Objective Colour Quality Assessment for Lighting

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Abstract. In this contribution, the colour quality of lighting was evaluated with 21 typical objective colour quality metrics. A large dataset of 591 light sources was established. This database includes different kinds of sources including incandescent lamps, LEDs, fluorescent lamps, high intensity lamps as well as theoretical lights. A multidimensional scaling analysis method was adopted to reduce the dimensionality of colour quality evaluation, by which 6 typical measures were obtained for the final assessment. At last, the overall performance of the 591 light sources was comprehensively analyzed, together with a deep discussion on the colour quality of 14 typical sources for gallery lighting in China.

Keywords: Colour quality of lighting · Objective evaluation · Multidimensional scaling analysis · Gallery lighting

1 Introduction

Nowadays, due to the fact that people always pay much attention to the visual colour perception of lighting conditions, the assessment of colour quality has become the hotspot of current research [1–5]. It is quite clear that subjective evaluation based on psychophysical studies is the most reliable and rigorous evaluation method [2, 5]. However, limited by time, space, and test environment, subjective evaluation is difficult to achieve in most of the applications.

According to previous studies, it is a fast and relatively effective method to evaluate the colour quality of lighting with typical objective metrics [1–5]. Therefore, in this work with the aim of systematically assess the colour quality of lighting, 591 light sources (including 14 typical light sources of gallery), were objectively evaluated with 21 typical color quality metrics. To our knowledge, the objective evaluation of so many of SPDs with so many colour quality measures has not been reported in current literature.

A multidimensional scaling analysis method was adopted to reduce the dimensionality of 21 typical color quality metrics. It is found that six of them in colour

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fidelity and colour gamut dimensionalities could be defined as typical measures. Therefore, the corresponding six typical measures were used for the final assessment and their sum of ranking orders was used to represent the overall colour quality of each source.

To be specific, the aims of the study are as follows: (1) To find the optimal Spectral Power Distributions (SPDs) which exhibit best colour quality from the light source dataset. (2) To investigate the impact of Correlated Colour Temperature (CCT) upon the overall colour quality. (3) To compare the performance of 14 typical light sources of the galleries.

2 SPD Dataset

A large dataset of 591 light sources was established, the detail information is shown in Table 1. There is no repetition in this dataset and the wavelength ranges were uniformly set to 400–700 nm, with 5 or 10 nm intervals.

Table 1. The 591 light sources adopted in this dataset

No.	Psychophysical study or dataset	SPDs adopted
1	Wang et al. (Multi-CCT, 2017) [4]	10
2	Wei et al. (Metameric lighting, 2014) [6]	2
3	Narendran et al. (Multi-CCT, 2002) [5]	7
4	Szabó et al. (Metameric lighting, 2016) [7]	20
5	Feltrin et al. (Multi-CCT, 2017) [8]	5
6	Royer et al. (Metameric lighting, 2016) [9]	50
7	Dangol et al. (Metameric lighting, 2013) [10]	8
8	Islam et al. (Metameric lighting, 2013) [11]	24
9	Jost-Boissard et al. (Metameric lighting, 2009) [12]	14
10	Jost-Boissard et al. (Metameric lighting, 2014) [13]	17
11	He et al. (Multi-CCT, 2015) [14]	4
12	Dikel et al. (Multi-CCT, 2014) [15]	6
13	Huang et al. (Multi-CCT, 2017) [16]	9
14	Royer et al. (Metameric lighting, 2016) [9]	26
15	Khanh et al. (Metameric lighting, 2016–17) [17–20]	36
16	Typical sources for gallery exhibition in China	14
17	CRI2012 excel [21]	36
18	CQS 9.0.3 excel [22]	83
19	MCRI excel [23]	30
20	TM30-15 excel [24]	190
Sum	——	591

3 Twenty-One Colour Quality Metrics

Twenty-one typical color quality metrics are used for objective evaluation, including Color Rendering Index [25], Gamut Area Index [26], Color Quality Scale (Qa, Qf, Qg, Qp) [22], Full Spectrum Color Index [27], Color Preference Index [28], Feeling of Contrast Index (CAM02) [29], Color Discrimination Index [30], Cone Surface Area [31], CRI-CAM02UCS [25, 32], CRI2012 [21], Memory Color Rendering Index [33], IES-TM 30 (Rf and Rg) [34], ΔC* [18, 19], Color Quality Index (CQI [19], CQI′ [18]), GAI-RA [13] and Gamut Volume Index GVI [2]. Limited by the length of this paper, this section only serves as a short list for the metrics. Please refer to the relevant citations for detailed information.

4 Result and Discuss

4.1 Multi-dimensional Scaling

Multi-dimensional scaling (MDS) is a visualization method to display high-dimensional multivariate data in low-dimensional space. The method looks similar to plotting scores with principal component or plotting scores. The basic goal of multi-dimensional scaling is to minimize any deformation caused by dimensionality reduction by "fitting" the original data into a low-dimensional coordinate system [35]. The problems involved in multidimensional scaling can be described as: when the similarity (or distances) between each item in n project is certain, the representation of these items in low-dimensional space is obtained, and the degree of proximity among the projects is "general match" with the original similarity (or distance).

MDS subdivision can be divided into several types. This article only introduces one of the most commonly used requirements of raw data: non-metric MDS. The idea of this method is to create points based on the similarity matrix such that the Euclidean distance between them can represent the original similarity approximately.

Based on the MDS method and the relevant research findings mentioned in the above citations, six typical measures (CRI, Rf, GAI, Qg, MRCI, GVI) were selected, as shown in Fig. 1. In the following, these six measures will be used to analyze the colour quality of 591 SPDs and the overall performance of each candidate could be assessed by the sum of rank orders with regard to each measure.

4.2 Overall Analysis of 591 light Sources

The results of overall analysis of 591 light sources indicate that the gamut-based measures and fidelity-based measures could not reach an optimum simultaneously. For instance, among the 591 sources a LED of 6500 K exhibits smallest sum of rank order, whose rank (CRI) = 266, rank (GAI) = 11, rank (Qg) = 116, rank (MCRI) = 5, rank (Rf) = 149, rank (GVI) = 5. Obviously, such a measure exhibits better colour-gamut attribute than that of colour fidelity. As for other SPDs, quite similar results (i.e. the gamut-based metrics and fidelity-based metrics do not vary simultaneously) were obtained.

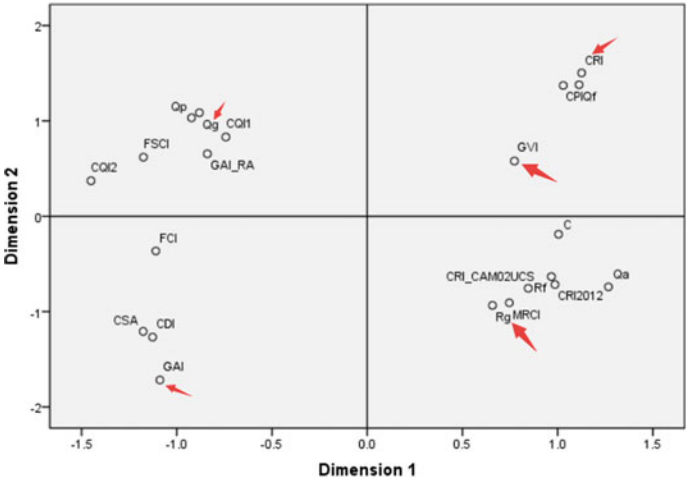

Fig. 1. Multidimensional scaling of the 21 colour quality measures based on 591 SPDS

Figure 2 illustrates the correlation between Correlated Colour Temperature and Sum of rank order. From this picture, it is quite clear that although a certain CCT may corresponds to different sum of rank orders, in general there is a trend that a higher CCT correlates with a smaller sum of rank order.

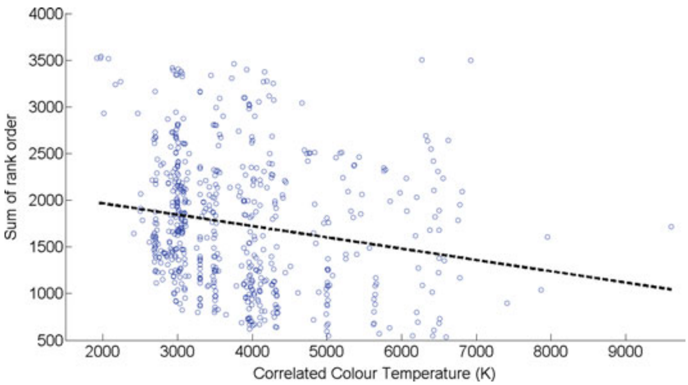

Fig. 2. Correlation between Correlated Colour Temperature and sum of rank order

4.3 Analysis of 14 Typical Light Sources for Gallery Lighting

The colour quality performance of the 14 typical light sources for gallery was further analyzed. Such light sources were provided by 7 suppliers of gallery lighting in China (each supplier provides two light sources, 3000 and 4000 K). Due to the fact that the

CRI, Qg and Rf measures are relative measures (i.e. their calculation is based on certain reference source of a same CCT), only the sources of similar CCT were grouped and compared together. Therefore, 130 SPDs from the dataset with a CCT between 2900 and 3100 K were adopted to evaluate the performance of 7 gallery lights with a CCT of 3000 K, while 83 SPDs with a CCT between 3800 and 4100 K were adopted to evaluate the performance of seven 4000 K sources.

Tables 2 and 3 summarize the colour quality of the gallery lightings. From these two tables, several conclusions could be drawn. First, the light sources for gallery lighting always exhibit sound performance in colour fidelity (i.e. CRI, Rf) while their performance in colour gamut (GAI, GVI, Qg) is relatively poor. This could be ascribed to the fact that the light sources suppliers actually pay much attention on the colour fidelity attribute while relatively ignore the colour gamut attributes, although many psychophysical studies have revealed that the gamut-based measures are in closer relationship with human visual appreciation [2, 12, 13, 16, 36]. Secondly, interestingly, the light sources of supplier 4 exhibit smallest sum of rank order compared to other suppliers (9/137 for 3000 K, 24/90 for 4000 K), which indicates that such sources tend to perform best, at least from the aspect of overall colour quality.

Table 2. The colour quality of light sources for gallery lighting (3000 K-LED) compared with a pool of 137 SPDs

ID	Rank (CRI)	Rank (GAI)	Rank (Qg)	Rank (MRCI)	Rank (Rf)	Rank (GVI)	Rank (Sum)
3000 K-supplier 1	21	83	97	43	24	74	342
3000 K-supplier 2	17	74	67	28	13	72	271
3000 K-supplier 3	23	73	49	28	24	61	258
3000 K-supplier 4	4	61	49	17	6	56	193
3000 K-supplier 5	24	79	88	43	16	68	318
3000 K-supplier 6	22	90	88	43	12	75	330
3000 K-supplier 7	12	84	58	28	7	69	258

Table 3. The colour quality of light sources for gallery lighting (4000 K-LED) compared with a pool of 90 SPDs

ID	Rank (CRI)	Rank (GAI)	Rank (Qg)	Rank (MRCI)	Rank (Rf)	Rank (GVI)	Rank (Sum)
4000 K-supplier 1	28	62	57	43	27	45	262
4000 K-supplier 2	11	44	42	29	18	47	191
4000 K-supplier 3	26	58	57	35	30	38	244
4000 K-supplier 4	6	42	38	29	6	37	158
4000 K-supplier 5	15	49	42	35	8	39	188
4000 K-supplier 6	25	69	50	43	14	52	253
4000 K-supplier 7	32	46	42	43	28	46	237

The followings are the metric values for the sources of supplier 4 (T825-CF26-3WB and T825-CF26-4WB): CRI-3000 K = 98; GAI-3000 K = 58; Qg-3000 K = 101; MCRI-3000 K = 91; Rf-3000 K = 95; GVI-3000 K = 81; CRI-4000 K = 96; GAI-4000 K = 76; Qg-4000 K = 100; MCRI-4000 K = 91; Rf-4000 K = 93; GVI-4000 K = 87. At last, it must be mentioned that there are several criterions when judging the lighting quality for gallery, such as glare, UV level and temperature rise. Therefore, for gallery lighting design, those factors should be taken into consideration as well.

5 Conclusions

The objective assessment of colour quality for lighting is of crucial importance for lighting design and applications. In this study, the colour quality of lighting was evaluated with 21 typical objective colour quality metrics and the SPD data of 591 light sources. A Multidimensional scaling method is used to get 6 representative measures (CRI, Rf, GAI, Qg, MRCI, GVI) and the sum of rank orders of those 6 measures were used to quantify the colour quality of light sources. At last, the overall performance of the 591 light sources was comprehensively analyzed, together with a deep discussion on the colour quality of 14 typical sources for gallery lighting in China.

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