Publication 250-89 Spectral Irradiance Calibration.