Latest Results on LED Museum Lighting: Colour Quality and Artwork Preservation

Abstract. This paper describes a comprehensive study on museum lighting: one part of the study investigates the damage potential of LED museum lighting by generating composite LED spectra with the help of a mathematical algorithm, while the other part investigates the effects of LED lighting on the appearance of artworks. Spectral optimization of LED light has been carried out by using historical pigment reflectance samples instead of the test colour samples used in the CIE CRI method [CIE 1995], because the reflectance of these historic pigments is significantly different from the reflectance of today's pigments.

Keywords: museum lighting, colour rendering, damage potential.

Introduction

Display of art is a challenging field for lighting designers. In museums not only general lighting requirements should be fulfilled, but also many special issues should be addressed. Such special issue is to present the intention of the artist, to save the artwork from damage and to help the visitor to understand the artwork.

The European Commission is funding a three year research project entitled HI-LED [EU FP7 2014] (Human Centric Intelligent Light Engines for the uptake of SSL in Europe) which has the aim to develop SSL based light engines for advancing human alertness, horticulture and museum lighting. The task of the Virtual Environments and Imaging Technologies Research Laboratory is to find optimal lighting solutions for museums exhibiting artworks from different epochs of European art. Our research team started this research task based on its experiences from a previous research project (LED4ART) [EU FP7 2011], where the aim was to produce high quality SSL lighting for the Sistine Chapel.

In European Museums, there are thematic exhibitions from one of the European art periods, but most of the largest museum exhibits artwork from different epochs.

Damage potential analysis of LED based museum lighting

Many natural substances (especially organic materials, like pigments used in painting) are subject to degrade over time. This process greatly depends on the material itself and the environmental conditions (including the irradiation). In this analysis, we focused on the deterioration effect (more specifically, the photochemical action) caused by the spectral composition of the light source used for presenting artistic creations. Formulae and principles about damaging effects are based on the CIE 157:2004 technical report [CIE 2004].

A computer software had been developed, which is capable to optimize the spectrum of different spectral components by the use of a simulation model. The goal was to create a series of spectra for each simulated light source and compare their minimum achievable damage potential (DI - damage index) to conventional museum lighting solutions. Also the maximum achievable DI values were also presented in order to show how high damage is possible, if this aspect is not taken into account, while choosing a

spectral composition setting in a multi channel LED luminaire for museum lighting. We used two types of test light sources: One was based on an existing 12 channel "HI-LED first prototype luminaire", and the other was a 31 channel theoretical source based on an existing 20 channel tuneable LED light source present in our laboratory extended with the missing LED spectra.

Minimum and maximum DI values were calculated for each composite spectra realized by the two luminaires in the 2000 K – 6500 K CCT (Correlated Colour Temperature) interval, with the restriction on u_v to be within the ± 0.005 range, and minimum Ra (CIE General colour rendering index [CIE 1995]) of 80, 85 and 90. We compared the damage potential of these luminaires to black body radiators (a close approximation of incandescent light sources) and daylight sources (CIE D series illuminants) at each CCT, and also to a standard 2856 K black body source with and without using a cut off filter at 400 nm. Figure 1 shows generated spectra with minimum DI.

Figure 1. Optimized spectra for minimum and maximum CIE Damage Index by using a 12 channel or a 31 channel tuneable LED luminaire.

In worst case (using the 400 nm cut off filter and Ra above 90), the LED light sources perform 30 % and 36 % (the 12 or the 31 channel LED source respectively) better at 2856 K than the standard 2856 K black body source. Also, the CCT of the LED sources can be tuned up to 4300 K and 4700 K (12 and 31 channel) to have less or equal DI than the standard 2856 K source. By increasing the minimally required Ra the minimum achievable DI increases only slightly, but that is insignificant in practical terms,

which means that no compromise have to be made between colour rendering and damage potential while using properly selected LEDs for lighting solutions. Also the investigation of the gathered spectra showed, that LEDs placed in the 460 nm – 620 nm range (in peak wavelength, which means 430 nm – 660 nm effective range taking LED spectral bandwidth into account) is enough to achieve excellent colour rendering and low damage at the same time. This can be utilized during light source development and manufacturing.

Effects of LED lighting on visual appearance of artworks

Three real, painted pictures with artistic pigments were received (see Figure 2) from University of Fine Arts (Budapest), which had been used during the visual experiments.

Figure 2. Three paintings and the marked measuring points.

The paintings were presented in a darkened experimental room (Figure 3), where three special museum lighting luminaires (HI-LED prototype luminaires with 12 LED channels, see primary spectra in Figure 4) were installed in order to provide fully controllable illumination of the paintings.

Figure 3. Experimental setup.

Two series of testing processes were carried out. In the first phase the effect of illuminance level and correlated colour temperature on the test persons' judgements had been investigated. During the second phase of the testing process the corresponding colour theory had been examined.

Figure 4. Primary channels of the HI-LED prototype luminaires.

Twelve test lights have been developed and the effect of illuminance level and correlated colour temperature on test persons' judgements has been investigated with the participation of 19 observers. Table 1 shows the measured lighting conditions at the start phase of the experiment. The experimental setup was designed at four CCTs (2850 K, 4500 K, 5500 K and 6500 K) and three illuminance levels (50 lx, 100 lx, 200 lx).

Table 1. Parameters of the twelve test lights.

Test light #	Target illuminance [lx]	Target CCT [K]	Measured illuminance [lx]	d_{uv}	CRI R_a
1	50	2850	49.97	0	98
2	100		100.41	-0.0004	98
3	200		199.23	0.0003	98
4	50	4500	50.02	0.0008	99
5	100		99.48	0.0009	99
6	200		199.05	0.0003	99
7	50	5500	49.55	0.0012	99
8	100		99.29	0.0013	99
9	200		198.92	0.0009	99
10	50	6500	49.19	0.0013	99
11	100		99.29	0.0001	99
12	200		199.20	0.0008	99

In the experimental room three observers at the same time observed the paintings from a distance of 2.5 meters from the pictures. The task of the observers was to scale their visual impression with the help of a questionnaire. The first part of the questionnaire (see Figure 5) contained six scales with contrary word pairs for evaluating each painting under the different test SPDs.

Light #1	Light #2	Light #3	Light #4	Light #5	Light #6
Contrast low - high ☐	Contrast low - high ☐	Contrast low - high ☐	Contrast low - high ☐	Contrast low - high ☐	Contrast low - high ☐
Appearance cold - warm ☐	Appearance cold - warm ☐	Appearance cold - warm ☐	Appearance cold - warm ☐	Appearance cold - warm ☐	Appearance cold - warm ☐
dark - bright ☐	dark - bright ☐	dark - bright ☐	dark - bright ☐	dark - bright ☐	dark - bright ☐
colourless - colourful ☐	colourless - colourful ☐	colourless - colourful ☐	colourless - colourful ☐	colourless - colourful ☐	colourless - colourful ☐
Detail soft - crisp ☐	Detail soft - crisp ☐	Detail soft - crisp ☐	Detail soft - crisp ☐	Detail soft - crisp ☐	Detail soft - crisp ☐
Atmosphere unpleasant - pleasant ☐	Atmosphere unpleasant - pleasant ☐	Atmosphere unpleasant - pleasant ☐	Atmosphere unpleasant - pleasant ☐	Atmosphere unpleasant - pleasant ☐	Atmosphere unpleasant - pleasant ☐
Comment ____	Comment ____	Comment ____	Comment ____	Comment ____	Comment ____

Figure 5. First part of the questionnaire.

Four of the scales were associated with appearance of the painting (low contrast – high contrast, cold – warm, dark – bright, pale – colourful)

while two others were associated with atmosphere (soft – crisp details, unpleasant – pleasant). Each scale was evaluated by using a four-point categorical scale. The negative word was recorded with score values 1 or 2. For example in case of answer 1 observer judged his/her visual experience significantly negative, in case of score value 2 the observer judged his/her experience slightly negative. In case of score values 3 or 4 the impression of the observer was slightly or very positive, respectively.

The second part of the questionnaire was (see Figure 6) related to the similarity of appearance under the test SPDs compared to the appearance under the natural (reference) light. The evaluation was also made on a four-point scale, where 1 meant that there is no similarity between the two scenarios, 2 meant that the two scenarios is slightly similar, 3 meant that the two scenarios are similar and 4 meant that they are identical.

Figure 6. Second part of the questionnaire.

The reference light was defined as the best spectral approximation of CIE D65 illuminant which could be realized by the HI-LED 12 channel prototype LED luminaire (having 10 different LED channels). This spectrum can be seen below together with CIE D65 illuminant (see Figure 7).

Figure 7. Approximation of CIE D65 illuminant with HI-LED prototype luminaire.

Results

Preferred illuminance level and Correlated Colour Temperature

Diagrams in Figure 8 show the impact of CCT and illuminance on observers' judgements for the six scales stressed by contrary word pairs. It can be seen that atmosphere is most pleasant in case of light with 5500K CCT, but there is no significant difference among visual results at 4500 K – 5500 K – 6500 K. The role of the illuminance level is less appreciable: atmosphere is more pleasant, when illuminance level is at least 100 lux, but there is no significant difference among 50 lux, 100 lux and 200 lux. Contrast is significantly higher than in case of 2850 K, when CCT is at least 4500 K. It can be seen that details are crisper when CCT increases and the appearance (clarity) is brighter when CCT increases as well. In most cases the role of the illuminance level is less, there is no significant difference among 50 lux, 100 lux and 200 lux.

Figure 8. Impact of CCT and illuminance on observers' judgements for the six scales stressed by contrary word pairs.

“Similar to daylight” appearance – testing “corresponding colour” theory

In the second phase of the experiment the corresponding colour theory [Schanda 2014] was

investigated and further tests were carried out where the effect of the correlated colour temperature and illuminance level was investigated as well. These tests were performed with nine observers. The experimental setup was designed at three CCT values (3500 K, 4500 K and 5500 K) and five illuminance levels (50 lx, 100 lx, 200 lx, 400 lx and 600 lx). Light trios were composed from these SPDs based on the following principle: the first light in each trio was the SPD with maximum R_a , the second (reference) light was the spectral approximation of CIE illuminant D65 and the third was the spectrum developed based on the corresponding colour theory.

Table 2 – Parameters of spectra used in light trios.

	Max R_a 5500K	Max R_a 4500K	Max R_a 3500K	Correspon ding 5500K	Correspondin g 4500K	Correspondin g 3500K	D65
x	0.3325	0.3611	0.4057	0.3307	0.3578	0.4010	0.3128
y	0.3432	0.3648	0.3912	0.3382	0.3613	0.3894	0.3292
CCT [K]	5497	4498	3494	5576	4588	3586	6497
d_{uv}	0.0010	0.0005	0.0001	-0.0007	0.0000	0.0004	0.0032
R_a	99.1	99.2	99.1	96.9	91.9	94.1	98.1
DI	0.2083	0.1721	0.1447	0.2095	0.1824	0.1454	0.2138

During the first part of the experiment the sufficient illuminance level for the illumination of paintings has been investigated in case of each CCT. Settings with maximum R_a can be seen in the first three columns of Table 2. The task of the observers was to decide which lighting level is ideal for the appearance of the paintings. CCT of test lights kept constant (3500 K, 4500 K or 5500 K). Table 3 shows the questionnaire.

Table 3 – First part of the questionnaire, illuminance level.

3500 K					4500 K					5500 K				
50 lx	100 lx	200 lx	400 lx	600 lx	50 lx	100 lx	200 lx	400 lx	600 lx	50 lx	100 lx	200 lx	400 lx	600 lx

In the second part of the experiment the role of CCT had been investigated. Settings with maximum R_a were tested similarly to the first part of the experiment. The task of the observers was to decide that which CCT is ideal for the appearance of the paintings. Table 4 shows the used part of the questionnaire.

Table 4 – Second part of the questionnaire, CCT.

50 lx			100 lx			200 lx			400 lx			600 lx		
35 00 K	45 00 K	55 00 K	35 00 K	45 00 K	55 00 K	35 00 K	45 00 K	55 00 K	35 00 K	45 00 K	55 00 K	35 00 K	45 00 K	55 00 K

In the third part of the experiment the question of similarity has been investigated (see Table 5). Light trios have been created, that included those settings what the observers perceived as ideal in the first part of the experiment. I.e.: if the observer judged the 200 lx illuminance level appropriate in case of 3500 K series, then in the third part of the experiment the light trio containing the following settings was presented and they all had illuminance level of 200 lx:

- 3500 K – Max R_a ,
- D65,
- 3500 K – Corresponding Colour.

Table 5 – Third part questionnaire, similarity.

1 st light trio			2 nd light trio			3 rd light trio		

After the evaluation of the light trios the observers' task was the ranking of the three test lights according to their visual preference. When setting up the sequence the order may be equal between two light sources as well.

Table 6. Fourth part of the questionnaire, visual preference.

1 st light trio			2 nd light trio			3 rd light trio		
1. max R_a	2. Ref. D65	3. CC	1. max R_a	2. Ref. D65	3. CC	1. max R_a	2. Ref. D65	3. CC

If the observer perceived 400 lx illuminance level appropriate in case of 4500 K series, then in the third part of the experiment the light trio with the following settings was presented (all with equal illumination level of 400 lx):

- 4500 K – Max R_a ,
- D65,
- 4500 K – Corresponding Colour.

The CIE D65 setting was the reference illuminant in all cases and the observers' task was to rate the similarity of appearance in case of the other two test SPDs compared to the appearance under the natural (reference) illumination. Table 6 shows the questionnaire according to this part of the experiment.

The evaluation was also made on a four-point scale, where the value of 1 meant that the appearance of the paintings in case of the first light source is substantially similar to the appearance under the reference light source, the value of 2 meant that the appearance of the paintings in case of the first light source is similar to the appearance under the reference light source, the value of 3 meant that the appearance of the paintings in case of the second light source is similar to the appearance under the reference light source and the value of 4 meant that the appearance of the paintings in case of the second light source is substantially similar to the appearance under the reference light source.

Corresponding colour theory investigations

Based on the results (in case of 3500 K and 4500 K lighting), the appearance of the paintings showed more resemblance to the reference (under the D65 lighting), if the lighting spectrum was optimized according to the corresponding colour theory, and not based on the CRI.

In case of the CCT of 5500 K the appearance of the paintings is more similar under the setting which was developed based on the Maximum R_a .

In the future, another series of visual experiments going to be planned to investigate further aspects of museum lighting, and corresponding colour theory will be investigated as well.

After the evaluation of the similarity the observers' task was to set the order of the three test light settings of the light trios according to their visual preference. Figure 9 shows the order of the settings. It can be seen when the colour temperature was 3500 K the most preferred setting was the reference light (CIE illuminant D65) of the light trio.

Figure 9. Ranking order of the test light sources.

This reference light is on the first place according to 66.7 % of the participants. Based on the observers' judgement the spectrum developed based on the corresponding theory is more pleasant compared to the setting with maximum R_a . The light source with 3500 K and with maximum R_a was perceived as the worst setting in this section.

When the colour temperature was 4500 K then the setting with maximum R_a was judged as best. According to 55.6 % of the observers' preference this setting is on the first place and none of the observer is placed it on the 3rd place. The spectrum based on the corresponding colour theory is on the 2nd place and CIE D65 illuminant is on the last place. More than 40 % of the participants placed the CIE D65 setting on the last place.

In case of the CCT of 5500 K the most preferred spectra was the setting with maximum R_a and at least preferred was the setting developed based on the corresponding colour theory. More than 50 % of the participants placed this spectrum on the 3rd place.

Conclusions

Based on the observers' opinion the sufficient illuminance level for museum lighting is 200 lx. More than 77 % of the observers have judged this illuminance level as appropriate.

The most ideal correlated colour temperature for the most pleasant appearance of the paintings is 4500 K when the illuminance level is 50 lx, 100 lx, 400 lx or 600 lx. Based on our experiment when the illuminance level is 200 lx then the most ideal CCT is 3500 K.

The appearance of the paintings rather under the corresponding colour spectrum is similar compared to the appearance under the reference light source in case of 3500 K and 4500 K. When the correlated colour temperature is 5500 K then the appearance of the paintings is similar under the setting which is developed to have maximum R_a .

The appearance of the paintings is more pleasant under the CIE D65 illuminant when the CCT is 3500 K, while in case of 4500 K and 5500 K this reference D65 setting is perceived as the worst. This proves that the observers prefer the warm-white lights at least for museum lighting. In case of the correlated colour temperature of 4500 K and 5500 K the most pleasant appearance can be achieved by the setting which is developed to have maximum R_a .

Acknowledgement

Authors would like to say thank you for the University of Fine Arts, Budapest for producing and borrowing

test paintings for the experiments. The authors would like to express thanks for the financial support of the HI-LED EU FP7 project (grant number: 619912) in producing the above research.

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