VISION EXPERIMENT ON PERCEPTION OF CORRELATED COLOUR TEMPERATURE

KWAK, Y.[1], HA, H.[1], OHNO, Y.[2]
[1] Ulsan National Institute of Science and Technology, Republic of Korea
[2] National Institute of Standards and Technology, Gaithersburg, USA
yskwak@unist.ac.kr

Abstract

The correlated colour temperature (CCT) is defined by the closest point on the Planckian locus from a light source on the CIE 1960 (*u, v*) diagram (now obsolete), while the current standard uniform colour space is the CIE 1976 (*u', v'*) diagram. To re-visit the question whether using the (*u', v'*) coordinate improves the correlation between the CCT values and perception, vision experiments were conducted with 12 subjects using a double-booth with non-haploscopic and haploscopic methods. The overall results show that the perception of test lights at CCT 3000 K and Duv -0.015 and 0.015 is closer to the CCT calculated based on CIE 1976 (*u', v'*) coordinate. The perception of CCT at 5500 K with the same Duv shifts appears to be between CCTs based on the (*u, v*) coordinate and the (*u', v'*) coordinate. It is suggested that the definition of CCT be re-examined for possibly using the CIE 1976 (*u', v'*).

Keywords: correlated colour temperature, (*u, v*) diagram, (*u', v'*) diagram; visual perception, white light

1 Introduction

The Correlated Colour Temperature (CCT) is an important quantity for specifying the colour of white light (warm to cool) in lighting applications and others (display and photography). CCT is defined, by International Commission on Illumination (CIE), as “the temperature of the Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on a diagram where the (CIE 1931 standard observer based) *u*', 2/3 *v*' coordinates of the Planckian locus and the test stimulus are depicted” (CIE, 2011). This means that the CCT is calculated using the CIE 1960 (*u, v*) diagram (now obsolete), though the current CIE recommendation for uniform colour space is 1976 (*u', v'*) diagram. The CIE 1960 (*u, v*) has been used historically for CCT calculation for decades.

A change to the (*u', v'*) coordinates for CCT calculation was discussed when the CIE 15 (CIE, 2004) was revised in 2004, but no change was made at that time due to lack of research data that would indicate that the (*u', v'*) coordinates would give better correlation with the perception of CCT. There was also no interest from the industry on such a question. However, recently, research on white points below Planckian locus is gaining attention for possibly more natural lighting colour quality (e.g., Ohno and Fein, 2014, Ohno and Oh, 2016) and a fairly large deviation from Planckian locus in negative Duv[1] direction was suggested as white light points perceived most natural. At such white points with large Duv shifts, there would be fairly large differences between CCT values calculated from (*u, v*) and from (*u', v'*). It was also observed during the previous experiments (Ohno and Fein, 2014) that lights having chromaticity below Planckian locus appeared to be at higher CCT. Some users of neodymium lamps (having Duv of approximately -0.005) report the same observation. This shift of perceived CCT is in the same direction as the shift when CCT is calculated based on (*u', v'*).

To specify the position of a white point with respect to Planckian locus, a distance from the Planckian locus on CIE 1960 (u, v) has historically been used because the calculation of CCT has been based on the (u, v) diagram but this term had not been defined in any standard. Duv was defined for the first time in a standard in 2008 (ANSI, 2017). Duv is calculated using CIE 1960 (u, v) coordinates. On the other hand, colour differences and colour shifts of light sources are expressed by the distance $\Delta_{u'v'}$ on (*u', v'*) coordinates as defined by the CIE [CIE, 2014],

[1] Duv, symbol D_{uv}, is the closest distance from the light source chromaticity point to Planckian locus on CIE *u*', 2/3 *v*' coordinates, with + sign for above and - sign for below Planckian locus (ANSI, 2017).

and there is occasionally confusion in the industry between Duv and $\Delta u'v'$, and question is raised why Duv is based on 1960 (*u, v*). Since Duv is getting widely used, it needs to be defined by CIE but it should be consistent with the CCT definition. Toward such an effort, we determined that the question on the definitions of CCT based on the 1960 (*u, v*) coordinates need to be revisited.

For this purpose, a series of vision experiments have been conducted at National Institute of Standards and Technology (NIST) to investigate which coordinates, (*u, v*), or (*u', v'*), agree more closely with visual perception, when the illumination source chromaticity is deviated from the Planckian locus. The experiments used 12 subjects having normal colour vision and were conducted at a double-lighting booth with spectrally tunable light sources. Two methods, haploscopic and non-haploscopic, were used, as it was not clear which method would work better. The experimental methods and the results are discussed.

2 Experimental Facility

A double-lighting booth with spectrally tunable light sources was used for the experiment. The booth is a commercially available product for visual inspection of products, but the light source part was replaced by the spectrally tunable light sources, which are also commercially available products. The source has 16 channels of light-emitting diode (LED) spectra and provided with a computer control program that allows colour settings by entering CCT and Duv values. The photo of the double-booth is shown in Figure 1. The size of the viewing area on each side is 51 cm wide and 46 cm high, and 64 cm deep.

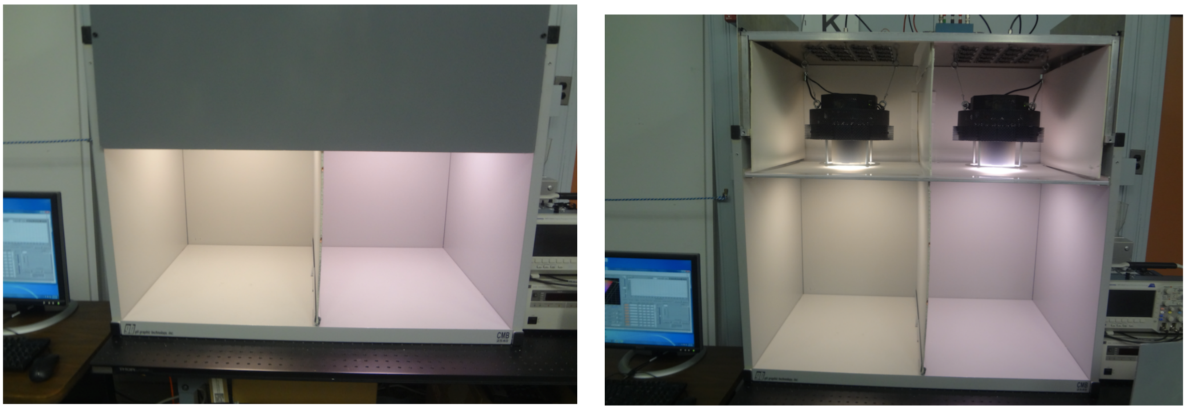

Figure 1 – Photograph of the double-booth used for the experiment. The photos show when the top cover is placed during experiment (left) and when it is removed (right).

The light-emitting surface of the light source is a diffuser with a 10 cm diameter, and there is a large light-transmitting diffuser between the light source compartment and viewing compartment, with which good spatial colour uniformity is provided in the viewing area. It takes a long time (several hours) for the light sources to reach sufficient stability required for this experiment, thus these sources were operated continuously (24 h 7 days) at the reference setting (see section 3.) during the whole experiment period. The spectral distributions (at the centre of the bottom surface) were measured with a spectroradiometer on several light settings before each experiment session (each subject) every day, and the chromaticity drifts during the whole experimental period (about 10 days) was monitored. The drifts were within ± 0.0005 in *u'* or *v'* with a maximum within ± 0.001 from the initial set values and the illuminance was within ± 1.5 % from initial 500 lx setting. The spatial nonuniformity of colour on the booth inner surfaces (bottom surfaces and surrounding wall panels) were within ±0.0008 in *u', v'* from the average value.

Measurements of the booth throughout this experiment was made with an array spectroradiometer in irradiance geometry. The spectroradiometer was calibrated immediately before the experiment period, with a NIST spectral irradiance scale standard lamp. The expanded uncertainty (*k*=2) of the measured chromaticity of the broadband lights used in this experiment was estimated to be within 0.001 in *u', v'*, and the uncertainty of the measurement of colour differences (as the case of drifts and spatial uniformity) was estimated to be 0.0002 in *u', v'*. The expanded uncertainly (k=2) of the illuminance measurements was 3 % and that of relative changes was 0.2 %.

3 Experimental Settings

The experiments were conducted at two CCT conditions, 3000 K and 5500 K, representing an average for low CCT lamps and an average for high CCT lamps common in the market. A test light, above or below Planckian locus (D_{uv} = +0.015 and $D_{uv=}$ -0.015) was visually compared with the lights on Planckian locus to determine which point on Planckian locus appear closest to the test light. The Duv values are chosen as the values determined as perceived most natural on the average in the previous NIST study [Ohno and Fein, 2014].

The right side of the booth (see Figure 1) was set to a test light, which was at $D_{uv=}$ 0.015 or D_{uv} = -0.015. The left side of the booth was set for nine points on the Planckian locus as shown in Figure 2 (the case for 3000 K). In the figure, point No.5 (labelled "uv") is at exactly the same CCT as the test lights based on the current definition of CCT (calculated based on the 1960 (*u, v*) coordinate), point No. 3, labelled "u'v'(-)", is at the same CCT (3179 K) of the test light (D_{uv} = -0.015) calculated based on the CIE 1976 (*u', v'*) coordinate, and No. 7, labelled "u'v'(+)", is at the same CCT (2882 K) of the test light (D_{uv} = 0.015) calculated based on the (*u', v'*) coordinate. Points No. 4 and 6 are the intermediate points between No. 3 and 5 and between No. 5 and 7, respectively. The intervals of these intermediate points were calculated to be equal from both neighbouring points in Δu'v' measure. Additional two points are extended on each side; No. 1, 2 and No. 8, 9, at the same Δu'v' intervals as the neighbouring intervals. Note that the intervals from No. 1 to 5 and those from No. 5 to 9 are slightly different, but these intervals need not be equal for the experimental methods used (see 4.2 and 4.3).

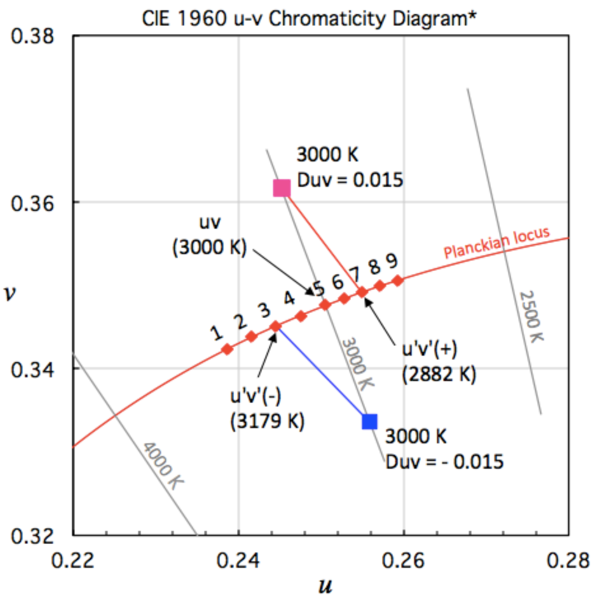

Figure 2 – Chromaticity points set for the double-booth for the experiments (haploscopic) for 3000 K.

The spectral distributions of the sources were set to be as broad as possible using all the 16 channels of the light source, for all these chromaticity points. The spectral data of the lights in all the chromaticity points in Figure 2 (3000 K) and the same set for 5500 K are shown in Figure 3. The calculated chromaticity and colour quality values of all these lights used in the experiment (set values and measured values example) are shown in Table 1. The illuminance for all test lights was set to 500 lx at the bottom surface of the booth. The measurement was made at ≈10 cm above the bottom surface due to the integrating sphere input optics of the spectroradiometer. The illuminance values in Table 1 should be multiplied by 0.85 to convert to the values at the bottom surface of the booth.

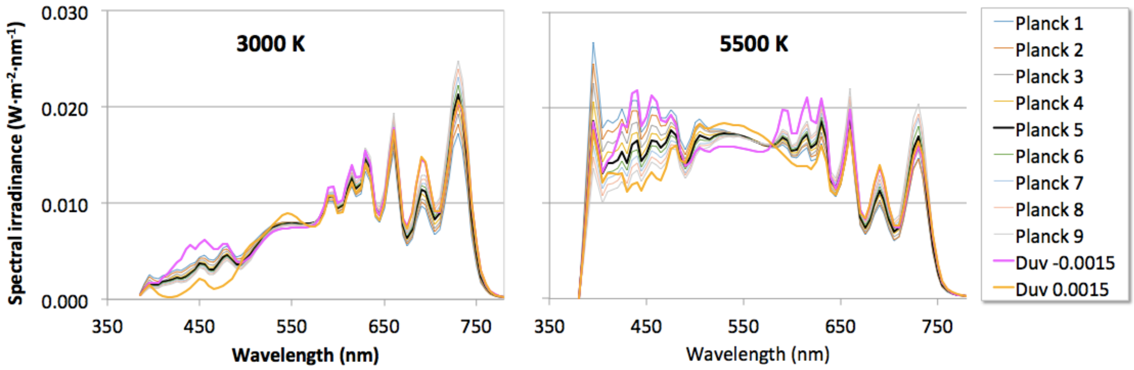

Figure 3 – Spectral power distributions of the lights used in the experiments, for 3000 K (left) and 5500 K (right).

Table 1 – Chromaticity and colour quantity values for the lights used in the experiment.

		Set values						Measured data (an example)				
		CCT	duv	u	v	u'	v'	CCT	CCT dev	duv	Illum. (lx)	CRI (Ra)
Test	Duv=-0.015	3000	-0.015	0.2559	0.3336	0.2559	0.5004	3001	1.4	-0.0153	587.92	92.7
	Duv= 0.015	3000	0.015	0.2452	0.3616	0.2452	0.5424	2998	-2.0	0.0148	587.56	92.0
3000 K Planckian points	1	3384	0.0000	0.2387	0.3424	0.2387	0.5136	3390	6.0	-0.0003	584.34	98.4
	2	3280	0.0000	0.2416	0.3438	0.2416	0.5157	3287	7.2	-0.0003	583.60	98.4
	u'v' - 3	3181	0.0000	0.2446	0.3451	0.2446	0.5177	3186	4.3	0.0003	583.33	98.5
	4	3088	0.0000	0.2476	0.3464	0.2476	0.5195	3093	4.7	0.0003	583.96	98.3
	uv 5	3000	0.0000	0.2506	0.3476	0.2506	0.5214	3006	6.4	0.0002	584.36	98.2
	6	2940	0.0000	0.2527	0.3484	0.2527	0.5226	2945	4.7	0.0002	583.22	98.2
	u'v' + 7	2882	0.0000	0.2549	0.3492	0.2549	0.5238	2887	4.1	0.0001	584.03	98.2
	8	2827	0.0000	0.2571	0.3499	0.2571	0.5249	2832	4.7	0.0001	583.56	98.2
	9	2773	0.0000	0.2593	0.3506	0.2593	0.5259	2777	3.8	0.0002	583.65	98.0
		CCT	duv	u	v	u'	v'	CCT	CCT dev	duv	Illum. (lx)	CRI (Ra)
Test	Duv=-0.015	5500	-0.015	0.2181	0.3084	0.2181	0.4625	5494	-6.3	-0.0154	587.28	90.5
	Duv= 0.015	5500	0.015	0.1957	0.3283	0.1957	0.4925	5506	6.3	0.0149	586.16	91.4
5500 K Planckian points	1	6728	0.0004	0.1993	0.3088	0.1993	0.4632	6722	-6.3	0.0001	585.61	97.9
	2	6375	0.0001	0.2011	0.3113	0.2011	0.4669	6375	-0.7	-0.0002	585.39	97.8
	u'v' - 3	6056	0.0000	0.2030	0.3137	0.2030	0.4705	6055	-1.3	0.0006	585.28	98.0
	4	5765	0.0000	0.2049	0.3160	0.2049	0.4740	5763	-2.1	0.0004	585.06	98.1
	uv 5	5500	0.0000	0.2069	0.3184	0.2069	0.4775	5501	0.7	-0.0003	585.30	98.1
	6	5301	0.0000	0.2086	0.3202	0.2086	0.4802	5305	4.3	0.0004	585.15	98.1
	u'v' + 7	5115	0.0000	0.2103	0.3220	0.2103	0.4830	5118	2.2	0.0003	585.23	98.1
	8	4942	0.0001	0.2120	0.3237	0.2120	0.4856	4945	2.9	0.0004	585.48	99.1
	9	4779	0.0002	0.2138	0.3254	0.2138	0.4881	4783	4.0	0.0004	585.30	99.2

4 Experimental Methods

The experiments were conducted at two CCTs, 3000 K and 5500 K, and at two Duv levels 0.015 and -0.015, therefore, four chromaticity points of the test light. The test light and one of points at Planckian locus were presented side by side. The goal is to determine which Planckian point appear closest to the test light by observation of subjects.

12 subjects having normal colour vision participated in the experiment; 8 males and 4 females, from 20 to 71 years old, 7 white and 5 Asians.

When comparing different colours visually, the adaptation condition of the observer is critical, as perceived colours change depending on adaptation. The adaptation condition must be clearly defined and applied in the experiment. To handle the adaptation conditions appropriately, two methods were used in our experiment. The first method is the non-haploscopic method, in which a subject directly compared different Planckian lights (left side of booth) against the test light (right side). We first tested this method, but we experienced that comparing two fairly different colours of light (one on Planckian, another much off from Planckian) was often difficult. The second method is the haploscopic method, where the subject’s left eye and right eye are adapted separately to the light at each side of the booth. With this method, the colours of the two lights will appear much closer colours due to chromatic adaptation of each eye, thus it was considered that comparisons would be easier.

In non-haploscopic method, subjects looked at the left side of booth (Planckian) and right side (test light with shifted Duv) sequentially by eye movement of both eyes, thus subjects' adaptation was approximately at an average chromaticity of the Planckian and the test light. In the haploscopic method, the subject was adapted to each of Planckian and the test light by separating the view of each eye. This method is considered from the situation in lighting, where observers are always adapted to the illumination and the impression of CCT is given under the adapted condition, thus this method was considered appropriate for lighting situation. As we were not sure which would be the best method, we used both methods under limited resources available.

In addition, in both methods, comparison of colours of the two sides of the booth, when no objects were placed, were found rather difficult, as there is no target to compare for the subjects. We decided to put a large white target sheet at the bottom of the booth so that subjects could compare the colours of the white sheet on both sides, while the surrounding area of the booth was used for subject's adaptation. We did pre-tests with a few subjects, and verified that comparison was easier with the white sheets for the subjects than empty box. This sheet (size, 28 cm x 28 cm) is made of a material based on polytetrafluoroethylene (PTFE) and has very high and spectrally flat reflectance factors (0.96 to 0.97 in 410 nm to 780 nm) as well as near-Lambertian diffuse characteristics. The sheet was also tested to have no fluorescence by excitation around 400 nm. The differences between the chromaticity coordinates of the light source (from spectral irradiance measured at the bottom of the booth) and those of the white target sheet (from spectral radiance measured) are practically negligible (within ±0.0004 in *u', v'*). The spectral reflectance factors of the booth inner surfaces (measured at the center of front wall) was fairly flat, 0.37 to 0.40 in 410 nm to 720 nm. There are slight differences between the chromaticity coordinates of the white target sheet and those of booth inner walls (used for adaptation), but they are within ±0.0016 in *u', v'* and considered insignificant to affect the experimental results.

For haploscopic experiment, a front plate was added to separate the view of each eye of the observer completely. The experimental scenes of the haploscopic and non-haploscopic methods are shown in Figure 4. The subject's eye position was ≈50 cm from the front edges of the booth for non-haploscopic experiment, but it varied to some extent, as a chin rest was not used. In haploscopic experiment, the subject's forehead was contacting the edges of the separating plate mounted in front of the booth having a width of 25 cm. The height of subject eye was at ≈38 to 44 cm from the height of bottom surface of the booth. The height of the chair could be adjusted if the subject was very tall or very short. The cover panel is lower than the height of the diffuser to ensure that light emitting area is shielded from subject's view.

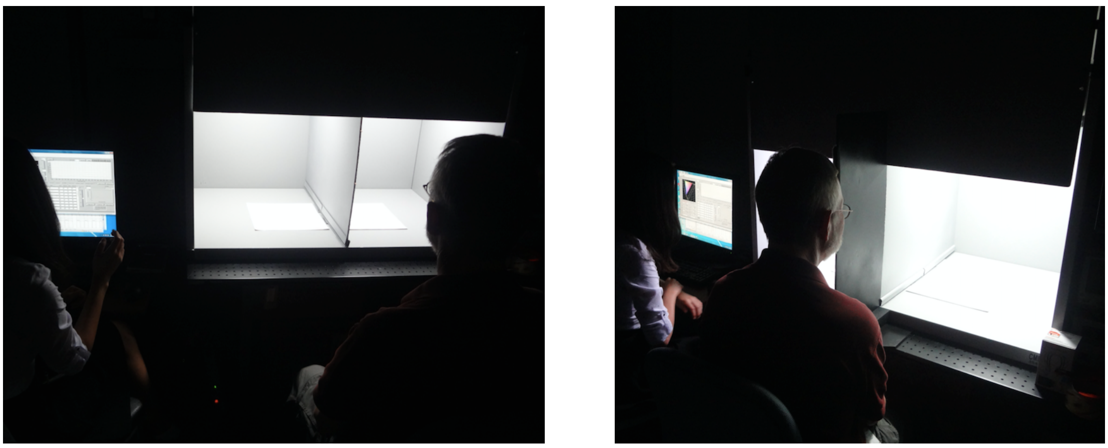

Figure 4 – Experimental scenes of the non-haploscopic method (left) and the haploscopic method (right).

4.1 Initial procedures

These procedures are common with both non-haploscopic and haploscopic methods. When a subject came into the laboratory, he/she was first tested for normal colour vision using Ishihara Test book under room light. Then, room lights were turned off, the subject was adapted for at least 5 min sitting in front of the booth, when both sides of the booth were set for Planckian No. 5 (see Figure 2) of the first CCT (3000 K or 5500 K). Which CCT to start with was randomized for each subject. During this adaptation time, the operator gave introduction of the experiment, instructions for the experiment procedures, then one or two practice runs. Non-haploscopic experiment was always done first, then haploscopic method. Before haploscopic experiment, the subject was asked if their two eyes were not balanced (one eye is dominant). If this is the case (actually there were no such case), the subject would not have participated in the haploscopic experiment.

Due to limitation of experiment time for subjects and limitation of the number of subjects available, the experiments were arranged so that all 12 subjects participated in the haploscopic experiment at both CCT conditions, but they participated in the non-haploscopic experiment at one of CCTs (randomly assigned), thus data for each CCT was obtained for 6 subjects. After all experiments were done, the operator asked the subject which method was easier or any comments, which were also recorded with the results.

4.2 Non-haploscopic experiment procedures

To handle chromatic adaptation appropriately, comparisons were made in pairs of light. In this method, six pairs of Planckian lights were prepared as shown in Figure 5. The Planckian lights are marked number 1 to 9. The light pairs are marked as ① to ⑥ and the adaptation points are green circles between Planckian lights and the test light. A group of comparison experiments for these six pairs is called a “run”, and there are four runs; for 3000 K negative Duv, 3000 K positive Duv, 5500 K negative Duv, and 5500 K positive Duv. The order of these four runs was randomized for each subject. Before each run of experiment, the subject was adapted to the first adaptation point (for each CCT and Duv condition) presented on both sides of the booth for 2 min. Then, before comparing each pair, the subject was adapted for 1 min at each adaptation point, which is the meddle point between the test light and the center of the pair of two Planckian points. There are six light pairs for each test light and there are six adaptation points for each light pair. The order of light pairs presented was randomized for each subject.

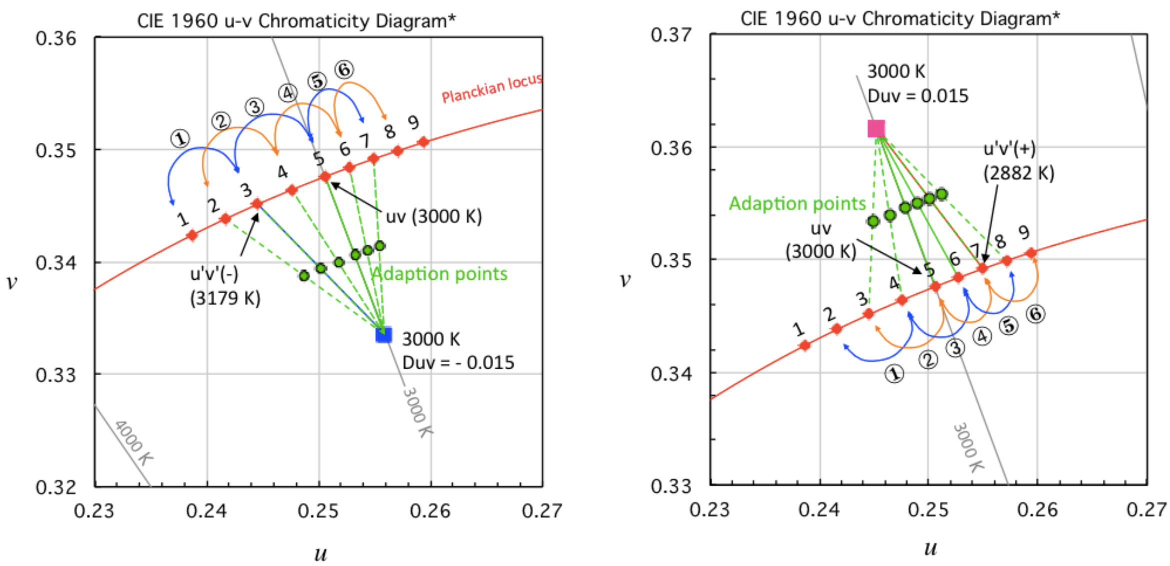

Figure 5 – Test light and pairs of light presented and compared by subjects in haploscopic method, for negative Duv test light (left) and positive Duv test light (right).

For example, in Figure 5 (left), both sides of the booth were first set to the adaptation point between No. 4 and the test light (D_{uv}= -0.015), and the subject was adapted for 2 min. During this time, the subject was instructed to look around the wall areas of booth, and not at the white sheets. Then, the subject was asked to close their eyes momentarily (approximately 10 s) while lights are changed. The left side of booth is switched to Planckian No. 3 and the right side is switched to the test light (D_{uv}= -0.015), then subject was asked to open their eyes. Then, on the left side of the booth, No. 3 and No. 5 were presented alternately for approximately 2 s each time and repeated, while the right side of booth stayed the same (test light). No. 3 is called "A" and No. 5 is called "B", and the subject is asked which light, A or B, is closer colour to the right side. The order of A and B (for lower or higher number of Planckian light) was randomized. For this comparison, the subject was instructed to compare the colours of the white sheets on the left and right side of the booth. A and B were alternated and repeated several times till the subject could make judgement. This was a forced choice, so the subject was instructed to answer A or B even if the judgment was difficult, but in that case, also tell the operator that judgement was difficult. The number of comment "difficult" would indicate how well the experiments were carried out. The operator recorded these comments together with the answers A or B. The closure of the eyes in the procedure above was necessary because only one side of the booth could be changed at a time, so the two sides had to be changed sequentially, which took several seconds, and occasionally with the light turned off and on, which would disturb subject's adaptation condition. In this example, if (*u', v'*) is the correct colour space for CCT, the subject would choose No. 3. If (*u, v*) is the correct colour space for CCT, the subject would choose No. 5.

After completing the first run of experiment, after a short break, next run started with adaptation of 2 min, and another run was performed. Note that only two runs of experiment for one of the CCT conditions were conducted for each subject. Each run took 10 min to 15 min, and the entire time for non-haploscopic experiment including introduction time for each subject was approximately 30 min.

4.3 Haploscopic experiment procedures

In this experiment, the procedures are nearly the same as those for the non-haploscopic experiment described above, except for the adaptation condition for the subjects was different. The experiments used the same nine Planckian chromaticity points, six pairs of light, and two test lights (D_{uv}= -0.015 and D_{uv}= 0.015) as shown in Figure 5 for each CCT condition, but the intermediate adaptation points were not used. Instead, subjects were adapted in a haploscopic condition, with their left eye adapted to the light of left side of the booth (one of Planckian points), and right eye with the light of the right side of the booth (one of the test lights).

Before each run of experiment, the subject was adapted to the first pair of light in haploscopic condition for 2 min. During the initial adaptation time (5 min, see 4.1), a practice run was made under the negative Duv condition, and subject was asked if the colours of left side and right side were becoming closer as his/her eyes are adapted to ensure haploscopic condition is effective for the subject, and also practiced choosing A or B in a light pair.

The order of presenting light pairs was randomized. For example, the left side of booth first presented Planckian No. 4 and the right side of booth presented the test light (D_{uv}= -0.015), and subject was adapted for 1 min in the haploscopic condition. During adaptation time, the subject was instructed to view the wall areas of the booth, and not look at the white sheets. Then, No. 3 is presented as "A" for approximately 2 s, then No. 5 is presented as "B" for 2 s, and these are repeated till the subject had an answer. The transition of the light sources from the adaptation condition to the pair comparison was instant because only the left side of the booth need to be changed, and the subjects did not have to close their eyes in this experiment. The comparisons of lights A and B were conducted in the same manner as described in detail for the non-haploscopic experiment. The comparison of light pairs is repeated for all six pairs for an experiment run.

The subjects had a short break (1 min or so) between the experiment runs with their eyes relaxed in non-haploscopic condition. Each run took 10 min to 15 min, and the entire time for the four runs of experiment for each subject including introduction time was approximately 50 min.

5. Results of experiments

Table 2 shows an example of the sorted raw results of four runs of non-haploscopic experiment filled by six subjects. For haploscopic experiment, this set of data was filled by 12 subjects. Light No. 3 is the CCT point calculated with (*u',v'*) diagram for D_{uv}= -0.015 test light, and No.7 is the that for Duv=0.015 test light (the table cells are marked green). No. 5 is the CCT point calculated with (*u, v*) diagram for both D_{uv}= -0.015 and D_{uv}= 0.015 test lights (the table cells are marked yellow). The column "selected" shows which light was selected by the subject for each adaptation point. The cells are coloured blue when higher CCT was chosen and pink when lower CCT was chosen. Therefore, the ideal scenarios for each case, when the perception follows the (*u, v*) coordinate and when the perception follows the (*u', v'*) coordinate, would be the answers as shown in Table 3.

Table 2. An example of the sorted raw results for comparison of six pairs by two subjects.

Subject #	9				10			
Run	1 (3000 K n)		2 (3000 K p)		3 (5500 K n)		4 (5500 K p)	
Test light	Adaptation	Selected	Adaptation	Selected	Adaptation	Selected	Adaptation	Selected
Planckian light No.	2	1	3	4	2	3	3	4
	3	2	4	5	3	4	4	3
	4	3	5	6	4	5	5	4
	5	4	6	5	5	6	6	5
	6	5	7	8	6	5	7	6
	7	6	8	9	7	6	8	7

Table 3. The ideal scenarios of the answers for Table 2.

Subject #	(u',v') scenario				(u,v) scenario			
Run	Negative Duv		Positive Duv		Negative Duv		Positive Duv	
Test light	Adaptation	Selected	Adaptation	Selected	Adaptation	Selected	Adaptation	Selected
Planckian light No.	2	lower CCT	3	lower CCT	2	lower CCT	3	lower CCT
	3	50%	4		3		4	
	4	higher CCT	5		4		5	50%
	5		6		5	50%	6	higher CCT
	6		7	50%	6	higher CCT	7	
	7		8	higher CCT	7		8	

The results for all subjects were sorted in the format of Table 2, and the percentages of higher CCT chosen are calculated for each condition, which are shown in Tables 4 and 5.

Table 4. Average results of the non-haploscopic experiment (n=6)

3000 K (Duv -)		3000 K (Duv +)		5500 K (Duv -)		5500 K (Duv +)	
Adapt.	high CCT %	Adapt.	high CCT %	Adapt.	high CCT %	Adapt.	high CCT %
2	50%	3	0%	2	0%	3	0%
3	67%	4	0%	3	17%	4	33%
4	67%	5	0%	4	50%	5	50%
5	100%	6	17%	5	50%	6	67%
6	83%	7	0%	6	83%	7	50%
7	83%	8	17%	7	83%	8	67%

Table 5. Average results of the haploscopic experiment (n=12)

3000 K (Duv -)		3000 K (Duv +)		5500 K (Duv -)		5500 K (Duv +)	
Adapt.	high CCT %	Adapt.	high CCT %	Adapt.	high CCT %	Adapt.	high CCT %
2	100%	3	0%	2	58%	3	33%
3	100%	4	17%	3	42%	4	42%
4	75%	5	25%	4	75%	5	50%
5	92%	6	25%	5	67%	6	67%
6	100%	7	17%	6	83%	7	33%
7	92%	8	42%	7	83%	8	75%

The results in Tables 4 and 5 are plotted in Figure 6 and Figure 7. In these figures, the ideal scenarios for the (*u', v'*) coordinate and for the (*u, v*) coordinate, from Table 3, are plotted as dashed lines. Theoretically, the plotted lines of results should be rising from 0 % on low CCT (left) side to 100 % on high CCT (right) side, and the 50% point is considered to be the perceived CCT of the test light.

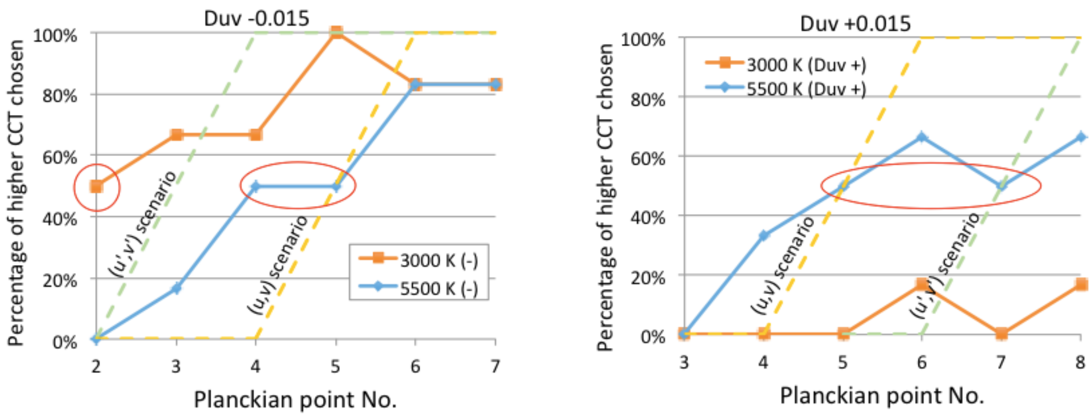

Figure 6 – The results of the non-haploscopic experiment

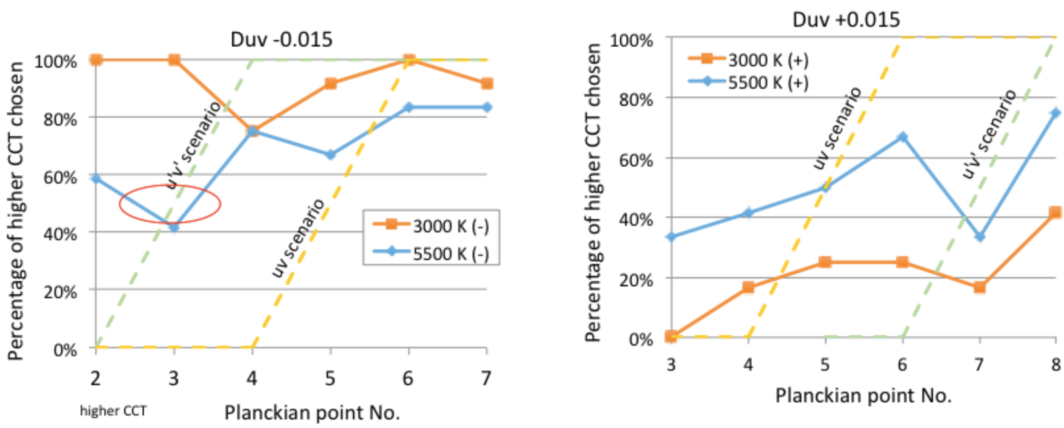

Figure 7 – The results of the haploscopic experiment

From these data shown in the figures, the results are summarized as below:
<Non-haploscopic>

3000 K / D_{uv} -0.015	perceived CCT is closer to the u'v' point.
3000 K / D_{uv} 0.015	perceived CCT is closer to the u'v' point (beyond).
5500 K / D_{uv} -0.015	perceived CCT is closer to uv point.
5500 K / D_{uv} 0.015	perceived CCT is between the uv point and u'v' point.

<Haploscopic>

3000 K / D_{uv} -0.015	perceived CCT is closer to the u'v' point (beyond).
3000 K / D_{uv} 0.015	perceived CCT is closer to the u'v' point (beyond).
5500 K / D_{uv} -0.015	perceived CCT is closer to the u'v' point.
5500 K / D_{uv} 0.015	perceived CCT is between the uv point and u'v' point.

The results above are further summarized that the perceived CCT at 3000 K is consistently closer to the u'v' point (or beyond), and the perceived CCT at 5500 K is between the uv point and u'v' point. The two methods produced fairly consistent results between them. These results may be explained by observation of MacAdam ellipses (e.g., see Figure 3 of CIE, 2014). The ellipses are close to a circle at 3000 K on the (*u', v'*) diagram, but they are closer to a circle on the (*u, v*) diagram at 6500 K. The results above are consistent with this observation on MacAdam ellipses.

Both methods worked fairly well. But for comparison, judging from the rate of “difficult to judge”, it seems that non-haploscopic method was more difficult (16 %) than haploscopic method (9 %). Comparing CCT conditions, 5500 K condition was more difficult (14 %) than 3000 K (8 %). Comparing positive and negative Duv, it appears that negative Duv was more difficult (14 %) than positive Duv (9 %). However, these differences are not so significant.

Conclusions

Vision experiments for perception of correlated colour temperature were conducted with 12 subjects. The results in this study indicate that the perception of CCT at 3000 K is closer to the CCT calculated based on CIE 1976 (*u', v'*) coordinate and possibly with even further shifts. The perception of CCT at 5500 K is shown as between the (*u, v*) coordinate and the (*u', v'*) coordinate and is less conclusive. The results obtained agree with general experience in lighting that negative Duv lights, especially those at lower CCTs (e.g., neodymium lamp), appear higher CCT than currently specified values based on (*u, v*) coordinate. While further experiments are desired with more number of subjects and/or by different laboratories, it is suggested that the definition of CCT be re-examined for using the CIE 1976 (*u', v'*) coordinate for the calculation and possibly reforming the definition of Duv accordingly.

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