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Light dominates colour preference when correlated colour temperature differs

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Colour preference for lighting is generally influenced by three kinds of contextual factors, the light, the object and the observer. In this study, a series of psychophysical experiments were conducted to investigate and compare the effect of certain factors on colour preference, including spectral power distribution of light, lighting application, observers' personal colour preference, regional cultural difference and gender difference. LED lights with different correlated colour temperatures were used to illuminate a wide selection of objects. Participant response was quantified by a 7-point rating method or a 5-level ranking method. It was found that the preferred illumination for different objects exhibited a similar trend and that the influence of light was significantly stronger than that of other factors. Therefore, we conclude that the light itself (rather than, e.g. the objects that are viewed) is the most crucial factor for predicting which light, among several candidates with different correlated colour temperatures, an observer will prefer. In addition, some of the gamut-based colour quality metrics correlated well with the participants' response, which corroborates the view that colour preference is strongly influenced by colour saturation. The familiarity of the object affects the ratings for each experiment while the colour of the objects also influences colour preference.

1. Introduction

The Commission Internationale de l'Eclairage (CIE) General Colour Rendering Index (CRI) *R*a[1] has been used as the standard criterion for assessing the quality of light for the past half century. Nowadays, particularly, as a consequence of developments in lighting technology, the defects of this metric have been exposed, especially for the light-emitting diode (LED) sources.[2–5] Researchers are beginning to agree that a full description of light quality actually includes many different aspects, such as fidelity,[1,6] preference,[7,8] naturalness,[2,9] vividness,[3,10,11] harmony[12] and discrimination.[13,14] Therefore, describing the quality of a light source with only one metric is not sufficient.[15–18] To solve this problem, numerous efforts have been made.[2–5,10–14,19,20] The CIE has also set-up two Technical Committees (TC1-90 and TC1-91), with the aim of comprehensively

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investigating the measures on different subjective aspects of lighting quality.[19]

Among the above-mentioned aspects, colour preference is widely acknowledged as a very important dimension, since for general lighting conditions end users may pay much attention to the visual appreciation of the illuminated scenes. Colour preference has been reported to be impacted by several contextual factors which include the lighting application,[19,21] regional cultural difference,[22–24] illuminance[25,26] and age difference.[27] Such research has contributed to the development of light quality evaluation but has also highlighted new problems. That is, many factors are now considered to be important when choosing an appropriate light source. In many cases, such a task is not simple even for experts, let alone for naïve users. Therefore, for general applications, a simple and universal approach is actually needed, which could achieve a reasonable balance among these contextual factors and thus help end users to make the right decision.

In addition, it is also gradually being accepted that it is difficult to characterize colour preference with only one colour quality measure.[19] Several researchers have indeed suggested that more complicated and comprehensive approaches (such as multi-measure methods and graphical methods[6,28–31]) should be adopted. Such approaches would definitely improve the performance for predicting colour preference, since they provide much more useful information than a single measure. However, they are too complicated and too overwhelming for most end users in general applications. Therefore, to set up a better single measure for colour preference and eventually help end users to choose a suitable light, the influence of different contextual factors on colour preference should also be considered.

Psychophysical experiments are primarily used to investigate such topics. However, it must be acknowledged that it is impossible for researchers to design and conduct a psychophysical experiment which includes every contextual factor,[28] and there are indeed certain obvious limitations in the current literature as discussed below.

First, most contributions on colour preference have only discussed the colour quality of light sources with almost the same correlated colour temperature (CCT).[2,5,10,11,19,21–23,28,32] Such a design may inadvertently help to reveal the influence of other contextual factors on colour preference, since it relatively weakens the impact of light when compared to the conditions where CCT differs. However, unlike colour fidelity, colour preference should not be restricted by a reference light source, since in many cases people actually want to choose a favourite light in irrespective of the CCT.[4,26,33–37]

Second, the experimental object is also an important concern. The quantity and type of experimental objects varied considerably between different reported studies. Some researchers invited the participants to perceive a single type of object under different lights, such as fruit and vegetables,[2,9] skin tones,[38] artworks,[25,33] printed images,[36] cosmetic products[10] or consumer goods.[4,11] Meanwhile, in other contributions, groups of mixed objects were used.[3,28,34] Lin *et al.*[19] pointed out that the colour preference was significantly influenced by lighting application. However, other than the works from Islam *et al.*,[23] Wei *et al.*[32] and Lin *et al.*,[39] there is limited research involving a wide range of experimental objects to study the impact of object characteristics on colour preference.

In this study, therefore, a series of psychophysical experiments have been designed to address the above-mentioned shortcomings. Certain spectral power distributions (SPDs) (five or nine SPDs) were generated with uniformly sampled CCT values ranging from 2500K to 6500K using LED lights. A broad range of objects were adopted in the psychophysical experiments, which included four groups of fruit and vegetables with different colours, five Chinese traditional calligraphies with different background colours, four pieces of artwork with different colour features and one bunch of artificial multicolour flowers (In a recent study of Royer *et al.*,[28] such kinds of objects were found to be very crucial when observers evaluated the lighting conditions). Groups of observers with different personal colour preference, or from different native places in China, were also involved in order to study the influence of the corresponding human factors on colour preference. The aim of this work was to systematically investigate and compare the influence of the above contextual factors on colour preference. To our knowledge, no past studies have been conducted in this manner, especially with such a wide range of experimental objects and under the condition where CCT differs.

2. Method

2.1. Experimental setup

In this study, most of the experiments were implemented in a light booth apart from where a wall-painting experiment which was carried out in a museum, as shown in Figure 1. For the light booth experiments, a booth (width 89 cm × depth 60 cm × height 51 cm) was located in a room without ambient light. The inner surfaces of the booth were coated with matt medium grey paint (Munsell N5), and the wall surfaces of the room were also painted with spectrally neutral paint. A commercially available and colour-tunable light source (Philips Hue) was installed in the inner top surface of the booth. The light source was mechanically and thermally stable as was demonstrated by a preliminary experiment.

A chair was set in front the light booth at a distance of approximately 40 cm. The height of the chair was adjustable so that when the participants observed the objects, they could not see the luminaire in the booth.

Nine SPDs (Figure 2) were generated by the light source for the experiments. A calibrated spectroradiometer (Photo Research PR 705) together with a white standard were used to obtain the SPDs of the lights, as well as the spectral reflectance factors of the objects.

An illuminance meter (Testo 540) was used to measure the illuminance. In this study, the illuminance in the centre of the objects for the experiments carried out in the light booth was always set at 200 lx. Note that the illuminance spatial distribution of some experiments was not perfectly uniform, with a non-uniformity of 20%–30%. This problem could be solved

Figure 1 The experimental scenes. Left: light booth, Right: museum (in a simulated cave)

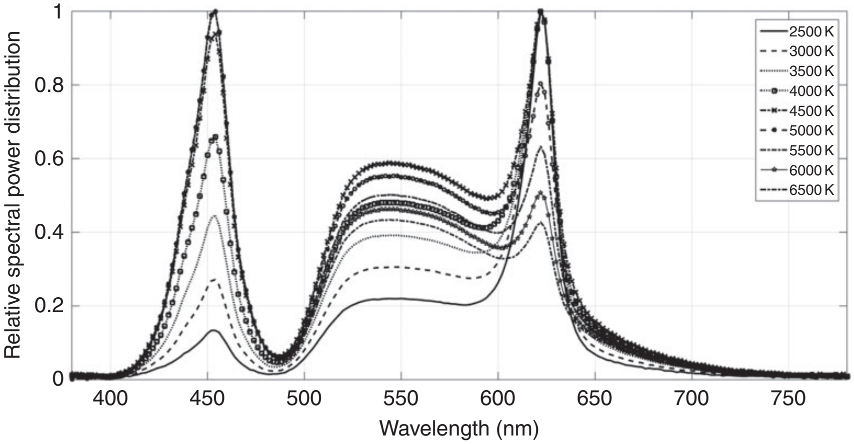

Figure 2 Relative spectral power distributions of the experimental light sources generated by the phosphor converted RGB light bulbs equipped with five lime green LEDs, two blue LEDs as well as four red LEDs

Table 1 The colorimetric properties of the experimental SPDs and their typical colour quality metric values

ID	2500 K	3000 K	3500 K	4000 K	4500 K	5000 K	5500 K	6000 K	6500 K
Measured CCT	2445 K	2932 K	3451 K	3817 K	4471 K	4767 K	5538 K	6102 K	6637 K
x	0.478	0.437	0.405	0.385	0.360	0.351	0.332	0.321	0.313
y	0.408	0.397	0.383	0.371	0.354	0.347	0.331	0.321	0.313
Duv	−0.003	−0.004	−0.005	−0.006	−0.007	−0.007	−0.007	−0.007	−0.008
CRI	91	92	89	87	84	83	81	79	79
GAI	50	67	78	85	91	93	96	97	97
FSCI	28	45	57	63	67	68	70	70	70
Q_a(v9.0.3)	87	87	85	83	80	78	76	74	73
Q_f(v9.0.3)	82	82	81	80	78	76	73	71	70
Q_p (v7.4)	96	95	92	90	87	85	83	82	81
Q_g(v9.0.3)	113	110	107	105	103	101	101	99	98
FCI(CAM02)	107	105	102	100	94	92	87	83	81
CDI	73	97	114	123	133	135	139	141	142
CSA	0.034	0.042	0.048	0.052	0.056	0.058	0.060	0.061	0.062
CPI	142	143	139	136	131	129	126	124	123
CAM02UCS	85	85	84	83	80	79	75	74	73
CRI2012	83	84	84	83	82	81	78	77	77
MCRI	89	90	90	90	89	88	87	86	85
Rf	81	82	81	79	77	75	74	72	72
Rg	110	108	106	104	102	102	101	100	99

CRI: Colour Rendering Index; GAI: Gamut Area Index; FSCI: Full Spectrum Colour Index; FCI: Feeling of Contrast Index; CDI: Colour Discrimination Index; CSA: Cone Surface Area; CPI: Thornton's Color Preference Index; MCRI: Memory Colour Rendering Index.

by adding a diffuser in front of the luminaire. However, a diffuser was not used so as to mimic everyday lighting conditions.

Table 1 summarizes the colorimetric property of the nine SPDs generated by the light source. The scores of typical colour quality metrics for those SPDs were calculated for the General CRI,[1] Gamut Area Index (GAI),[40] Full Spectrum Colour Index (FSCI),[41] Colour Quality Scale (CQS: Q_a, Q_f, Q_p, Q_g),[6] Feeling of Contrast Index (FCI),[42] Colour Discrimination Index (CDI),[43] Cone Surface Area (CSA),[44] Thornton's Color Preference Index (CPI),[45] Luo's CAM02UCS-CRI,[46] Smet's CRI2012,[47] Memory Colour Rendering Index (MCRI)[48] and the IESNA TM-30 metrics (Rf and Rg).[49] Note that in some scenarios only five of the values of CCT (2500K, 3500K, 4500K, 5500K and 6500K) were used.

It can be seen from Table 1 that the chromaticities of the nine SPDs were all below the blackbody locus (the Duv values are all negative). According to a recent study, such chromaticities are generally preferred by observers because they are more likely to have higher scores for relative gamut while maintaining high scores for fidelity.[7]

The wall-painting experiment which took place in a museum (Wan Lin Museum of Wuhan University, China) used a different experimental geometry. The same chair was set in front of the centre of the wall painting. The height of the chair was adjusted in order to keep the participants' eyes at the same horizontal level as the centre of the painting. Two of the same luminaires were used to illuminate the wall painting from either side of the observer at an angle of 45° to the plane of the painting. Since the vertical distance between participant and wall painting (127 cm) was less than that between light sources and wall painting (176 cm), the participants could not see the luminaires when observing the painting. In this experiment, the same five SPDs (2500K, 3500K, 4500K, 5500K and 6500K) were used, but the centre illuminance of the wall painting was set to 50 lx, which was the maximum recommended illuminance in the real caves of Dunhuang.

2.2. Experimental design

To comprehensively investigate the influence of different contextual factors on colour preference, a wide range of objects were selected for the psychophysical experiments (Figure 3). The spectral reflectances of some of the objects are shown in Figure 4.

As summarized in Table 2, the objects were divided into five groups for the experiment. In each group, the order of objects and light sources was randomized and counterbalanced between observers. In order to test the intra-observer variability for each participant, a randomly selected light source was always used twice in the scale rating trials, without informing the observers.

Most of the observers only participated in one experimental trial. All the observers passed the Ishihara test and thus had normal colour vision. None of them was aware of the research purpose before the experiment. In addition, during the experiment, the experimenter reminded the observers to focus on the overall appearance of the lighting scene, rather than the colour of the light.

Two psychophysical methods, a 7-point scale rating and a 5-level rank ordering, were adopted for quantifying the observers' responses (the reason for adopting two psychophysical experiment methods was to test whether different methods would lead to significantly different results in the form of the preference rank order for each light).

According to the scale rating method, the participant could rate the lighting condition using seven values (−3, −2, −1, 0, 1, 2, 3), which respectively represented *strongly dislike*, *moderately dislike*, *slightly dislike*, *neutral*, *slightly like*, *moderately like* and *strongly like*. As for the rank ordering approach, observers would rank the five lighting conditions according to their individual preference (5 for relatively *most liked* and 1 for relatively *least liked*).

The details of the five experimental groups are summarized in Table 2. Therefore, in the following two paragraphs, only the unique features of certain experiments are described.

The fruit and vegetables scenario was designed for investigating the influence of

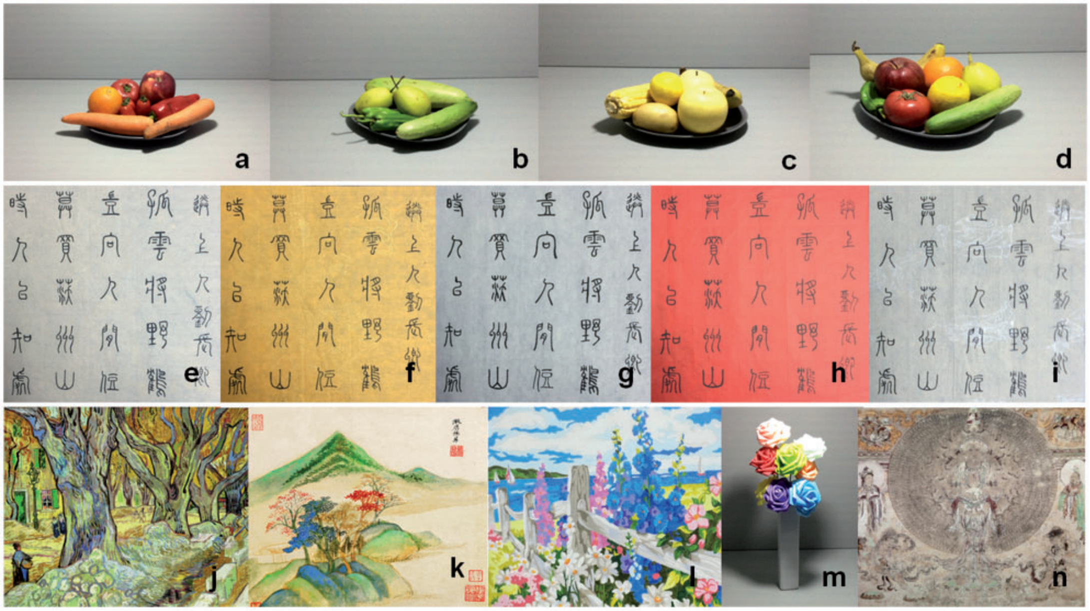

Figure 3 Different objects adopted in the psychophysical experiments. (a)–(d) Fruit and vegetables of different colours, (e)–(i) Chinese calligraphies with different paper colours (40 cm × 40 cm), (j) fine art reproduction of Van Gogh's *Sycamore tree* (38 cm × 29 cm), (k) fine art reproduction of Chinese traditional painting *Landscape* by Qichang Dong (27 cm × 27 cm), (l) modern oil painting painted by an anonymous student in our school in China (50 cm × 40 cm), (m) a bunch of multicolour artificial flowers and (n) fine art reproduction of Dunhuang mural painting (330 cm × 200 cm) (available in colour in online version)

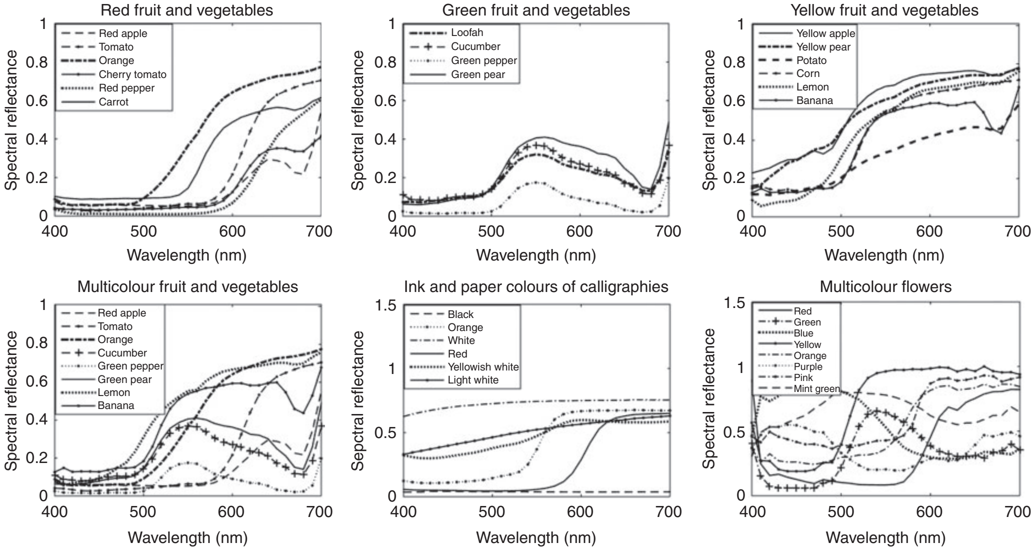

Figure 4 The spectral reflectances of fruit and vegetables, calligraphies (ink and paper colours) and multicolour flowers

Table 2 Details of the psychophysical experiment of each group

Group	Light	Observers	Place	Score	Time
Fruit and vegetables	Five SPDs 2500 K–6500 K 1000 K interval	45 observers 28 male, 17 female Age: 19.4 ± 0.9 year different personal colour preference	Light booth	7-point scale rating	20 min
Chinese calligraphies	Five SPDs 2500 K–6500 K 1000 K interval	40 observers 20 male, 20 female Age: 19.4 ± 0.8 year	Light booth	7-point scale rating	25 min
Van Gogh and Chinese traditional painting	Five SPDs 2500 K–6500 K 1000 K interval	60 observers 30 male, 30 female Age: 22.0 ± 1.6 year	Light booth	5-level rank ordering	25 min
Multicolour flowers and modern oil painting	Nine SPDs 2500 K–6500 K 500 K interval	36 observers 17 male, 19 female Age: 19.7 ± 1.1 year different native places of China	Light booth	7-point scale rating	25 min
Mural painting	Five SPDs 2500 K–6500 K 1000 K interval	20 observers 14 male, 6 female Age: 25.1 ± 1.8 year	Museum	7-point scale rating	12 min

SPDs: spectral power distributions.

personal colour preference on colour preference. Before the experiment, typical observers with different personal colour preference were collected by a questionnaire survey. In the questionnaire, the subjects were asked to rate their preference for abstract colours (red, green and blue, written in words with no real colours shown in the sheet) using the same 7-point rating method mentioned as above; 323 college students were invited to participate in the survey and an ideal observer should only prefer one colour (e.g. with a score no lower than 2) and dislike other colours (e.g. with a score no higher than 0). Among the finally selected 45 observers, 15 exclusively preferred blue, 15 exclusively preferred red and 15 exclusively preferred green. The fruit and vegetables experiment was finished in two days, so as to prevent deterioration of the fruit and vegetables. In the experiment, the relative positions of each fruit and vegetable were fixed.

The Van Gogh and Chinese traditional painting scenario was for exploring the influence of regional cultural heritage on colour preference. Similarly to the fruit and vegetables experiment, the observers were also collected by a prior questionnaire. This led to three groups of observers in this trial, each group of 20 students and they respectively came from eastern provinces (Jiangsu and Zhejiang), western provinces (Xinjiang and Xizang) and middle provinces (Hubei and Hunan) of China. According to current research, people from different parts of China actually show different cultural characteristics.[50]

2.3. Experimental procedure

Upon arrival, the participant was asked to put on a grey coat so as to avoid any reflectance from their clothes during the experiment. After that, the Ishihara test was implemented. The experimenter then asked the qualified participant to sign an informed consent form and complete a general information survey.

The experimenter described the experiment to the participant and escorted him\her to the preset chair. After the observer adjusted the height of the chair, the room lighting was switched off so the light from the experimental light source was the only illumination during the trial.

For the scale rating process, the observer was given 15 seconds to adapt to the welcome lighting condition which was randomly selected from the experimental light sources. Before the formal experiment, a training phase was provided to the participant with the welcome light and the first object to be evaluated. As suggested by Zhai *et al.*,[25] during the experiment, the questions were read out by the experimenter and the participant also responded orally. Such a procedure was to avoid incomplete chromatic adaption when writing answers on white paper.

After the training phase, the formal experiment began. The participant was asked to close his/her eyes and then the experimenter changed the light. (This procedure took about 15 seconds and was repeated every time the light was changed. Its aim was to eliminate any influence of the prior lighting condition caused by a short-term memory effect.) After that, the participant was asked to open their eyes and observe the object for about 10 seconds. The experimenter then asked the participant to assess the light quality basing on their personal preference, with the seven values (−3, −2, −1, 0, 1, 2, 3) as mentioned above. Once the participant had assessed the lighting condition and validated the answer, the experimenter changed the light and this procedure was repeated for every arrangement of the objects in each group. During the experiment, the participant was allowed to take as much time as necessary.

The procedure for the 5-level rank-ordering experiments was slightly different. The five experimental lighting conditions were shown twice for each participant, in the same randomized order. The participant was asked to make the decision in his/her mind after the first round, while in the second round to rate the preference order when seeing the light (5 for relatively *most like* and 1 for relatively *least like*). The participant was allowed more rounds in the case where s/he could not respond in two rounds. However, in fact all the observers in the experiment successfully gave their answers within two rounds.

3. Results and discussion

Table 3 summarizes the overall results from this study. Note that for the modern oil painting and the multicolour flowers scenarios, the trend of the rating scores under the five SPDs condition (2500K, 3500K, 4500K, 5500K and 6500K) was quite similar to that under the nine SPDs (2500K, 3000K, 3500K. . ..6500K); therefore, only the rating values of the five SPDs are shown here. As can be seen from Table 3, the ratings of the SPDs for the different objects showed a consistent tendency. That is, for the 2500K SPD, the average values of the observer rating were always low while for the 4500K SPD the values were mostly high.

Another interesting finding is the negative correlation *r* between the average value and standard deviation of each trial. Such a result is consistent with previous studies,[23,51] which indicates that when observers generally prefer certain lighting conditions, the distribution of their ratings will be concentrated, while if they generally dislike certain lighting conditions, the distribution will tend to be scattered.

The above-mentioned conclusion also holds in the Van Gogh and Chinese traditional painting groups, which indicates that the order ranking approach tends to have similar results with scale rating in form of the preference rank order for each light. Meanwhile, the reason for adopting the scale rating method in this study lies in its possibility of predicting the acceptance limit as well as its inter-observer variability for each scenario. Such an advantage enabled the

Table 3 The average value (avg) and standard deviation (SD) of observer rating for different objects under different CCTs, together with the Pearson correlation coefficient *r* between the average and the standard deviation of each scenario

Object	Stat	2500K	3500K	4500K	5500K	6500K	*r*
Red fruit and vegetables	Avg	−0.33	0.47	1.04	1.02	0.59	−0.86
	SD	1.96	1.32	1.15	1.35	1.68	
Green fruit and vegetables	Avg	−1.61	−0.12	1.24	1.04	0.92	−0.96
	SD	1.58	1.42	1.23	1.15	1.27	
Yellow fruit and vegetables	Avg	−1.35	0.29	1.20	1.27	0.82	−0.85
	SD	1.73	1.38	1.14	1.43	1.38	
Multicolour fruit and vegetables	Avg	−0.96	0.78	1.31	1.29	0.71	−0.88
	SD	1.89	1.25	1.06	1.14	1.67	
Calligraphy (orange)	Avg	−0.43	0.48	0.25	0.25	0.28	−0.67
	SD	1.93	1.52	1.08	1.10	1.43	
Calligraphy (red)	Avg	−0.25	0.10	0.63	0.40	0.25	−0.86
	SD	1.92	1.30	1.13	1.43	1.32	
Calligraphy (white)	Avg	−0.68	0.88	0.43	0.43	−0.10	−0.70
	SD	1.65	1.44	1.20	1.34	1.50	
Calligraphy (light white)	Avg	−0.25	0.75	0.73	0.28	0.03	−0.75
	SD	1.71	1.51	1.34	1.36	1.66	
Calligraphy (yellowish white)	Avg	−0.65	0.83	0.83	1.13	0.58	−0.95
	SD	1.78	1.30	1.17	1.04	1.47	
Van Gogh painting[a]	Avg	2.40	3.47	3.98	3.18	1.97	−0.63
	SD	1.49	1.22	1.04	1.13	1.21	
Chinese traditional painting[a]	Avg	1.75	3.43	4.07	3.45	2.32	−0.31
	SD	1.10	1.23	0.92	1.19	1.17	
Multicolour flowers	Avg	−1.33	0.36	0.64	0.72	0.08	−0.80
	SD	1.77	1.46	1.17	1.49	1.59	
Modern oil painting	Avg	−0.92	0.92	1.19	1.08	0.89	−0.79
	SD	2.03	1.30	1.04	1.44	1.79	
Mural painting	Avg	−0.45	0.85	0.65	0.35	0.20	−0.78
	SD	2.21	1.57	1.04	1.31	1.82	

[a] For the Van Gogh and Chinese traditional painting scenarios, the avg value represents the averaged rank order for each CCT (5 for most liked and 1 for least liked).

authors to straightforwardly investigate the influence of different object characteristics on colour preference. Besides, although the paired comparison approach is commonly believed to be easier for participants, current work[4] has also reported that such two methods have similar results.

It is worth mentioning that some researchers recommended transforming the observer ratings into *z*-scores before further analysis.[9] In this study, we analysed the data with and without *z*-score transform, and the results were quite similar. Therefore, the results of data analysis without *z*-score implementation were ultimately shown, since such a form of data was more straightforward for assessing the observers' preference.

3.1. Inter-observer and intra-observer variability

The inter-observer variability in each experimental trial was quantified by the standard deviations of the observers' ratings, as shown in Table 3. Considering the consistency among each trial as well as the results of related works,[23,25,28] such statistics seems to be reasonable.

As mentioned above, the intra-observer variability of this research (for the scale rating experiments) was assessed by asking the participants to observe a randomly selected lighting condition twice without informing them of this. A similar approach was adopted by Jost-Boissard *et al.*[2] As stated in such work, when the observers carried out the

Table 4 Statistical significance of the effect of the independent variables (SPD, object, personal colour preference and gender) on the dependent variable (preference rating) for the fruit and vegetables group

Independent variable or interaction	SS	df	MS	F	Sig
SPD	442.31	3.09	142.75	59.45	<0.001
Object	12.37	3	4.12	1.51	0.213
Personal colour preference	4.83	3	1.61	0.59	0.622
Gender	5.55	1	5.55	2.03	0.155
SPD × Object	45.24	9.29	4.86	2.02	0.033
SPD × Personal colour preference	79.99	9.29	8.60	3.58	<0.001
SPD × Gender	33.28	3.09	10.74	4.47	0.004
Object × Personal colour preference	13.24	9	1.47	0.54	0.844
Gender × Object	2.30	3	0.76	0.28	0.839
Gender × Personal colour preference	12.64	2	6.32	2.31	0.102

SPD: spectral power distribution; SS: sum of squares; MS: mean square.

same experiment twice, the results would not necessarily be the same, because there are many factors which could impact their decision. Therefore, in this work, we quantified the intra-observer variability by the absolute difference between the two ratings and set the threshold to a value of 2. That is, if the absolute difference of the two ratings was larger than 2 (for instance, -1 for the first time while 2 for the second time), such ratings would be considered as abnormal data. After calculating the ratio of abnormal data for all the scale rating experiments and comparing the results with the work of Jost-Boissard *et al.*,[2] we concluded that the intra-observer variability of each experiment was acceptable, with a range of 6%–17%. In addition, we strongly agree with Jost-Boissard's opinion that the intra-observer variability should be mainly ascribed to the inherent difficulties of the experiment, rather than the attitude of the observers, provided that the experiments were carried out with caution.[2] And we also found that removing the abnormal data would not significantly change the final results. Therefore, we retained all the data for further analysis.

3.2. Impact of different factors on colour preference

The effect of different contextual factors on colour preference was investigated using a repeated measures analysis of variance (rm-ANOVA). Tables 4 to 7, respectively, summarize the results for different experimental groups. Note that the outcomes for the three and four factor interactions were omitted, since none of them were statistically significant.

As can be seen from Table 4, the impact of light SPD on colour preference is significantly stronger than other factors, as well as their interactions. Meanwhile, the influence of personal colour preference is quite limited. Although we actually find something interesting in this topic, it is safe to conclude that the impact of personal colour preference is negligible when compared to that of light SPD. To our knowledge, no past study has discussed the relationship between personal colour preference and colour preference of lighting: the detailed analysis of such topic will be reported in another paper.

Table 5 describes the result for the calligraphy experiments. The reason for designing such a group was that the colour feature of such artwork is completely different from that of paintings. Palmer *et al.*[52] defined such a form of colour preference as *figural preference* (i.e. how much the foreground colour is liked when viewed against a coloured background), and they argued that such a preference was closely related to lightness and hue contrast between the foreground and background colours. However, as shown in Table 5,

Table 5 Statistical significance of the effect of the independent variables (SPD, object and gender) on the dependent variable (preference rating) for the calligraphy group

Independent variable or interaction	SS	df	MS	F	Sig
SPD	154.80	3.03	50.95	21.14	<0.001
Object	18.49	4	4.62	1.47	0.212
Gender	0.62	1	0.62	0.51	0.656
SPD × Object	45.09	12.15	3.70	1.53	0.105
SPD × Gender	24.37	3.03	8.01	3.32	0.019
Gender × Object	14.89	4	3.72	1.18	0.318

SPD: spectral power distribution; SS: sum of squares; MS: mean square.

Table 6 Statistical significance of the effect of the independent variables (SPD, object, gender and regional cultural difference) on the dependent variable (preference ranking) for the Van Gogh and Chinese traditional painting group

Independent variable or interaction	SS	df	MS	F	Sig
SPD	354.86	2.52	140.78	50.84	<0.001
Object	0.007	1	0.01	0.14	0.7
Gender	0.16	1	0.16	3.71	0.056
Regional cultural difference	0.14	2	0.07	1.59	0.207
SPD × Object	18.19	2.52	7.21	2.60	0.062
SPD × Gender	13.5	2.52	5.35	1.93	0.135
SPD × Regional cultural difference	21.37	5.04	4.24	1.53	0.180
Gender × Object	0.01	1	0.01	0.14	0.7
Object × Regional cultural difference	0.06	2	0.03	0.70	0.496
Gender × Regional cultural difference	0.14	2	0.07	1.59	0.207

SPD: spectral power distribution; SS: sum of squares; MS: mean square.

Table 7 Statistical significance of the effect of the independent variables (SPD, object and gender) on the dependent variable (preference rating) for multi-colour flowers and modern oil-painting group

Independent variable or interaction	SS	df	MS	F	Sig
SPD	204.48	2.51	81.57	21.38	<0.001
Object	26.66	1	26.66	12.56	0.001
Gender	3.66	1	3.66	1.72	0.193
SPD × Object	1.84	2.51	0.73	0.19	0.870
SPD × Gender	17.04	2.51	6.78	1.78	0.162
Gender × Object	1.15	1	1.15	0.54	0.463

SPD: spectral power distribution; SS: sum of squares; MS: mean square.

when compared to the impact of light SPD, the impact of lightness and hue contrast (demonstrated by the interaction between SPD and Object) was negligible.

The Van Gogh and Chinese traditional painting group was planned to explore the influence of regional cultural difference on colour preference. A prior study by Bodrogi *et al.*[8] has reported that the impact of cultural difference was stronger than that of other contextual factors, including light SPD, object and gender.[8] However, contrary results are shown in Table 6, which still highlights the impact of light. As far as we are concerned, there are two likely explanations for this condition. First, in Bodrogi's work, the observers were respectively from China and Germany, while our participants were only from different regions of China, so there is no doubt that the cultural difference in Bodrogi's work is much stronger. Second (and maybe more importantly), although Bodrogi's work also used several SPDs with different CCTs, their SPDs actually had certain special features. That is, the lights in their study were deliberately generated and the corresponding colour quality metrics (such as CRI, GAI and CQS) for those lights were almost the same. It is very likely that such an experimental design actually weakened the impact of the lights.

The purpose of the multicolour flowers and modern oil-painting group was to further test the influence of lighting application on colour preference. As shown in Table 7, although the SPD is still the key factor for colour preference, the impact of the object is significantly stronger when compared to former experiments. One possible explanation for this finding is that the extent of the object difference in this group (flowers and paintings) was much more profound compared to previous groups (same type of objects).

In conclusion, the rm-ANOVAs for the above-mentioned groups uniformly illustrate that light always plays a dominant role for human colour preference, at least under our experimental condition. Besides, we can also conclude that the divergence of the contextual factors is also crucial for the results of such a study.

3.3. Correlation analysis

Figure 5 visualizes the performance of current colour quality metrics on predicting colour preference. It is worth noting that most of those metrics were not deliberately proposed for assessing colour preference. However, the correlation analysis between such metrics and colour preference is quite common in the current literature,[2,3,5,9–11] since a proper metric for colour preference is actually needed. Note that it is not the intent of this paper to discuss the intricate details of these metrics, thus only the main findings which related to this topic are presented.

As shown in Figure 5, the GAI, FSCI, CDI and CSA metrics show relatively sound performance while the performance of other metrics was poor. A possible explanation for this condition is that these four metrics are all absolute measures which are independent of a reference light source (or with a constant reference) while most of the other metrics are reference dependent. In this case, we would like to conclude that unlike lighting fidelity which should be related to certain reference light source, colour preference is to some extent an absolute issue and thus should be quantified by some absolute measure.

Another possible explanation for the results in Figure 5 is that colour preference is correlated with saturation[22,32,37] while the increased gamut area is always related to saturation (or chroma) enhancement.[6,9,21,23,53] Maybe that is why in some related works,[2,11,23] the GAI was reported to be a good predictor for colour preference (the CDI and CSA are also gamut-based metrics but were less discussed in past studies).

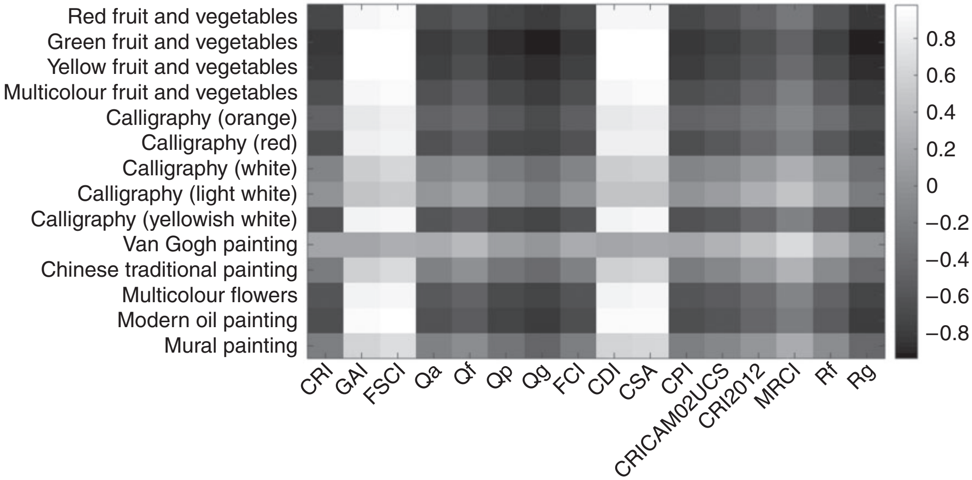

Figure 5 Pearson correlation coefficients between various metrics' predictions and visual scaling of colour preference of each object. The value of the correlation coefficients is denoted by colour with white for a strong positive correlation, black for strong negative correlation and mid-grey for zero correlation

Meanwhile, it is obvious that the two relative gamut-based measures (Qg and Rg) performed poorly in predicting colour preference, which conversely supports the necessity of an absolute gamut-based measure for this multi-CCT condition. Note, however, that not all the absolute gamut-based indices perform well according to our data, for example, the FCI (constant reference D65). A possible reason is that different gamut-based indexes adopt different colour samples for calculating the gamut area. If the colour samples were not reasonably selected, maybe the correlation between the subjective preference rating and the metric predictions would be masked.[48,54]

3.4. Other findings

Figure 6 illustrates another two findings of this work. The left graph shows the impact of observer familiarity on preference ratings. As can be seen from this graph, the rating interval for the familiar objects is obviously larger than that of unfamiliar objects. It seems that people always have a precise idea about the colours of the objects which they are familiar with, therefore, it is easier for them to respond with an explicit answer (e.g. *strongly dislike* or *strongly like*). On the contrary, since they are not familiar with certain other objects, a vague answer (e.g. *moderately dislike* or *moderately like*) is more likely to be provided. Meanwhile, it needs to be mentioned that the modern oil painting and yellowish white calligraphy were classified as familiar objects in this graph. For the modern oil painting, we believed that its colours together with the scene it depicted were much more familiar than those of the other paintings. While for the yellowish white calligraphy, such a yellowish white is actually the most popular colour for traditional Chinese rice paper. Such paper is the best seller in the store where we brought it and it also has a sound name ‘retro-paper’.

The right graph of Figure 6 depicts the influence of object colour features on colour preference. As shown in this picture, people always prefer a warm light for warm colours (see the 2500K condition) while they prefer a cool light for cool or cold colours (see the 6500K condition). In related works of Liu *et al.*[22] and Lasauskaite Schüpbach *et al.*,[55] similar results were also obtained. Note that

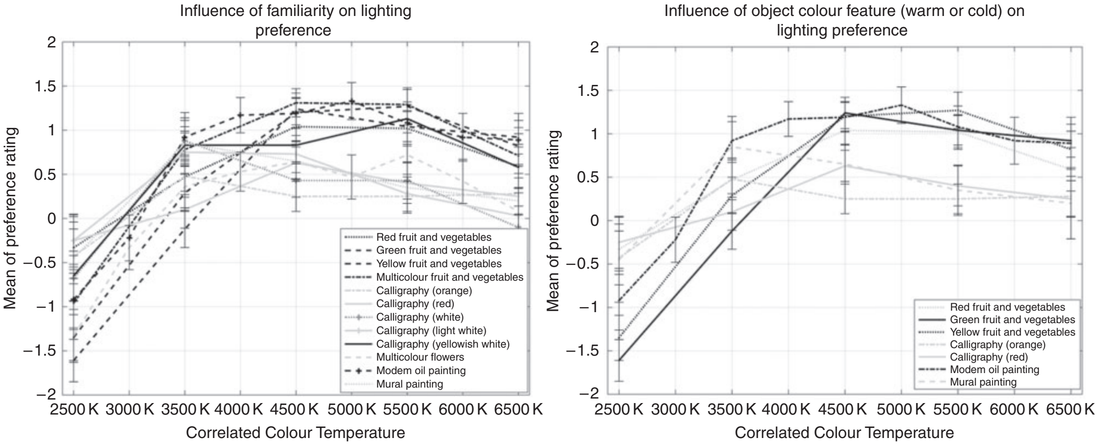

Figure 6 Left: Influence of observer familiarity (black for familiar objects while grey for unfamiliar objects) on colour preference. Right: influence of object colour (grey for warm colours and black for cold colours) on colour preference. Error bar: standard error of mean

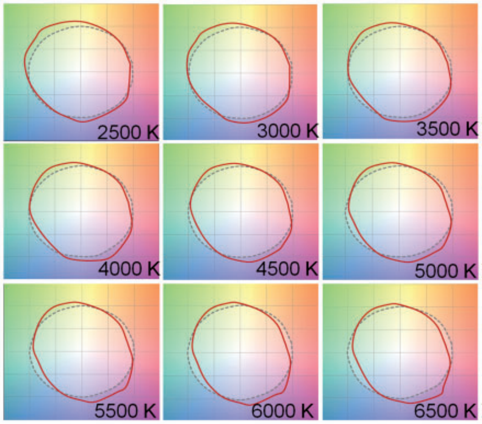

Figure 7 Gamut shape comparison based on the IESNA method[49]

since there was no object with real cold colours in our experiment, we could only consider the green fruit and vegetables, yellow fruit and vegetables and modern oil paintings as relatively cool colour objects.

In summary, Figure 6 illustrates that the observer familiarity and object colour actually has a certain impact on colour preference. Meanwhile, from the similar trend of preference rating for different objects, we may conclude again that light is still the dominate factor for colour preference.

4. General discussion and conclusion

The above discussion has profoundly demonstrated the dominant influence of light on colour preference, at least where CCTs differ. In fact, in the current literature even in metameric lighting conditions (SPDs with almost the same CCT), similar results were also reported.[2,9,32] Just as Jost-Boissard *et al.*[2] stated,

> *the subjects' judgment about lighting did not seem to depend a lot on the colour of the target. This suggests that it is possible for a given type of light to give a good rendering for all the different colours, and that separate lighting is not needed for each target colour.*

The reason for the dominant influence of light on colour preference should be attributed to gamut area. As mentioned above, people always prefer a light which would enhance colour gamut and thus make the objects more saturated.[6,9,21–23,32,37] Besides, several past studies have also stated that the GAI performed well in either multi-CCT or metameric lighting conditions.[2,4,5,10,11,23]

There are, however, other contributions which raise contrary views, such as the work of Bodrogi *et al.*[8] They intently generated the light SPDs with similar colour quality metrics (including GAI), so the influence of light on colour preference turned out to be weak. Another counter example is the work of Lasauskaite Schüpbach *et al.*[55] In this work, the colour preference of interior materials was discussed. Since such unfamiliar objects differed greatly in their structure, texture and colour features as well as optical properties, the experimental object became the key factor for colour preference, rather than light. Therefore, it is not safe to arbitrarily conclude that light dominates colour preference under any condition. When the divergence of other contextual factors is greatly enhanced, the influence of light will relatively weaken.

Meanwhile, it is also worth mentioning that according to a recent study of Wei *et al*, light sources with similar measures of relative gamut but different gamut shapes would also influence colour preference.[21] Such work actually points out the limitation of the gamut-based metrics, but maybe it is not applicable to this work, since we are discussing the colour preference for multi-CCT conditions (to our knowledge, no past studies have investigated the influence of gamut shape on colour preference for multi-CCT conditions).

Figure 7 illustrates the gamut shape of the nine experimental light sources using the

IESNA method. It is clear that the gamut shape of these lights is quite similar, which obviously belies their huge difference in predicting colour preference. Therefore, it is very likely that such a theory on gamut shape[21,28] may only be valid in a metameric lighting domain. If two light sources have different CCTs, they will correlate to different reference lights and thus their gamut shapes are incomparable. Just as in this study, the dot-line circles in Figure 7 actually refer to different reference sources (It is also a good explanation for the failure of the reference-based measures, as mentioned above.). Furthermore, as for such multi-CCT cases, except for the condition that one light source has a large gamut but extremely abnormal gamut shape, maybe the influence of gamut size is still greater than that of gamut shape. This topic should be explored in further studies.

In light of the above, we would like to firstly state the prerequisites so as to make a safe conclusion. The aim of this study was to investigate and compare the influence of several contextual factors on colour preference, especially for general lighting conditions when CCT differs. In such conditions, the gamut sizes of different SPDs are likely to be different. As for the issue of gamut shape, the authors agree that it is actually a very important concern, but as mentioned above, it may only be valid for metameric light conditions. Furthermore, we suppose that it should be the manufacturer's responsibility to provide a product with reasonable gamut shape according to the relevant theory. For naïve users and general applications, we believe that light dominates colour preference when CCT differs.

To sum up, in this paper, the impacts of different contextual factors on colour preference for a multi-CCT condition were systemically investigated, with a wide range of experimental objects. It is found that the familiarity with the object, as well as the colour of the object to some extent impacts colour preference. Meanwhile, our most important conclusion lies in the dominating influence of light on colour preference. We therefore recommend that for daily use, ordinary consumers should mainly be concerned about the property of light – an absolute gamut-based metric seems to be a good indicator for this issue, which is much better than the reference-based metrics.

The experimental data of this research are available upon request.

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