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White Appearance for Optimal Text-Background Lightness Combination Document Layout on a Tablet Display under Normal Light Levels

*Hsin-Pou Huang; Department of Information Management, Chihlee University of Technology, New Taipei City, Taiwan
Hung-Chung Li; Department of Cosmetic Science, Chang Gung University of Science and Technology, Taoyuan, Taiwan
Minchen Wei; Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong
Yu-Cheng Huang; Department of Information Management, Chihlee University of Technology, New Taipei City, Taiwan
*bobhuang@mail.chihlee.edu.tw

Abstract

In the study, two psychophysical experiments are carried out to understand the visual comfort and white appearance of a tablet display. Twenty-four observers assess the visual comfort of document layouts, and eleven observers rate the whiteness percentage of the stimulus under normal light levels with a CCT of 6500 K. The result of the experiment for visual comfort indicates that a combination of black text with a light grey background presents the better visual comfort. On the other hand, the finding of the white appearance experiment shows that the observers rate the stimulus with CCT of 6515 K and a D_{uv} of 0 as the whitest.

Introduction

With the rapid development of display technology in recent years, the use of display devices has become more closely related to our daily lives. Portable electronic devices, especially tablet displays, made message transmission and entertainment more convenient and timely. Since coronavirus disease 2019 (COVID-19) ravaged the world in 2019, it much has changed to the way of life. Many activities have been carried out in video mode, which has greatly increased the requirement for monitors. White is a color with a high degree of brightness without any hue, and plays an important role in display color appearance. It could be associated with the color of the surface, light source, and display. Many manufacturers set the white point of the display device according to the correlated color temperature (CCT) to improve consumer preferences and visual perception. A higher CCT setting could create a cooler or bluer image tone, such as providing a more saturated sky color. On the other hand, using a white point with a lower CCT brought a warmer and yellower feeling to the displayed image.

Some previous studies have pointed out that when viewing display devices, environmental lighting factors such as light source illuminance, color temperature and Planckian locus (D_{uv}) will affect visual color perception. Human's white perception of tablet display under different 17 ambient lighting conditions was discussed from our previous study. The study indicated that the lower degree of chromatic adaptation presented under the lighting condition with lower CCT, whereas a D_{uv} of −0.02 showed a higher degree of chromatic adaptation with the same CCT [1]. We also conducted a psychophysical experiment with pairwise comparison to find the optimal text-background lightness combination for visual comfort under different lighting conditions and investigated the effect of white appearance on visual comfort. From the study, the combination of a black text with a light-gray background was evaluated as the most comfortable under the ambient light and the third most comfortable for dark surrounding conditions. Besides, using the second whitest color and the tablet's default white point as the color of the background was evaluated as the most comfortable under 3500 K and 6500 K, respectively [2]. Choi recommended the optimal white point settings of consumer televisions under different viewing conditions. They found that the current white point settings of television are too bluish. In addition, the perception of the white point was significantly affected by the image content and ambient lighting conditions [3]. Wei adopted a self-luminous display under different adapting conditions with the variance of adapting luminance and CCT to evaluate its whiteness. The change in adapting luminance and CCT would influence the degree of chromatic adaptation, and the effect of adapting luminance became stronger under lower adapting CCTs [4]. Cao investigated the preference and naturalness of adaptive white points under different CCTs. The observers tended to evaluate the colors below the Blackbody (D_{uv} <0) as preferred colors and natural white points [5].

A pilot study was proposed by Chen et al. to test if the different chromaticities for producing a white appearance were induced by the viewing medium or the viewing mode. From their report, viewing modes were the primary factor that caused the different chromaticities for producing the white appearance of color stimuli from physical color samples and displays [6]. Huang carried out a similar experiment for the augmented reality (AR) display. The whitest color appearance of a virtual stimulus was acquired under different real environments. The results were similar to that of the past studies, but the influence of adapting CCT decreased. Also, a lower degree of chromatic adaptation was found when viewing stimuli by an AR display [7]. An experiment was implemented to study the perception of neutral white and chromatic adaptation on a display under different chromaticities and illuminance levels. The results showed a difference in the degree of adaptation among the different ambient lighting conditions. It would be affected by ambient CCT and luminance levels, and the lower CCT and dimmer ambient conditions might lead to an incomplete chromatic adaptation [8].

Although the white appearance of the display has been obtained more attention recently, and some related studies have been published. Its research in the field of display technology is still relatively in the minority. Coupled with the influence of various external lighting factors, the quantitative assessment for a display will become more complicated. Therefore, this research obtains the best text-background lightness combination under specific lighting conditions through psychophysical experiments first and then explores the effect of the white appearance for the best combination. This study can provide suggestions to achieve the most comfortable lighting conditions and settings on the use of tablet displays.

Methods

This article is composed of two psychophysical experiments—experiment 1 for investigating the visual comfort of the text-background lightness combination document layout and experiment 2 for investigating the white appearance of optimal text-background lightness combination—both of them are conducted with the same experimental setup, as shown in Figure 1. Figure 1 is a photograph captured from the observer's eye position, in which the viewing distance is around 45 cm between the observer's eye and the iPad. An iPad (6th generation) with a black boundary is placed on a 45° viewing table locating at the center of the viewing booth. The peak white of the iPad achieves a luminance of 549 cd/m^2 with chromaticities of (0.3133, 0.3299) after a 30-minute warm-up period. The viewing booth has dimensions of 60 cm × 60 cm × 60 cm in size, and the interiors are covered with Munsell N7 spectrally neutral paint. A lighting device (LEDCube), with 11-channel spectrally tunable LED, is placed above the viewing booth to produce uniform illumination. Each channel of spectrally tunable LED is carefully adjusted to provide two light sources, including two levels of illuminance (i.e., 600 lx and 1200 lx) with a horizontal CCT of 6500 K. The relative spectral power distribution (SPD) is shown in Figure 2, and Table 1 lists the colorimetric characteristics of the two light sources measured using a white reflectance standard and a calibrated spectroradiometer (JETI specbos 1211TM).

Figure 1. *Experimental setup (photograph captured from the observer's eye position)*

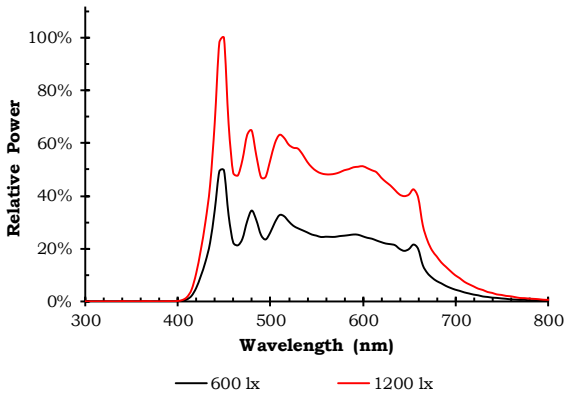


Figure 2. *The relative spectral power distribution of the two light sources*

Table 1 The colorimetric characteristics of the ambient lighting conditions

CCT (K)	E (lx)	CRI R_a	D_{uv}
6526	600	97.948	0.004
6481	1200	97.67	0.003

A total of 35 naïve observers (18 males and 17 females), between 19 and 25 years of age, participate in this study. Twenty-four naïve observers, including 13 males and 11 females, age between 19 and 20 years old (mean = 19.4, std. dev. = 0.8), assess the visual comfort in experiment 1. For experiment 2, eleven naïve observers, including 5 males and 6 females, age between 19 and 20 years old (mean = 19.2, std. dev. = 0.4), assess the visual whiteness. All observers are Taiwanese based in New Taipei City and have passed the Ishihara Color Vision Test for color deficiency before starting the tasks.

Experiment 1

For finding the optimal text-background lightness combination document layout under normal light levels, five achromatic colors are adjusted to produce 20 text-background lightness combinations (20 document layouts) with one for the text and one of the others for the background. 20 document layouts consist of 10 positive polarity document layouts (the dark text with a light background) and 10 negative polarity document layouts which means that the text is brighter than the background. The same calibrated spectroradiometer (JETI specbos 1211TM) is placed on the observer's eye position to obtain the colorimetric characteristics. The chromatic information of the five achromatic colors is summarized in Table 2. These 20 document layouts are always presented with a paired comparison, as shown in Figure 3. For all possible patterns in pairs, a total of 190 paired comparisons are produced.

Table 2 The colorimetric characteristics of the five achromatic colors produced on the iPad under dark surround condition

Color	Luminance (cd/m^2)	L^*	(x, y)
Black	0.67	1.101	(0.262,0.255)
Dark grey	25.3	25.58	(0.314,0.329)
Medium grey	102.4	50.27	(0.314,0.327)
Light grey	266.4	75.14	(0.313,0.329)
White	549.3	100	(0.313,0.33)

Before the experiment, the observers are requested to seat in front of the viewing booth with the chin rest for fixing their heads. The viewing distance is around 45 cm between the observer's eye and the iPad (note: the iPad has been displayed full screen of white for 30 minutes for stabilization). Thus, twenty-four observers can face the iPad with a similar viewing angle as possible. Under each ambient lighting condition, two minutes of adaption is required. For each paired comparison, the observer compares two document layouts and chooses the one that gives better visual comfort. The neutral grey color is displayed for a second before the next test pattern shows for preventing the visual afterimage from the previous one. Under different ambient lighting conditions, each observer needs to judge 190 general paired comparisons and estimate 20 of

the 190 paired comparisons twice for verification. Hence, each observer compares a total of 210 paired comparisons in random order under each lighting condition. The right-left order set of the paired-comparison also in random order The entire experiment 1 takes around 30 minutes for an observer.

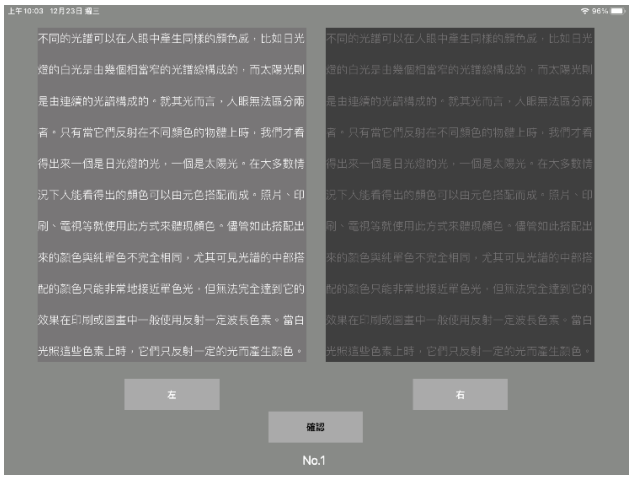


Figure 3. *An example of the paired-comparison presented on the iPad (6th generation)*

Experiment 2

For investigating the white appearance of optimal text-background lightness combination according to the result from Experiment 1 (i.e., the luminance of background = 266.4 cd/m^2; the luminance of text = 0.67 cd/m^2), the iPad (6th generation) is utilized to present 76 stimuli which are uniformly distributed in CIE1976 UCS, as shown in Figure 4 (labeled with 75 circles and a cross). The RGB values of 76 full screen stimuli (9.7-inch) are carefully adjusted to reach the background luminance levels for optimal text-background lightness combination at 265 ± 10 cd/m^2, and measured by a calibrated spectrophotometer (JETI specbos 1211TM) that is placed on the observer's eye position.

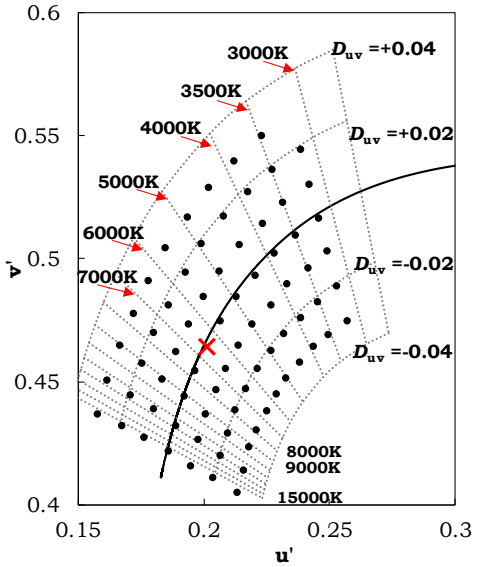


Figure 4. *The chromaticity coordinates of the 76 stimuli are displayed on the iPad in CIE1976 UCS (Red cross represents the u' and v' of the whitest stimulus judged by the observers)*

Upon arrival, the observer also requires to seat in front of the viewing booth with the chin rest to fix the observer's head. Also, the viewing distance is around 45 cm which is consistent with that of Experiment 1. Thus, eleven observers face the iPad with a similar viewing angle as possible. To display stably, the iPad shows a full screen of white for 30 minutes before the experiment. During the task, the observer is asked to look into the viewing booth for adapting two minutes and then evaluate the white appearance of 76 stimuli under different lighting conditions. Each stimulus is displayed on the iPad for five seconds then the screen changes to black. During the period of iPad becoming black, the experimenter asked the observer to evaluate the whiteness percentage of the stimulus, where the 0% represents purely chromatic, and 100% represents pure white. The entire experiment 2 takes around 30 minutes for each observer.

Results and Discussions

Results of Experiment 1

For the 40 paired comparisons (i.e., 20 pairs × 2 illuminances) that are compared twice under 600 lx and 1200 lx with a horizontal CCT of 6500 K, the observers made the same judgments for the 85 % pairs on average. These indicates that experiment 1 is a high repeatable experiment.

The statistical data for the visual comfort judgments under two illuminance levels are analyzed by converting to a visual comfort interval scale using Thurstone case V method [9]. For better knowing the impact of illuminance on the visual comfort interval scale, the scale under 600 lx is plotted against the scale under 1200 lx. It is clear to see the judgments under the two illuminance levels are highly correlated (Pearson correlation coefficients = 0.96), as shown in Figure 5. Figures 6(a) and 6(b) are the visual comfort interval scale plotted against the contrast in terms of lightness difference between text and background under 600 lx and 1200 lx respectively. It can be seen that the higher the lightness difference between text and background, the better visual comfort interval scale can be perceived until the lightness difference approaching 80. Referring to Figure 6(a), when the lightness difference approaching 80, the document layout with a light grey background receives a higher visual comfort interval scale than the document layout with a white or black background.

In a similar trend, Figure 6(b) shows that the document layout with a light grey background and a dark grey background had a higher visual comfort interval scale than the document layout with a white or black background when the lightness difference approaching 80. It shall be noted that both Figure 6(a) and 6(b) indicate that a document layout—black text with a light grey background (i.e., the luminance of background = 266.4 cd/m^2; the luminance of text = 0.67 cd/m^2)—is consistently judged the better visual comfort when the surround condition is the normal light level. According to the results of experiment 1, a background with a luminance level approaching 265 cd/m^2 (i.e., light gray) is recommended to use in a document layout rather than using another background under normal light level. Therefore, our study tends to discuss the white appearance with luminance level approaching 265 cd/m^2 under normal light level.

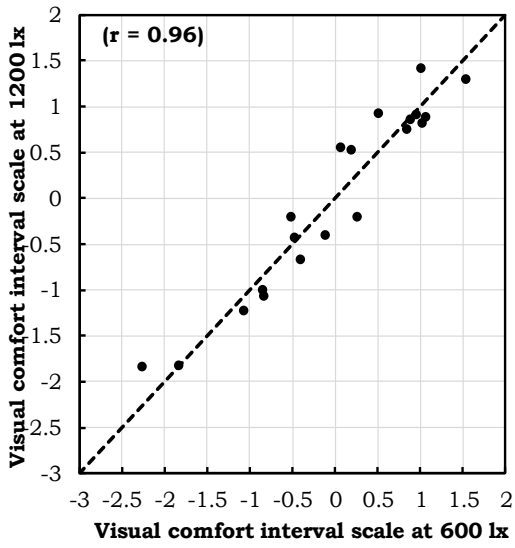
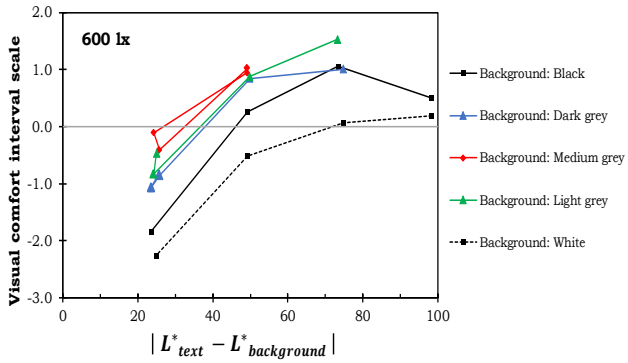
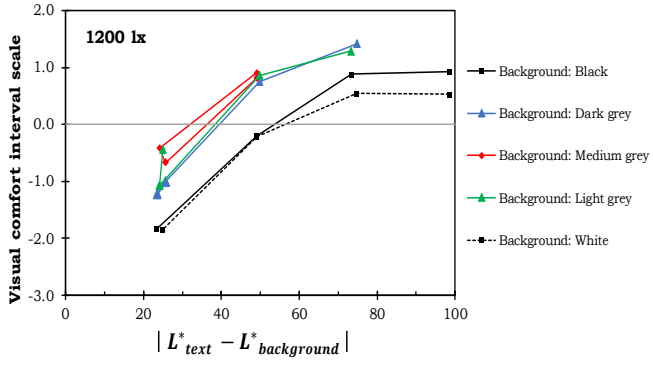


Figure 5. *Scatter plot of the visual comfort interval scale under 600 lx against under 1200 lx*



(a) 6500 K, 600 lx



(b) 6500 K, 1200 lx

Figure 6. *Visual comfort Interval scale of the 20 document layouts evaluated by the observers under two illuminance level (a) 6500 K, 600 lx; (b) 6500 K, 1200 lx*

Results of Experiment 2

The intra-observer (20.34) and inter-observer (22.8) variations is calculated using the Standardized Residual Sum of Squares (STRESS) [10]. The whiteness percentage judgments on average for 76 stimuli under two illuminance levels are summarized in Table 3. From Table 3, the chromaticity coordinates of the whitest stimulus are highlighted with a red cross in Figure 4. The whitest stimulus under two illuminance levels with a horizontal CCT of 6500 K has an identical chromaticity coordinate (i.e., $CCT = 6515$ K; $D_{uv} = 0$).

Table 3 The whiteness percentage of the 76 stimuli under two illuminance levels with a horizontal CCT of 6500 K

Stimulus	CCT	D_{uv}	600 lx	1200 lx	Stimulus	CCT	D_{uv}	600 lx	1200 lx
1	3139	0.02	8%	6%	39	5662	-0.01	34%	58%
2	3155	0.01	6%	7%	40	5659	-0.02	28%	32%
3	3159	0	6%	8%	41	5686	-0.03	11%	9%
4	3172	-0.01	9%	13%	42	6450	0.03	8%	6%
5	3184	-0.02	4%	6%	43	6494	0.02	19%	13%
6	3178	-0.03	7%	7%	44	6471	0.01	76%	76%
7	3471	0.03	6%	8%	45	6515	0	91%	86%
8	3489	0.02	7%	5%	46	6573	-0.01	62%	77%
9	3505	0.01	6%	9%	47	6537	-0.02	23%	27%
10	3498	0	13%	6%	48	6539	-0.03	13%	17%
11	3480	-0.01	9%	11%	49	7583	0.03	9%	10%
12	3525	-0.02	6%	10%	50	7601	0.02	16%	11%
13	3551	-0.03	9%	7%	51	7589	0.01	56%	53%
14	3876	0.03	4%	8%	52	7641	0	90%	83%
15	3876	0.02	6%	8%	53	7645	-0.01	77%	75%
16	3867	0.01	8%	8%	54	7741	-0.02	30%	42%
17	3874	0	9%	14%	55	7824	-0.03	11%	10%
18	3895	-0.01	6%	11%	56	9095	0.03	10%	7%
19	3921	-0.02	9%	9%	57	9116	0.02	8%	9%
20	3933	-0.03	10%	6%	58	9146	0.01	50%	36%
21	4343	0.03	8%	7%	59	9126	0	60%	61%
22	4352	0.02	7%	8%	60	9279	-0.01	63%	66%
23	4348	0.01	10%	13%	61	9447	-0.02	41%	39%
24	4356	0	20%	29%	62	9349	-0.03	16%	17%
25	4354	-0.01	19%	33%	63	11498	0.03	8%	8%
26	4416	-0.02	18%	9%	64	11579	0.02	7%	10%
27	4412	-0.03	8%	8%	65	11450	0.01	16%	13%
28	4877	0.03	7%	5%	66	11741	0	42%	35%
29	4930	0.02	18%	12%	67	11691	-0.01	43%	50%
30	4935	0.01	50%	46%	68	11929	-0.02	34%	27%
31	4921	0	57%	61%	69	12021	-0.03	14%	13%
32	4979	-0.01	23%	39%	70	15706	0.03	9%	6%
33	4948	-0.02	15%	16%	71	15706	0.02	8%	10%
34	5028	-0.03	8%	9%	72	15601	0.01	10%	11%
35	5598	0.03	14%	8%	73	15695	0	39%	34%
36	5583	0.02	25%	26%	74	16390	-0.01	36%	43%
37	5610	0.01	71%	52%	75	16286	-0.02	32%	31%
38	5651	0	66%	74%	76	16985	-0.03	11%	17%

According to Table 3, the whiteness percentage rated by the observers for 76 stimuli under the two illuminance levels is highly correlated, as shown in Figure 7. When the stimuli close to the Planckian locus (i.e., $D_{uv} = 0$), the observers rate a higher whiteness percentage than those far away from the Planckian locus (i.e., $D_{uv} \neq 0$). Under the ambient lighting conditions with CCT of 6500 K, the observers judge a higher whiteness percentage than those far away from the CCT of 6500 K as the stimuli close to the CCT of 6500 K.

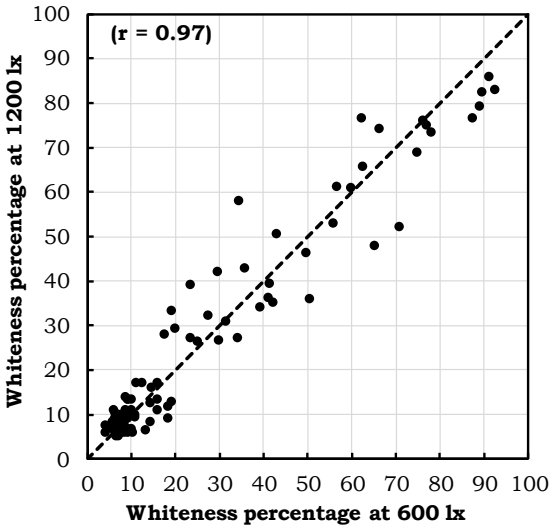


Figure 7. *Scatter plot of the whiteness percentage under* 600 lx against *under* 1200 lx.

Conclusions

In the study, experiment 1 is carried out to investigate the visual comfort of the text-background lightness combination document layout, and experiment 2 is conducted to study the white appearance of optimal text-background lightness combination. Both two experiments are carried out under normal light levels. A total of 35 naïve observers, including 24 observers for experiment 1 and 11 observers for experiment 2, participate in this task.

Referring to the results of experiment 1, a document layout—black text with a light grey background (i.e., the luminance of background = 266.4 cd/m^2; the luminance of text = 0.67 cd/m^2)—is consistently judged the better visual comfort when the surround condition is the normal light level. A background with a luminance level approaching 265 cd/m^2 (i.e., light gray) is recommended to use in a document layout rather than using another background under normal light level. Therefore, experiment 2 tends to investigate the white appearance with luminance level approaching 265 cd/m^2 under normal light level. According to the results of experiment 2, the whiteness percentage rated by the observers for 76 stimuli under the two illuminance levels is highly correlated. Thus, under 600 lx and 1200 lx with a horizontal CCT of 6500 K, the observers rate the same stimulus with CCT of 6515 K and a D_{uv} of 0 as the whitest. Based on the findings of this work, it is considered worthwhile to further expand the whiteness percentage range of background for a document layout to improve the visual comfort of the tablet display.

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Author Biography

Hsin-Pou Huang is an Assistant Professor in the Department of Information Management at the Chihlee University of Technology. He received his bachelor's degree at Tamkang University in 2011. In 2013 and 2019, He received a Master's degree and Doctoral Degree from National Taiwan University of Science and Technology. He was an exchange student at the Hong Kong Polytechnic University in Aug 2017-Aug 2018.

Hung-Chung Li is currently an Assistant Professor at the Department of Cosmetic Science at the Chang Gung University of Science and Technology (CGUST). He has been a postdoctoral research fellow in the Research Center for Information Technology Innovation of Academia Sinica Taiwan. He was awarded his Ph.D. at the Graduate Institute of Applied Science and Technology of National Taiwan University of Science and Technology, 2017. Expert in Color Science, Color Imaging Computer Vision, Digital Image Processing, Image Quality Estimation, Machine Learning, Deep learning, Lighting Engineering, and Ergonomics.

Minchen Wei is an Associate Professor in the Department of Building Services Engineering at the Hong Kong Polytechnic University. He earned his Bachelor of Engineering at Fudan University (Shanghai, China) in 2009. In 2011 and 2015, he obtained his Master of Science and Doctoral Degrees from the Department of Architectural Engineering at the Pennsylvania State University (University Park, USA). His research mainly focuses on color science and illumination.

Yu-Cheng Huang is a student in the Department of Information Management at the Chihlee University of Technology. His research mainly focused on color science and image processing.