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A NEW METRIC FOR MEMORY COLOUR PREFERENCE EVALUATION IN LIGHTING APPLICATIONS – EXPERIMENTS, MATHEMATICAL DEFINITION, AND COMPARISON WITH OTHER COLOUR RENDERING INDICES

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A NEW METRIC FOR MEMORY COLOUR PREFERENCE EVALUATION IN LIGHTING APPLICATIONS – EXPERIMENTS, MATHEMATICAL DEFINITION, AND COMPARISON WITH OTHER COLOUR RENDERING INDICES

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Abstract

Due to their potential use as an internal reference, memory colours have proven to provide an excellent conceptional approach for the colour rendition evaluation of white light sources in terms of predicting visual appreciation. However, there are still some major drawbacks that can be identified in the principal design of existing memory-based or memory-related colour quality metrics. For this reason, a new experiment was devised trying to overcome the shortcomings of these previous approaches. Based on the experimental output, the main goal of the current study consequently was to derive an improved version of a memory-based colour quality metric, which provides a superior tool for developers and manufacturers that can be used for the optimization of state-of-the-art lighting solutions in cases where visual appreciation and high user acceptability are more important than colour fidelity.

Keywords: Memory Colours, Colour Rendering, Colour Preference, Lighting Applications

1 Introduction

In order to appropriately describe visual appreciation and colour preference in real lighting applications, focusing on internal references such as preferred (Sanders 1959a, Yano 2016, Bartleson 1962, Fernandez 2005, Park 2006, Sanders 1959b, Saito 1996, Schloss 2013, Siple 1983, Jost-Boissard 2016, He 2017, Yano 1998, Zeng 2013a, Zeng 2013b) or memory colours (Siple 1983, Hering 1920, Bartleson 1960, Bartleson 1961, Bodrogi 2002, Bruner 1951, Pérez-Carpinell 1998, de Fez 2001, Duncker 1939, Granzier 2012, Hansen 2006, Olkkonen 2008, Hurlbert 2005, Smet 2011a, Babilon 2018a, Tarczali 2006, Yendrikhovskij 1999, Zeng 2010, Xue 2014, Zhu 2017) seems to be a very promising approach.

In the literature, several attempts can be found to specify colour rendering properties of white light sources in terms of a single preference- or memory-based colour quality metric (Thornton 1974, Smet 2010a, Judd 1967, Sanders 1959a, Smet 2016, Smet 2010b, Smet 2012). However, previous work does usually not consider the impact of realistic adaptation and viewing conditions on the observer ratings while, at the same time, making use of a more or less arbitrary and in most cases even arguable test object selection used for deriving the respective colour quality metric. Hence, a new experimental setup providing more realistic adaptation and viewing conditions had to be designed in order to overcome the shortcomings of previous approaches and to derive an improved version of a memory-based colour quality metric intended for being applied to optimize visual appreciation in real lighting applications.

In the following, this new experimental setup shall be explained in further details. Afterwards, the definition of the new metric proposal derived from the experimental outcome will be presented and its performance in predicting observers' visual appreciation will be validated in a meta-correlation analysis. Eventually, some concluding remarks will be given.

2 Method and Test Procedure

In order to investigate the impact of long-term memory on visual appreciation, a set of twelve different familiar real test objects was used to perform a series of colour preference rating experiments (Babilon 2018a) whose conceptual design was intended to incorporate realistic viewing and adaptation conditions that go beyond the simple viewing cabinet approach that can usually be found in the literature. The objects were selected based on an online-survey in which participants were asked to indicate object names that first came into their minds when thinking of a specific given colour or, more precisely, hue region (Babilon 2018b). The object that was most frequently associated with a certain hue region was finally chosen as the prototypical memory colour object for that part of the hue circle adopted for the experiments. In total, 1009 people took part in the online-survey, eventually leading to the following test object selection: banana, green salad, broccoli, blue jeans, blue berry, red cabbage, red rose, carrot, butternut squash, and concrete flowerplot. In addition two different kinds of human complexion, i.e., Asian and Caucasian skin, were added for testing, which, in the end, gave a set of twelve different familiar real test objects being well distributed around the hue circle.

The experiments were subsequently conducted in a real-sized, white-painted, furnished room at two different adaptation conditions with correlated colour temperatures (CCTs) of 3200 K and 5600 K, respectively, where each test object was individually presented first to a group of 15 German observers and eventually, in a follow-up experiment, to a group of 15 Chinese observers. In each case, the ambient illumination settings of the experimental room were realized by driving a four-channel LED illuminant of Lambertian light emission (consisting of R, G, B, and warm-white LEDs) to match the desired white point of adaptation at a given CCT as good as possible. In addition, an LCD projector was used for shifting the chromatic appearance of the respective test object, while keeping its lightness component constant, resulting in a total number of approximately 65 colour variations per test object.

For each colour variation, the observers were asked to rate the perceived colour appearance of the currently presented test object according to their preference of how they thought the respective object should look like in reality on a semi-semantic five-level scale. The mean colour appearance ratings and, therefore, the prototypical memory colour representations of the twelve familiar test objects were subsequently modelled in CIECAM02-UCS chromaticity space by fitting bivariate Gaussian distribution functions to the mean observer ratings obtained for the different colour variations of each individual test object assessed by either German or Chinese observers which were adapted to either 3200 K or 5600 K ambient illumination. Hence, in total, four different sets of memory colour representations were derived.

With these memory colour representations for each of the twelve familiar test objects being known, the assessment of the colour quality of a certain test light source can eventually be based on the evaluation of the degree of similarity between the colour appearance of these objects rendered by the test light source and their respective memory colour representations in CIECAM02-UCS chromaticity space given by the corresponding Gaussians. This similarity evaluation gives for each test object i a so-called specific memory color preference index (MCPI) $R_{\mathrm{MCPI},i}$. Bearing in mind that for the visual appreciation of a perceived lighting scene, as shown in the literature, certain colours are more important than others, additional weighting factors for the specific indices had to be included, so that the final general MCPI R_{MCPI} is obtained by calculating the weighted geometric mean of the twelve individual $R_{\mathrm{MCPI},i}$ values.

In addition, both the impact of the adapted white point and of the observers' cultural background were considered in the definition of the final MCPI calculation scheme, which, in particular, differs from previous work on this topic.

3 Definition of the New Metric Proposal

In order to model the Chinese and German observers' mean colour appearance ratings in chromaticity space for each familiar test object i with $i = 1, \ldots, 12$ assessed under the two different adaption conditions, bivariate Gaussian functions of the form

$$\begin{aligned} f_i(\boldsymbol{x}_i) &= a_{i,1} + a_{i,2} \cdot \exp\left(-\frac{1}{2}\left((\boldsymbol{x}_i - \boldsymbol{\mu}_i)^\top \begin{pmatrix} a_{i,5} & a_{i,7} \\ a_{i,7} & a_{i,6} \end{pmatrix} (\boldsymbol{x}_i - \boldsymbol{\mu}_i)\right)\right) \\ &= a_{i,1} + a_{i,2} \cdot S_i(\boldsymbol{x}_i), \end{aligned} \tag{1}$$

were used to fit the rating data. Hence, the functions' centroids $\boldsymbol{\mu}_i = (a_{i,3}, a_{i,4})^\top$ give the most likely representations of the test objects' memory colours and the covariance matrices $\boldsymbol{\Sigma}_i$

defined by the parameters $a_{i,5}$ to $a_{i,7}$ determine the size, shape, and orientation of the similarity distributions $S_i(\boldsymbol{x}_i)$. For a better overview, Tables 1 and 2 summarize the different sets of fitting parameters modelling the assessments of Chinese and German observers at the two different adaptation conditions for all twelve familiar test objects.

Table 1 – Overview of the fitting parameters of the similarity distribution functions of the twelve familiar test objects modelling the Chinese and German colour appearance ratings at 3200 K ambient illumination.

	Chinese observers at 3200 K adaptation					German observers at 3200 K adaptation				
Test Object	a_3	a_4	a_5	a_6	a_7	a_3	a_4	a_5	a_6	a_7
Asian Skin	12.9180	10.1611	0.0778	0.0524	-0.096	13.0361	10.0919	0.0870	0.0507	-0.0094
Banana	3.8769	28.2924	0.0199	0.0075	0.0043	5.0739	31.7735	0.0206	0.0054	0.0035
Blueberry	-2.8453	-12.8145	0.0409	0.0127	-0.0032	-3.5445	-12.6203	0.0535	0.0166	-0.0044
Blue Jeans	-7.6266	-17.1651	0.0357	0.0107	-0.0015	-8.1133	-19.7052	0.0455	0.0126	-0.0036
Broccoli	-9.6176	14.3775	0.0093	0.0013	0.0005	-8.6225	9.2019	0.0131	0.0060	-0.0004
Butternut	15.7546	20.6420	0.0160	0.0116	-0.0011	14.7260	20.4684	0.0265	0.0201	-0.0032
Carrot	27.4901	26.6343	0.0100	0.0149	-0.0003	25.0920	25.0149	0.0136	0.0127	-0.0009
Caucasian Skin	12.7231	9.4047	0.0788	0.0539	-0.0060	12.1936	9.2285	0.0879	0.0563	-0.0038
Concrete	-0.8219	-3.5351	0.0200	0.0087	-0.0054	-0.8031	-3.3339	0.0369	0.0150	-0.0057
Green Salad	-13.5223	23.1321	0.0313	0.0114	-0.0012	-13.5855	24.1868	0.0240	0.0193	0.0004
Red Cabbage	11.9059	-16.9319	0.0186	0.0092	-0.0061	12.8639	-13.6538	0.0360	0.0137	-0.0067
Red Rose	37.1120	13.2141	0.0440	0.0099	0.0043	36.6615	12.7504	0.0259	0.0278	-0.0064

With the similarity distribution functions being known, the colour quality of an arbitrary test light source can be calculated in terms of its capability of rendering the test objects to match their corresponding memory colour representations, i.e., the better the accordance, the higher the associated metric value.

From the spectral distribution of the test light source, which can be measured with the help of a spectroradiometer, and the mean spectral reflectance curves of the twelve familiar test objects, which have been published elsewhere (Babilon 2018a), the respective CIECAM02-UCS chromaticities $\boldsymbol{x}_i = \left(a'_{\mathrm{M},i}, b'_{\mathrm{M},i}\right)^{\mathrm{T}}$ as perceived under the test light source shall be calculated first by using the CIE standard 10° observer in combination with the same parameters as recommended by the CIE for the calculation of the R_{f} colour fidelity index (CIE 2017). Next, the corresponding similarity distribution functions $S_i(\boldsymbol{x}_i)$ are evaluated at these chromaticities, which gives a measure for the degree of similarity of the perceived appearance under the test illuminant with each object's memory colour, i.e., the closer the function value is to one, the better the agreement. Depending on the correlated colour temperature (CCT) of the test light source and the observers' cultural background, the various $S_i(\boldsymbol{x}_i)$ functions are defined with the parameters given in Tables 1 or 2, respectively. Here, the following decision algorithm is used: If the CCT of the test illuminant is smaller than 4000 K, it is considered to be rather warm white which implies the selection of the parameters from Table 1 to define the test objects' similarity distributions. If, on the other hand, the calculated CCT is greater or equal 4000 K, the test illuminant is assumed to be rather cool white and the parameters from Table 2 are chosen to calculated the similarity indicators S_i. By rescaling theses values to a 0-100 range, one obtains the object specific MCPIs $R_{\mathrm{MCPI},i}$ given by

$$R_{\mathrm{MCPI},i} = 100 \cdot S_i. \tag{2}$$

Table 2 – Overview of the fitting parameters of the similarity distribution functions of the twelve familiar test objects modelling the Chinese and German colour appearance ratings at 5600 K ambient illumination.

	Chinese observers at 5600 K adaptation					German observers at 5600 K adaptation				
Test Object	a_3	a_4	a_5	a_6	a_7	a_3	a_4	a_5	a_6	a_7
Asian Skin	10.2878	10.8645	0.0615	0.0465	-0.0101	10.2923	10.3590	0.0627	0.0336	-0.0050
Banana	4.4418	30.8273	0.0195	0.0121	0.0029	5.0830	32.5946	0.0237	0.0126	0.0052
Blueberry	-2.4215	-10.5405	0.0351	0.0153	-0.0046	-3.3163	-12.2902	0.0365	0.0161	-0.0044
Blue Jeans	-7.1205	-14.7482	0.0294	0.0122	-0.0035	-7.7858	-17.3582	0.0486	0.0134	-0.0053
Broccoli	-8.3038	16.1013	0.0419	0.0167	0.0025	-8.2703	15.3796	0.0367	0.0391	0.0043
Butternut	14.1887	19.6973	0.0143	0.0138	-0.0018	15.3767	20.5664	0.0205	0.0180	-0.0033
Carrot	24.9891	24.6469	0.0230	0.0183	0.0022	25.6425	25.6319	0.0198	0.0154	-0.0034
Caucasian Skin	8.4641	8.2530	0.0481	0.0302	-0.0060	9.7097	8.7088	0.0620	0.0362	-0.0064
Concrete	-0.4814	-1.3515	0.0289	0.0109	-0.0040	0.0840	-1.1743	0.0395	0.0162	-0.0048
Green Salad	-9.5558	26.0556	0.0312	0.0257	0.0067	-10.4320	26.6978	0.0288	0.0262	0.0029
Red Cabbage	10.4067	-14.6458	0.0262	0.0128	-0.0057	10.5638	-14.0777	0.0262	0.0146	-0.0080
Red Rose	34.8656	11.2483	0.0724	0.0206	0.0066	34.6755	11.1227	0.0719	0.0353	-0.0049

With the introduction of additional weighting factors giving more or less weight to certain parts of the hue circle (see Sec. 2), the final general MCPI R_{MCPI} is obtained by calculating the weighted geometric mean of the twelve individual $R_{\mathrm{MCPI},i}$ values. Hence, we have

$$R_{\mathrm{MCPI}} = \prod_{i=1}^{12} \left(R_{\mathrm{MCPI},i}\right)^{p_i}, \tag{2}$$

where p_i with $i = 1, \ldots, 12$ denotes the individual weighting factors determined from a meta-correlation analysis described in the following Section.

In addition to the two different cultural-specific MCPIs (Chinese and German), which take into account the impact of the observers' cultural background on the memory-based evaluation of colour rendition, a further MCPI version based on the assumption of a global average observer was defined by pooling and averaging for each test object and adaptation condition the rating data of both cultural observer groups. The corresponding fitting parameters are given in Table 3.

Table 3 – Overview of the fitting parameters of the similarity distribution functions of the twelve familiar test objects assessed by an assumed global average observer at both adaptation conditions.

	Global observer at 3200 K adaptation					Global observer at 5600 K adaptation				
Test Object	a_3	a_4	a_5	a_6	a_7	a_3	a_4	a_5	a_6	a_7
Asian Skin	12.9776	10.1264	0.0822	0.0515	-0.0095	10.2899	10.6429	0.0621	0.0398	-0.0075
Banana	4.5023	29.7617	0.0197	0.0063	0.0038	4.8156	31.7194	0.0214	0.0120	0.0038
Blueberry	-3.2205	-12.7014	0.0461	0.0144	-0.0037	-2.9071	-11.5154	0.0389	0.0171	-0.0052
Blue Jeans	-7.8787	-18.4912	0.0404	0.0115	-0.0027	-7.7717	-15.6493	0.0360	0.0116	-0.0048
Broccoli	-8.8949	10.8201	0.0124	0.0031	0.0000	-8.2913	15.6197	0.0406	0.0270	0.0037
Butternut	15.1462	20.5524	0.0208	0.0153	-0.0018	14.8458	20.1952	0.0173	0.0157	-0.0025
Carrot	26.1198	25.9112	0.0113	0.0127	-0.0007	25.2292	25.0584	0.0211	0.0165	-0.0005
Caucasian Skin	12.4669	9.3178	0.0828	0.0551	-0.0052	9.0753	8.4607	0.0522	0.0320	-0.0062
Concrete	-0.8350	-3.4252	0.0266	0.0155	-0.0056	-0.1393	-1.1642	0.0324	0.0130	-0.0043
Green Salad	-13.5297	23.7977	0.0286	0.0148	-0.0004	-9.9728	26.3866	0.0305	0.0261	0.0052
Red Cabbage	12.5222	-14.9915	0.0261	0.0113	-0.0066	10.4791	-14.3666	0.0264	0.0138	-0.0069
Red Rose	36.9028	12.8961	0.0362	0.0174	0.0007	34.7823	11.1809	0.0717	0.0279	0.0008

Furthermore, to increase the overall metric performance for a wide range of lighting applications, a distinction between its application for metameric and multi-CCT lighting scenarios has to be made. Whereas the former describes scenarios in which all tested light sources to be assessed and compared within a single experimental trial show the same CCT but different spectral characteristics, the latter includes the variation of both the spectral composition and the CCT of the light sources assessed by the observers. The resulting weighting factors for the different cases were obtained from meta-correlation analysis and are summarized in Table 4.

4 Results of the Meta-Correlation Analysis

In order to confirm the excellent predictive performance of the new metric proposal, the experimental data of several different psychophysical studies on the perception of colour preference in metameric and multi-CCT lighting scenarios were collected (Jost-Boissard 2009, Jost-Boissard 2015, Wei 2014, Szabó 2016, Smet 2010a, VanRie 2009, Imai 2012, Imai 2013, Jost 2013, Tsukitani 2013, Lin 2016, Houser 2005, Huang 2018, Narendran 2002, Wang 2017) and a comprehensive meta correlation-analysis as proposed by Hunter and Schmidt (Hunter 2004) was eventually performed on these data to evaluate and compare the predictive power of the MCPI in terms of visual appreciation with those of other colour quality metrics. These included Sanders' preferred colour index R_p (Sanders 1959a), Judd's flattery index $R_\mathrm{flatt.}$ (Judd 1967), Thornton's colour preference index (CPI) (Thornton 1974), Smet et al.'s memory colour rendition index (MCRI) (Smet 2010a, Smet 2010b, Smet 2012, Smet 2016), the general colour rendition index R_a (CIE 1995), the general colour fidelity index R_f (CIE 2017), the gamut area index (GAI) (Freyssinier 2010), the arithmetic mean of GAI and R_a (Smet 2011b, Jost-Boissard 2015), the color quality scale by Davis and Ohno (Q_a, Q_f, Q_p, Q_g) (Davis 2010), the CRI2012 (Smet 2013), the feeling of contrast index (FCI) (Hashimoto 2007), and the IES TM-30 R_g measure (David 2015). Please note that the collected experimental data contained the spectral power distributions of the investigated light sources together with the corresponding observer preference ratings and that, based on the principle study design of the underlying experiments, the collected data were first assigned to one of the two different lighting scenario categories (i.e., metameric or multi-CCT) before running the meta correlation-analysis for either of them separately.

Table 4 – Summary of the weighting factors introduced in Eq. (2) for the definition of the global and both cultural-specific MCPIs intended to be applied for either metameric or multi-CCT lighting scenarios. The individual p_i values from left to right represent the weighting factors for the test objects of Asian skin, banana, blueberry, blue jeans, broccoli, butternut, carrot, Caucasian skin, concrete, green salad, red cabbage, and red rose.

	Metameric lighting scenarios											
Type	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}
Global	0.001601	0.001689	0.001624	0.001658	0.736855	0.001655	0.001692	0.001547	0.229577	0.000219	0.001038	0.020844
German	0.000123	0.002870	0.000899	0.001725	0.915560	0.0030100	0.014343	0.000109	0.002164	0.000954	0.000362	0.057790
Chinese	0.002971	0.007384	0.006925	0.006015	0.726700	0.006835	0.005173	0.002482	0.215285	0.002584	0.003707	0.013939
	Multi-CCT lighting scenarios											
Type	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}
Global	0.246416	0.003331	0.023070	0.025772	0.231410	0.078222	0.179669	0.041295	0.019311	0.091012	0.048690	0.011802
German	0.200039	0.014890	0.065191	0.011156	0.128922	0.009938	0.313526	0.021616	0.073243	0.089176	0.072061	0.000243
Chinese	0.129331	0.043434	0.023668	0.037430	0.220705	0.078088	0.067109	0.094445	0.028116	0.162172	0.090688	0.024814

It could be found that the newly proposed MCPI significantly outperformed all alternative approaches considered in this study – in particular even those that, like the MCPI, were based on memory- or preference-related evaluation. In addition, it was investigated whether the reported impact of the observed inter-cultural variations on the colour appearance ratings of familiar objects also had a significant effect on the predictive performance of the MCPI metric. For this purpose, the global average observer defined by pooling and averaging for each test object and adaptation condition the rating data of both cultural observer groups was taken as a reference.

From performing the meta-correlation analysis, no significant differences in the predictive power of the cultural-specific MCPIs and the global reference could be observed. Therefore, indication is given that it would be sufficient to propose a single, universally valid MCPI that is capable of well predicting the rank order of various light sources with respect to their visual appreciation representing an average global observer. With the predictive performance of both cultural-specific MCPIs being comparable to the performance of the global MCPI, the latter can be considered as a good approximation to a globally valid colour quality metric inducing only minor errors in the absolute level of the predicted results compared to those obtained for the cultural-specific MCPIs, which however are considered to be negligible in practice.

5 Conclusion

In this study, an improved version of an updated memory-based colour quality metric for the evaluation of the colour rendering properties of white light sources in terms of visual appreciation denoted as memory colour preference index (MCPI) has been proposed. It is based on the evaluation of the degree of similarity between the colour appearance of certain familiar test objects rendered by an arbitrary test light source and their respective memory colour representation. The degree of similarity is assessed by using a set of Gaussian similarity distribution functions fitted to the results of colour appearance rating experiments of Chinese and German observers. The key features of this newly proposed MCPI are the adoption of the perceptionally uniform CIECAM02-UCS as the working colour space, the implementation of a CCT-based decision algorithm to choose a suitable set of similarity functions better approximating the impact of the adapted white point on the memory colour assessments, and the introduction of additional weighting factors allowing i) to model the varying importance of certain test colours in the evaluation of light sources with respect to colour preference and ii) to counterbalance the metric errors in the memory colour assessments introduced by chromatic adaptation.

By performing a comprehensive meta-correlation analysis on colour preference rating data of several different psychophysical studies collected from the literature, it could be shown that the MCPI, in its global and cultural specific versions, outperformed all alternative colour-quality metrics in predicting visual appreciation. Offering such an excellent predictive performance, the MCPI algorithm is supposed to also provide a reliable and easy-to-implement tool for the spectral optimization of modern state-of-the-art LED light sources which is capable of finally replacing the CIE R_a metric in a broad variety of different lighting applications where achieving high visual appreciation and observer preference are more important than achieving colour fidelity. Nevertheless, further validation is still necessary.

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