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Colour Preferences and Energy Consumption in Retail Lighting Applications

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Abstract. Colour preference and energy efficiency have long been considered significant characteristics that cannot be maximized simultaneously. Numerous investigations on colour preference and evaluation have been carried out. Sources with larger gamut generally enhance object chroma, which has been found to be preferred by previous studies, however, excessively large gamut may lower preference due to oversaturation. This paper describes a psychophysical experiment for the comparison of the colour preference evaluation among sources of different hue-specific chroma changes and how preference affects energy efficiency. A retail lighting application was created in two side-by-side presentations. A two-metric colour rendering system, consisting of average fidelity and gamut metrics, cannot fully describe colour quality and underscore the importance of a colour rendering graphic. Different spectras with the same correlated colour temperature, average fidelity and average gamut were implemented using an optimized spectral power distributions calculation in order to have systematic variation in gamut shape. Participants of different ages made preference assessments of chromatic objects in a forced-choice protocol, where they evaluated the pairs in a sequential mode. Specific colours strongly influenced participants' assessments, indicating that gamut shape, additionally to gamut area, is an important component of predicting colour preference and energy efficiency.

1 Introduction

Energy usage and lighting needs are emphasised in lighting research. Lighting manufacturers have created an increasing number of light sources with highly structured spectral power distributions (SPDs) as lighting technology has advanced. Combining the present efficiency improvements with lighting management systems might further reduce the energy consumption of lights [1, 2]. If it functions regularly, a daylight control system can significantly reduce energy consumption as compared to a manual control system. Basic design concepts for artificial lighting include uniformity, glare reduction, and the physical appearance of the hue of the light source. Buildings are designed to be practical and meet the requirements of their users and applications [3, 4]. Even if energy consumption is increasing, it is still important to consider user preferences for various applications [5]. People have been observed to prefer certain light sources because they offer greater colour quality [6–11]. "The natural agent that stimulates sight and enables vision" is how light is described [12]. Lighting conditions are crucial for some types of applications, such as retail lighting, even within the visible spectrum of light, where just a small portion of the electromagnetic spectrum of light can be detected by the human eye, which runs between 380 and 780 nm [13]. Users, however, undervalue light because they only consider its expenses rather than accurately gauging its advantages [14]. Since lighting demands vary depending on the various uses, it is apparent that some unique applications, such as retail lighting, have even higher light energy requirements.

Based on the eight-band method, which Bouma suggested in 1937 [15], the Commission Internationale de l'Eclairage (CIE) initially recommended colour rendering in 1948. CIE introduced a method to define the visual rendering characteristics of light sources in 1965. It gauges how well a light source maintains the items it illuminates' ability to retain their colour. The method was modified in 1974, and it described the saturated red colour shift that resulted from comparing the mean colour shift of eight test colour samples under an illuminant to a reference illuminant of the same CCT. In 1995, the Colour Rendering Index (CRI) was still in use with a few minor modifications [6]. The CIE modified the CRI index as well, recommending Ra96 in 1999, however it was not accepted. After several years of research, the CIE issued an improved calculation technique in 2017 [16] to clarify the relationship between the other components of colour quality and the colour rendering index and prevent user confusion. With a few minor modifications, this was given the term colour fidelity index (CIE Rf), which is based on the IES TM-30-15 Fidelity Index (Rf) [17]. Numerous lighting metrics for defining the colour rendering of light sources had been presented prior to the CIE guideline in 2017 [16]. The CIE Ra has been used by the lighting industry

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for more than 50 years, even if it hadn't changed in the last 40. With the introduction of new technologies and applications, its shortcomings are generally acknowledged [9, 18–23], and the CIE has been working on a successor or alternative for more than 25 years. The way colour rendering is used has to alter as a result of the numerous limits and inadequacies of CRI that have been revealed in recent years by further research and published standards [16, 19–23].

In 2013, the Colour Metrics Task Group of the Illumination Engineering Society (IES) was founded. After reviewing the available research, IES formalised a new suggested method. As a result, ANSI/IES TM-30-18 [24], a version to TM-30-15 [17], was created. This was the first release of 2015, and it included three changes to bring it into line with the CIE's most recent publication from 2017 [16]. The IES TM-30 metric system, which consists of multiple connected measurements and graphics, has the potential to affect how colour rendering characteristics of light sources are assessed and communicated. As of the publication of TM-30-18 [24], the two measures have been harmonised, making the CIE Rf and the recently revised IES Rf identical. This is an important step in ensuring that the index is accepted by more people.

Understanding that no one average statistic can adequately represent all aspects of colour rendition is essential to improving colour rendering. Sources with the same fidelity index value may be desaturated, saturated, or have a shift impact on an object's colours or colours. An improved indicator of a source's the suitability for a certain application is provided by the inclusion of the average level of saturation, visual descriptions of hue, saturation changes, and many other indices. Because all calculations are based on the source's spectral power distribution (SPD), which is already evaluated to establish the well-known CIE CRI, a potential modification in the colour rendition measurement technique may be swiftly and readily applied. Utilising the new assessment colour rendition techniques requires adapting the understanding of how to engineer, define, and classify sources. High colour fidelity is an assumption of high colour quality. Higher fidelity is not necessarily preferable, though [19, 25–28]. Although it appears to be a suitable option, the fidelity index of a test source determined using a target illuminant as reference [29].

It is challenging to quantify the colour quality of a light source since it depends, at the very least, on the final use for which it will be used, individual preferences (including cultural ones), the things being viewed, brightness, and observer expectations. On the other hand, it is not too difficult to measure objective colour-metric properties, such as average object-colour shifts between a given light source and a reference illuminant (i.e., average fidelity) [6, 8-11, 30], average increases or decreases in saturation (i.e., average gamut area) [17, 19, 27, 31-40], and the specific (or average) chroma or hue change of objects [17, 34, 41]. To assess and validate the new measures of colour quality, psychophysical studies [7, 26, 30, 32, 41–47] and meta-analyses [48–49] have been carried out. The majority of tests tested various characteristics of the colour quality as seen by observers in a viewing booth with various items while exposed to various light sources. Few studies used full-scaled rooms, which more accurately reflect the lighting conditions found in real-world settings. When compared to evaluations and judgements made, the more realistic setting and surroundings may lead to changes [50]. Realistic lighting conditions can influence how an environment is viewed and how emotions are felt, according to Quartier et al.'s findings [51].

Average fidelity has been modified in some manner by several psychophysical experiments [20, 26, 30, 37, 42, 47, 52–53]. A few modifications changed average fidelity and gamut at the same time [31–33, 54]. Only a few studies [38–39] have modified fidelity, gamut, and gamut form at the same time. Gamut shape was explicitly separated by Wei and colleagues [33–37] and is not reliant on average fidelity or average gamut. Few studies, in general, have directly and consistently changed one or more of these characteristics as part of the experimental design. To assess skin preference, no research that concurrently and systematically altered average fidelity, average gamut, and gamut shape are known to exist.

Colour fidelity has been linked to perceptions of naturalness [52,55], however this relationship isn't always present [26, 53, 56], perhaps because of the colour-difference calculation's comparison to supposedly natural illuminants [15, 57]. Colour preference has frequently been connected to object saturation, average gamut area [31–33], object chroma [30–56], average gamut area [52–53], and occasionally a combination of several metrics [38–39, 54]. According to some [26, 31, 38, 47], fidelity and saturation are both factors that influence colour choice. Impressions of vividness have been linked to measurements of gamut area [32, 52] and are strongly connected to saturation [26]. According to Smet et al., fidelity/naturalness and vividness are the other two perceptual characteristics that make up a two-dimensional colour quality space [26]. It has been consistently noted that red colour have a considerable impact on these different impressions [7, 20, 32, 37-40, 42, 56].

1.1 Defining gamut shape

The computation space bounded by colour samples in a chromaticity diagram or colour space is referred to as the gamut area [19, 24, 27, 31, 33, 34]. The enclosed space resembles a skewed polygon. The normalised form of the enclosed polygon, the IES TM-30-18 Colour Vector Graphic (CVG), has been shown to imitate known elongated shapes, notably different versions of circles and ellipses [24, 34]. Gamut shape in this article refers to the IES TM-30-18 CVG's general form or appearance. Shapes with an extended gamut have a propensity to tilt towards a specific colour. The nominal hue (or lower hue angle bin) to which these forms are orientated is referred to as the gamut orientation. The IES TM-30-18 CVG's particular hue angle chroma shift is described in Rcs,hj. In comparison to the reference source, a positive number indicates an average chroma increase, whilst a negative value indicates an average chroma decrease. Theoretically, Rcs,h1 and Rcs,h16 are red.

1.2 Defining reference sources

Metrics for measuring colour rendering are based on difference between a test source and a reference illuminant. The term "colour rendering" refers to an illuminant's "effect on the colour appearance of objects by conscious or unconscious comparison with their colour appearance under a reference illuminant." Only a small number of proposed measures have used a target for comparison rather than a conventional benchmark like the Colour Preference Index or Memory Colour Rendition Index (MCRI). The reference source and test source's CCT are often coupled. As an alternative, the Gamut Area Index (GAI) employs the CIE Standard Illuminant E as a single fixed reference regardless of chromaticity that is equivalent in energy. Alternative reference sources include Planckian radiators and CIE D Series Illuminants, which are located slightly above the Planckian locus (see Figure 1 for an illustration). For instance, P27 is Planckian radiation at 2700K. Planckian radiation and a CIE D Series illuminant differ at any CCT due to the Earth's atmosphere's filtration of sunlight. Lower CCT sources have been calculated using the same equation to satisfy the demands of this study, as the CIE D Series is only specified at or above 4000K, off-Planckian reference illuminants with positive or negative Duv, and bespoke reference illuminants. The definition of a reference source and how the output values of the TM-30 would vary if a different reference framework were employed are addressed in this area of the literature.

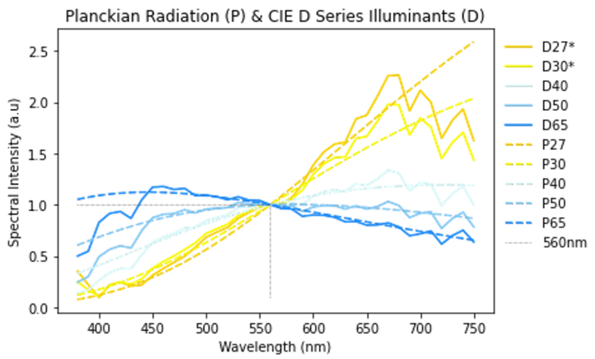


Fig. 1. Planckian Radiation (P) and CIE D Series Illuminants (D) comparisons at five CCTs, with each source's wavelength being normalised at 560nm.

The reference source receives the highest rating and maximises the value in single-number measurements like CIE CRI. The possibility of misconception the reference source for the ideal is reduced when an assessment framework with numerous measures, such as TM-30-18, is employed. The CIE Test Colour Method serves as the foundation for the majority of TM-30, preserving a level of consistency to aid in the adoption of the new assessment framework. Additionally, because Planckian radiation and certain of the CIE D Series illuminants are mathematically established worldwide standards that can be estimated across a variety of CCTs, the IES Colour Metrics Task Group chose to utilise them. CIE. CIE Ra applies references on the Planckian radiation at CCTs below 5000K, whereas models on the CIE D Series use illuminants above 5000K, as illustrated in Figure 2. This is one distinction between TM-30-18 and CIE Ra reference illuminants. Instead, TM-30-18, with a straightforward example at CCT 4500K as shown in Figure 3, provides blended sources from 4000K to 5000K to eliminate the sharp step of CIE Ra and applies the same models at both the higher and lower ends of the CCT range. The outcome is a smooth transition that works well with contemporary, colour-tunable test sources.

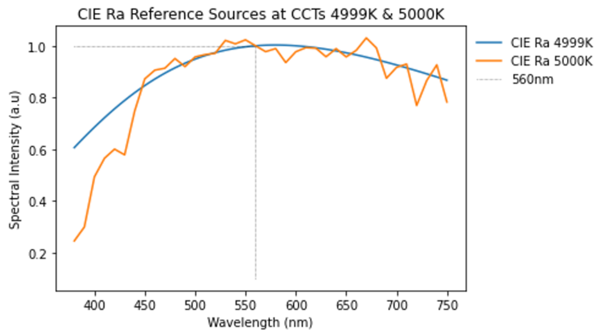


Fig. 2. CIE Ra reference source comparisons at CCTs 4999K and 5000K, with each source's wavelength being normalised at 560nm.

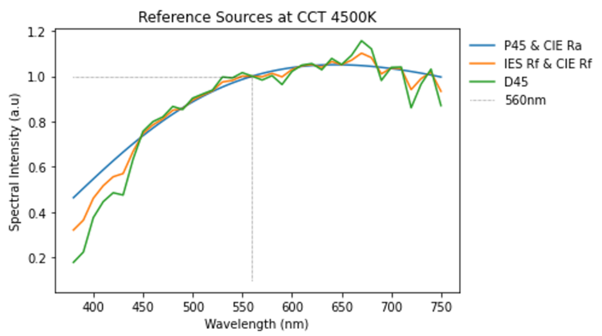


Fig. 3. Sources with a CCT of 4500K that are Planckian Radiation, CIE Ra, IES Rf, CIE Rf, and CIE D Series Illuminants are compared, with each source's wavelength being normalised at 560nm.

According to research, utilising just Planckian radiation or only CIE D Series illuminants tends to have a comparatively less impact on values that are not random due to the special characteristics of the varying reference illuminants [11, 21–22, 31–32, 61]. The variances between the referred illuminants' gamut shapes represent most of the discrepancies when compared to the industry-standard reference scheme, which are often fewer than a few points. A fixed reference was used to demonstrate that sources with CCTs that varied from the reference will often have lower values. Different colours show this pattern to varying extents, which is probably caused by correlations between gamut shapes. Finally, the outcome would be graded as desaturated with lower fidelity when employing off-Planckian or saturating reference illuminants in most extant sources.

Although reference is the foundation of communication, no reference has an inherent advantage. Because people are familiar with these two natural light sources, Planckian radiation, daylight, or a mix of the two, has been established as a reference source. They may not always show colours perfectly in every application, but they do offer a better foundation for determining out how a test source differs from the reference source. Future revisions to the colour rendering metrics should pay particular attention to the reference schemes, especially if new standard illuminants are developed.

1.3 Goals and hypotheses

To assess the colour preferences of five LED sources for one retail lighting application, this paper examines a psychophysical experiment. The experiments were carried out using two parallel images of objects from this application. The reviews of the various LED sources compare and debate the best ways to describe a light source's colour quality.

This article's main objective is to model how people evaluate how well light sources render colour while considering diverse gamut shapes as well as similar average fidelity and average gamut values. Average fidelity (IES Rf), average gamut (IES Rg), and gamut form (i.e., opposing orientations of the CVG) were all described using the IES TM-30-18 [24, 25].

2 Methodology

2.1 Light spectras

For this investigation, an optimised SPD calculation for target illuminants was constructed using the LuxPy library [62]. The sources with hue-specific chroma variations are the study's illuminants. Each source is a blend of gaussian, monochromatic, and phosphor LEDs that provide a multi-component spectrum. For CCT, IES TM-30 Rf, Rg, Rcs,hj and Rhs,hj target values, the peak wavelengths, full-width-half-maxima of the components, as well as the contribution and strengths of phosphors, were optimised. Table 1 contains SPD values, while Figure 4 shows CVG values. A metameric match to the CIE D Series illuminant at 5700 K was intended for all spectra. The CIE D Series illuminant at 5700 K as a reference light result is the source with ID 1. The Sources with IDs of 2 to 5 are optimised SPDs with hue-specific chroma changes on the influence colours of red, orange, yellow, green, and blue. Despite having varied Luminous Efficacy of Radiation (LER), all the study's sources had comparable CCT, IES TM-30 Rf, and Rg, which suggests that any choice will affect the energy efficacy. Actual stimuli had a Duv range from -0.0031 to +0.0032 and were 5723K ±93K.

2.2 Object selection

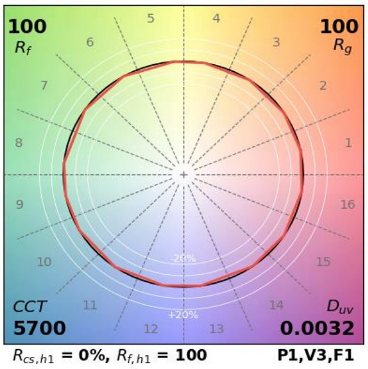
Insofar as possible, fewer objects were chosen with the intention of making it feasible to inquire specifically about each one. As far as was logistically practicable, nine well-known items with strong memory associations [26, 48] that theoretically meet the labels "Red," "Orange," "Yellow," "Green," and "Blue" were selected to span the hue circle. To reflect both manufactured and natural goods, items were divided into two categories: Consumer Goods (Figure 5, back row) and Real Produce (Figure 5, front row). The nine experimental items and the 99 Colour Evaluation Samples (CES) employed in the IES TM-30 calculating technique have a strong correlation (Rf and Rg). The investigations were carried out in two side-by-side images, thus there was no need for replacement because the items did not appear to have deteriorated. On this basis, identical items and lighting outcomes were rated by each participant.

Table 1. Features of the five lighting conditions.

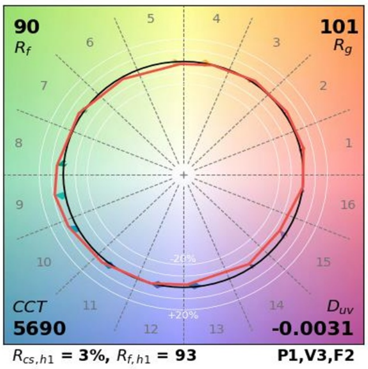
ID	1	2	3	4	5
CCT	5700	5630	5672	5690	5815
Duv	+0.0032	-0.0015	-0.0006	-0.0031	+0.0023
Rf	100	89	88	90	90
Rg	100	100	102	101	105
LER	203.37	165.09	129.24	235.46	174.90
Rcs,h1	+0%	+10%	-1%	+3%	+3%
Rcs,h2	+0%	+5%	-3%	+2%	+3%
Rcs,h3	+0%	+3%	+2%	+2%	+2%
Rcs,h4	+0%	+0%	+2%	-0%	+1%
Rcs,h5	+0%	+0%	+3%	-3%	+3%
Rcs,h6	+0%	-5%	+5%	-2%	+6%
Rcs,h7	+0%	-6%	+9%	+2%	+5%
Rcs,h8	+0%	-2%	+5%	+5%	+1%
Rcs,h9	+0%	-1%	+2%	+9%	-5%
Rcs,h10	+0%	+0%	+2%	+5%	-4%
Rcs,h11	+0%	-2%	-4%	+2%	-3%
Rcs,h12	+0%	-4%	-3%	+0%	-1%
Rcs,h13	+0%	-5%	-1%	-4%	+3%
Rcs,h14	+0%	-1%	+1%	-4%	+5%
Rcs,h15	+0%	+3%	-4%	-6%	+10%
Rcs,h16	+0%	+5%	-1%	-0%	+5%
Rhs,h1	+0.00	+0.02	-0.01	+0.02	-0.01
Rhs,h2	+0.00	-0.05	+0.04	+0.00	-0.02
Rhs,h3	+0.00	-0.04	+0.03	-0.04	+0.01
Rhs,h4	+0.00	+0.01	-0.02	-0.07	+0.05
Rhs,h5	+0.00	-0.01	-0.04	-0.04	+0.04
Rhs,h6	+0.00	-0.04	+0.01	+0.02	+0.02
Rhs,h7	+0.00	-0.01	+0.01	+0.05	-0.04
Rhs,h8	+0.00	+0.02	-0.05	+0.03	-0.02
Rhs,h9	+0.00	+0.03	-0.12	-0.03	+0.01
Rhs,h10	+0.00	+0.03	-0.13	-0.08	+0.05
Rhs,h11	+0.00	-0.01	-0.01	-0.11	+0.12
Rhs,h12	+0.00	+0.07	+0.05	-0.11	+0.14
Rhs,h13	+0.00	+0.15	+0.04	-0.11	+0.15
Rhs,h14	+0.00	+0.10	+0.01	-0.02	+0.10
Rhs,h15	+0.00	+0.20	+0.01	+0.02	+0.05
Rhs,h16	+0.00	+0.03	+0.01	+0.04	-0.00

2.3 Experimental setup

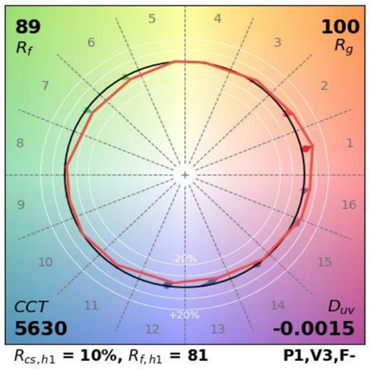
The spectral power distributions (SPD) of the light sources were used as the study's independent variables. For a retail application, two parallel images mirroring the application's usual products are used, as illustrated in Figure 5, so that viewers may assess the hue of the objects. Real fruits and veggies were used, too. Preference for colours was the dependent variable. Participants were required to make a forced choice from among all the pairings of light spectra, selecting the one in which they thought the colours of the objects would seem best.



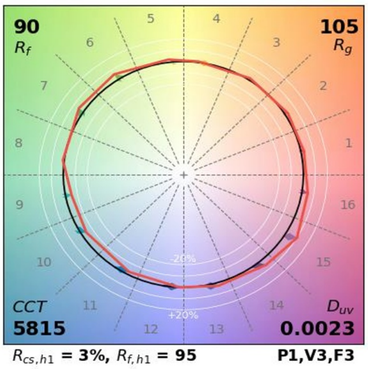
4.1. Source ID 1 - LER 203.37lm/W



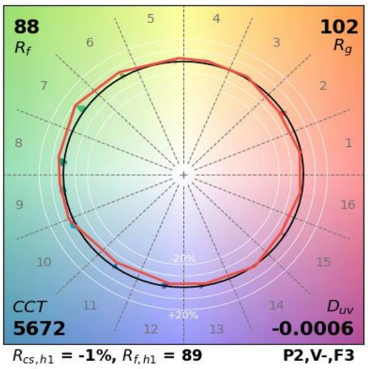
4.4. Source ID 4 - LER 235.46lm/W



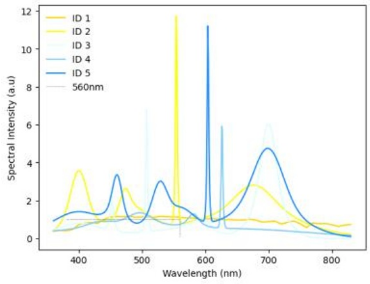
4.2. Source ID 2 - LER 165.09lm/W



4.5. Source ID 5 - LER 174.90lm/W



4.3. Source ID 3 - LER 129.24lm/W



4.6. Relative spectral radiant power distributions of the five sources, with each source's wavelength being normalised at 560nm.

Fig. 4. LER values, SPDs, and colour vector graphics for the five experimental sources.

Fig. 5. View of the test object arrangement. The 'Consumer Goods' category is represented by the products in the rear row, while the 'Real Produce' category is represented by the goods in the front row.

2.4 Experiment design

Each observer was tasked with comparing their perception of colour across all conceivable combinations of various light sources. These comparisons were made in a random sequence for each lighting application. Each observer compared a total of 25 pairs of light settings, including 20 pairs of mixed spectra and 5 pairs of null conditions. The observer answered a questionnaire on their overall favourite colour from the two sources for each comparison pair. The experiment was set up in this way to rule out any range effects and to encourage the observer to pay attention to how the colours in the two images compare rather than their appearance in the backdrop. When making the comparison, he or she was free to rotate their point of view and spend as much time as necessary.

2.5 Observers

25 observers, including 11 men and 14 women, took part in the study. The observers' ages ranged from 25 to 67, with a mean of 33 years (18 participants between 25 and 33, 5 participants between 33 and 41 and 2 participants 64 and 67). This study includes older participants; however, they are not the most important, and this is significant because ageing impacts eye health. [63]. The 24 Plate Ishihara Colour Vision Test [64] revealed that all individuals had normal colour vision.

3 Results

Each observer assessed several sets of lighting conditions. Each observer's assessments were not independent of one another. To ascertain the impact of SPD and illumination application on preference evaluation, a repeated measures analysis was used. To check for any interval bias between the first and second conditions in each pair, null condition pairs were included. No discernible difference in the participants' choices of the first vs the second spectrum was seen for the null condition pairs.

This article's main objective was to quantify the variation in human perceptual reactions over a range of gamut forms. After all comparisons, each participant was asked to pick and rate the top three booth hues that most influenced their assessment of their colour preferences. The predominant colours were colours of red, green, and yellow, as illustrated in Figure 6. Real goods were scored higher (more impactful) than its consumer goods equivalent for all couples within a single colour group (80% real and 20% consumer good scores). This supports Wei and colleagues' [34] result that "natural objects were generally given higher importance."

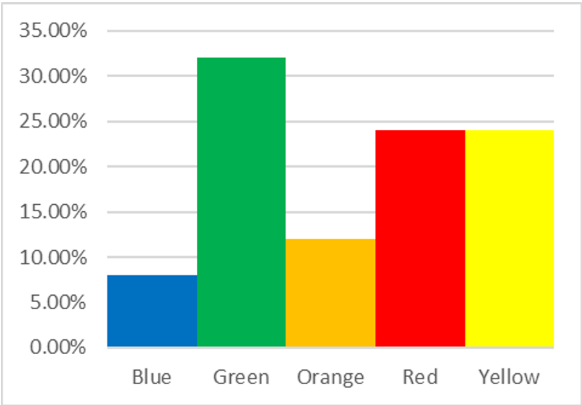


Fig. 6. Percentage of times that each colour was chosen as the one that most strongly influenced participants' assessments of their colour preferences.

4 Discussion

The individuals' judgement of their preferences cannot be precisely characterised, as other studies have shown [31, 66–67]. A mix of naturalness and vividness is likely to be preferred in terms of colour, according to factor and correlation meta-analysis [26, 48]. Higher vividness could be chosen for some applications while higher naturalness might be chosen for others.

Despite the limits of a single metric, it is nonetheless required for average customers since giving a consumer buying a light source too much information would be both confusing and overwhelming. Additionally, standards often only call for one measurement. The notion of general illumination should be carefully considered when developing such a single scale or metric. A word category, a classification, and a single metric are probably insufficient for lighting experts or expert users. Summarising the hue-specific colour quality data from the many test samples in the measure into an overall colour quality index necessarily results in information loss. In any case, any method that reduces the info to just one number is likely to fall short of satisfying the objectives of lighting specialists or professionals, who frequently need information on specific hues. Therefore, since a graphical representation really offers a lot more information than a single number, it may be useful to lighting specialists. Hue shift has a greater impact on specific applications, like a manufacturing line, than saturation enhancement. The colour vector plot is the most suitable method for giving lighting professionals and specialists extensive information about the whole colour rendering shifts - saturation and hue - connected with a test light source.

5 Conclusions

In a psychophysical investigation, sources for a retail lighting application with equal Rf and Rg values and various gamut shapes were compared for naturalness, vividness, and preference. The analysis's findings make it abundantly evident that the observers' standards for measuring hue preference varied.

The selection of the experimental object collection should be based on defensible criteria because it is a crucial decision [65]. The present object collection was chosen to include as equal a distribution of hues as feasible, along with some recognisable things (i.e., objects with strong memory connections). The experimental object collection is biased towards the red, green, and yellow colours because of the inability to establish a uniform hue distribution. As a result, sources with a higher Rcs,hi relative to these colours are more desired. In that situation, the most efficient sources were the experimental ones with IDs 2, 3, and 5. Further research may focus on the utilisation of a wider variety of experimental sources, observers, and experimental objects.

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