VISION EXPERIMENT ON CHROMA SATURATION PREFERENCE IN DIFFERENT HUES

OHNO, Y.[1], OH, S.[2], KWAK, Y.[2]
[1] National Institute of Standards and Technology, Gaithersburg, USA
[2] Ulsan National Institute of Science and Technology, Republic of Korea
ohno@nist.gov

Abstract

Increase of chroma is known to be a major factor for colour quality preference in lighting, and gamut area measures are often used to evaluate preference aspects. However, gamut area accounts for chroma differences equally for all hue directions. Experiences in lighting indicates that red is most dominant in such colour quality preference but experimental data has not been available. Vision experiments were conducted to evaluate different effects of chroma shifts in different hue directions on colour quality preference, using NIST Spectrally Tunable Lighting Facility simulating an interior room. 19 subjects viewed various fruits, vegetables, and their skin tones, under illumination of 11 different spectra of different gamut shapes. The 11 spectra were presented as pairs in all combinations, at correlated colour temperatures (CCT) of 2700 K, 3500 K, 5000 K, (D_{uv}= 0) and 3500 K (D_{uv}= -0.015). The average results show that chroma increases of red ($\Delta C^*_{ab} \approx$ 5 to 15) has the largest effect, green ($\Delta C^*_{ab} \approx$15) has the second effect, and yellow's effect is insignificant, in subjects' preference. The results will be useful to develop colour preference metrics that correlates well with perceived colour quality.

Keywords: colour preference, colour quality, chroma, hue, gamut area, lighting

1 Introduction

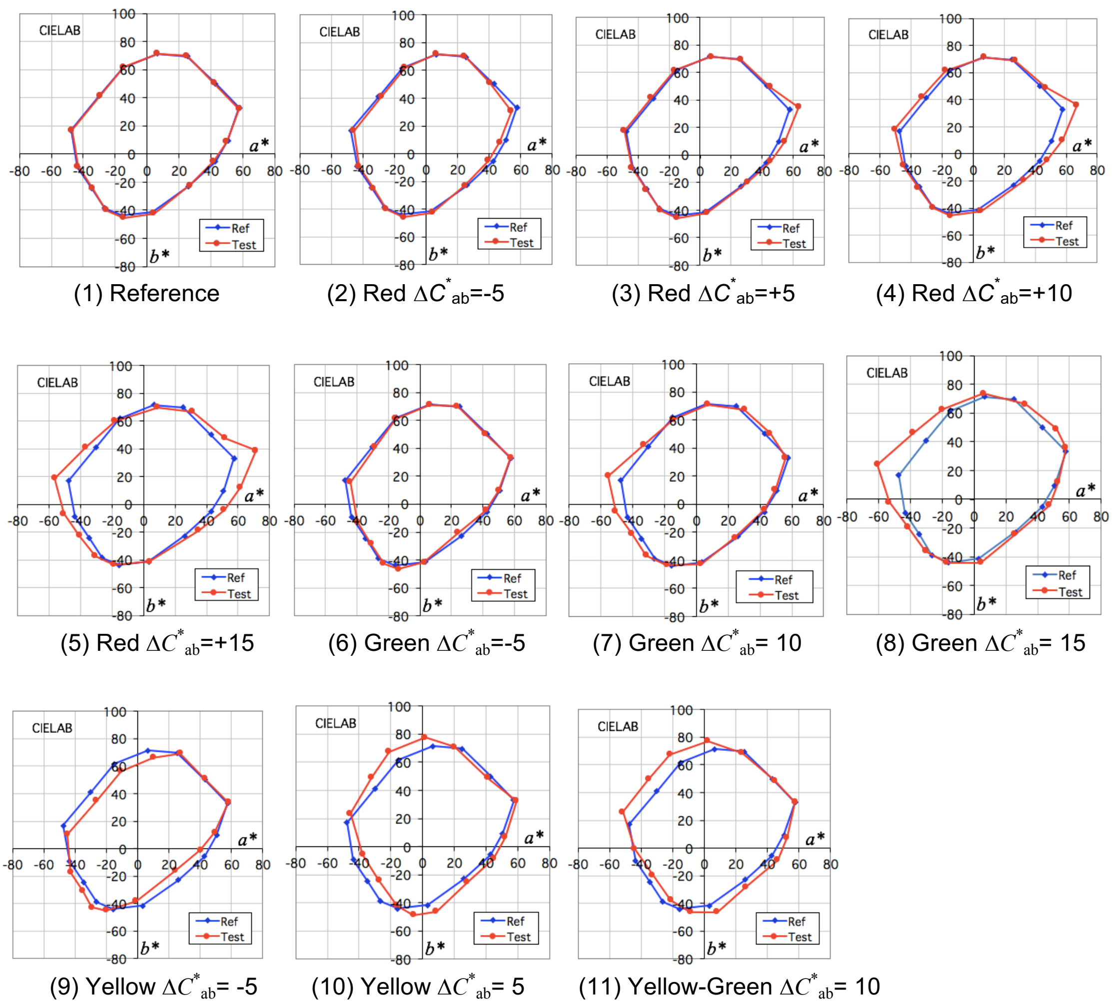
The overall colour quality of lighting as experienced by users is affected not only by colour fidelity such as International Commission on Illumination (CIE) Colour Rendering Index (CRI), but also other perception effects beyond colour fidelity, especially colour quality preference. Increase of chroma is known to be a major factor for colour quality preference in lighting, and gamut area metrics have been proposed as a preference measure. Gamut area metrics recently proposed include Feeling of Contrast Index (Hashimoto et al, 2007), Gamut Area Index (GAI) (Rea and Freyssinier, 2010), gamut area Q_g in Colour Quality Scale (CQS) (Davis and Ohno, 2010), and most recently, Gamut Index R_g in Illuminating Engineering Society (IES) TM-30 (IES, 2015). However, gamut area accounts for chroma differences equally in all directions of hue. Experiences in lighting indicate that preference effects depend much on hue of object colour, in particular, red is considered to be dominant in colour quality preference, but such experimental data for lighting have not been available.

Following the experiment on chroma saturation at National Institute of Standards and Technology (NIST) (Ohno et al, 2015), a series of vision experiments have been conducted to compare the effects of chroma increase or decrease in different hues on colour quality preference, using NIST Spectrally Tunable Lighting Facility (STLF) (Miller et al, 2009) simulating an interior room. 19 subjects participated in the experiments and evaluated their preference on colour quality of objects on the table, which were various real fruits and vegetables of mixed colours, and their skin tones also, under illumination of 11 different spectra of different gamut shapes presented as pairs in all combinations. The experiments were conducted at correlated colour temperatures (CCT) of 2700 K, 3500 K, 5000 K (each D_{uv}=0), and at a negative Duv [1] condition (D_{uv}= -0.015) at 3500 K. The experimental procedures and results are reported.

[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).

2 Experimental settings with NIST STLF

For the experiment at each CCT/Duv condition, 11 different chroma saturation conditions as shown in Figure 1 were prepared, which had chroma increase or decrease in red, green, and yellow directions, made as independent as possible from other colors. The figure shows the CIELAB (a^*, b^*) plots of 15 saturated Munsell samples as used in Colour Quality Scale (CQS) (Davis and Ohno, 2010). The red, green, yellow, and yellow-green samples used for chroma settings were 5R4/14, 2.5G6/12, 5Y8/12, and 7.5GY7/10, respectively. Figure 1 shows only data for 3500 K (D_{uv}=0) condition, and the same set of 11 lights were prepared also for 2700 K, 5000 K (both D_{uv}=0), and 3500K (D_{uv}= -0.015), thus total 44 lights were prepared. In the figure, the red lines show the gamut of the measured test light, and the blue lines show the gamut of the reference illuminant, which is the same as that used for Colour Rendering Index (CRI) calculation (Planckian radiation or a phase of daylight of the same CCT as the test light). The ΔC^*_{ab} values are shifts of the chroma from the reference illuminant. Positive and negative numbers mean increase or decrease, respectively, of chroma from the reference illuminant. The ΔC^*_{ab} values are chroma shifts from the reference illuminant to the test light, and these values are target values; measured values were slightly different. The spectra of STLF lights were tuned so that, when setting chroma shifts of one colour (e.g., green), the chroma of other colours (e.g., red) was kept as close as possible to ΔC^*_{ab} =0 (the point for the reference) so that the saturation effect of only one colour could be evaluated, though this was difficult and not always possible. The illuminance was set at ≈250 lx ±1 % on the table in STLF for all light conditions.



(1) Reference (2) Red ΔC^*_{ab}=-5 (3) Red ΔC^*_{ab}=+5 (4) Red ΔC^*_{ab}=+10

(5) Red ΔC^*_{ab}=+15 (6) Green ΔC^*_{ab}=-5 (7) Green ΔC^*_{ab}= 10 (8) Green ΔC^*_{ab}= 15

(9) Yellow ΔC^*_{ab}= -5 (10) Yellow ΔC^*_{ab}= 5 (11) Yellow-Green ΔC^*_{ab}= 10

Figure 1– Gamut shapes on CIE (a^*, b^*) plane of the 11 spectra at 3500 K (D_{uv}=0) used for the experiment. Blue curves show the (a^*, b^*) plots of the 15 saturated Munsell samples for the reference illuminant, and the red curves show those for the 11 test lights.

It was difficult to control the chroma in blue direction independently from chroma changes in other colours, and experiment for blue could not be implemented. There were also large hue shifts in blue when controlling blue chroma. It is also considered that increase or decrease in blue is unlikely with the actual lighting products having reasonable colour rendering.

All channels of STLF were utilized to produce these chroma settings, except the 405 nm channel, to avoid any effects of fluorescence from viewed objects. The spectral distributions of all 11 lights for all CCT/Duv conditions are shown in Figure 2. The reference lights had CRI R_a values of ≈ 98 except the D_{uv}= -0.015 condition where R_a value of the reference was 93. For other test lights, R_a values ranged from 63 to 95. ΔC^*_{ab} values were set mostly within ±1 unit from the target value, with a few exceptions of up to ±2 units from the target values.

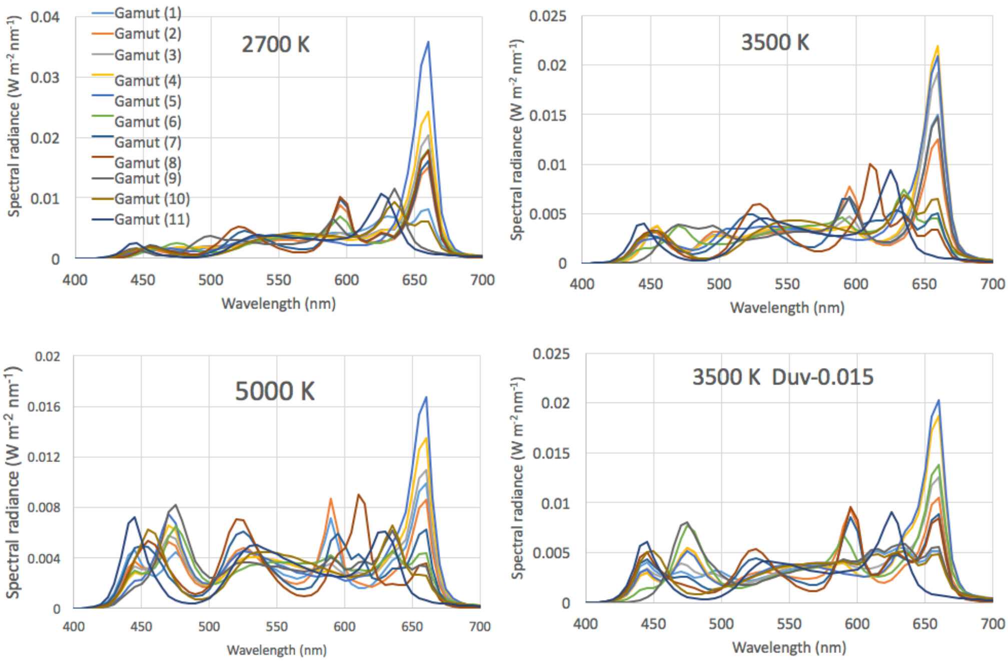


Figure 2 – The spectral distributions of the 11 lights used in the experiment at each CCT/Duv conditions

The STLF cubicle for the experiment was arranged as an interior room as shown in Figure 3, with a couch, a coffee table, a bookshelf with books, some artificial flowers, paintings on the walls. A mirror was also placed on the wall against the couch, to allow evaluation of skin tone of the face of the subject. On the table, there were two plates of real fruits and vegetables; apples, oranges, bananas, strawberries, green peppers, lettuce, tomatoes, red cabbage, and grapes (green and red).

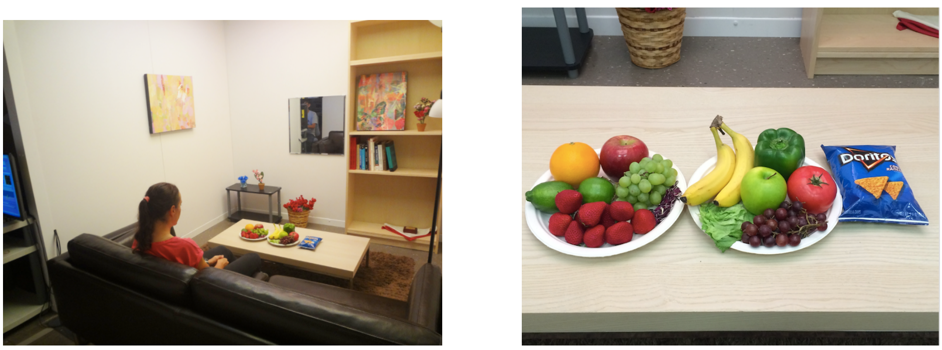


Figure 3 – The setup of the STLF cubicle (left), the fruits and vegetables on the table, used in the experiment

These fruits and vegetables were replaced every few days to keep them fresh during the experiment period of about three weeks. Pictures of these fruits and vegetables were taken, and when these were replaced, those having as similar colours and sizes as possible were purchased and used throughout the experiments.

3 Experimental Procedures

19 subjects having normal colour vision participated in the experiment; 11 males and 8 females, from 18 to 84 years old, 13 white and 6 Asians. Each subject evaluated their preference on colour appearance of the target objects under illumination of the 11 different spectra shown above as pairs of lights in all combinations (55 pairs total), which formed an experimental session. Therefore, each of 11 test lights was compared with all other 10 test lights in pairs under the same CCT and Duv condition. Five experimental sessions for different CCT/Duv conditions were conducted for each subject as shown in Table 1. The experiments on their skin tones (subject's hands and face in a mirror) were conducted only at 3500 K due to limitation of time. The experimental session at 3500 K for fruits and vegetables was repeated to test reproducibility. Thus, these five experimental sessions were conducted for each subject, requiring approximately two and half hours in total for each subject.

Table 1 – Conditions for the 5 experiment-runs for each subject

Session	CCT [K]	Duv	Viewing target
1	3500	0	Fruits and vegetables
2	2700	0	Fruits and vegetables
3	5000	0	Fruits and vegetables
4	3500	-0.015	Fruits and vegetables
5	3500	0	Skin tone

Each subject was first tested for normal colour vision using Ishihara Test. Then, instructions for experiment were given, with a few trial comparisons of pairs. The subject was instructed to pay attention to all of red, green, and yellow fruits and vegetables (not look at only one object) when comparing a pair of lights. These initial procedures were done at 3500 K setting, requiring about 10 min, which also served as the first adaptation for the subject. When CCT is changed, the subject was adapted for three min before pair comparisons started. The 55 pairs were presented in random order. Each pair of light was presented sequentially and repeatedly as "A" and "B", for two or three seconds each, and subjects answered which light, A or B, he or she preferred (forced choice), when viewing targets in the room. The order of the test light and reference light in each pair was also randomized. While the answer was forced choice, the subject was also instructed to say, "it is difficult" if the choice was difficult and it was recorded.

Typically, two subjects per day were scheduled for experiment. The STLF was stabilized for at least 30 min before experiments started each day. Before and after all the experiments for each day, the chromaticity (CCT and Duv) of all 44 lights were measured and recorded to verify that the STLF was working in stable conditions. The spectral power distribution of all 44 lights were measured before and after the entire experiment period, to verify that the light spectra were stable during the experiment period. These stability checks ensured that the SLTF for all settings reproduced and was stable to within ±0.001 in *u', v'* during the experiment period.

4 Results

From the raw results of 55 pair comparisons for 19 subjects, first the proportions that each light (No. 1 to No. 11) was chosen in comparison to other 10 lights in each CCT/Duv condition were calculated. **Table 2** shows such results for 3500 K as an example. No. 1 to 11 in the first column and the first row correspond to the 11 lights of different gamut shapes shown in Figure 1. The values in parenthesis are ΔC^*_{ab} values of chroma shift from the reference. For example, in a pair of Reference (0) and Red (5), 89% (17 out of 19) of subjects preferred Red (ΔC^*_{ab}= 5) to Red (ΔC^*_{ab}= 0). Similarly, in a pair of Reference (0) and Red (-5), only 11% (2 out of 19) of subjects preferred Red (ΔC^*_{ab}=-5) to Red (ΔC^*_{ab}= 0).

Table 2 – Proportions of light chosen in 55 pairs (3500 K)

	No. (i)	1	2	3	4	5	6	7	8	9	10	11
No. (j)		Ref (0)	Red (-5)	Red (5)	Red (10)	Red (15)	Green (-5)	Green (10)	Green (15)	Yellow (-5)	Yellow (5)	YG (10)
1	Ref (0)	0.50	0.11	0.89	0.89	0.74	0.26	0.63	0.84	0.42	0.53	0.68
2	Red (-5)	0.89	0.50	0.84	0.89	0.68	0.63	0.95	0.84	0.58	0.84	0.84
3	Red (5)	0.11	0.16	0.50	0.79	0.63	0.21	0.37	0.53	0.16	0.32	0.26
4	Red (10)	0.11	0.11	0.21	0.50	0.58	0.11	0.32	0.47	0.16	0.21	0.32
5	Red (15)	0.26	0.32	0.37	0.42	0.50	0.21	0.26	0.37	0.21	0.32	0.37
6	Green (-5)	0.74	0.37	0.79	0.89	0.79	0.50	0.68	0.84	0.42	0.68	0.53
7	Green (10)	0.37	0.05	0.63	0.68	0.74	0.32	0.50	0.84	0.37	0.53	0.47
8	Green (15)	0.16	0.16	0.47	0.53	0.63	0.16	0.16	0.50	0.16	0.21	0.21
9	Yellow (-5)	0.58	0.42	0.84	0.84	0.79	0.58	0.63	0.84	0.50	0.58	0.47
10	Yellow (5)	0.47	0.16	0.68	0.79	0.68	0.32	0.47	0.79	0.42	0.50	0.42
11	YG (8)	0.32	0.16	0.74	0.68	0.63	0.47	0.53	0.79	0.53	0.58	0.50

The data in Table 2 were then converted to z-scores, which are often used in psychophysics data analyses (Gescheider 2013). The z-score converts probability data into the scale of the evaluated quantity, which is subjects' preference of lighting in this case. The values in Table 2 are taken as probability $p_{i,j}$ that light i was chosen as preferred over light j. The z-scores $z_{i,j}$ for each pair of light i vs light j were calculated as follows.

A probability density function of the standard normal distribution (normal distribution with its mean equal to 0 and its standard deviation equal to 1) is considered:

$$f(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \tag{1}$$

The integrated value of this function from minus infinity to the value x is calculated, and $z_{i,j}$ is determined as the value of x when the integral is equal to $p_{i,j}$, as

$$z_{ij} = x; \quad \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \mathrm{d}x = p_{ij} \tag{2}$$

The calculated z-score values for 3500K condition are shown in Table 3 as an example. These values indicate the degree of preference of light i in the scale from negative (disliked) to positive (liked) with respect to light j. The average scores, $z_{\mathrm{ave},i}$, for each light i are calculated, then these are normalized by the values for the reference light, $z_{\mathrm{norm},i}$, as shown at the bottom two rows of Table 3. The normalized z-scores show the preference level of each light compared to the reference light (neutral saturation). Positive numbers mean preferred, negative numbers mean disliked, compared to the reference light, and their absolute values show the degrees of being preferred or disliked. Table 4 shows the average z-score values and Table 5 for the normalized z-score values for all other CCT/Duv conditions.

Table 3 – z-scores for all 55 pair comparisons (3500 K)

	No. (i)	1	2	3	4	5	6	7	8	9	10	11
No. (j)		Ref (0)	Red (-5)	Red (5)	Red (10)	Red (15)	Green (-5)	Green (10)	Green (15)	Yellow (-5)	Yellow (5)	YG (10)
1	Ref (0)	0.00	-1.25	1.25	1.25	0.63	-0.63	0.34	1.00	-0.20	0.07	0.48
2	Red (-5)	1.25	0.00	1.00	1.25	0.48	0.34	1.62	1.00	0.20	1.00	1.00
3	Red (5)	-1.25	-1.00	0.00	0.80	0.34	-0.80	-0.34	0.07	-1.00	-0.48	-0.63
4	Red (10)	-1.25	-1.25	-0.80	0.00	0.20	-1.25	-0.48	-0.07	-1.00	-0.80	-0.48
5	Red (15)	-0.63	-0.48	-0.34	-0.20	0.00	-0.80	-0.63	-0.34	-0.80	-0.48	-0.34
6	Green (-5)	0.63	-0.34	0.80	1.25	0.80	0.00	0.48	1.00	-0.20	0.48	0.07
7	Green (10)	-0.34	-1.62	0.34	0.48	0.63	-0.48	0.00	1.00	-0.34	0.07	-0.07
8	Green (15)	-1.00	-1.00	-0.07	0.07	0.34	-1.00	-1.00	0.00	-1.00	-0.80	-0.80
9	Yellow (-5)	0.20	-0.20	1.00	1.00	0.80	0.20	0.34	1.00	0.00	0.20	-0.07
10	Yellow (5)	-0.07	-1.00	0.48	0.80	0.48	-0.48	-0.07	0.80	-0.20	0.00	-0.20
11	YG (8)	-0.48	-1.00	0.63	0.48	0.34	-0.07	0.07	0.80	0.07	0.20	0.00
	$z_{\mathrm{ave},i}$	-0.27	-0.83	0.39	0.65	0.46	-0.45	0.03	0.57	-0.41	-0.05	-0.09
	$z_{\mathrm{norm},i}$	**0.00**	**-0.56**	**0.66**	**0.92**	**0.73**	**-0.19**	**0.30**	**0.84**	**-0.14**	**0.22**	**0.17**

Table 4 – The average z-score values, $z_{ave,I}$, for the 11 lights for all CCT/Duv conditions

	Ref (0)	Red (-5)	Red (5)	Red (10)	Red (15)	Green (-5)	Green (10)	Green (15)	Yellow (-5)	Yellow (5)	YG (10)
2700K	-0.05	-0.81	0.44	0.39	0.13	-0.37	-0.22	0.25	-0.18	0.22	0.20
3500K	-0.27	-0.83	0.39	0.65	0.46	-0.45	0.03	0.57	-0.41	-0.05	-0.09
5000K	-0.09	-0.84	0.40	0.73	0.66	-0.66	-0.10	0.37	0.11	-0.24	-0.34
3500K, -Duv	-0.26	-0.82	0.45	0.54	0.46	-0.08	0.10	0.08	-0.15	-0.24	-0.09
3500K (Skin)	-0.10	-0.59	0.50	0.46	0.21	0.07	-0.21	0.25	0.10	-0.26	-0.44
All CCT/Duv	**-0.15**	**-0.78**	**0.44**	**0.55**	**0.39**	**-0.30**	**-0.08**	**0.31**	**-0.10**	**-0.11**	**-0.15**

Table 5 – The normalized z-score values, $z_{norm,i}$, for the 11 lights for all CCT/Duv conditions

	Ref (0)	Red (-5)	Red (5)	Red (10)	Red (15)	Green (-5)	Green (10)	Green (15)	Yellow (-5)	Yellow (5)	YG (10)
2700K	0.00	-0.76	0.49	0.44	0.19	-0.31	-0.16	0.31	-0.12	0.28	0.25
3500K	0.00	-0.56	0.66	0.92	0.73	-0.19	0.30	0.84	-0.14	0.22	0.17
5000K	0.00	-0.75	0.50	0.82	0.75	-0.57	-0.01	0.46	0.20	-0.15	-0.25
3500K, -Duv	0.00	-0.56	0.71	0.79	0.72	0.17	0.36	0.34	0.11	0.02	0.17
3500K (Skin)	0.00	-0.50	0.60	0.55	0.31	0.17	-0.12	0.35	0.20	-0.17	-0.34
All CCT/Duv	**0.00**	**-0.63**	**0.59**	**0.71**	**0.54**	**-0.15**	**0.07**	**0.46**	**0.05**	**0.04**	**0.00**

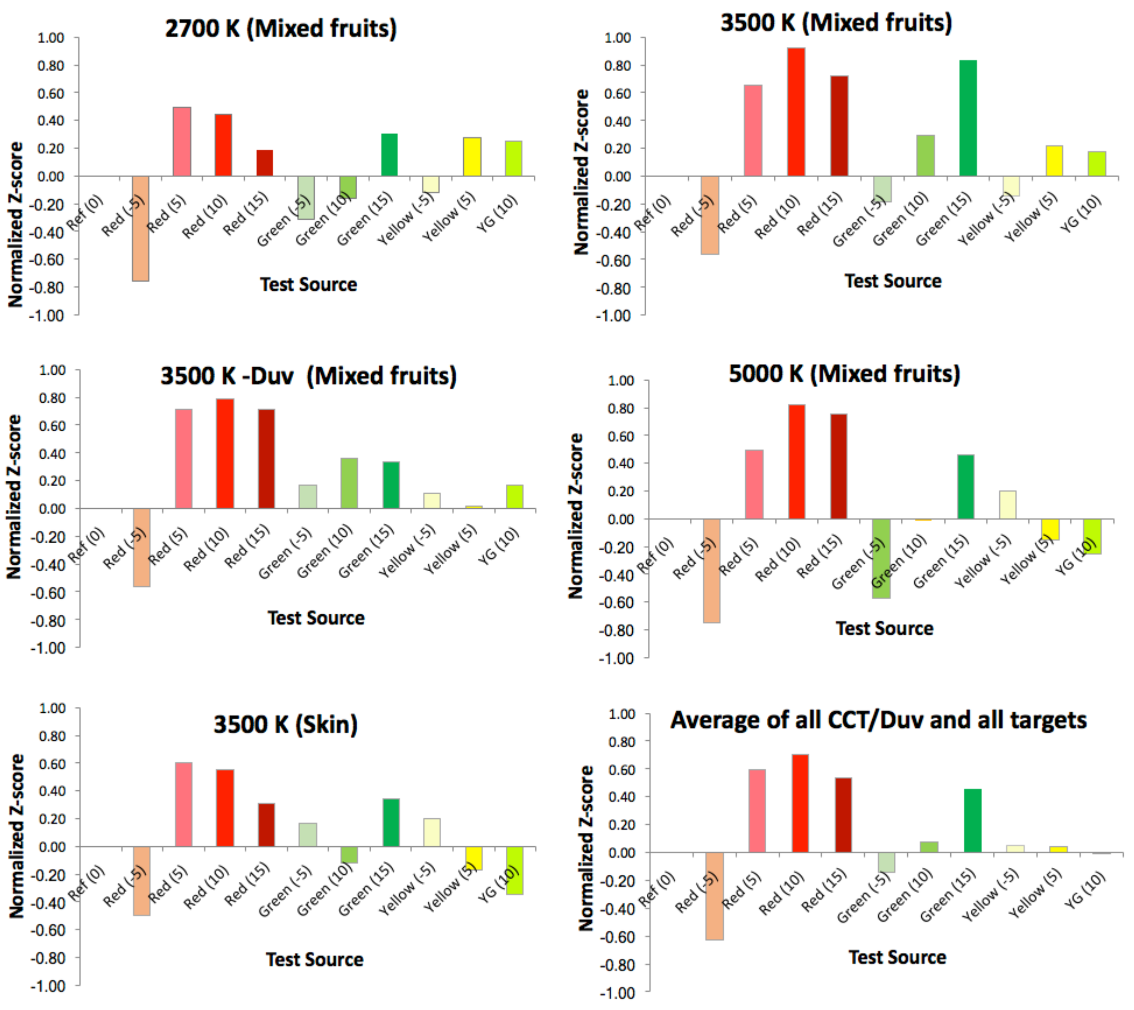


Figure 4 – Preference effects for chroma shift in different hues, for different CCT/Duv conditions and viewing targets.

Figure 4 shows all the results in Table 5 in a graphic form. While there are some variations for different CCT/Duv conditions, the results overall show that red has the dominant effect, and preference is sensitive to small increase or decrease of red chroma. Green is the second, however, preference for green chroma increase is less sensitive than red and it requires large chroma increase to be effective. Yellow and yellow-green show much less effect than red or green. In the 3500 K skin tone condition, green (15) shows high preference. It is considered that green should not affect much the preference of skin tone. It is observed that the gamut curve for Green ΔC^*_{ab}= 15 in Figure 1 shows slight increase of chroma in the red region, though the particular red sample's chroma is kept nearly equal to that of the reference. It is considered that this slight increase of chroma around the red region may have affected the results for the skin tone, and also for the green (15) results for fruits and vegetables, because red has strong effects.

Figure 5 shows the plots of the normalized z-score values from the same data in Table 5, arranged for each colour (hue), presented as a function of chroma shift. The curves for Red (Mixed fruits) and Red (Skin) have peaks around ΔC^*_{ab}= 5 to ΔC^*_{ab}= 10, which are very similar to the results in our previous study (Ohno et al, 2015). The curves for Green (Mixed fruits) show much less slopes than those for Red. The curves for yellow show varied slopes depending on CCT and the effects are not clear. These observations support earlier conclusion that red is clearly dominant in colour quality preference and there seem to be optimum levels of red chroma increase for high preference.

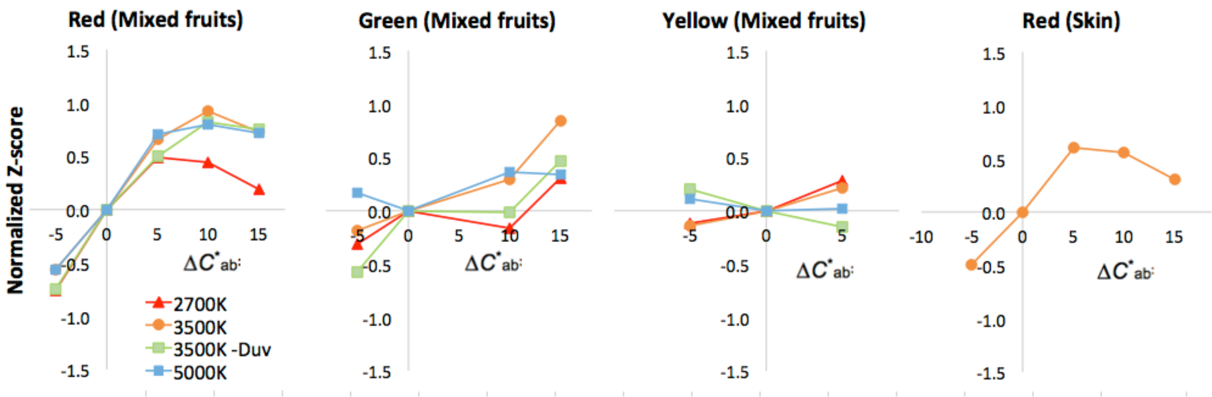


Figure 5 – Preference effects as a function of chroma shift, for different hues and targets.

5 Conclusions

A vision experiment has been conducted using 19 subjects, for the preference effect of chroma shifts in different hue directions, for red, yellow, yellow-green, and green. The chroma of other colors was kept close to the reference. The results proved that the chroma increase of red colour (hue) has the dominant effect on colour preference among these colours, and the results for red were consistent with the previous study (Ohno et al, 2015). The effect of green saturation is the second, but its effect is much less sensitive than red. The effects of yellow and yellow-green are found inconsistent and much less sensitive than red chroma shift.

These results suggest that, for evaluating colour preference of a light source, chroma shifts in different hues by the light source should be weighted differently, with highest weight for red, and much less weight for other colours. Further experimental data will be needed to develop an accurate colour preference model. In this experiment, though it was hoped to test all hues, only red – yellow – green region could be covered due to the difficulty in spectral control. Blue chroma could not be controlled independently from other colors. Yellow shifts also accompany large hue shifts and it was difficult to control yellow chroma independently. These imperfections of light settings may have affected some results. Further experiments are desired with more accurate independent control of chroma for a larger range of hue, e.g., by using a display simulating real objects as used in this study.

Acknowledgement

The authors thank Dr. Yuki Kawashima at NIST for his valuable discussions on the data analysis using z-score. This research was conducted when Youngshin Kwak and Semin Oh stayed as guest researchers at NIST.

References

ANSI 2017. ANSI C78.377-2017 Specifications for the Chromaticity of Solid State Lighting Products.

Davis, W. and Ohno, Y. 2010. Color Quality Scale, *Optical Engineering*, 033602 March 2010/Vol. 49 (3).

Gescheider, G. A. 2013. Psychophysics: The fundamentals, 3rd ed. Lawrence Eribaum Associates, Mahwah, New Jersey

Hashimoto, K., Yano, T., Shimizu, M., and Nayatani, Y. 2007. New method for specifying colour-rendering properties of light sources based on feeling of contrast," Colour Res. Appl. 32, 361–371.

IES 2015. IES TM-30-15 IES Method for Evaluating Light Source Colour Rendition, Illuminating Engineering Society of North America, New York, NY.

Miller, C., Ohno, Y., Davis, W., Zong, Y., Dowling, K. 2009. "NIST spectrally tunable lighting facility for colour rendering and lighting experiments," in Proc. CIE 2009: Light and Lighting Conference. 5 pages (2009).

Ohno, Y., Fein, M., Miller, C. 2015. Vision Experiment on Chroma Saturation for Color Quality Preference, Proc. 28th Session of CIE, CIE 216: 2015, pp. 60-69 (2015).

Rea, M., Freyssinier, J. 2010. Colour rendering: Beyond pride and prejudice, Colour Res. Appl. 35, Issue 6.