Artificial Lighting in Museums: an Interdisciplinary Approach towards Improving Museum Visitors' Emotive Experience

Zhisheng-Wang*,**, Yukari-Nagai*, Zhi-Sun**, Cong-Zhang** and Nianyu-Zou**

**School of Knowledge Science, Japan Advanced Institute of Science and Technology, Nomi, Japan*
***Research Institute of Photonics, Dalian Polytechnic University, Dalian, China*
**Corresponding Author: s1820006@jaist.ac.jp*

Submitted: 22/01/2019
Revised: 14/09/2019
Accepted: 15/09/2019

ABSTRACT

Based on an investigation by Liaoning Provincial Museum, the lighting environment brought by artificial lighting design was used to test visitors' emotive response levels. The investigation concentrated on visitors' emotive experience. Forty visitors were invited to participate in the evaluation of exhibits through simulation experiments. Keywords were recorded throughout the exhibits to be evaluated in order to assess the subjective factors that have the greatest impact on the emotive experience, including comfort, texture clarity, and colour (authenticity). The colour rendering index in the optical correlation properties was discussed in detail, and the color temperature was briefly described. The corresponding color table data (color table map) was obtained through the use of the theoretical formula of R, G, and B color signals and the color tone formula in Experiment 1 (building color vision model). Taking 2950 K tricolor fluorescent lamps in Liaoning Provincial Museum as an example, and the corresponding Kendall level correlation coefficients *Ra, Qa, FCI* were obtained via CIE colour rendering sample measurement method and also 2950 K fluorescent lamp spectral energy data as the research object in Experiment 2. The weight W was discussed in combination with the visitors' questionnaires to characterize the color fidelity evaluation of the light source. Finally, the characteristics and design concept of artificial lighting were analyzed and summarized, so as to come up with recommendations for improving the emotive response level to museum lighting. This research will have far-reaching significance regarding design of artificial lighting in museums.

Keywords: Museum Lighting Design; Artificial Lighting; Emotive; Visitors' Experience.

INTRODUCTION

In 1941, Kruithof proposed a method for achieving "pleasant effects" on account of the correlated colour temperature (CCT) map of the contrast in interior lighting design. In accordance with the CIE guidelines and the Kruithof rules, when the low illumination range is selected, the pleasure zone CCT should contain approximately 2700 K-4000 K. Nevertheless, whether this lighting condition is applicable to the general exhibition conditions of museums, in addition to artistic preservation, is also questionable (Kruithof AA. 1941). As the development of new lighting technology, the quality of lighting environment can affect visitors' emotions. However, in light of the definition of the International Commission on Illumination (Commission Internationale de Eclairage. 2004), the pleasant area is limited to 200 lx, which is the maximum illumination in museums. This means that it is difficult to apply the rules to lighting of museums. Furthermore, for general lighting forms, subsequent studies (Boyce PR, Cuttle C. 1990) did not fully agree with the Kruithof rules. However, it did provide a more efficient way to define illumination and CCT in the comfort zone. Researchers have a lot of different opinions about what kind of lighting environment is better and what the most influential condition is.

Davis and Ginthner both disagreed with the Kruithof rules. In a color-balanced environment with a color rendering index (CRI) of approximately 90 (Davis RG, Ginthner DN. 1990), their experimental results indicate that the subjective preference score is only affected by the illumination level of 270 lx to 1345 lx, while it is not affected within the CCT range of 2750 K to 5000 K.

Yoshizawa et al. and Luo et al. conducted visual evaluation experiments on paintings under LED lighting (Yoshizawa N, et al. 2013) (Luo H, et al. 2013). They all concluded that visual perception is subject to visibility and texture (warmth) when viewing museum paintings. In the model room and exhibition room of the Morohashi Museum of Modern Art in Japan, two independent experiments were carried out. Yoshizawa et al. studied the changes of CCT (from 2700 K to 5000 K), CRI (from 55 to 100), and illumination (up to 400 lx), respectively, on LED illumination. This paper goes into the lighting environment of several exhibition spaces in Liaoning Provincial Museum.

Museum lighting can be roughly classified into daylighting and artificial lighting. Most designs used in the exhibition are artificial lighting. The lighting environment is crucial to the creation of the atmosphere in museums. In this way, when the audience enter the museums, there is a dark adaptation process under the darker lightness than the outdoor, and then entering the exhibition hall will not feel excessive visual difference and thus form visual fatigue. Apart from creating a good visual environment for the audience, the museums lighting environment should also focus on protecting exhibits and reducing the damage to cultural relics caused by light radiation. It is observed that lighting plays a decisive role in the display space. Museum lighting not only needs art, but also calls for a high degree of integration of technology and art in order to satisfy the urgent need for high-quality museum space lighting and high-quality exhibition lighting.

Interdisciplinary creative artificial lighting design regards human visual factors as the core element. Through different lighting environments studies as reflected through emotional responses, including comfort evaluation, visibility evaluation, warmth evaluation, and preference evaluation, based on the theory of the conceptual optimization of emotional response levels, this paper comes up with the definition and subject of the results of the whole standard artificial lighting design.

This paper attempts to establish an evaluation method for the effect of indoor lighting environment quality on visitors' experience. Based on the theory of the conceptual optimization of emotive response levels, this paper brings forward the definition and subject of the results of the whole standard artificial lighting design.

In order to improve the emotive response level of lighting brought to visitors in museum lighting, this paper takes the evaluation of emotive response as its research goal including comfort evaluation, visibility evaluation, warmth evaluation, and preference evaluation.

EXHIBIT PROTECTION LIGHTING STANDARDS AND DISPLAY METHODS

This study takes the environment and exhibits of Liaoning Provincial Museum in China as samples. Participants were invited to take part in the experiment. The results show that the higher the illuminance, the better most of the evaluations. However, the illuminance evaluation between 200 lx and 800 lx did not improve significantly. Meanwhile, many evaluation indexes decrease with the increase of color temperature. Most subjects prefer lighting conditions with low color temperature. The popular color temperature range of high visual comfort is 3000 K to 4000 K, which is bright and makes people feel more comfortable. Besides, when the Duv of the light source is negative, the evaluation value is slightly better than that of the light source on the blackbody radiation line; that is, the light source is slightly smaller than that of the blackbody radiation source with the same color temperature. All the evaluation indicators can be divided into two parts: clear and warm. The former shows that the visual comfort of the subjects is related to the color temperature and illuminance during observation. The increase in illuminance below 200 lx greatly improves clarity. The latter is in connection with the color tone or texture of the vision, which is greatly influenced by the color temperature.

In the museum, the indicators of lighting include uniformity, contrast, colour rendering, glare, and stereoscopic impression. The materials with color temperature that are not sensitive to light sources comprise metal, stone, glass, ceramics, stone tools, enamel, etc. It is recommended that these sources be less than or equal to 6500 K. Light sensitive materials such as bamboo ware, wood ware, rattan ware, lacquer ware, bone ware, oil painting, murals, natural leather, horn products, and animal specimens are proposed to have a color temperature of less than or equal to 4000 K; exhibit categories that are particularly sensitive to light sources, such as paper paintings, textiles, printed matter, gum paintings, dyed leather, and plant specimens, are suggested, having a color temperature of 2900 K or less.

During studying and appreciating the exhibits in the museum exhibition hall, the quality of the exhibits' lighting directly determines that of visitors' visual information reception (Commission Internationale de Eclairage. 2004). The lighting quality of good exhibits is supposed to meet the following requirements:

- Clearly outline the overall shape of the exhibits;
- Show the details of the exhibit;
- Accurately express the color material of the exhibition products;
- Show the stereoscopic impression of the exhibited products.

Table 1. Lighting parameters for the conservation of artworks.

Sensitive to light	E_{max} **(lx)**	Q **(lx_ch/year)**
Low (e.g. marble and metal objects)	300	Over 500.000
Medium (e.g. oil paintings and frescoes)	150	500.000
High (e.g. textiles and manuscripts)	50	50.000

The degree to which exhibits can be identified is shown in Table 1, Q is the overall yearly energy exposure, expressed by hourly conventional lx per year (lx_ch/year). Based on the above principles, aiming at the display types of museums, the following lighting methods are proposed.

PLANE DISPLAY EXHIBITS

In general, the plane display exhibits are arranged on vertical walls and usually involve paintings, printed matter, manuscript documents and description labels, etc. A large number of plane exhibits can cause difficulties to the lighting design. In the event of the display case is made of acrylic or transparent glass and the lamps are not properly arranged, many uncontrollable light curtain reflections will occur on its surface, causing glare to disturb visitors. As a consequence, for plane exhibits, uniform light distribution is often selected for lighting. Based on the installation height of the lamp and the height of the displayed products, the incident angle and the reflection angle range of the lamp projection are limited. Generally, in order to avoid glare, the most appropriate projection angle for light distribution illumination is vertical 30 degrees, as shown in Figure 1.

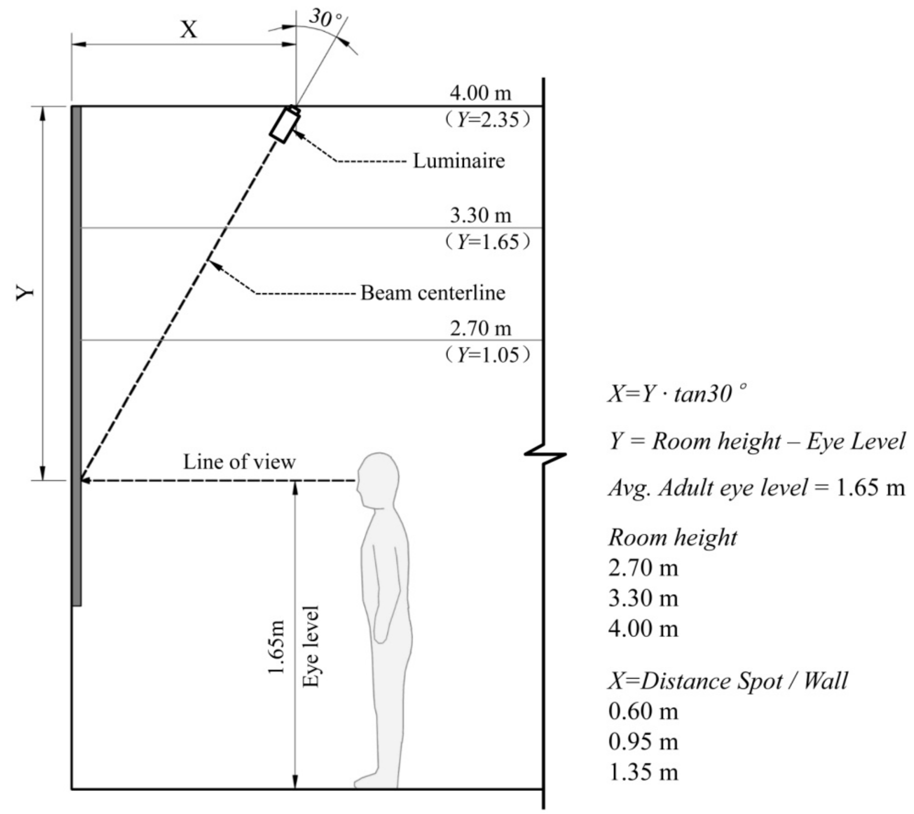


Fig. 1. Floodlight installation distance calculation.

DISPLAY CABINET

Display cabinets are also a common means for museums to display indoors. The display cabinet offers the audience with the conditions to look at the exhibits at close range, and meanwhile it protects the exhibits from damage or theft. There are normally two types of display cabinets: stand-alone cabinets and wall-to-wall cabinets. The size of the cabinets should be determined by the exhibits, such as jewelry and jade articles, stone and stone vessels, clothes, calligraphy and painting, and other items of various sizes and materials. Showcase lighting usually encounters the following problems:

- Reflection of glass walls;
- Shadows caused by visitors or exhibits;
- Heat accumulation in the case.

Hence, the balance of lighting inside and outside the display cabinet is of great importance. Lighting outside the display cabinet is generally used in low-rise display cabinets (Schanda, et al. 2014). When the lamps and lanterns are installed outside the cabinet, they should be placed directly in front of the cabinet and project forward and downward. If the lamps and lanterns are located in other positions, shadows may easily appear near the edges and corners of the cabinet. Lighting outside the cabinet will cause the temperature inside the cabinet to rise because of the greenhouse effect. Adding filters can reduce such kind of phenomenon (Kruithof AA. 1941).

Lighting inside the display cabinet means that a lamp interlayer or light box is arranged on the top of the display cabinet. It is mainly aimed to hide and fix the lamps and lanterns to provide illumination for the old products displayed in the cabinet. It is divided into two types: local lamp interlayer and integral lamp interlayer. Furthermore, lamps and lanterns can be installed at local positions at the inside, back and bottom of the cabinet, adding some auxiliary lighting to show the material and shape of the three-dimensional exhibits. This kind of lighting can strengthen the texture and texture of materials such as ceramics, glass, and polished metal sheets.

THREE-DIMENSIONAL EXHIBITION

The lighting of three-dimensional exhibits should highlight the morphological features of exhibits (Royer MP, et al. 2012). As a result, the light distribution on the surface of the exhibits shall have a bright and dark effect, which requires the selection of multiple light source for projection lighting from different directions. Two-point light distribution is one of the most basic lighting methods for three-dimensional exhibition lighting, adopting one main light and one auxiliary light. The main light is crucial to form a clear image. It determines the basic level of illumination of the exhibition products, while all other lights play a regulatory role on account of the intensity and position of the main light.

SCENERY

In the museum display space, some scenery displays are often erected. The scenery itself is the main body of the display, which is usually called scene restoration. The lighting of such scenery should respect the authenticity of historical scenes while meeting the basic visual requirements of visitors. The original lighting level of special scenes such as dark night and ancient caves is very low, which cannot guarantee the safety of the audience and the actual needs of viewing because of the requirements of scene restoration. In consequence, some compromises should be made to the lighting design.

The lighting of scenery environment and scenery objects can be designed in the light of the requirements and purposes of the theme of the scene display, using the lighting methods of plane display and three-dimensional display. For the sake of achieving a good display lighting, two aspects should be taken into consideration: the position of hidden lamps and the control of lighting. In order to minimize the impact on the authenticity of the exhibition scenery, lamps and other equipment unrelated to the content of the scenery should be hidden as far as possible. The exhibition set often needs a variety of lighting environments so as to meet the requirements of light changes in the exhibition scene. As a result, the lighting control system should be adjustable.

INFLUENCE OF COLOUR RENDERING AND COLOR TABLE

There are three kinds of cone-shaped color-sensing cells in the retina of human eyes. When stimulated by light, their induction generates color information, which is expressed in RGB. The intensity of the received color information is directly related to the intensity of the incident spectrum, and also the spectral sensitivity of such cone-shaped cells (Michael Scuello, et al. 2004).

In Equation (1), the formula below simulates the intensity of signal information that the human eyes feel, which is caused by objects in the lighting environment in museum pavilions:

$$\boldsymbol{R} = \frac{\mathbf{0.3982X+0.704Y-0.0804Z}}{\mathbf{0.3982Xm+0.704Yn-0.0804Zn}} \times \mathbf{100}$$

$$G = \frac{-0.2268X+1.1679Y+0.0458Z}{-0.2268Xn+1.1679Yn+0.0458Zn} \times 100$$

$$B = \frac{Z}{Zm} \times 100 \qquad (1)$$

In the formula, it contains *X, Y, Z* and *Xm*, *Yn* and *Zn* as the three stimulus values of the light source, respectively. In Equation (2), the combination of these three kinds of color information produces non-color information *A* and color difference information.

$$A = 2R^{1/2} + G^{1/2} + 0.05B^{1/2}$$

$$C_1 = R^{1/2} - G^{1/2}$$

$$C_2 = G^{1/2} - B^{1/2}$$

$$C_3 = B^{1/2} - R^{1/2} \quad (2)$$

In Equation (3), the formula for calculating hue, chroma, and lightness is thus established.

To make $C = C_1 - \frac{C_2}{11}$, $D = \frac{C_2 - C_3}{9}$, there are $h = h' + 180$ C<0

h' +360 C>0, D<0

h' +360 $0 < h' < 20.14$

h' Other cases. (3)

In Equation (4), asymmetry factor is *e*. If subscripts 1 and 2 represent the two main colors whose hue angle is closest to *h*, there is

$$e = e_1 + \frac{(e_2 - e_1)(h - h_1)}{(h_2 - h_1)} \quad (4)$$

The hue angle, asymmetry factor, and hue value of each main color are shown in Table 2.

Table 2. Each main color parameter.

Parameter	Red	Yellow	Green	Blue	Purple
h	20.14	90.00	164.75	231.00	320.48
e	0.8	0.7	1.0	1.2	1.0
h	0	100	200	300	400

COLOUR RENDERING EVALUATION

The effect of the light source on the color appearance of the object in the museum is known as colour rendering, which is the inherent colour rendering property of the light source. According to the spectral power distribution of different light sources in museum lighting, it is determined that their colour rendering properties are different, and the mixed light sources composed of specific color lights have good colour rendering effects.

Table 3. Color table value of each color sample under two kinds of illumination.

Color sample	Reference light source illumination			Lighting of light source to be tested		
	H	C	L	H	C	L
1	21.2	44.4	61.5	18.1	44.0	64.5
2	96.4	43.2	61.8	102.5	47.3	61.2
3	152.4	86.2	61.2	160.2	110.5	63.3
4	197.4	70.0	58.5	192.5	75.5	58.5
5	276.4	53.5	59.5	270.4	48.5	58.8
6	331.2	66.8	59.5	335.4	66.5	59.5
7	389.7	56.5	61.2	387.5	67.8	62.0
8	438.5	65.5	65.5	423.5	66.5	65.2
9	5.7	172.5	51.2	7.5	139.5	48.5
10	111.7	118.2	83.5	121.5	140.5	85.5
11	215.2	78.5	48.5	200.4	78.5	48.4
12	324.1	85.5	26.5	330.5	74.5	23.8
13	52.2	45.4	81.5	50.5	46.5	82.0
14	165.4	45.8	42.1	168.0	60.8	41.7
15	25.1	47.5	61.5	34.5	48.5	66.3

Traditionally, the method for evaluating colour rendering properties (Yoshizawa N, et al. 2013) is CIE test color method, which specifies that the low color temperature light source below 5000 K adopts Planck radiator as the reference light source, and the reference light source is 100. CIE specifies fourteen test color samples, among which samples No. 1 to No. 8 represent various common colors, and its eight color samples have lightness of 6 from Mansell's color atlas, and also medium color samples for calculating the general colour rendering index of light sources.

That is enough to meet the requirements. Fourteen color samples evaluated by CIE and 1YR 6 / 4 oriental women's skin color samples were selected as test color samples, and a recombined light source with the same color temperature of the light source to be measured was selected as reference light source. The color tables of the two light source illumination color samples (Kruithof AA. 1941) can be calculated through using the above color vision model. Taking a tricolor compact fluorescent lamp with a color temperature of 2950 K as an example, the color table of each color sample under two illumination conditions can be got from the spectral energy of the lamp and the reference light source. Color table value of each color sample under two kinds of illumination is listed in Table 3.

Fig. 2. Hall of the museum.

The museum hall has an average illuminance of 126.6 lx and a uniformity of 0.916, with lighting environment as shown in Figure 2.

Fig. 3. Exhibition hall 8 of the museum.

Exhibition hall 8 has an average illuminance of 3.107 lx and a uniformity of 0.354, with lighting environment as shown in Figure 3.

Fig. 4. Exhibition hall 2 of the museum.

Exhibition hall 2 has an average illuminance of 6.030 lx and a uniformity of 0.476, with lighting environment as shown in Figure 4.

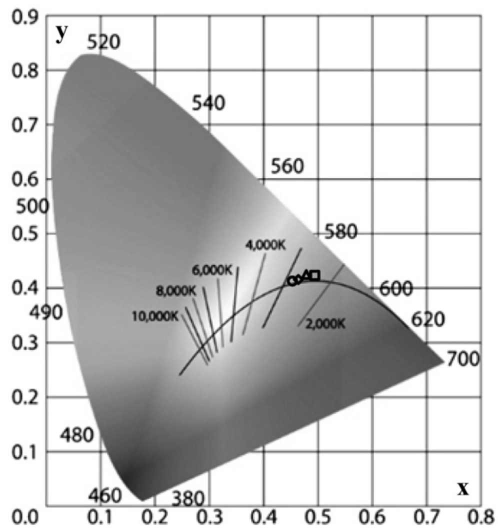
Fig. 5. Corridor of the museum.

The corridor has an average illuminance of 121.2 lx and a uniformity of 0.866, with lighting environment as shown in Figure 5.

MEASUREMENT OF COLOR TEMPERATURE AND COLOUR RENDERING INDEX

From the view of the simple and omitted functions of the museum, there are three basic functions with higher requirements for light quality and color. One is the exhibition function, which requires lighting achieving higher display clarity. This is related to lighting, fidelity, and color gamut. Secondly, the preservation and maintenance functions of cultural relics or works of art require minimal light damage to the illumination of the target object, while traditional light sources, such as halogen lamps and fluorescent lamps, have the most harmful ultraviolet and infrared spectral components. In contrast, LED light sources can easily adjust and control the spectrum to reduce harmful bands (Ezrati JJ. 2013).

The third is the educational function. For example, the lighting requirements of maintenance personnel or cultural relic researchers in the workbench environment require maximum fidelity of lighting. Apart from the fidelity index, color gamut, and correlation index mentioned above, the spectral characteristic parameters that affect the apparent color quality of museum LED lighting mainly include illuminance and color temperature. Spectral radiometer is adopted to measure the color temperature and colour rendering index of the site. The number of measurement points in each station is not less than 9, and the arithmetic average serves to test the color temperature and colour rendering index of the lighting station.



	○ Location (1)	□ Location (2)	△ Location (3)	◇ Location (4)
Museum area	Hall lighting	Exhibition hall2 lighting	Exhibition hall8 lighting	Corridor lighting
CCT	3094 K	2656 K	2834 K	2993 K
x	0.4335	0.4707	0.4553	0.4423
y	0.4085	0.4241	0.4195	0.4142

Fig. 6. CIE 1931 color coordinates of lighting environments.

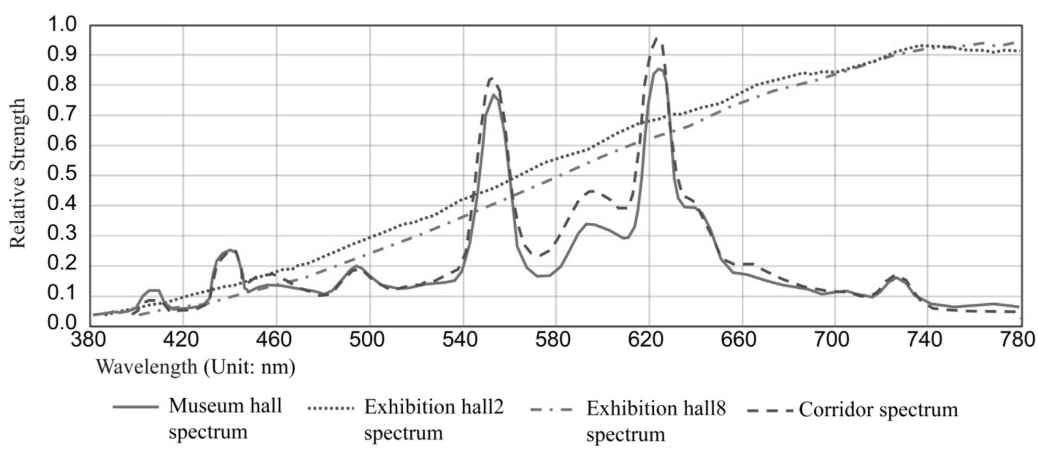
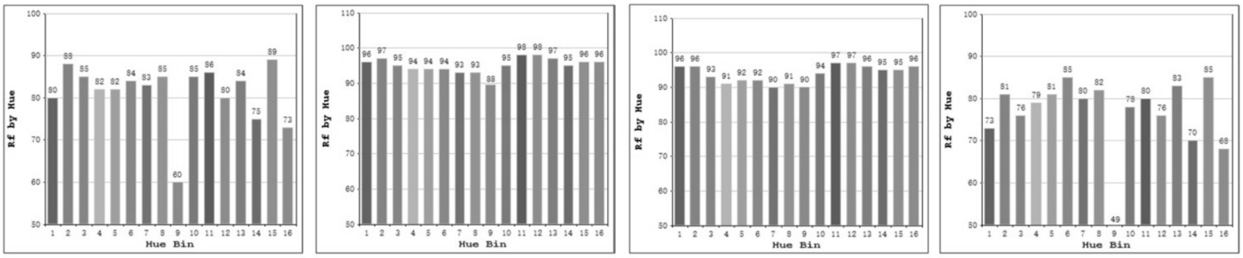


Fig. 7. Spectrum analysis of lighting environments.



Museum hall lighting colour rendering index Ra=87, R9=60 | Exhibition hall8 lighting colour rendering index Ra=95, R9=88 | Exhibition hall2 lighting colour rendering index Ra=96, R9=90 | Corridor lighting colour rendering index Ra=80, R9=49

Fig. 8. Colour rendering index of lighting environments.

Each functional area has more than 3 measuring points. When different light sources are used for mixed illumination, the colour rendering index and color temperature of each light source are measured, respectively, and also the colour rendering index and color temperature after mixing are measured. Through the test of Liaoning Provincial Museum, combined with CIE 1931, you will see from the graph that the CCT of the four regions is about 2600 K to 3200 K (Figure 6), which is in the pleasure zone. Also perform spectrum analysis of the lighting environment (Figure 7) and then obtain the colour rendering index of lighting environments in four different areas in Figure 8. There are different R9 values in the four lighting environments.

EXPERIMENTAL DESIGN

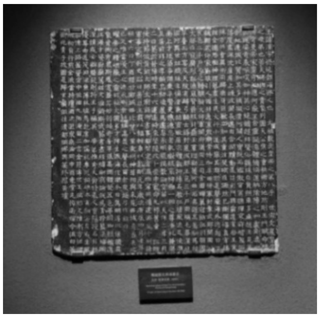
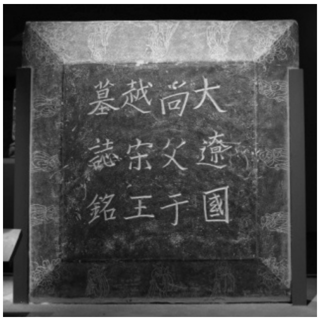
The exhibit model used for the experiment was the artworks from Liaoning Provincial Museum, as shown in Table 4. The exhibition hall contains different types of exhibits.

Via inviting viewers to scan *QR* codes on site and fill out questionnaires for subjective evaluation, statistics can be carried out conveniently and effectively. A total of 106 sets of data were collected from 40 people. The display areas used involve the drawing area of exhibition hall 2, the embroidery nude display area of exhibition hall 4, the epitaph display area of exhibition hall 8, and the stereoscopic display area of exhibition hall 17. The non-display areas used are museum halls and corridors. As a result of too much data, this article only lists the relevant data of exhibition hall 2, exhibition hall 8, museum hall, and corridor and analyzes it. In relation to the exhibition space of the museum, this setting is measured by the following grades: A + is 10 points, and A - is 8 points, B + is 7 points, and B - is 6 points, C + is 5 points, and C - is 4 points, D + is 3 points, and D - is 0 points. The indicators specify the color performance of the exhibits, the clarity of the details of the exhibits, the comfort of the lighting environment, and the artistic performance of the overall lighting space (Meyer Schapiro. 1994). Testers are marked with 1, 2, or 3 for each score, then we can use the following equation to get the total subjective evaluation score.

$$S = S_1 \times 10 \times W \tag{5}$$

In Equation (5), S and S_1 represent the total subjective evaluation score and average score of testers, respectively. And W represents the weight coefficient, and the weight of safety score of non-display space temporary exhibition evaluation is 0.4. The weight of the actual distribution score of light in the environment is 0.3.

Table 4. Lighting test exhibits title and type.

No.	Title		Type
1		Embroidered curtain for Fengxi peony	Embroidery
2		Epitaph of king of Xiangcheng county	Stone tablet
3		Epitaph of Yelvxin	Stone tablet
4		Dragon - grain sarcophagus board	Sarcophagus plate

SENSORY TEST QUESTIONNAIRES

The statistical indicators and objective data in the program are classified into three levels: the first level indicators, the second level indicators, and the total score. For scoring, the score of the survey points is calculated first, then the score and total score of the secondary index and the primary index are calculated comprehensively. Calculate the first-class index score of each survey point: the actual score of the first-class index = score *X* weight value.

Through calculating the score of the secondary index (out of 100 points), the experiment will take data on emotive responses.

$$X = X_1 \times 10 \times W \quad (6)$$

In Equation (6), where X and X_1 represent the actual score of the secondary index and the average score of the survey and evaluation, W represents the weight coefficient. In line with the results of each evaluation, it can be divided into four levels, as shown in Table 5. Then the subjective evaluation results of the basic exhibition are analyzed.

Table 5. Evaluation grade classification.

Items \ Rank	Excellent	Good	Average	Poor
Subjective Evaluation (100 Points)	100~80	79~70	69~60	59~0
Objective Evaluation (100 Points)				
Light Maintenance (100 Points)				

The highest average value is artistic preference for evaluating light use, which is 8.4, while the lowest average value is visual adaptability and appeal preferences, which is 7.6 in Table 6. The basic exhibition subjective evaluation final score is 81.2, reaching the excellent level. The temporary exhibition of subjective evaluation results is shown in Table 7. The highest average value of subjective visual comfort is 8.5, and the lowest average value of light source color preference is 7.6. The temporary exhibition subjective evaluation results also reach the excellent level. From these data, we can know the difference between the basic exhibition and the temporary exhibition, and then adjust based on it.

Table 6. The subjective evaluation results of the basic exhibition.

Items \ Samples	A	B	C	D	Value		
					Mean score	The second weight	The weight x10
Real	16	4	2	0	8.2	20%	16.4
Preference	13	8	1	0	8.0	5%	4.0
Detail	14	6	2	0	8.2	10%	8.2
Dimensional	13	8	1	0	8.1	5%	4.1
Visibility	15	5	2	0	8.1	5%	4.1
Clear	16	5	1	0	8.0	5%	4.0
Brightness	16	5	1	0	8.3	5%	4.2
Visual adaptability	11	8	3	0	7.6	5%	3.8
Subjective visual comfort	13	6	3	0	8.1	5%	4.1
Pleasant	12	8	2	0	7.8	5%	3.9
Artistic	14	6	2	0	8.4	20%	16.8
Appeal	12	7	3	0	7.6	10%	7.6
SUM						100%	81.2

Table 7. Temporary exhibition of subjective evaluation results Mean score.

Items \ Samples	A	B	C	D	Value		
					Mean score	**The second weight**	**The weight x10**
Real	14	5	1	1	8.1	20%	16.2
Preference	13	7	2	0	76	5%	3.8
Detail	14	6	1	0	8.3	10%	8.3
Dimensional	15	4	2	0	8.1	5%	4.1
Visibility	14	5	2	0	8.2	5%	4.1
Clear	14	6	1	0	7.9	5%	4.0
Brightness	14	6	1	0	8.1	5%	4.1
Visual adaptability	14	6	1	0	8.0	5%	4.0
Subjective visual comfort	14	6	1	0	8.5	5%	4.3
Pleasant	14	6	1	0	7.9	5%	4.0
Artistic	15	5	1	0	8.2	20%	16.4
Appeal	13	7	1	0	7.7	10%	7.7
SUM						100%	81

In the subjective evaluation of the museum hall, 10 people are very satisfied with the light art preference, and the average score is also the highest (Table 8), and the final score of the subjective evaluation of the museum hall is 81.3; it is at the excellent level as well. In the subjective evaluation of the corridor, people feel the best for the subjective visual comfort of the corridor (Table 9). Nevertheless, the appeal scores in the museum hall and corridors have the lowest scores. The final score of the subjective evaluation of the corridor is 70.8, which is the lowest.

Table 8. The subjective evaluation results of the museum hall.

Items \ Samples	A	B	C	D	Value		
					Mean score	**The second weight**	**The weight x10**
Brightness	5	14	1	0	8.1	10%	8.1
Visual adaptability	5	14	1	0	7.7	10%	7.7
Visibility	7	12	1	0	8.0	10%	8.0
Pleasant	4	15	1	0	7.9	10%	7.9
Artistic	10	9	1	0	8.6	40%	34.4
Appeal	5	13	2	0	7.6	20%	15.2
SUM						100%	81.3

Table 9. The subjective evaluation results of museum corridors.

Items \ Samples	A	B	C	D	Value		
					Mean score	**The second weight**	**The weight x10**
Brightness	3	19	0	0	7.4	10%	7.4
Visual adaptability	2	20	0	0	6.9	10%	6.9
Visibility	5	17	0	0	7.5	10%	7.5
Pleasure	3	17	1	1	7.0	10%	7.0
Artistic	3	18	1	0	7.3	40%	29.2
Appeal	2	15	3	1	6.4	20%	12.8
SUM						100%	70.8

Taking the museum hall for example, after statistical processing of the data, the importance of each factor is calculated one by one, and the matrix obtained is as follows:

$$A=\begin{bmatrix} 1 & 3 & 6 & 1 & 2 & 3 & 2 & 8 & 2 \\ 0.33 & 1 & 2 & 0.5 & 0.5 & 1 & 0.5 & 4 & 2 \\ 0.167 & 0.5 & 1 & 0.143 & 0.2 & 0.5 & 0.25 & 2 & 0.2 \\ 1 & 2 & 7 & 1 & 2 & 3 & 2 & 9 & 3 \\ 0.5 & 2 & 5 & 0.5 & 1 & 2 & 1 & 6 & 1 \\ 0.33 & 1 & 2 & 0.33 & 0.5 & 1 & 0.5 & 3 & 0.5 \\ 0.5 & 2 & 4 & 0.5 & 1 & 2 & 1 & 6 & 0.5 \\ 0.125 & 0.25 & 0.5 & 0.11 & 0.167 & 0.33 & 0.167 & 1 & 0.167 \\ 0.5 & 0.5 & 5 & 0.33 & 1 & 2 & 2 & 6 & 1 \end{bmatrix}$$

In Equation (7), on condition that the maximum eigenvalue of the comparison matrix is 9.3112, the consistency index *CR* is

$$CR = CI/RI = 0.0266 \tag{7}$$

In Equation (8), where *CI* is 0.0266, i.e., less than 0.1, the surface matrix satisfies the consistency requirement. Normalized weight vector *W* is

$$W = (0.2118,\ 00902,\ 0.0317,\ 0.2206,\ 0.1254,\ 0.0647,\ 0.1157,\ 0.0205,\ 0.1193)^T \tag{8}$$

The nine indicators including color performance (EM Greene, Eric M. 2016), clarity of exhibit details, comfort of lighting environment, color of light source, expression of three-dimensional feeling, artistic preference of lighting use, exhibition details, (authenticity), and visual adaptability are the strong weight indicators among human emotion factors. And Table 10 is obtained by integrating the data of museum hall, corridor, exhibition hall 2, and exhibition hall 8 in the same way.

Table 10. Data sheet of human emotion index.

	Museum hall	Corridor	Exhibition hall 2	Exhibition hall 8
Color representation	0.1960	0.2035	0.2297	0.2244
Detail clarity of exhibits	0.1953	0.1829	0.2089	0.2113
Lighting environment comfort	0.1401	0.1455	0.1422	0.1252
Light source color	0.1367	0.1233	0.1301	0.1170
Three - dimensional sensory expressive force	0.1025	0.1064	0.1064	0.1132
Light Art Preference	0.0798	0.0828	0.0709	0.0859
Details of the exhibition	0.0723	0.0750	0.0604	0.0647
True degree	0.0481	0.0500	0.0317	0.0317
Visual adaptability	0.0293	0.0305	0.0207	0.0214

The degree of influence on people's emotion is arranged as follows: color performance, clarity of display details, comfort of lighting environment, and color of light source, expression of three-dimensional feeling, artistic preference of lighting use, exhibition details, (authenticity), and visual adaptability. When designing the museum's lighting environment, the above factors should be taken into account, which will improve the audience's emotive experience.

EMOTIONAL QUANTITATIVE EVALUATION AND CALCULATION

The research of light source color quality evaluation is on account of an evaluation method with universal adaptability and as few indicators as possible. The test data of each evaluation index are analyzed based on the correlation coefficient expressing Kendall grade. The evaluation method involves four evaluation indexes (*Qa, Qf, Qp, Qg, RCRI, FCI*) in CIE general colour rendering index *Ra* and *CQS*.

Table 11. Kendall rank correlation coefficient diagram between different indexes.

Metrics	*Ra*	*Qa*	*Qf*	*Qp*	*Qg*	*RCRI*	*FCI*
Ra	1.000						
Qa	0.805	1.000					
Qf	0.845	0.892	1.000				
Qp	0.607	0.760	0.652	1.000			
Qg	0.206	0.325	0.222	0.549	1.000		
RCRI	0.817	0.811	0.840	0.610	0.199	1.000	
FCI	0.077	0.150	0.069	0.338	0.557	0.073	1.000

It can be seen from Table 11 that there exists a certain correlation between most indicators, and the correlation coefficient between some indicators is close to 0.9, such as *Qa* and *Qf*. This is largely due to the high similarity of their calculation methods. *Qf* indicates the value of color fidelity in *CQS* supplementary index. The difference from *Qa* is that it does not include saturation coefficient; namely, any change in color saturation of the sample under the illumination of the tested light source will reduce *Qf*, while for *Qa*, only a decrease in saturation will affect *Qf*, and the difference between the two values is quite small in actual calculation and has the same changing trend.

The correlation coefficient with P value greater than 0.01 mainly appears in typical evaluation indexes, for instance, *FCI* and other indexes (*Ra, Qf, RCRI*).

The relative spectral power distribution data of the illumination bodies and light sources used in the experiment come from the existing illumination source types. The relative spectral power distribution of all illumination bodies and light sources covers 1950 K to 7500 K in the wavelength range of 380nm to 780nm with 5nm intervals; i.e., the color temperature range of common illumination sources is included. Aimed to fully characterize the color quality of the light source, the principal component analysis technology is adopted to extract the features of multiple evaluation indexes, and finally three principal components are acquired, designated as *F*, *P*, and *D*, which contain more than 95 % of the information content of the original evaluation indexes, thus effectively representing the original evaluation indexes. The variance contribution rate of each principal component is taken as the weight to synthesize (Christopher J, et al. 2015). The principal components, namely,

$$C_e = 0.693F + 0.172P + 0.135D \qquad (9)$$

In Equation (9), the comprehensive color quality attributed to the light source, which is the main component of each evaluation index, can supply an optimized basis for further constructing the comprehensive index. In the meantime, based on the previous clustering analysis, the paper attempts to explore the construction of comprehensive evaluation indexes on account of color fidelity and color gamut area evaluation methods.

The characterization and fusion of color fidelity take the test samples of the two methods as those of the new color fidelity index, thereby avoiding the two outstanding problems existing in the test samples of CIE colour rendering index, i.e., the lack of high saturation color in the samples and the possibility of being targeted by light source manufacturers to optimize the light source spectrum to obtain unreal colour rendering. The difference in the calculation process of the color fidelity index is that the root mean square of the color difference finally calculated is converted in the light of the S-shaped function taking into account the visual characteristics of human eyes. As a consequence, a new color fidelity index is proposed, namely,

$$C_f = M_{eet} \times \left[\frac{2}{\exp(k|\Delta E|^{1.5})+1}\right] \qquad (10)$$

In Equation (10), M_{eet} is the saturation coefficient, and *ERMS* calculates the root mean square of color difference from 32 groups of test samples. For standard chromaticity observers, in addition to calculating CCT using standard chromaticity system, coefficient *K* is spectrally optimized according to CIE's 12 groups of fluorescent lamps FL1~12; in consequence, its C_f average value is equal to the corresponding CIE colour rendering index average value, thus maintaining the consistency between the traditional illumination source *Cf* and CIE colour rendering index to a certain extent, and at last obtaining K=1/101.

The color gamut area is featured by Q_g in GAI and CQS. Hence, the new color fidelity index C_f and color gamut area indexes GGAI and Q_g are weighted and combined to construct a comprehensive color quality index C_{CQI} (Kumar, et al. 2013), namely,

$$C_{CQI} = \omega C_f + 0.5(1-\omega)(G_{GAI} + Q_g) \qquad (11)$$

In Equation (11), W is the weight, which is obtained via the optimization method, so that it can comprehensively represent the color quality information of light sources described by different evaluation indexes.

CE is derived based on all kinds of test lighting bodies and light sources, and the weight *W* = 0.489 in *CQI* can be optimized with this as the goal. In general, for ordinary users or industrial applications, the weight *W* of 0.489 can comprehensively represent the color quality of light sources; that is, it can give consideration to the evaluation of quality attributes such as color fidelity, preference, and color discrimination of light sources. Nevertheless, for professional applications, weight *W* can be appropriately adjusted in accordance to the actual needs. When the color fidelity of the light source is more emphasized, *W* takes a larger value to the maximum value of 1. When more emphasis is placed on the influence of light sources on color preference and color discrimination, W takes the minimum value up to the minimum value of 0. *W* takes 1 or 0, respectively, for two extreme cases: when *W* = 1, *CQ*I contains only color fidelity indicators and is suitable for occasions where only color fidelity of light sources is specifically required; when *W* = 0, *CQI* contains only color gamut area index; it is applicable to the case where only color preference and color discrimination of light sources are explicitly needed (Athanassio, Protopapas. 2014).

There are few studies on the evaluation of human visual health comfort in museum lighting environment. However, most of these focus on physical indicators of products but lack of consideration of human factors. The emotive response data of human factors are obtained through questionnaires, and the conversion relationship is established through formulas.

The evaluation of basic exhibition lighting art preference is relatively high, and visual adaptability and attraction preference need to be improved. The subjective visual comfort of the temporary exhibition is considerably high, and the color preference of the light source needs to be improved. The museum hall lighting environment takes high illumination and good uniformity, which creates a bright space for visitors and forms a contrast with the lighting of the exhibition hall. Corridor holds good subjective visual comfort, but there is still room for improvement, and attraction preference can usually be improved.

In line with the optical parameters of each exhibit, halogen lamps show strong infrared radiation, thus the amount of infrared radiation will increase, especially for display cabinet lighting. The color reduction degree of the display, the color preference degree of the light source, the detail ability of the display, the three-dimensional display ability, the texture definition of the display, the outline definition, the brightness acceptance degree, the visual adaptability, and the happiness in the heart are all crucial factors for evaluating museum lighting. It must accord with the real judgment of daily testers on the color of exhibits. The color of the light source is quite consistent with the evaluation expectation. The three-dimensional effect and color contrast of the exhibits are precisely the same. With respect to the artificial nature of museums, attention should also be paid to the artistic expression of light. The overall artistic effect and important theme conform to the museum's own positioning and collection characteristics (Ercan, Nilüfer. 2013), and the display content should signify a unified and coordinated whole.

CONCLUSION

The impact of lighting parameters including CCT, colour rendering index, and duv for exhibits in a museum was investigated. The evaluation of basic exhibition lighting art preference is relatively high, and visual adaptability and attraction preference need to be improved. The subjective visual comfort of the temporary exhibition is considerably high, and the color preference of the light source needs to be improved. The corridor has good subjective visual comfort, but there is still room for improvement, and attraction preference can usually be improved. The artistic taste of hall lighting is fairly high and its attraction needs to be enhanced. In the museum lighting, the colour temperature of 2500K-3500K is the most suitable without regard to light-induced damage. Aimed to improve the visitors' preference for the museum, the colour rendering index is better than 90, and the high colour temperature and high illumination will make the visitors feel more comfortable. Through the comparative analysis of the evaluation index data of the lighting environment through the questionnaires, the methods of key lighting and mixed lighting are added to create a better lighting environment experience for the museum hall space.

This paper makes a quantitative analysis of the optical indicators of museum lighting environment from a statistical point of view and shows that there exists a certain correlation among the evaluation indicators under CIE.

The cluster analysis method is used to summarize the evaluation methods based on fidelity, and the feasibility and effectiveness of the indicators are verified through combining the tested evaluation of light sources and the evaluation of audience questionnaires in Liaoning Provincial Museum, providing data accumulation and basis for in-depth study of light source color quality evaluation. The conclusion is the main factor "visibility". Visitors prefer feeling lighting with a CCT of about 2800 K, a CRI as high as possible, and a colour on the underside of the blackbody locus for observing museum exhibits, which improves the emotive response of the visitors. This work can offer guidance to the optimization design of lighting environment evaluation methods.

ACKNOWLEDGMENT

This research is financed by Liaoning Science Research Program of the Education Department (J2019025) and Dalian Institute of Social Sciences Major Research Program (2019dlsky058).

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