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Effects of Illuminance Level of Light Source on White Appearance of a Tablet Display

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Abstract: The appearance of white significantly impacts display image quality, requiring a neutral white point for optimal performance. This study explores how perceived whiteness changes under ambient illumination levels (150, 300, 600, and 1200 lx) and correlated color temperatures (3500 K and 6500 K). As a result, the adapted white points of light sources with different correlated color temperatures are similar at lower ambient illuminance levels. In comparison, their adaptation trends exhibit significant differences at higher illuminance levels. At 150 lx, adapted white points for 3500 K and 6500 K light sources shift toward higher color temperatures and converge. With increased illumination, the 3500 K white point shifts toward its light source, while the 6500 K white point shifts to a higher correlated color temperature. The neural network-based prediction model developed in this study accurately forecasts perceived whiteness across conditions, offering valuable design guidance for the display and lighting industries.

Keywords: white appearance; adapted white; tablet display; illuminance; ambient lightings

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1. Introduction

The widespread use of tablet devices in daily life has made them a common sight, and they are utilized in various ambient lighting conditions ranging from darkness to extremely high illuminance levels. Since ambient light significantly influences how humans perceive the color stimuli on displays, manufacturers have focused on adjusting the white point to enhance user experience. Numerous studies have highlighted that different ambient illuminance levels affect the perception of the white appearance on tablet displays, underscoring the importance of investigating this phenomenon and its impact on visual perception.

Choi and Suk investigated white perception on self-luminous mobile displays under dark-adapted and chromatic-adapted conditions [1]. Whiteness ratings of 97 chromaticity points were evaluated and fitted using an error ellipse and a bivariate Gaussian distribution. The study revealed that the correlated color temperature (CCT) alone was insufficient to represent white perception fully and that white perception was highly dependent on the chromaticity of the ambient illuminant. The findings also indicated that existing standards for self-luminous displays may not ensure accurate white perception under certain viewing conditions; therefore, a white region ranging from 6179 to 7479 K (CCT) and from −0.0038 to 0.0144 (D_{uv}) was recommended. Wei and Chen conducted a psychophysical experiment in which human observers adjusted the color of a self-luminous display stimulus to appear as white as possible under varying adapting luminance and CCT conditions. The results showed that the adjusted chromaticities closely aligned with the adapting chromaticities at higher adapting luminance levels [2]. They reported that adapting luminance and CCT influenced the degree of chromatic adaptation, with adapting luminance having a stronger effect under lower CCT conditions. Since the study found incomplete chromatic adaptation under low CCT adapting conditions, the team subsequently increased the adapting luminance to clarify whether complete color adaptation cannot occur under low adapting color temperatures. The follow-up experiment tested chromatic adaptation under 12 adapting conditions, including four CCT values (2700, 3200, 4000, and 6500 K) and three white luminance levels (1200, 2100, and 3000 cd/m^2). The results confirmed that, despite significantly increasing luminance, incomplete chromatic adaptation still occurred under 2700 K and 3200 K adapting conditions. However, increasing adapting luminance was found to enhance the degree of adaptation more effectively [3].

Huang et al. conducted a psychophysical experiment to investigate the white appearance of tablet displays under various ambient lighting conditions, including complete darkness, chromaticity on the Planckian locus, and chromaticity deviations from the Planckian locus, to understand human perception of white stimuli and chromatic adaptation [4]. This study found that the chromaticity coordinates of the whitest stimuli and the boundaries of white appearance varied across lighting conditions. At lower ambient color temperatures, the whitest chromaticity shifted off the Planckian locus, while at higher temperatures, it aligned with it. Under conditions with the same color temperature but different D_{uv} values, the chromaticity of the whitest stimuli shifted perpendicularly to the Planckian locus. Additionally, the team investigated how the combination of tablet display luminance, text background lightness, and display white points affected visual comfort. They found that the whitest display color was not rated as the most comfortable for e-reading, whereas the second whitest color was preferred under 3500 K ambient light [5]. These findings highlight that ambient lighting affects visual comfort and influences white perception.

Kim et al. studied how ambient illuminance affects the perceivable white luminance of displays, suggesting that automatic luminance adjustment should depend on each display's maximum white luminance. They recommended a white luminance range of 200–500 cd/m^2 for indoor use to balance visibility and power consumption [6]. Peng et al. explored white points (neutral and preferred) under various lighting conditions, finding that both shifted with ambient chromaticity, with neutral white ranging from 6600 K to 7300 K and preferred white from 5900 K to 6300 K. They also showed that chromatic adaptation is incomplete under lower color temperatures, with greater shifts and lower adaptation in those environments [7,8]. Cao and Luo examined display white point preferences under five color temperatures, showing that the preferred white points were close to natural ones and shifted with the ambient CCT. Their research also indicated incomplete chromatic adaptation in low color temperature environments and proposed a function to optimize the CAT02 model based on these findings [9,10].

Kwak et al. developed a model predicting the optimal display white point CCT based on ambient lighting CCT [11]. They found that transparent and opaque displays have similar preferred CCTs, which increase linearly with the ambient CCT. The preferred CCT is higher when the ambient CCT is below 5600 K and lower above 5600 K. Their research also highlighted the use of forced-choice experiments to track chromatic adaptation, showing that the white point CCT first increases and then stabilizes when transitioning from 3000 K to 6500 K [12]. Later studies found that the ambient CCT significantly affects display neutral points, with higher CCT environments leading to higher neutral points. The ratio of ambient light to display brightness strongly correlates with neutral point changes [13]. Zhang et al. modified a CIE-based model to improve white point predictions and found that the ambient CCT positively correlates with the white point CCT while adapting luminance has a negative correlation [14].

While previous studies have explored the impact of various illuminance levels, CCT, and D_{uv} on perceptual whiteness, the effects of a wide range of illuminance levels remain underexplored, especially for lower illuminance. To address this gap, this study aims to investigate a broader range of illuminance levels to better understand their impact on human visual perception of white appearance and contribute to developing a more comprehensive evaluation model. In addition, given the above findings from the related research, appropriate ambient lighting enhances visual perception when using displays. Since visual comfort is influenced by perceived whiteness, it is essential to investigate the effects of various illuminance levels and combinations of CCT on users' perceived whiteness. This research can optimize ambient lighting configurations and improve the overall user experience.

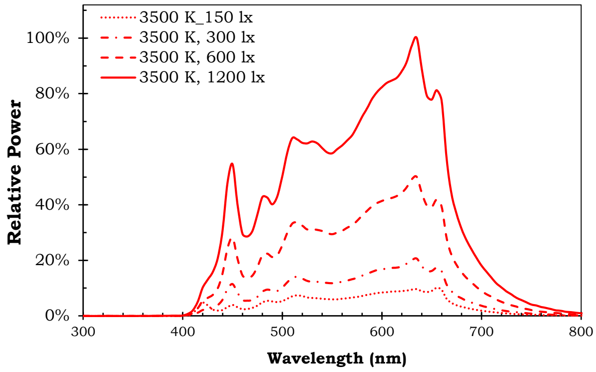
2. Methods

A psychophysical experiment is conducted to investigate the whiteness percentage on the 6th generation iPad with a black boundary to understand the white appearance of an e-reading device under varying illuminance levels. Observers are asked to rate the whiteness percentage under eight ambient lighting conditions comprising two levels of correlated color temperature (CCT) and four levels of illuminance.

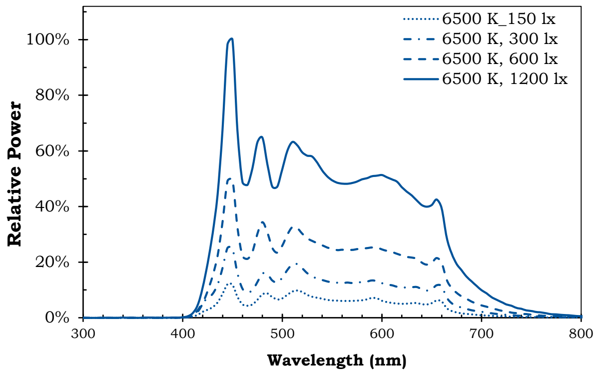
2.1. Experimental Setup

The experiment is conducted in a viewing booth, and the interior walls are painted using Munsell N7 spectrally neutral paint. The booth measures 60 cm in length, 60 cm in width, and 60 cm in height. A 9.7-inch e-reading device (6th generation iPad with a black border) is positioned on a custom table, tilted at a 45-degree angle to the horizontal plane. This table is centrally located within the booth and is also coated with Munsell N7 neutral paint. A chin rest is mounted outside the booth, aligned with the center of the opening, allowing the observers to view the screen at a perpendicular angle. Figure 1 illustrates the experimental setup from the observer's point of view, with the viewing distance between the eye and the iPad being approximately 45 cm. After a 30 min warm-up period, the iPad's peak luminance reaches 549 cd/m^2, with a chromaticity of (x = 0.3133, y = 0.3299) in the CIE 1931 xy chromaticity diagram. An 11-channel spectrally adjustable LEDCube (Thouslite Ltd., Changzhou City, China) is used to generate uniform illumination within the viewing booth. The experimenter meticulously adjusted the 11 channels of the LED to create eight different light sources, which include four levels of illuminance (1200 lx, 600 lx, 300 lx, and 150 lx) and two CCT levels (3500 K and 6500 K). During the experiment, the space had no general lighting, with the tunable LEDCube being the sole light source. The relative spectral power distributions are displayed in Figure 2, and the characteristics of the eight light sources are listed in Table 1. These measurements are taken using a reflectance standard, a calibrated illuminance meter (CL200A, Konica Minolta, Inc., Tokyo, Japan), and a calibrated spectroradiometer (Specbos 1211TM, JETI Technische Instrumente GmbH, Jena, Germany).

Figure 1. Experimental setup (picture captured from the observer's eye).



(**a**)



(**b**)

Figure 2. The relative spectral power distribution of the light source: (**a**) 3500 K (**b**) 6500 K.

Table 1. The colorimetric characteristics of the ambient lighting conditions.

Illuminance (lx)	CCT (K)	CRI Ra	D_{uv}
150	3535	95.62	0.00206
300	3481	95.94	0.0026
600	3496	96.49	0.00411
1200	3481	96.66	0.00206
150	6541	94.78	0.01233
300	6550	96.51	0.00893
600	6526	97.67	0.00893
1200	6481	97.97	0.01233

A total of 47 observers (26 males and 21 females) participated in this study, consisting of 20 young adults aged between 18 and 20 years (mean = 19.848, standard deviation = 0.942). However, one observer failed the Ishihara test, so their data were excluded from the analysis. As a result, this study is conducted using valid data from 46 observers with normal color vision.

The iPad's RGB values are modified to create 76 stimuli, with their chromaticities evenly uniform in the CIE1976 UCS. These stimuli were also adjusted to achieve a horizontal luminance level of approximately 265 ± 10 cd/m², measured using a JETI Specbos 1211TM placed at the observer's eye level. Each observer rated the 76 stimuli on the iPad under two different illuminance levels with a single correlated color temperature (CCT). The chromaticity details for the 76 stimuli are shown in Figure 3 and Table 2.

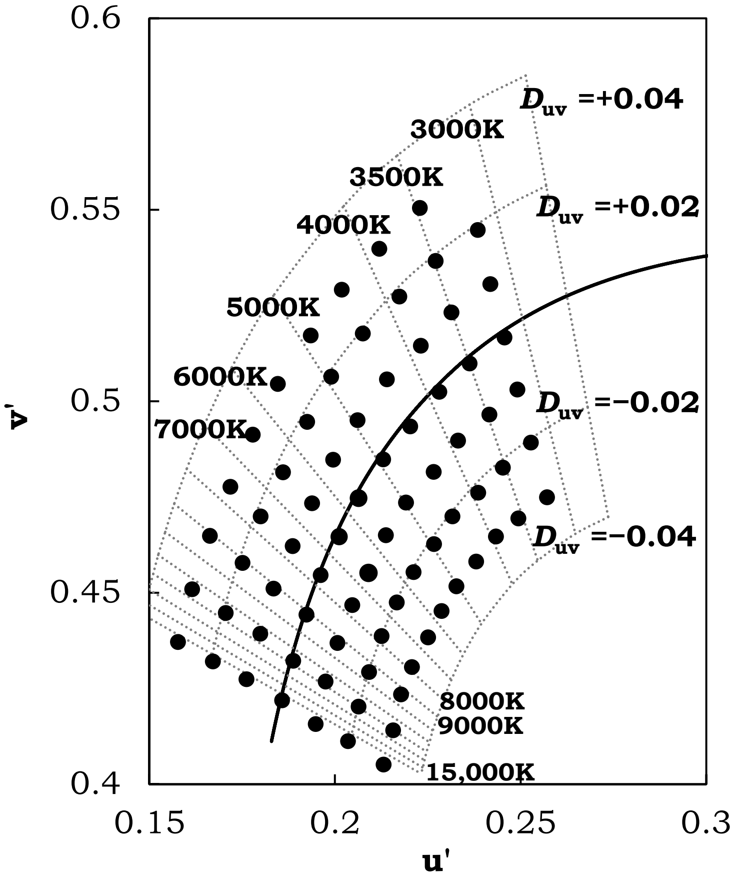


Figure 3. The chromaticity coordinates of the 76 stimuli presented on the iPad.

Table 2. The colorimetric characteristics and the luminance of the 76 stimuli produced on the iPad.

Color	Luminance (cd/m²)	u′	v′	Color	Luminance (cd/m²)	u′	v′	Color	Luminance (cd/m²)	u′	v′
1	267	0.239	0.545	27	268.3	0.238	0.458	53	267.7	0.205	0.447
2	269.5	0.242	0.531	28	267.4	0.193	0.517	54	267.7	0.213	0.439
3	266.8	0.246	0.517	29	268.1	0.199	0.506	55	268.3	0.221	0.431
4	268.9	0.249	0.503	30	267.7	0.206	0.495	56	268.4	0.166	0.465
5	268.8	0.253	0.489	31	268	0.213	0.485	57	268.7	0.175	0.458
6	267.1	0.257	0.475	32	268.1	0.219	0.473	58	269.1	0.183	0.451
7	267.9	0.223	0.550	33	267.9	0.227	0.463	59	267	0.192	0.444
8	268.2	0.227	0.537	34	268	0.233	0.452	60	266.5	0.201	0.437
9	268.1	0.231	0.523	35	269.1	0.185	0.504	61	266.5	0.209	0.429
10	267.8	0.236	0.510	36	268	0.192	0.495	62	268	0.218	0.423
11	267.1	0.242	0.496	37	266.9	0.200	0.485	63	267	0.162	0.451
12	267	0.245	0.483	38	266.7	0.206	0.475	64	267.8	0.171	0.445

13	268.5	0.249	0.469	39	267.9	0.214	0.465	65	268.3	0.180	0.439
14	267.9	0.212	0.540	40	266.9	0.221	0.455	66	266.8	0.189	0.432
15	267.1	0.217	0.527	41	267.9	0.229	0.445	67	266.7	0.197	0.427
16	267.7	0.223	0.514	42	268.9	0.178	0.491	68	267.3	0.206	0.420
17	267.5	0.228	0.502	43	266.1	0.186	0.481	69	265.8	0.216	0.414
18	266.3	0.233	0.490	44	267.1	0.194	0.473	70	266.2	0.158	0.437
19	266.5	0.239	0.476	45	267.9	0.201	0.465	71	267.5	0.167	0.432
20	269	0.243	0.465	46	265.1	0.209	0.455	72	268.2	0.176	0.427
21	267.8	0.202	0.529	47	268.6	0.217	0.447	73	268.9	0.186	0.422
22	268.4	0.208	0.518	48	266.5	0.225	0.438	74	267.3	0.195	0.416
23	268.1	0.214	0.506	49	268.3	0.172	0.478	75	267.8	0.203	0.411
24	266.3	0.220	0.493	50	266.8	0.180	0.470	76	267.1	0.213	0.405
25	267.3	0.227	0.481	51	267.3	0.189	0.462	77	-	-	-
26	268.6	0.232	0.470	52	268	0.196	0.455	78	-	-	-

2.2. Experimental Procedures

Upon arriving at the laboratory, the experimenter asks the observer to sit in front of the e-reading device, with a headrest to stabilize the observer's eye position. The distance between the observer's eyes and the device is approximately 45 cm, ensuring that all 46 observers maintain a similar posture while facing the device. In the rating task, the observer is instructed to focus on the interior of the viewing tablet for a two-minute adaptation period to adjust to the environment for each lighting condition. Then, they evaluate the whiteness percentage of the 76 stimuli under two out of eight lighting conditions. Each stimulus is displayed on the full screen of the iPad for five seconds, after which the screen turns black. When the screen goes black, the observer is asked to rate the whiteness percentage of the stimulus, where 0% indicates the screen color is purely chromatic and 100% represents pure white. In addition, observers are asked to avoid directly viewing reflected light within their line of sight during the experiment to minimize the influence of reflected light. The entire process of rating the 152 stimuli under two lighting conditions takes approximately 30 min for each observer. Thus, a total of 6992 evaluations are collected.

3. Results

The chromaticity coordinate of the whitest stimulus under different illuminance levels is summarized in Figure 4, where the whitest stimulus rated by the observers is highlighted with a square (blue for the light source of 6500 K and orange for the light source of 3500 K), and the chromaticity coordinates of the light source are highlighted with a cross (blue for the light source of 6500 K and orange for the light source of 3500 K). According to Figure 4a–d, all chromaticity coordinates of the whitest stimulus are on the Planckian locus (i.e., D_{uv} = 0). The main difference for the whitest stimulus is the image CCT of the e-reading device. The display CCT of the whitest stimulus chromaticity coordinate is around 6500 K, provided the light source CCT is approximately 6500 K under easy illuminance levels (below 300 lx). However, under normal illuminance levels (above 600 lx) with the light source CCT around 6500 K, the display CCT of the whitest stimulus chromaticity coordinate increases to approximately 7500 K. Alternatively, under the light source, CCT is approximately 3500 K under easy illuminance levels (below 150 lx), and the display CCT of the whitest stimulus chromaticity coordinate is also around 6500 K. Under illuminance levels above 300 lx with the light source CCT around 3500 K, the display CCT of the whitest stimulus chromaticity coordinate decreases to around 5500 K.

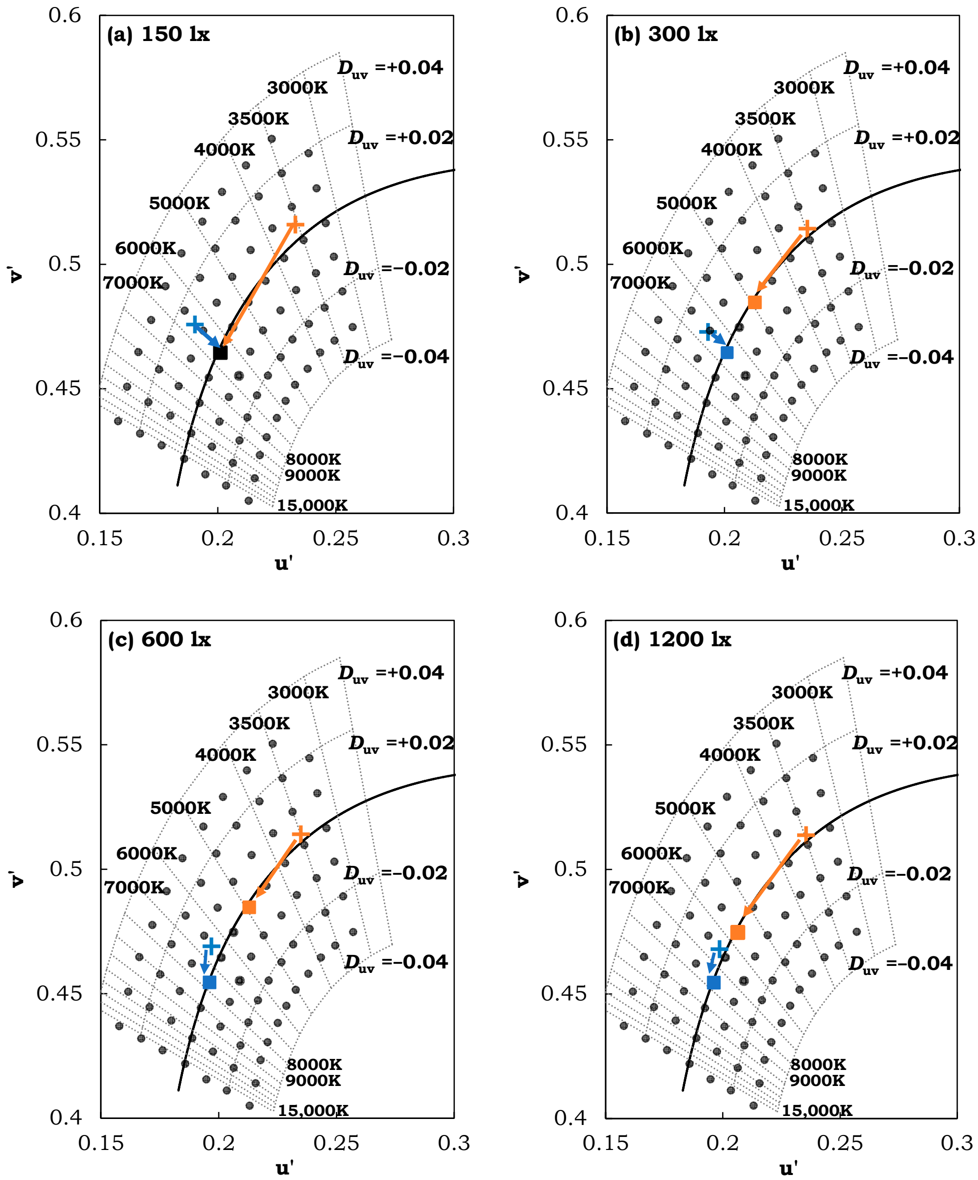


Figure 4. The u′ and v′ of the whitest stimulus judged by the observers under four illuminance levels (labeled with a blue square for the light source of 6500 K and orange for the light source of 3500 K).

4. Discussion

In order to better understand the effect of illuminance level on white appearance, the white appearance ratings across the four illuminance levels are compared, as shown in Figure 5 for the 3500 K light source and Figure 6 for the 6500 K light source. At both 3500 K and 6500 K, a strong correlation is evident between any two of the four illuminance levels, with the lowest correlation coefficient being 0.87 when comparing the results between 150 lx and 300 lx under the 3500 K light source. This seems to indicate that when the observers rate the white appearance at the same CCT, the evaluation for the whiteness percentage under different illumination is highly correlated.

Alternatively, to better understand the impact of the CCT on white appearance, Pearson's coefficient (R) is adapted to analyze the linear correlation between them. The white appearance responses at the two CCT levels are plotted against each other for each illuminance level, as shown in Figure 7. According to Figure 7, it is clear that the correlation coefficient is between 80% and 90%. When comparing the white appearance ratings of the two CCTs at illuminance levels above 150 lx, the correlation coefficients are both lower than or equal to 80%. This suggests that the CCT level has a more significant impact on white appearance rating than the illuminance level by comparing Figures 5–7.

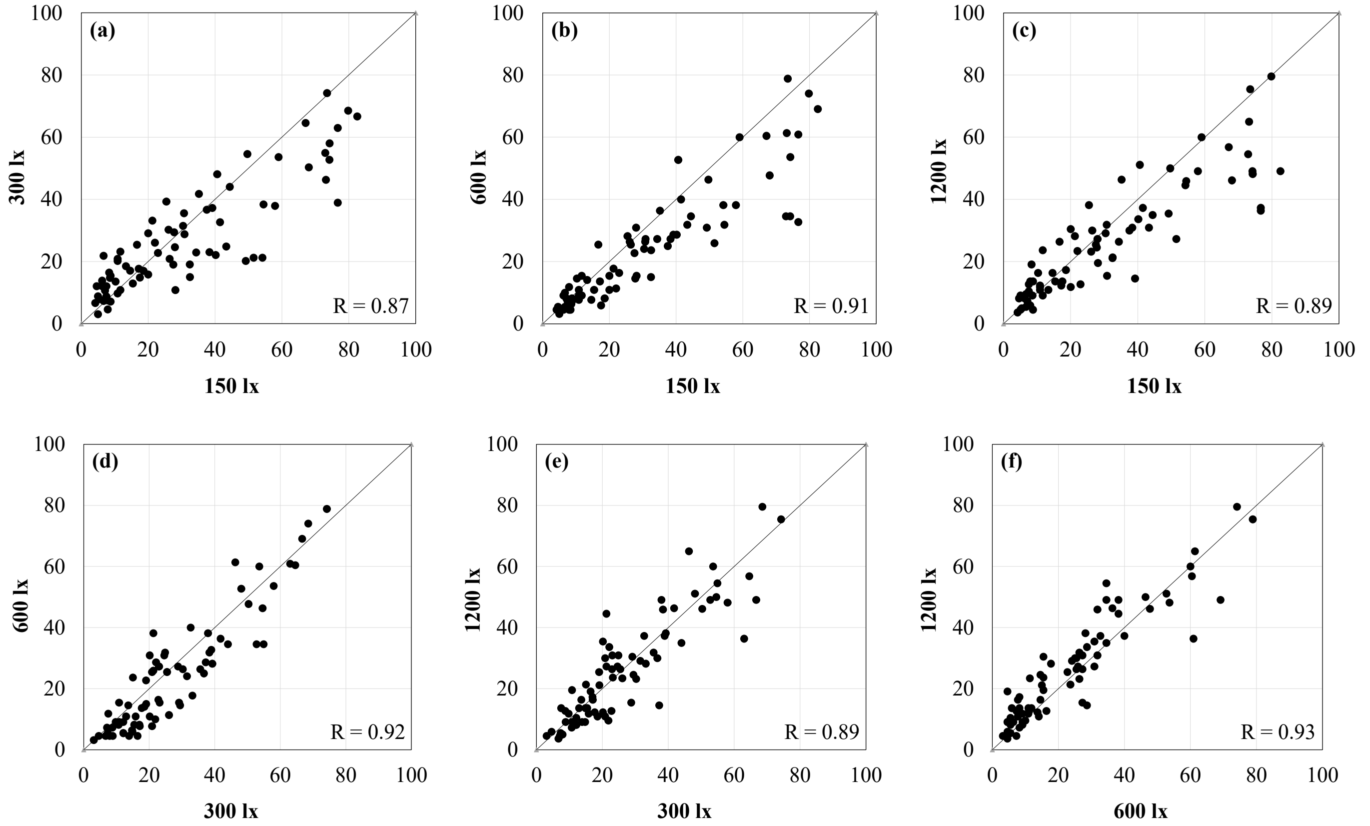
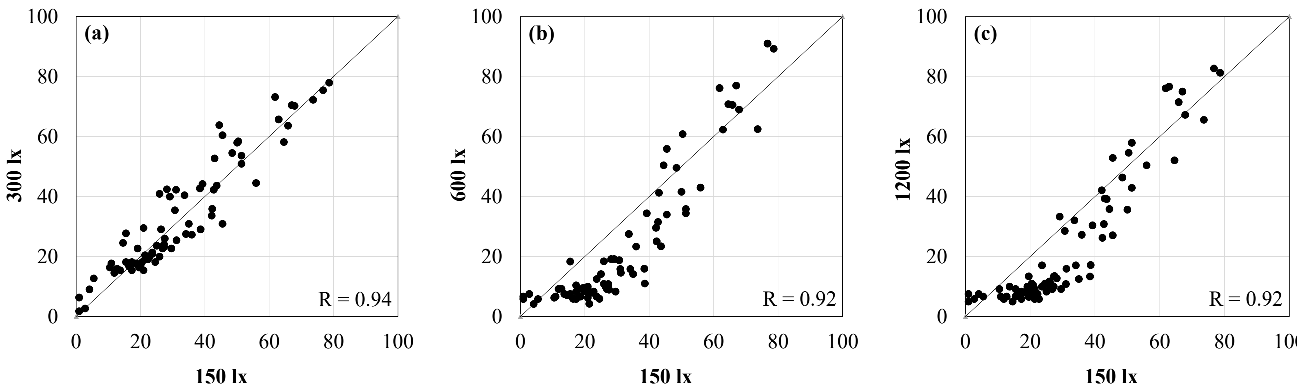


Figure 5. Correlation (r) between various combinations of ambient illuminance levels under 3500 K. (**a**) 150 lx vs. 300 lx; (**b**) 150 lx vs. 600 lx; (**c**) 150 lx vs. 1200 lx; (**d**) 300 lx vs. 600 lx; (**e**) 300 lx vs. 1200 lx; (**f**) 600 lx vs. 1200 lx.



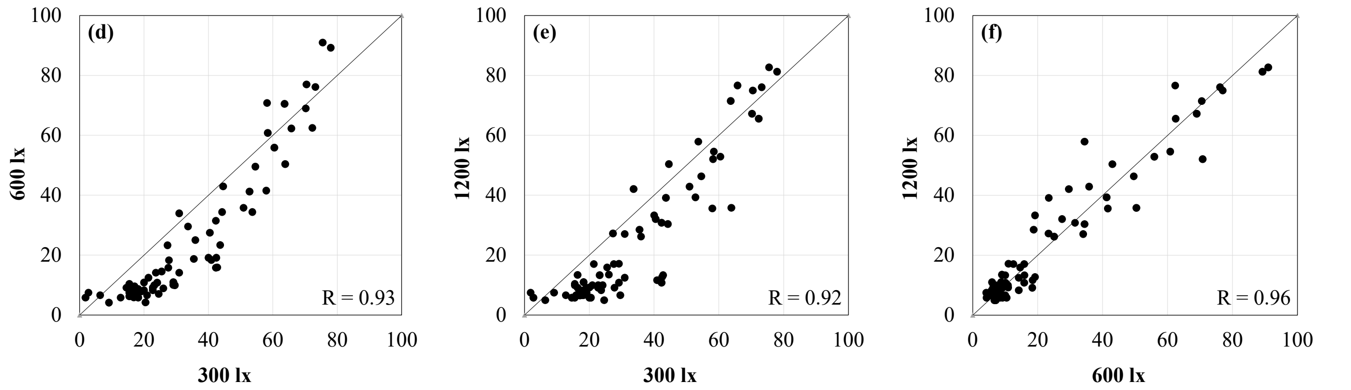


Figure 6. Correlation (r) between various combinations of ambient illuminance levels under 6500 K. (**a**) 150 lx vs. 300 lx; (**b**) 150 lx vs. 600 lx; (**c**) 150 lx vs. 1200 lx; (**d**) 300 lx vs. 600 lx; (**e**) 300 lx vs. 1200 lx; (**f**) 600 lx vs. 1200 lx.

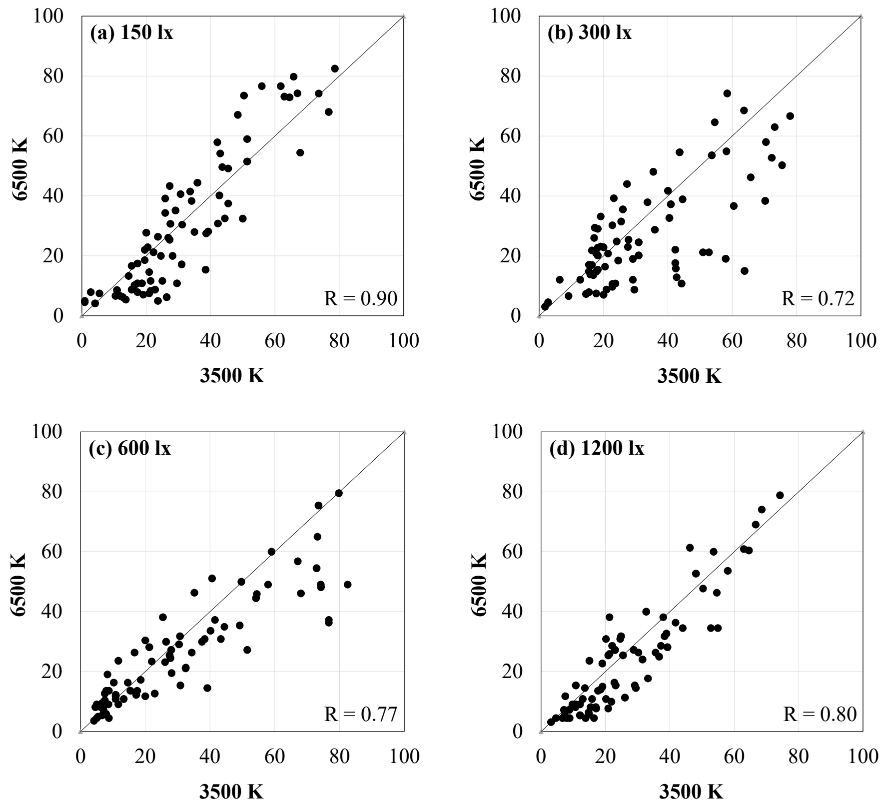


Figure 7. Correlation (r) between the 3500 K and 6500 K light source at each illuminance level (150 lx, 300 lx, 600 lx, and 1200 lx).

Based on the above results, this phenomenon is further organized in Figure 8, where the black square represents the chromaticity coordinates of the whitest stimulus rated by the observers under 150 lx, the orange cross represents the chromaticity coordinates of the whitest stimulus rated by the observers under 1200 lx at 3500 K, and the blue cross represents the chromaticity coordinates of the whitest stimulus rated by the observers under 1200 lx at 6500 K. According to Figure 8, as the illumination increases, the whitest stimulus for the 3500 K light source moves closer to its original light source, whereas the whitest stimulus for the 6500 K light source shifts towards a higher correlated color temperature.

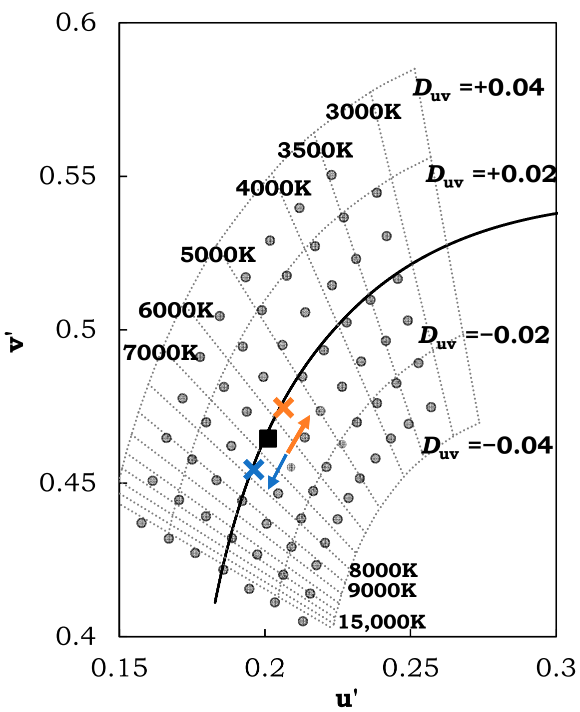


Figure 8. The u′ and v′ of the whitest stimulus judged by the observers under 150 lx and 1200 lx at two CCTS (labeled with a cross-blue for the light source of 6500 K and orange for the light source of 3500 K).

The limitations of this study lie in the limited environmental lighting parameter settings. This study only investigates the effect of four illuminance levels on white appearance at two CCTs. For further research, more illuminance levels and CCTs will be included, providing more comprehensive recommendations for lighting design applications.

5. Modeling

In applications, a predictive model can be developed to evaluate changes in perceived whiteness, serving as a reference for adjustments to provide optimal ambient lighting and display white point settings when using a display. This study employs an artificial neural network (ANN) to propose a perceived whiteness prediction model. Determining the input parameters is the initial step in training the machine learning model. This experiment used variables including CCT, illuminance levels, and the CIE 1931 (x, y) chromaticity coordinates of display stimuli as inputs to the model. The output was the whiteness response values from psychophysical experiments, ranging from 0 to 100. During the data preprocessing stage, the illuminance levels were first log-transformed. Subsequently, all inputs are standardized using z-score normalization, transforming the data with a mean of 0 and a standard deviation of 1. This ensures a standard normal distribution, speeding up convergence during model training. The dataset consisted of 608 records, split into training and test sets using the holdout method at an 80–20% ratio, resulting in 486 training and 122 test samples. Furthermore, 10% of the training set is used as a validation set during model training.

The model architecture, as shown in Figure 9, included an input layer with four neurons, two hidden layers with fifty neurons each, and an output layer with a single neuron. Batch normalization was applied before the tanh activation function in each layer to make the training process faster and more stable. The loss function used is a mean square error

(MSE). Additionally, a 25% dropout is added at the end of each layer to prevent overfitting. For hyperparameter settings, the Adam optimizer was employed with a learning rate of 0.001. The model was trained over 3000 epochs with a batch size of 128. Figure 10 shows the training history of the mean absolute error (MAE) and loss of the ANN model for each epoch, respectively.

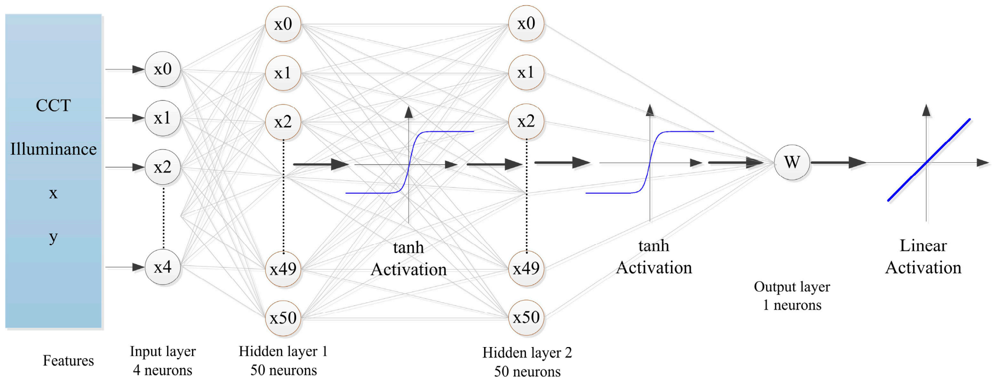


Figure 9. Architecture of whiteness prediction model.

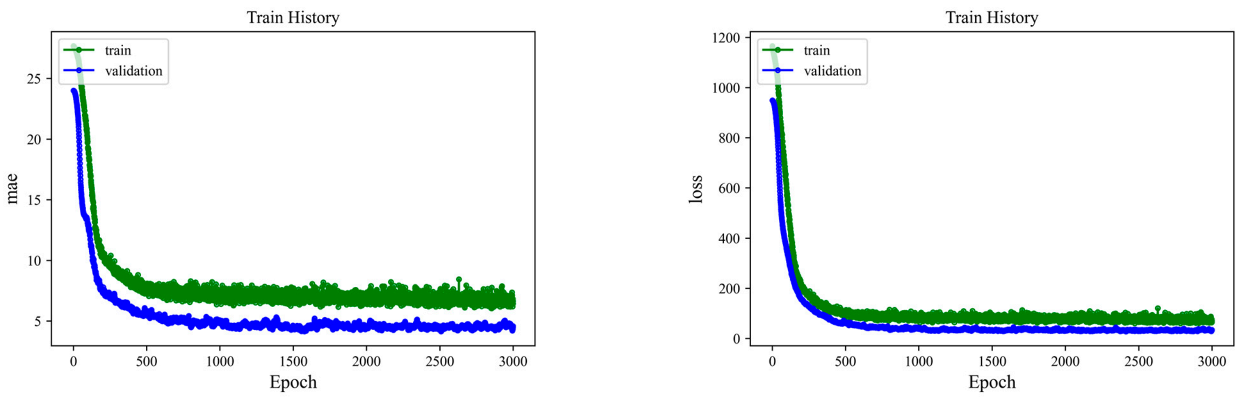


Figure 10. The history of training (**Left**: MAE; **Right**: loss).

For regression analysis, the coefficient of determination (R-squared) and root mean square error (RMSE) are primarily used to evaluate the machine learning models. The average test results for RMSE, MAE, R-squared, and Pearson's correlation coefficient are 7.128, 5.162, 0.892, and 0.956, respectively. Based on the evaluation metrics, the results demonstrate that the model can accurately predict subjective perceived whiteness, as indicated by the high R-squared value and acceptable RMSE. Figure 11 shows a scatter plot of the predicted values and the ground truth, where the distribution of the data points is closely aligned with the 45-degree line, representing a perfect prediction.

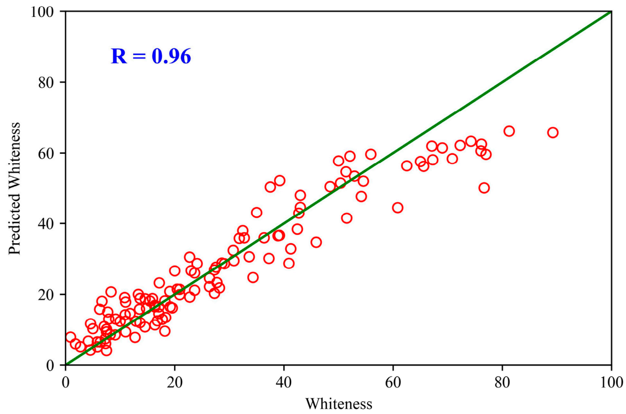


Figure 11. Scatter plot of prediction.

6. Conclusions

In conclusion, a psychophysical experiment is carried out to examine white appearance using a tablet display under eight different ambient lighting conditions, which includes two levels of correlated color temperature and four levels of illuminance. A total of 6992 whiteness percentage evaluations are collected from thirteen observers to identify the whitest stimulus under these eight lighting conditions.

The appearance of white is critical to the imaging quality of display devices. A proper display white point should be set to neutral to enhance image quality. However, variations in ambient lighting can alter the perception of white. This study investigates changes in perceived whiteness under different ambient illumination levels, including 150, 300, 600, and 1200 lx, and correlated color temperatures of 3500 K and 6500 K. The experimental results indicate that under an illumination level of 150 lx, the adapted white points for light sources at 3500 K and 6500 K tend to shift toward higher color temperatures, with both white points being similar. As the illumination level increases, the adapted white point under the 3500 K light source approaches the light source's color temperature. In comparison, the adapted white point under the 6500 K light source shifts toward an even higher color temperature. This study developed a perceived whiteness prediction model using an artificial neural network based on the experimental data. The testing results show that the model can effectively and accurately predict perceived display whiteness under various environmental conditions. The model can be a design reference for the display and lighting industries.

Author Contributions: H.-P.H., concept provider, project administration, conducting experiments, data analysis, and writing manuscript preparation. H.-C.L., data analysis, modeling, and writing manuscript preparation. Y.-M.F., data analysis and writing manuscript preparation. M.W., concept provider, supervision, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: The authors declare no conflicts of interest.

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