VISION EXPERIMENT ON ACCEPTABLE AND PREFERRED WHITE LIGHT CHROMATICITY FOR LIGHTING

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Abstract

Standards on white light chromaticity of fluorescent lamps have been available for more than three decades, but the specifications in these standards have not been based on human vision perception data. Anecdotally, lights with chromaticities below the Planckian locus are expected to provide more preferred lighting for interior. A series of vision experiments have been conducted with 18 subjects on their response to Duv (distance from the Planckian locus on CIE 1960 (*u, v*) coordinates) using the NIST Spectrally Tunable Lighting Facility, with 18 subjects for 6 Duv points (-0.03, -0.02, -0.01, 0, 0.01, 0.02) at four correlated color temperatures (2700 K, 3500 K, 4500 K and 6500 K). The results show that Duv of around -0.015 (below Planckian locus) on average is perceived as the most natural. This Duv level is outside the ranges specified by existing standards. This indicates that new lighting products having more preferred chromaticity than the current products may be possible.

Keywords: chromaticity, lighting, light sources, white light, Duv, visual perception, Planckian locus

1. Introduction

The chromaticity coordinates of light sources for lighting have been designed to be around the Planckian locus for decades since fluorescent lamps were developed. Standards for chromaticity of fluorescent lamps are available (IEC, 1997, ANSI, 2001) and recently for solid state lighting products (ANSI, 2011). In these standards, the center points of the chromaticity ranges are mostly on or slightly above the Planckian locus. In this paper, shifts away from the Planckian locus (yellowish/pinkish shift) is expressed by *Duv* (Symbol: D_{uv}), which is defined as the shortest distance from the chromaticity of the source to the Planckian locus on the CIE (u', $2/3v'$)[1] coordinates, with plus sign for above and minus sign below the Planckian locus (ANSI, 2011), and also discussed in a recent article (Ohno, 2013).

These white light center points for light sources have been widely accepted for many years. However, it is often questioned whether the lights at Planckian locus are really the most natural or preferred white light for indoor lighting, and it is anecdotally said that white points below Planckian locus on chromaticity diagrams is preferred. As evidence, neodymium incandescent lamps, popular in the USA and some other countries for a long time, have slightly pinkish shift with $D_{uv} \approx -0.005$. There have been some researches available on white perception (e.g., Hurvich, 1951) but these are not applicable to judgment of light sources for lighting, and there have been very few researches available on white chromaticities for lighting. CIE (CIE, 2004) specifies the range of (*u, v*) chromaticity to be ±0.05 for calculation of correlated color temperature (CCT), but it is not a definition of white light and not based on visual perception.

A recent report on a vision experiment (Rea, 2013) shows that perceived neutral white points are at $D_{uv} \approx -0.01$ at 2700 K to 3500 K, $D_{uv} \approx 0.00$ at 4000 K, and $D_{uv} \approx 0.005$ at 6500 K (though the report did not use Duv). These results vary with CCT, and no good explanation is given. This experiment was done with a lighting booth with white inner walls and no objects inside. It is considered that, due to chromatic adaptation conditions used in this experiment, the results may

[1] Equal to CIE 1960 (*u, v*) diagram now obsolete.

have been affected by the different ranges of chromaticity points used for different CCTs.

To study perception of white light for lighting, it is considered that that the experiments should be conducted by observing illuminated scenes of real objects including human skin tone. Further, chromatic adaptation needs to be strictly controlled, as perception of color is strongly affected by chromatic adaptation state. Considering these, a series of vision experiments has been conducted at the National Institute of Standards and Technology, using the NIST Spectrally Tunable Lighting Facility (STLF) (Miller et al, 2009), to investigate perceived naturalness of different Duv levels of illumination for simulated interior lighting environment, with full chromatic adaptation conditions. Experiments were conducted using broadband spectra at four Correlated Color Temperatures (CCTs) from 2700 K to 6500 K and at 6 different Duv levels at each CCT.

2. Experimental settings with NIST STLF

The NIST Spectrally Tunable Lighting Facility (STLF) (Miller et al, 2009), as shown in Fig. 1, was used, which has 25 channels of LED spectra (from 405 nm to 650 nm peak) and can control spectral distribution, CCT, Duv, and illuminance, independently, illuminating a real-room size cubicle (2.5 m x 2.5 m x 2.4 m). There are two cubicles side by side, independently controlled, and the walls of different colors and textures can be replaced easily. The facility can produce up to about 300 lx to 800 lx of illumination of white light illumination on the table depending on the spectrum of light.

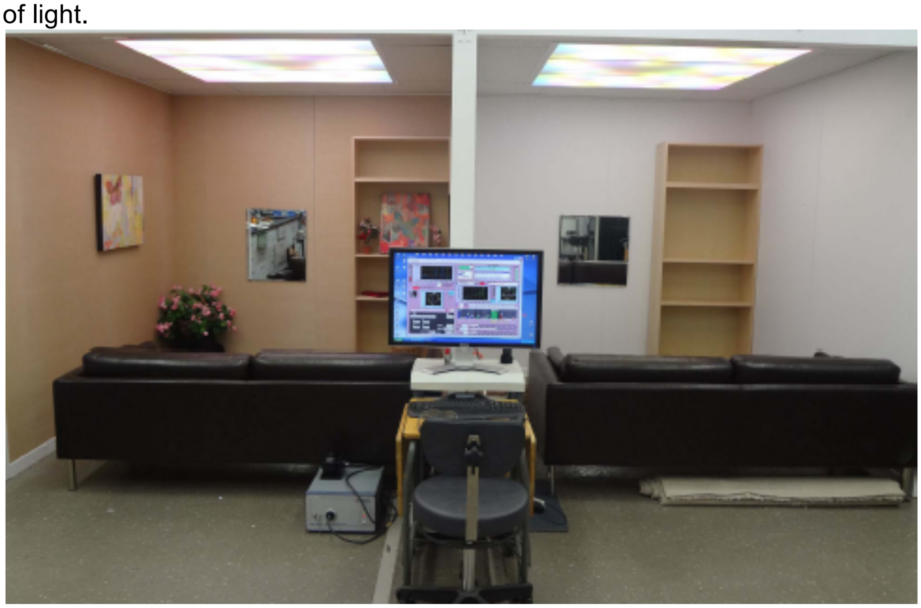

Figure 1. View of the two cubicles of NIST Spectrally Tunable Lighting Facility.

The light source unit of the STLF has very large heat sinks which are cooled by forced air and the temperature of the heat sink is only about 27 °C when these spectra at ~300 lx are produced, while the room temperature is kept to 25 °C ±1 °C. The STLF needs only about 15 minutes to stabilize, after which the chromaticity is stable to within ± 0.0005 in (*u', v'*) for four hours, and reproduces the set chromaticity to within ± 0.001 in (*u', v'*) over one month.

The experiments were conducted mainly using the right side cubicle in Fig.1 with off-white (achromatic) walls, and in addition, experiments with a limited number of subjects were conducted at the left side cubicle with brownish walls.

The experiments were conducted at six different Duv levels (-0.03, -0.02, -0.01, 0, 0.01, 0.02) at four different CCTs (2700 K, 3500 K, 4500 K, 6500 K), except for 2700 K where D_{uv}=0.02 was removed as it is too close to the spectrum locus and perceived as yellow light, and acceptable color rendering could not be achieved. Therefore, a total of 23 points were set up as experimental chromaticity points.

In addition, the Duv levels at ± 0.005 from the six Duv points at each CCT were also needed in the experimental procedures (see section 3). The chromaticities of these points were initially adjusted to be within ±0.0003 from the intended point and were maintained within ±0.0006 throughout the experiment. With these points added, lights at total 50 chromaticity points as shown in Fig. 2 were prepared on the STLF. The Duv ranges were originally set symmetrically from -0.02 to 0.02, but preliminary experiments clearly showed that -0.02 was not sufficient, thus, lower limit was set to D_{uv} = -0.03 in the official experiments. The upper limit of D_{uv} =0.02 was judged sufficient in the preliminary experiments.

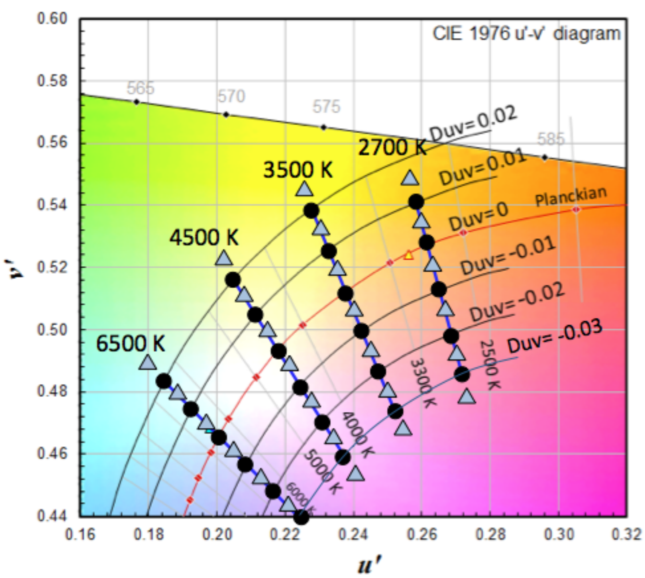

Figure 2 The 50 chromaticity points on STLF prepared for the experiments.

The color quantities of the lights were measured on the center of the table in the cubicle, using an array type spectroradiometer with a small integrating sphere input for cosine response, calibrated with a NIST spectral irradiance standard scale (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 spectra, but in all cases, they were within 0.0012 in *u'*, 0.0011 in v', 0.0009 in Duv, 24 K in CCT at 2700 K and 92 K at 6500 K. The repeatability of the spectroradiometer was 0.0002 in u' and v'. Also, when the spectrum is changed on STLF, the spectrum and color are switched instantly and stable immediately so that sequential comparison of lights is possible.

Broadband spectra with high color fidelity were used in this experiment to avoid possible effects of narrow-band spectra. The measured light spectra for the 50 chromaticity points used for the experiments are shown in Fig. 3. The spectral distributions at D_{uv}=0.000 were first set for the highest CRI R_a or CQS (Davis and Ohno 2010) Q_a value achieved at each CCT at about 300 lx, then lights at other Duv levels were set. The R_a values were 98, 98, 97, 97 and Q_a values were 97, 96, 96, 95 at 2700 K, 3500 K, 4500 K and 6500 K, respectively, at D_{uv}=0. Then the spectra at different Duv levels were prepared. The STLF automatically maintains constant CCT and illuminance when Duv level is changed, only with very small variations due to the system imperfection. The variations of CCT at different Duv points were within ±13 K from the average at 2700 K and ± 40 K from the average at 6500 K, and illuminance was kept within 1 % from an average value for all Duv levels at each CCT.

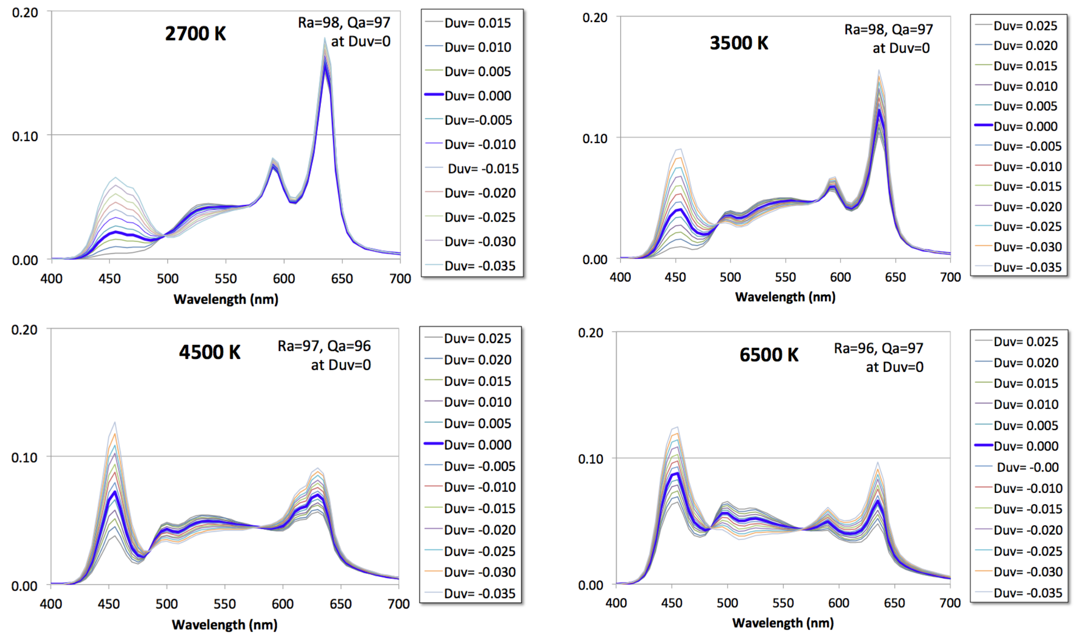

Fig. 2 Spectral power distributions of the lights in STLF used in the experiments at each CCT condition. The thick curves (blue line) are at D_{uv}=0.

The spatial uniformity of color in the room was also evaluated. The uniformity of chromaticity over the tabletop was with ±0.001 in (*u', v'*). The uniformity of chromaticity on the table and on the wall up to 1.5 m high from the floor (measured on a vertical plane) was within ±0.003 in (*u', v'*). The chromaticity on the position of the mirror was within 0.001 in (*u', v'*) from the table top. These values are similar with all lights used in the experiment.

The CCT, Duv, and illuminance (at 4 CCTs at D_{uv}=0) were measured and recorded each day before and after each experimental session, with special attention to the stability of Duv. The Duv values were reproduced to within ±0.0002 each morning in most cases, and to 0.0005 at largest difference from the initial day. Even if there is a small shift in Duv, the same shift appeared in all Duv levels so that the intervals between different Duv points were always kept constant (to within 0.0004).

Fig. 3 shows the experimental settings for the subjects. The subject sat on a coach placed at the open side of the cubicle so that he/she viewed the entire room, and was completely immersed in the lighting environment and his/her full view was adapted to the illumination. For the subjects to be able to judge naturalness and preference, we selected common real objects often seen in daily life. In the cubicle, two dishes of real fruits and vegetables (red apple, yellowish apple, orange, green pepper, lettuce, tomato, banana, strawberries, and grapes) were placed on a table. The fruits and vegetables were replaced at one to several days' intervals depending on the item to keep them fresh. Items with as similar color and shape as much as possible were obtained each time the items were replaced. There was a mirror in front of the subject, and he/she could look at their face skin tone in the mirror, as well as their hands skin tone. Along the wall of the cubicle, there was a bookshelf with some books, artificial flowers, and two paintings hung on the sidewalls (as shown in Fig. 3 left), simulating a small living room.

Eighteen subjects having normal color vision were used in the experiments. They were 11 males and 7 females with their ages from 19 to 70. The subjects were workers at NIST, who are not experts on color, including seven summer students (ages 19 to 22).

The experiments were conducted in June to July 2013. The CCT, Duv, and illuminance were recorded before and after each experimental session for a subject, and they were measured at the center of the table.

Figure 3. The experimental settings for subjects – the room setting (left) and fruits and vegetables on the table (right).

3. Experimental Procedures

At each CCT, the subject was first adapted to the illumination at one end of Duv (e.g., D_{uv}= 0.02) for five minutes, then after adaptation, the subject was asked whether this light is acceptable or not. Then, a pair of lights, ± 0.005 from the adapted light (so, in this case D_{uv} =0.025 and 0.015) was presented and asked which light looked more natural. The subject was instructed to see the fruits, skin tone, the entire room, as they liked, and made overall judgment. The pair of lights was flipped at 3 seconds interval with a computer sound, and the subject clicked the mouse when the light that appeared more natural was presented. If the negative shift was chosen, the adapted light was judged to be too yellowish (greenish) to the observer or vice versa.

Then, next Duv is presented (e.g., 0.015) and the subject was adapted to the illumination for one minute, then the same trial with a pair of lights (± 0.005 shifts) was made.
This was repeated for the six levels of Duv, which completes one run of one CCT. Then, the same run of experiment was made at different CCT. Then another run at the first CCT in reverse order of Duv (start from D_{uv} = –0.03 and ends at D_{uv} = 0.02) was conducted. A run for each direction at each CCT was repeated twice, so there were total four runs for each CCT. The order of CCT and forward/reverse directions were pre-determined and the same combination was used for all subjects.

Special attention was paid to the adaptation time, as the experimental results would depend on the state of chromatic adaptation. Our experiment was intended for the condition of full chromatic adaptation. Previous studies (Hunt, 1950 and Fairchild et al, 1995) indicate that about two minutes would be sufficient for full chromatic adaptation. Due to overall time limitation, we chose one minute adaptation time at each experimental point after the very first point (given 5 min), expecting that adaptation time may be shorter for the very small color changes, but one minute may not be sufficient. Taking this into consideration, the experimental runs were made in both forward and reverse directions and results averaged so that any remaining effects due to incomplete chromatic adaptation would be cancelled.

Each run typically took 12 to 15 minutes, about 1 hour for one CCT (with four runs), and total about 4 hours for each subject. Experiments were typically done in two sessions of 2 hours each. Ishihara color deficiency test was done for each subject. In addition to the experiments using the off-white wall, six of the 18 subjects repeated similar set of experiments in the cubicle with brownish walls, to check whether there is any effect of the color of the walls. The whole experiment with all subjects took over one month.

4. Results

Table 1 and Fig. 4 show an example of results of one subject at one CCT. Table 1 shows the responses of the subject at each Duv point at each CCT run. "0" means the subject chose the higher Duv light (shift in yellowish direction) in the pair as more natural, and "1" means he/she chose the lower Duv light (shift in pinkish direction) in the pair. In this example, the subject always selected higher Duv of the pair at D_{uv}= -0.03 and always lower Duv of the pair at D_{uv}=0.02, which is a typical case. The arrows show the direction of experimental run. Some effects due to the direction are also observed in this example. These results for the four runs of the subject were averaged in the bottom row in Table 1. These average values in percentage are plotted in Fig. 4. From the plotted curve, the Duv value at 50 % crossover point is read. This point is considered to be the light perceived as most natural for this condition.

Table 1. An example of raw results of one subject at one CCT.

Duv=	-0.03	-0.02	-0.01	0.00	0.01	0.02
4500K backward	0	1	1	1	1	1
4500K forward	0	0	0	1	1	1
4500K backward	0	1	1	1	1	1
4500K forward	0	0	0	1	1	1
Average	0	0.5	0.5	1	1	1

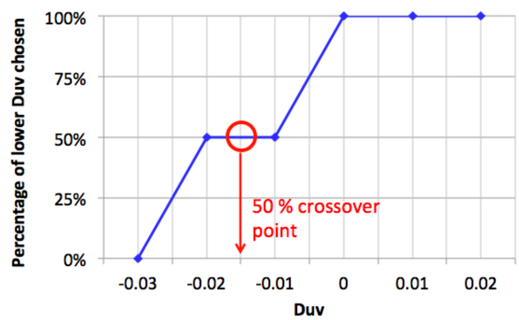

Figure 4. An example of data of one subject - Percentage of the lower Duv in each pair chosen.

The data of all the subjects were analyzed as described above, and the 50 % crossover points of Duv for all subjects at all CCTs are presented in Fig. 5. Note that the four lines at the bottom are flat lines at -0.03. The positions of these lines are shifted slightly to show that there are multiple lines here. This also indicated that these subjects may have chosen Duv even lower than -0.03 but it was the limit in this experiment. Also, data of one subject was removed as the result curves did not follow the typical slope and difficult to find crossover points, so data of total 17 subjects are used. The averages and standard deviations of all 17 points for each CCT are shown in Table 2.

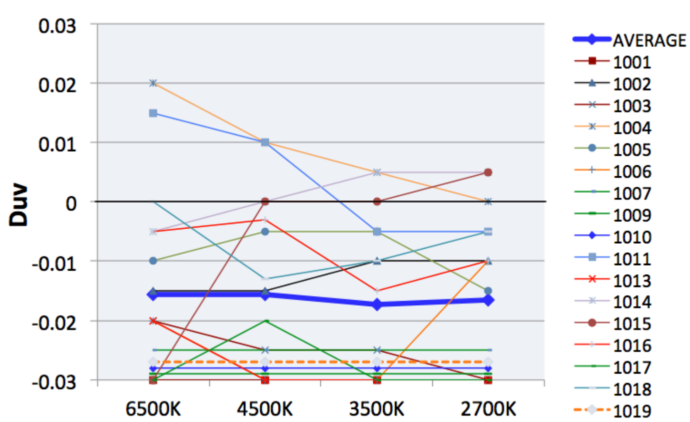

Table 2. Duv values at 50 % crossover points and standard deviation.

CCT	Duv at 50 % crossover	St.dev
2700K	-0.016	0.013
3500K	-0.017	0.014
4500K	-0.016	0.015
6500K	-0.016	0.016

Figure 5. Duv at 50 % cross-over points for all subjects
at all CCTs.

These Duv points are far below the Planckian locus and outside the current chromaticity specification for LED lighting products in the USA (ANSI 2011). In Fig. 6, the results of this experiment are plotted over the chromaticity quadrangles in ANSI C78.377. The average crossover points at all four CCTs are at similar Duv levels, in comparison to the results by the other study (Rea, 2013), which showed different results at higher CCTs.

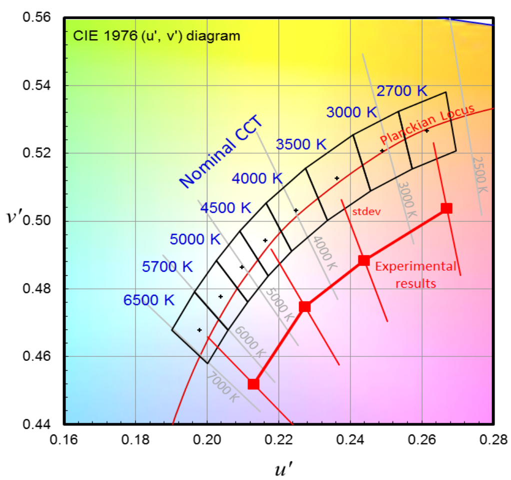

Figure 6. The results of the experiment plotted on ANSI C78.377 chromaticity specifications for SSL products.

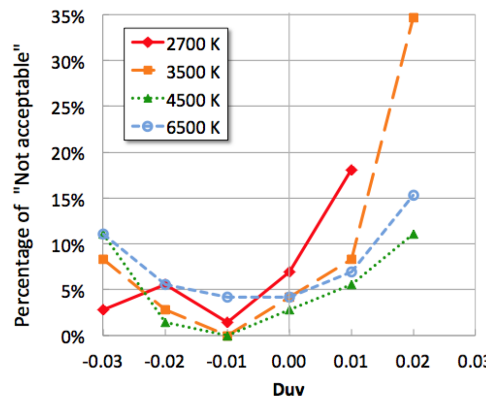

Figure 7. The percentages of subjects' response of "Not acceptable" for lights with different Duv levels.

Figure 7 shows the plots of percentages of subjects who responded "Not acceptable" for presented light after adaptation. The curves are much steeper for positive Duv at low CCTs, and broader at higher CCT, which means that positive Duv is more disliked at low CCTs than at high CCTs. This may be explained by the fact that the Planckian locus at 2700 K is much closer to the spectrum locus (pure yellow) than at other CCTs and thus the effects of positive Duv at 2700 K is much pronounced. Also, the curves generally have a minimum at around Duv =-0.01, which is fairly consistent with the main experimental results.

The experiments with different wall colors were also conducted by five subjects among the 17 subjects. Due to time limitation, only two runs at each CCT were made, and results were compared between the white wall room and the brownish wall room. From these limited data, on the average, no notable differences between the two rooms were observed.

Conclusions

A series of vision experiments were conducted on acceptable or preferred ranges of Duv of white light for indoor illumination under full chromatic adaptation conditions. The results indicate that the chromaticities of lighting sources below the Planckian locus (around $D_{uv} \approx -0.015$) are well preferred for natural appearance of objects in typical indoor lighting environment in the CCT range from 2700 K to 6500 K, and that chromaticities above the Planckian locus are less acceptable or preferred. This indicates that new lighting products having more preferred chromaticity than the current products may be possible. The experimental conditions in this study, however, were limited; e.g., transient effects (when a person comes from outdoor into a room with negative Duv) have not been investigated. Further studies are desired to verify applicability of these results in various real application conditions.

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