A STUDY OF ROAD LIGHTING PREFERENCES BASED ON VIDEO EVALUATION FROM THE PEDESTRIAN'S PERSPECTIVE

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ABSTRACT

This study explores pedestrians' psychological preferences for road lighting. Through field research in Beijing, road lighting materials of six CCT and three illuminance were obtained, and videos from the pedestrian's perspective were taken. The study verified the validity of the video evaluation through a pre-experiment and constructed an evaluation questionnaire of seven factors. In addition to the research on driving safety, it provides a reference for the revision of road lighting standards and planning from the pedestrian's perspective. The results show that different road lighting brings different psychological feelings to pedestrians, and there is an interaction between illuminance and CCT. The optimal CCT range is 2700 to 3200 K. There is a strong correlation between color temperature preference and overall preference.

Keywords: White LED, Road lighting, Video evaluation, Pedestrian's perspective, Color temperature preferences

1. INTRODUCTION

White LEDs have been widely used in road lighting and are gradually replacing traditional low-color temperature HPS lamps [1]. However, it has also brought a series of problems, including uncomfortable visual and psychological perceptions and nighttime rhythmic effects. The road nightscape should not only guarantee function and safety but also create a good atmosphere to support the all-weather function of roads [2]. In recent years, research has focused on the design of LED luminaires to respond to the needs of road lighting with different characteristics [3-4].

Road surface illuminance and color temperature are important parameters of road lighting. The improved color rendering and spectral luminous efficiency of LEDs provide the basis for reducing the illuminance [5]. For roads with high traffic flow, CIE, IESNA, Japanese industrial standards, and Chinese road lighting standards specify an average illuminance of 20 lx [6]. The typical road illuminance intervals in Beijing include 10–30 lx, 30–50 lx, and 50–100 lx, which may produce visual comfort problems such as glare. The current standards and studies focus on the driver's perspective, and the illuminance is discussed in more depth, but the color temperature is more broadly defined. This study will focus on the color temperature preferences of pedestrians in different illuminance situations.

The difference in luminous efficiency of LEDs in different color temperature zones is gradually being reduced. The contradiction between luminous efficacy and color temperature is no longer the main issue, and the harmony between color temperature and the road environment becomes the focus of attention [7]. One of the most recent research hotspots is determining what color temperature range is appropriate for urban road lighting.

The spectral power distribution and lighting level of road lighting affect the visual performance of drivers [8-10] and pedestrians [11-13]. Road lighting is in the mesopic visual range, and visual efficacy can be used to assess the light efficiency while driving [14]. Feng S et al. suggested a road lighting color temperature in the range of 2800–4200 K in hazy weather [7]. Zhang Q et al. suggested the best visual efficacy of 3500 K through actual measurements and surveys [15]. Yang B et al. pointed out that the use of light sources with a larger color gamut could improve the visual efficacy [16]. From the pedestrian perspective, identity recognition and intention determination are important vision tasks [17]. A field study by Lin Y et al. concluded that MH streetlights (2726 K) are more likely to achieve better facial recognition than LED streetlights (5298 K) and HPS lamps (1930 K) [18]. Yuan J et al. found that for pedestrian paths on campus, a lighting color temperature of approximately 3000 K had higher recognition [19]. However, studies on visual efficacy are oriented towards the driver's perspective, and studies on sidewalk lighting are conducted on stand-alone pedestrian lighting systems with dedicated luminaires. Studies on sidewalk lighting, which is indirectly provided by functional road lighting, are lacking.

Color temperatures affect the feelings of safety and psychological preferences of motorways and sideways. For example, LED color temperatures that are psychologically considered most suitable for motorway include 4000 K [20], 4100–4300 K [21], while too high a color temperature [22] or 5500–6000 K [21] are uncomfortable. Lighting is strongly correlated with the perception of safety on sideways [23], and the LED lighting that are psychologically considered most suitable for sideways include 3000 K [19, 24-25] and 3800 K [26]. In summary, motorways should have a higher acceptable color temperature than sideways. The distinction between the two is important since it occurs frequently in China where sideway lighting is indirectly provided by road lights.

When it is difficult to conduct evaluation studies in real scenarios, images can be used to present real situations [27]. Video has also been used as a research tool of environmental psychology, capable of reflecting the dynamic properties of urban environmental horizons [28]. High dynamic range (HDR) image technology is able to perform image simulation of original scenes based on multi-exposure dynamic range [29-30], which has great potential for road lighting measurement with high luminance contrast. Therefore, this study uses HDR video evaluation to solve the problems of disturbing factors of field experiments, and also to achieve a greater degree of restoration of real scenes.

The current Chinese standard states that the CCT should be lower than 5000 K and that it is advisable to choose medium/low CCT [31]. The LED color temperature range has been widened to 1700–18000 K [32]. In Beijing, the typical color temperature intervals of road lighting measured include 1600–2200 K, 2200–2700 K, 2700–3200 K, 3600–4300 K, 4300–4900 K, and 4900–5400 K. Usually, research on the color temperature of road lighting focuses on functional lighting based on the driver's perspective. Instead, this study focuses on the psychological preferences of pedestrians and explores whether their preferences are related to illuminance. It can also help to better understand pedestrian preferences for urban functional lighting and provide data support because most roads have functional lighting that also serves as sidewalk lighting.

2. METHODS

2.1 Pre-experiment

In order to verify the effectiveness of video evaluation, a pre-experiment was conducted in Tsinghua University. Photographs and videos of 14 locations were captured at 20–21PM, and evaluation questionnaires were completed by 20 participants in the lab. The same participants were invited to the field for evaluation at the same time the next night. The factors included brightness, color temperature sensation, color temperature preference, and overall preference. T-tests were conducted, and statistically significant differences were obtained for photo and field evaluations ($P < 0.05$), while the differences between video and field evaluations were not significant ($P > 0.05$). That is, the video evaluation was closer to the on-site evaluation results.

Figure 1. Part of the road scenes of the campus pre-experiment

2.2 Video materials for evaluation

Field research and measurements of road lighting in Beijing were categorized into 6 color temperatures and 3 illuminances, for a total of 18 combinations of actual roadway sections. In the 18 typical sections, after holding a motion camera (DJI OSMO POCKET) to human eye height and adjusting the white balance on site until there was no difference between eye perception and the camera display, 4K HDR videos were taken at an angle of 30 degrees from the sidewalk near the motorway to the opposite side, moving at an even pace to simulate the road scenes seen on foot. The clips with less obscured vehicles and road signs in the videos were intercepted as samples, and each video was about 15–30 seconds in length, as the materials.

Figure 2. Images of roads with different color temperature and illuminance combinations

2.3 Site and participants

A classroom was used as the evaluation lab. Ten participants were seated in two rows. Their sight lines were not blocked and the difference in viewpoint was small. The room temperature was controlled to 24℃ by using air conditioners, and the relative humidity was controlled at about 35%–40%. All lamps inside and outside the classroom were turned off during the experiment.

Figure 3. Experimental scene of road lighting evaluation (Lighting turned off during the experiment)

77 students (24 males and 53 females, 20–22 years old) from the School of Architecture participated in the experiment. They had a relatively in-depth understanding of the built environment and lighting. Each participant evaluated 18 videos, with myopic students wearing glasses and no participants with color vision weakness or abnormalities.

2.4 Experimental procedure

The videos were tuned by image processing software and measured to ensure that the illuminance and color temperature at the participant's location would be approximately the same as the lighting at the pedestrian location in the real situation. The processed videos were randomly sorted and stored in groups.

The laboratory was prearranged, and the air conditioning was adjusted until the participant area reached 24℃. Each group of ten participants entered the classroom and underwent a 5-minute dark and temperature adaptation. Then the screen looped the first video, and participants could fill in the questionnaire at any time during viewing. The questionnaire used a 7-level Likert scale to evaluate 7 factors of road lighting. After everyone filled out the evaluation of the first video, they moved on to the second one, thus completing the 18 videos and the evaluation.

2.5 Data analysis

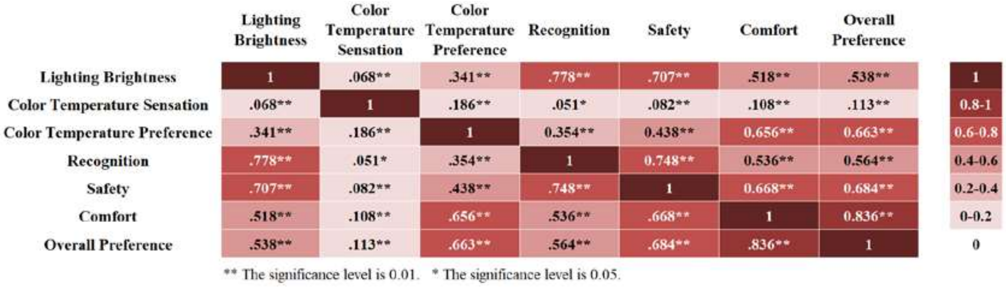
The study used a mixed experimental design, and the independent variables included one between-subjects factor (gender) and two within-subjects factors (color temperature and illuminance). The dependent variables included 7 semantic difference scales: lighting brightness (insufficient/sufficient), color temperature sensation (cold/warm), color temperature preference (dislike/like), recognition (cannot be accurately recognized/can be accurately recognized), sense of safety (danger/safety), comfort (discomfort/comfort), and overall preference (dislike/like).

IBM SPSS Statistics was used for data analysis. Descriptive statistics were used to obtain the basic information of the results. Correlation and factor analysis were used to explore the correlation between the evaluation factors and extract the principal components. Next, a two-factor repeated measures ANOVA was performed on color temperature and illuminance to explore whether there was an interaction between the two and whether there was an effect on the evaluation. To explore the effect of gender, a three-factor repeated measures ANOVA with a mixed design was used.

3. RESULTS

3.1 Factor analysis of evaluation factors

The results of correlation analysis were as follows: (1) a weak correlation between lighting brightness and color temperature sensation, color temperature preference; between color temperature sensation and color temperature preference, recognition, safety, comfort, and overall preference; (2) a moderately strong correlation between brightness and comfort, overall preference; between color temperature preference and recognition, safety, comfort, and overall preference; between recognition and comfort, overall preference; and between safety and comfort, overall preference; (3) a strong correlation between brightness and recognition, safety; between recognition and safety; and between comfort and overall preference. A Among them, comfort has the highest correlation with color temperature preference and overall preference, and there is also a strong correlation between color temperature preference and overall preference.



	Lighting Brightness	Color Temperature Sensation	Color Temperature Preference	Recognition	Safety	Comfort	Overall Preference
Lighting Brightness	1	.068**	.341**	.778**	.707**	.518**	.538**
Color Temperature Sensation	.068**	1	.186**	.051*	.082**	.108**	.113**
Color Temperature Preference	.341**	.186**	1	0.354**	0.438**	0.656**	0.663**
Recognition	.778**	.051*	.354**	1	0.748**	0.536**	0.564**
Safety	.707**	.082**	.438**	.748**	1	0.668**	0.684**
Comfort	.518**	.108**	.656**	.536**	.668**	1	0.836**
Overall Preference	.538**	.113**	.663**	.564**	.684**	.836**	1

** The significance level is 0.01. * The significance level is 0.05.

Figure 4. Heat map of the correlation coefficient matrix between evaluation factors

For the evaluation factors, the principal components with the top 2 eigenvalues were extracted to explain 63.076% and 17.292% of the total data variance, respectively. Component 1 has a high correlation with brightness, color temperature preference, recognition, safety, and comfort, which can be referred to as the psychological perception. Component 2 has a high correlation with color temperature sensation, which can be referred to as the warm and cold perception.

Table 1. Rotated component matrix

	Component 1	Component 2
Safety	0.936	
Recognition	0.915	
Lighting Brightness	0.903	
Comfort	0.863	
Color Temperature Preference	0.666	0.414
Color Temperature Sensation		0.938

3.2 Factors influencing overall preference

The interaction between color temperature and illuminance had a statistically significant effect on overall preference ratings, F = 43.156, $P < 0.001$. And that effect of color temperature was statistically significant at 10–30, 30–50, and 50–100 lx, $P < 0.001$. Most of the differences in ratings between two of the six color temperatures were statistically significant ($P < 0.001$).

The top three for overall road lighting preferences were all 2700–3200 K: CCT3E2 (30–50 lx), CCT3E3 (50–100 lx), and CCT3E1 (10–30 lx). The last three were: CCT1E1 (1600–2200 K, 10–30 lx), CCT1E2 (1600–2200 K, 30–50 lx), and CCT6E1 (4900–5400 K, 10–30 lx), that is, lighting conditions with low color temperature and low illuminance, or high color temperature and low illuminance.

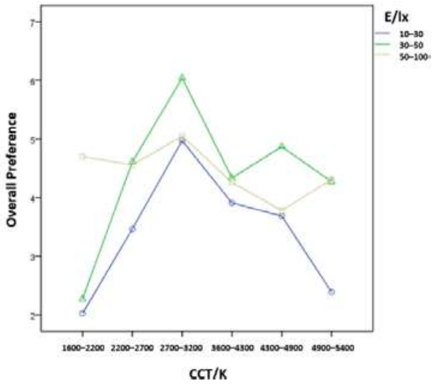


Figure 5. Interaction trend of color temperature and illuminance on the overall preference scores

3.3 Factors influencing the psychological perception

The interaction between color temperature and illuminance had a statistically significant effect on recognition and safety ratings. For recognition, F = 84.524, P < 0.001. For safety, F = 81.239, P < 0.001. The effects of color temperature on recognition and safety ratings were statistically significant at 10–30, 30–50, and 50–100 lx, P < 0.001. Most of the differences in ratings between two of the six color temperatures were statistically significant (P < 0.001).

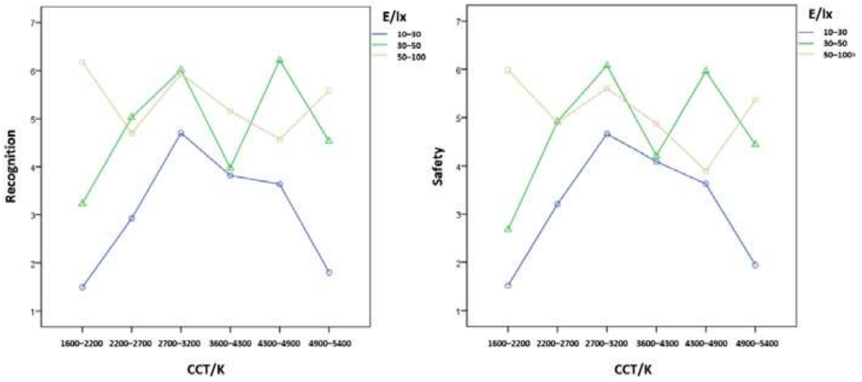


Figure 6. Interaction trend of color temperature and illuminance on recognition and safety scores

When the illuminance is 10–30 lx, the optimal color temperature for both pedestrian recognition and safety is 2700–3200 K. When the illuminance is 30–50 lx, the optimal color temperature for pedestrian recognition is 4300–4900 K, and for pedestrian safety is 2700–3200 K. When the illuminance is 50–100 lx, the optimal color temperature for both pedestrian recognition and safety is 1600–2200 K. The results show that the optimal color temperature for both pedestrian recognition and safety is 2700–3200 K overall, which is lower than the applicable lighting for motorway safety and visual efficacy compared with the existing studies, but basically in line with the pedestrian sideway lighting safety perception and recognition requirements.

Table 2. The optimal CCT and mean values of participants' scores correspond to recognition and safety

E/lx	Recognition		Safety	
	Optimal CCT/K	Mean	Optimal CCT/K	Mean
10–30	2700–3200	4.70	2700–3200	4.66
30–50	4300–4900	6.22	2700–3200	6.08
50–100	1600–2200	6.18	1600–2200	5.96

3.4 Factors influencing cold and warm perception

The interaction between color temperature and illuminance had a statistically significant effect on the ratings of color temperature sensation, F = 22.260, P < 0.001. The effect of color temperature on the ratings of color temperature sensation was statistically significant at 10–30, 30–50, and 50–100 lx, P < 0.001. Most of the differences in ratings between two of the six color temperatures were statistically significant (P < 0.001).

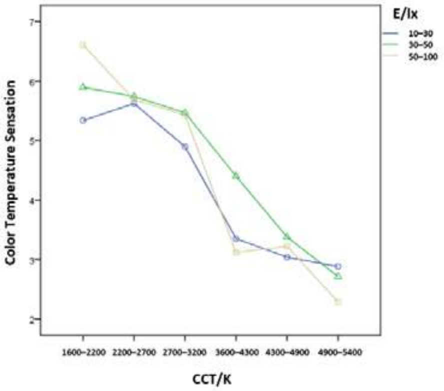


Figure 7. Interaction trend of color temperature and illuminance on the color temperature sensation scores

Higher illuminance conditions made the participants perceive the color temperature as warmer. For example, at 1600–2200 K, 2200–2700 K, 2700–3200 K, and 4300–4900 K, participants perceived the color temperature warmer at 30–100 lx than at 10–30 lx. Interestingly, at 50–100 lx, the participants thought that the color temperature of 3600–4300 K felt cooler than 4300–4900 K.

3.5 Effects of participant's gender

Analysis of the overall preference showed that there was no interaction between gender, color temperature, and illuminance. The interaction between color temperature and illuminance was significant, $P < 0.001$. And there was a significant difference in the overall preference scores by gender, $P = 0.048 < 0.05$. The overall preference score was 4.211 (95% CI: 4.060–4.361) for males and 4.027 (95% CI: 3.926–4.129) for females. That is, overall, males have more positive psychological preferences for the same road lighting scenario compared to females.

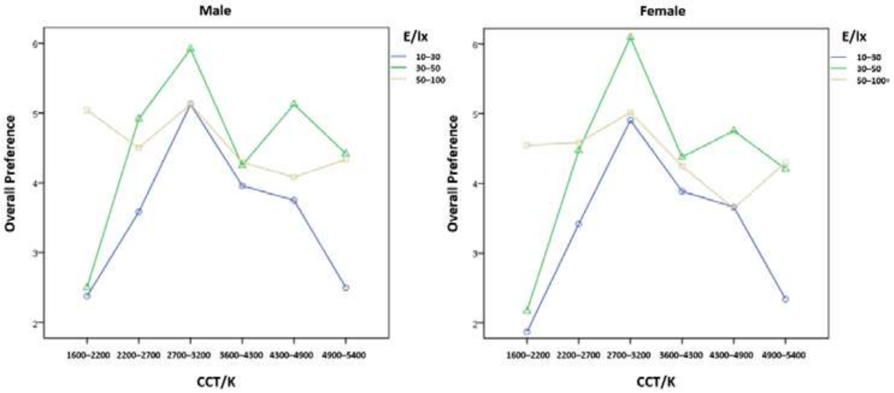


Figure 8. Interaction trends in the overall preference ratings of different lighting scenes by gender

Most motorway lighting in China is below 30 lx, i.e., the 10–30 lx interval in this study, with an overall preference score of 3.549 for males and 3.346 for females. Except for the 3600-4300 K case, the overall preference scores for males was higher than those for females, and this effect was particularly reflected in the 1600–2200 K light color interval.

4. CONCLUSION

24°C	1600–2200 K			2200–2700 K			2700–3200 K			3600–4300 K			4300–4900 K			4900–5400 K		
	10–30 lx	30–50 lx	50–100 lx	10–30 lx	30–50 lx	50–100 lx	10–30 lx	30–50 lx	50–100 lx	10–30 lx	30–50 lx	50–100 lx	10–30 lx	30–50 lx	50–100 lx	10–30 lx	30–50 lx	50–100 lx
Overall Preference	18	17	5	15	6	7	3	1	2	12	8	10	14	4	13	16	11	8
Safety	18	16	2	15	7	6	9	1	4	12	11	8	14	2	13	17	10	5
Recognition	18	15	2	16	7	8	9	3	4	13	12	6	14	1	10	17	11	5
Lighting Brightness	18	15	1	16	7	8	9	2	4	12	13	6	14	3	11	17	10	5
Comfort	18	17	5	15	6	6	4	1	2	12	8	10	13	3	14	16	9	11
Color Temperature Preference	17	18	8	9	5	3	2	1	4	13	7	10	15	6	12	16	11	14
Color Temperature Sensation	8	2	1	5	3	4	9	6	7	11	10	14	15	12	13	16	17	18

Figure 9. Evaluation rankings of different road lighting scenes

The results of subjective evaluation differed for 18 road lighting scenes with different color temperatures and illuminances. For all seven factors, the interaction between color temperature and illuminance was statistically significant. And in different illuminance intervals, color temperature had a significant effect on all ratings of lighting perception.

The overall preference scores and the recognition, safety, comfort, and color temperature preference scores showed similar trends. According to the Chinese road lighting standard [31], most of the motorway lighting is below 30 lx, i.e., for the 10–30 lx interval in this study, the optimal color temperature is 2700–3200 K, with large differences in preference between different color temperatures. For 30–50 lx, the best color temperature is 2700–3200 K, followed by 4300–4900 K. For 50–100 lx, the optimal color temperature is 2700–3200 K, with little difference in preference between different color temperatures. It should be noted that in the 10–30 lx interval, participants had the lowest safety score of 1.537 for 1600–2200 K lighting. To avoid causing unsafe feelings to pedestrians, the use of a low color temperature of 1600–2200 K should be minimized.

5. DISCUSSION

Priority should be given to the visual requirements of drivers, such as identification from a safety standpoint, in the design of urban road lighting. The findings of this study prove that LED motorway lighting is usually high in color temperature for the sidewalks that borrow its lighting. Lower color temperature lighting of 2700–3200 K should be appropriately supplemented in the pedestrian area, taking into account the visual preference of pedestrians.

Other non-optical factors may affect the overall preference, such as temperature, noise, and other environmental physical parameters. Cross-sensory factors should also be taken into account. If the psychological preference of pedestrians for road lighting is dynamic, the settings can be adjusted according to characteristics such as ambient temperature and road type.

The physiological-psychological effects of spectral power distribution and color rendering performance should be explored in road lighting research, in addition to the CCT. In this study, a video evaluation method was used to obtain data. If supplemented with physiological data monitoring methods such as electroencephalogram (EEG), galvanic skin response (GSR), eye tracking, and heart rate, it will improve the assessment of lighting preference.

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