

DOI: <https://doi.org/10.38027/ICCAUA2025EN0063>

## Investigation of the Impact of Light Colour on Surface Colour Perception: A Case Study on Red Surfaces

Havva Gül Sümer<sup>1</sup>, Leyla Dokuzer Öztürk<sup>2</sup>

Yildiz Technical University, Faculty of Architecture, Department of Architecture, Istanbul, Türkiye<sup>1</sup>

Yildiz Technical University, Faculty of Architecture, Department of Architecture, Istanbul, Türkiye<sup>2</sup>

<sup>1</sup> E-mail: [gul.yazici@std.yildiz.edu.tr](mailto:gul.yazici@std.yildiz.edu.tr), <sup>2</sup> E-mail: [dokuzer@yildiz.edu.tr](mailto:dokuzer@yildiz.edu.tr)

### Abstract

**Received:** 10 January 2025  
**Revised:** 18 June 2025  
**Accepted:** 18 June 2025  
**Available online:** 5 July 2025

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This article has been selected and peer-reviewed for publication in this journal as part of the 8th International Conference of Contemporary Affairs in Architecture and Urbanism, held on 8–9 May 2025 in Alanya, Türkiye.

The perceived colour of a surface is governed by the spectral reflectance properties of the surface and the spectral power distribution of the illuminating light source. Accurate perception of surface colours is of paramount importance in museums and art galleries. The chromatic characteristics of the light used in exhibition spaces must be carefully chosen, considering the diverse attributes of the exhibits, and it is crucial to maintain the stability of this light colour across time and space. In galleries illuminated by natural daylight, the intensity and colour of light entering through windows vary throughout the day. Moreover, the use of supplementary artificial lighting at different times of the day can amplify changes in the ambient light colour, potentially altering the impact and meaning of artworks and diminishing the artist's intended message. This study investigates the variation in perceived surface colour as a function of the colour of the illuminating light. Red surfaces with varying levels of value and saturation, two spectral power distributions representative of daylight, and nine LED light sources were analysed as lighting conditions. The colour appearances of different surface-light combinations were calculated using the Yxy colour space. To illustrate how the perceived colour of an artwork shifts under different light sources, a geometric graphic design was developed and coloured according to specific colour schemes. The changes in the colours within this graphic, corresponding to varying light sources, were visualized using computer software. The findings emphasize the critical role of light colour in determining the perceived colours of artworks. These results offer valuable insights for the selection of suitable light sources not only for art exhibition spaces but also for other environments featuring colourful objects.

**Keywords:** Surface colour; Light colour; Colour appearance; Daylight; Electric lighting.

### 1. Introduction

The perceived colour of a surface is influenced not only by its intrinsic physical properties but also by the prevailing lighting conditions and the perceptual characteristics of the observer. This perception is governed by the interaction between the surface's spectral reflectance properties and the spectral power distribution of the incident illumination.

Such considerations are particularly critical in environments like museums and art galleries, where accurate colour perception is essential. Works of art communicate aesthetic and conceptual messages through their colour schemes in addition to their form and content. In this regard, the characteristics of the lighting design employed in exhibition spaces can have a direct impact on the viewer's experience and interpretation of the artwork. In interiors illuminated by daylight, both the quantity and spectral composition of incoming light through windows vary throughout the day. When this variability is compounded by electric lighting activated at different times, temporal and/or spatial fluctuations in the perceived colours of artworks may occur. These perceptual variations have the potential to alter the viewer's interpretation, possibly deviating from the meaning originally intended by the artist.

The perceived colour of a surface is primarily determined by the surface's intrinsic colour properties and the spectral characteristics of the incident light. Moreover, it is modulated by several additional factors, including the size, shape, structure, and surround of the stimulus area, the state of adaptation of the observer's visual system, and the observer's prior experience with prevailing and similar situations of observation (CIE, 2020). A considerable body of literature has addressed the influence of the light source on perceived colour, examining this relationship for a range of purposes. Some studies have concentrated on the variation in the perceived colour of architectural façades under daylight conditions (Küçükılıç-Özcan & Ünver, 2022; Asarzadeh et al., 2019; Kwiatkowska & Kowalska, 2018; Sochocka & Fridell Anter, 2017). Others have investigated how perceived colour shifts under artificial lighting (Yavuz & Ünver, 2009) or how lighting conditions affect the colour appearance of moist soil (Baek et al., 2023). In addition, several studies have explored viewer preferences regarding the lighting of artworks in museum settings. In an experimental

study, paintings exhibiting varying chromatic characteristics were illuminated using light sources with correlated colour temperatures (CCTs) of 3000 K, 3500 K, 4000 K, 5000 K, and 6000 K. Regardless of the specific colour content of the paintings, participants showed a general preference for intermediate colour temperatures ranging between 3500 K and 5000 K, while the lowest (3000 K) and highest (6000 K) CCTs were evaluated less favorably (Feltrin et al., 2017). Comparable findings have been reported in other studies investigating observer preferences for the colour temperature of light used to illuminate artworks, with optimal values typically clustered around 3500 K (Németh & Kosztyán, 2016), 3600 K (Scuello et al., 2004-1), and 3700 K (Scuello et al., 2004-2). Furthermore, some scholars have suggested that artists may prefer their works to be displayed under lighting conditions that closely resemble daylight (Csuti et al., 2014).

A review of the literature indicates that the appearance of surface colours under varying illumination conditions is most commonly assessed by observers through successive evaluations. Such sequential observation constrains the ability to conduct simultaneous comparisons of colour perception under different lighting environments and imposes limitations on the interpretation of perceptual colour shifts. Furthermore, the majority of existing research on the impact of light colour on surface colour perception predominantly relies on qualitative assessments derived from subjective visual observations. In contrast, systematic methodologies that integrate quantitative analysis with visual modeling remain scarce. Evaluations grounded in personal aesthetic judgment cannot often yield objective, reproducible, and comparable data concerning the magnitude and direction of perceptual colour changes. To address this methodological gap, the present study aims to systematically investigate the perceptual behavior of a specific surface colour—specifically, red surfaces exhibiting variations in value and chroma—under a range of natural and electric light sources. By employing a hybrid methodology that combines quantitative assessment with visual representation, this study seeks to provide a more objective framework for evaluating the influence of illuminant on surface colour perception. In doing so, it aspires to contribute a novel and comprehensive perspective to the existing body of knowledge concerning surface-light interactions.

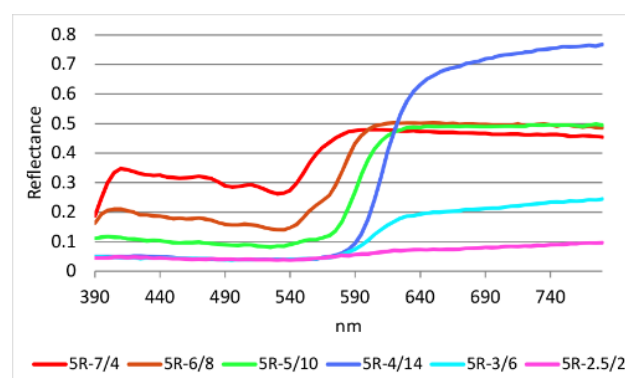
## 2. Methodology

The methodological framework of this study is designed to investigate variations in the perceived colour of surfaces as a function of the spectral power distribution of the illuminating light. Additionally, it seeks to elucidate the influence of different types of light sources on the visual appearance of colour arrangements. The research was carried out through the following sequential steps:

1. Selection of surface colours and light sources
2. Characterization of the perceived colour of surfaces utilizing the CIE xyY colour space
3. Development of colour compositions
4. Visualization of colour compositions depending on the light source

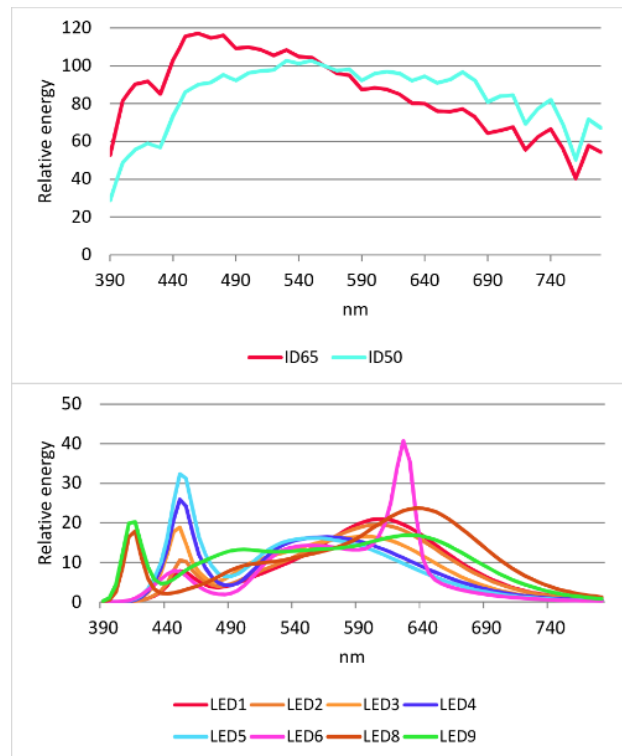
## 3. Selection of Surface Colours and Light Sources

The colours examined in this study were selected by the Munsell Color System. The focus of the study was on the hues of red (5R), yellow (5Y), green (5G), blue (5B), and purple (5P), which are uniformly distributed along the hue circle of this system. The findings presented in this paper specifically pertain to the colour red. Spectral reflectances for 40 colour samples, representing various values and chromas of red, were generated (University of Eastern Finland, n.d.). The spectral reflectances of six selected colours are presented as examples in Figure 1.



**Figure 1.** Examples of Spectral Reflectances for Red Surfaces.

Two types of daylight (ID65, ID50) (Figure 2a) and eight distinct LED light sources (LED1, LED2, LED3, LED4, LED5, LED6, LED8, LED9) (Figure 2b) were utilized as light sources (International Commission on Illumination, n.d.). Following the computations for the 5R-4/14 Munsell colour under LED7 illumination, an 'out of range' warning was triggered when the corresponding data were input into the Munsell Conversion Software (WallkillColor, n.d.) to derive the RGB values of the visible colour. This limitation prevented to determine the colour shift under the LED7 light source and, as a result, hindered the ability to perform comparative analysis with other light sources. Consequently, LED7 was excluded from the scope of the study. The spectral power distributions for all light sources utilized in the study are presented collectively in Figure 2.



2a. Daylight Sources.

2b. LED Light Sources.

Figure 2. Spectral Power Distributions of Light Sources.

The x and y chromaticity coordinates of the light sources examined in this study were computed using the 2° observer values (Colour & Vision Research Laboratory, n.d.). These computed coordinates were subsequently utilized to determine the colour temperatures of the respective light sources (Table 1) (Waveform Lighting, n.d.).

Table 1. x, y coordinates and colour temperatures of light sources.

Light source	x	y	Colour temperature
ID65	0.3115	0.3324	6549 K
ID50	0.3461	0.3626	4992 K
LED1	0.4625	0.4100	2658 K
LED2	0.4424	0.4042	2912 K
LED3	0.3807	0.3759	3989 K
LED4	0.3467	0.3551	4949 K
LED5	0.3154	0.3305	6354 K
LED6	0.4528	0.4063	2768 K
LED8	0.4536	0.3976	2682 K
LED9	0.3782	0.3734	4038 K

As presented in Table 1, ID65 daylight exhibits a cool light colour, whereas ID50 daylight displays a neutral light colour. Among the LED light sources, one (LED5) is characterized by a cool light colour, three (LED3, LED4, LED9) by a neutral light colour, and four (LED1, LED2, LED6, LED8) by a warm light colour.

**4. Specification of the Perceived Colour of Surfaces Using the CIE xyY Colour Space**

The perceived colour of surfaces for 440 distinct combinations of 40 colours and 11 light sources was computed within the framework of the CIE xyY colour space. In these calculations, energy (S) values (International Commission on Illumination, n.d.), reflectances (ρ) (University of Eastern Finland, n.d.), and 10° observer data values ( $\bar{x}, \bar{y}, \bar{z}$ ) (Colour & Vision Research Laboratory, n.d.) were taken at 5 nm intervals. The tristimulus values X, Y, and Z of the perceived colour were derived using Formula 1, the chromaticity coordinates x, y were calculated using Formula 2, and the Y component was obtained through Formula 3. The resulting xyY values are exemplified in Tables 2-3, following the procedural steps outlined below.

$$X = \int S(\lambda) * \bar{x}(\lambda) * \rho(\lambda) d\lambda; \quad Y = \int S(\lambda) * \bar{y}(\lambda) * \rho(\lambda) d\lambda; \quad Z = \int S(\lambda) * \bar{z}(\lambda) * \rho(\lambda) d\lambda \tag{1}$$

$$x = X / (X + Y + Z); \quad y = Y / (X + Y + Z); \quad z = Z / (X + Y + Z) \tag{2}$$

$$Y = (100 / (\int S(\lambda) * \bar{y}(\lambda) d\lambda)) * (\int S(\lambda) * \bar{y}(\lambda) * \rho(\lambda) d\lambda) \tag{3}$$

**Table 2.** Examples of CIE xyY values for red surfaces: ID65, ID50, LED1, LED2, and LED3.

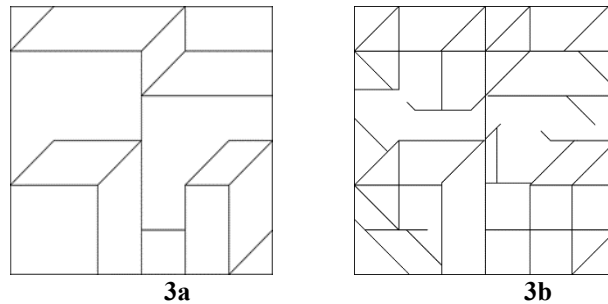
Munsell color system	ID65			ID50			LED1			LED2			LED3		
	x	y	Y	x	y	Y	x	y	Y	x	y	Y	x	y	Y
5R-7/4	0.36	0.33	36.59	0.39	0.36	37.23	0.50	0.39	40.54	0.48	0.39	40.04	0.42	0.37	38.56
5R-6/8	0.41	0.33	25.56	0.45	0.35	26.60	0.55	0.38	31.57	0.53	0.38	30.69	0.48	0.36	28.30
5R-5/10	0.46	0.33	14.78	0.50	0.35	17.79	0.58	0.36	22.05	0.57	0.36	21.20	0.52	0.35	18.97
5R-4/14	0.53	0.32	10.30	0.57	0.33	11.30	0.63	0.34	14.51	0.62	0.34	13.74	0.58	0.33	11.69
5R-3/6	0.43	0.33	6.20	0.47	0.34	6.51	0.57	0.36	7.67	0.55	0.36	7.42	0.49	0.35	6.75
5R-2.5/2	0.35	0.33	4.67	0.39	0.35	4.75	0.50	0.39	5.10	0.49	0.38	5.03	0.42	0.36	4.85

**Table 3.** Examples of CIE xyY values for red surfaces: LED4, LED5, LED6, LED8, and LED9.

Munsell Color System	LED4			LED5			LED6			LED8			LED9		
	x	y	Y	x	y	Y	x	y	Y	x	y	Y	x	y	Y
5R-7/4	0.39	0.35	37.91	0.36	0.33	37.21	0.50	0.39	39.45	0.50	0.39	39.78	0.43	0.37	38.02
5R-6/8	0.44	0.35	26.98	0.41	0.33	25.93	0.55	0.37	30.55	0.55	0.37	31.12	0.48	0.36	28.05
5R-5/10	0.48	0.34	17.57	0.45	0.33	16.65	0.58	0.36	22.02	0.58	0.36	22.37	0.53	0.35	19.26
5R-4/14	0.54	0.33	10.29	0.51	0.32	9.49	0.63	0.33	15.77	0.63	0.33	16.00	0.59	0.33	12.76
5R-3/6	0.45	0.34	6.32	0.42	0.32	6.06	0.57	0.36	7.88	0.57	0.36	7.95	0.51	0.35	6.97
5R-2.5/2	0.39	0.34	4.74	0.35	0.32	4.67	0.50	0.38	5.06	0.50	0.38	5.11	0.42	0.36	4.86

**5. Construction of Colour Compositions**

To illustrate the impact of changes in the perceived colour of surfaces, caused by varying illuminating light sources, on the perception of colour compositions, a colour design was created on a two-dimensional surface. The colour composition was constructed through a graphic representation intended to symbolize terraced architectural structures, evoking the impression of stacked prisms (Figure 3a). This design was developed using the artificial intelligence program LookX.ai, culminating in the final form of the composition. The completed composition was subsequently visualized in Photoshop (Figure 3b).



**Figure 3.** Graphic Composition Prepared for the Creation of a Colour Arrangement.

The aim is to demonstrate the differences in the perception of red surface colours, which vary according to the type of light source illuminating them, as they function as components of a unified whole. To achieve this, the designed achromatic graphic composition was colourized by applying seven distinct colour arrangements, which included two value contrasts, one chroma contrast, and four same-hues arrangements. Each colour arrangement incorporated six different colours, with the hue-value/chroma notations for the selected colours provided in Table 3. To convey a specific artistic message, the areas within the composition where each of the six colours in each arrangement would be applied were carefully determined. The results about the same-hues arrangement, denoted by number 7 in the final column of the table, are discussed in this paper.

**Table 4.** Colour arrangements applied to the composition.

Arrangement No.	1	2	3	4	5	6	7
Colour No.	Value contrast	Value contrast	Chroma contrast	Same-hue	Same-hue	Same-hue	Same-hue
1	5R-7/1	5R-7/2	5R-5/10	5R-5/10	5R-7/4	5R-4/14	5R-7/4
2	5R-6/1	5R-6/2	5R-5/8	5R-7/4	5R-4/8	5R-4/1	5R-6/8
3	5R-5/1	5R-5/2	5R-5/6	5R-6/4	5R-4/6	5R-4/2	5R-5/10
4	5R-4/1	5R-4/2	5R-5/4	5R-5/4	5R-4/4	5R-4/4	5R-4/14
5	5R-3/1	5R-3/2	5R-5/2	5R-4/4	5R-4/2	5R-4/6	5R-3/6
6	5R-2.5/1	5R-2.5/2	5R-5/1	5R-3/4	5R-4/1	5R-4/8	5R-2.5/2

**6. Visualization of Colour Compositions Based on the Illuminating Light Source**

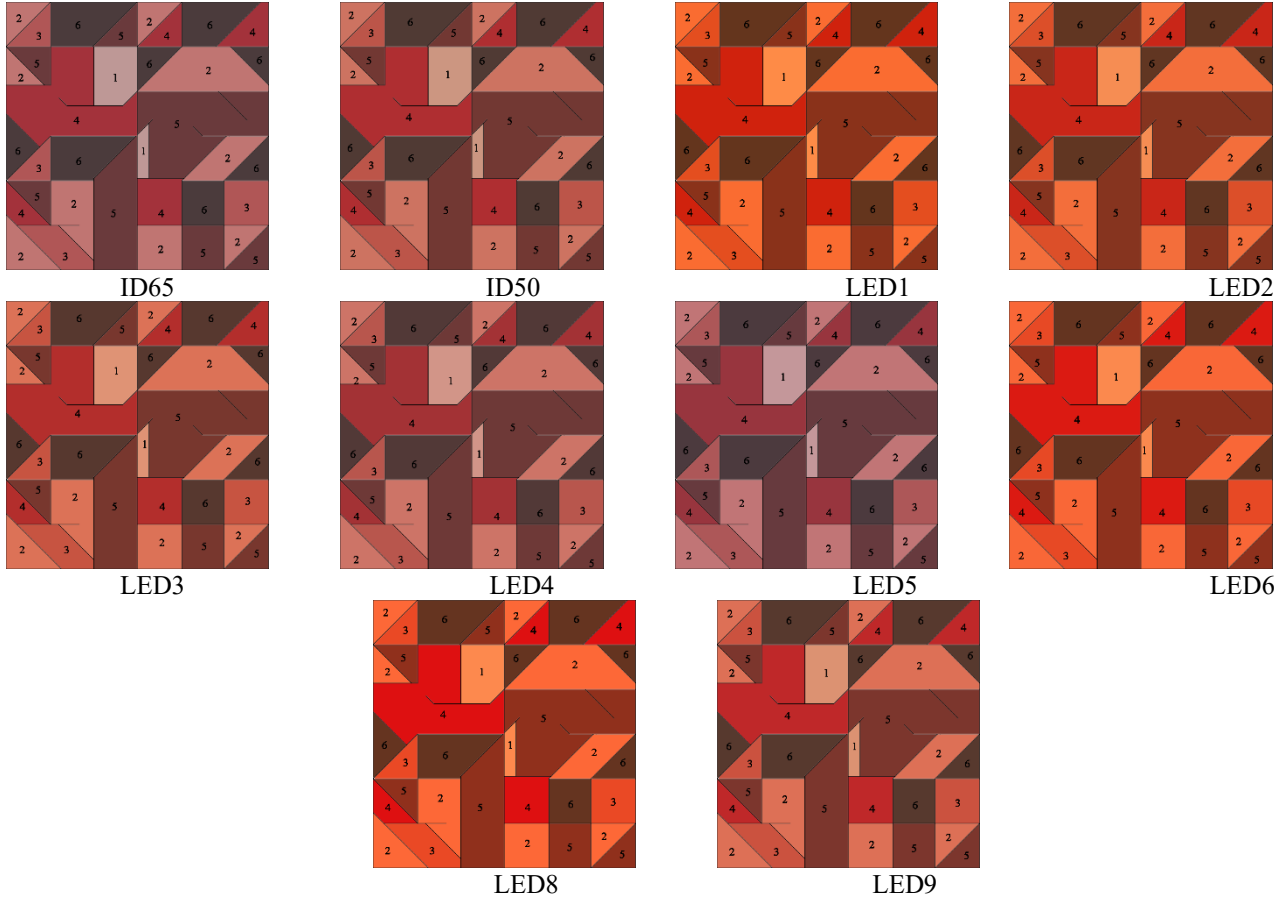
The appearance of the colours in the same-hue arrangement (colour arrangement 7) under eleven different light sources has been visualized using Photoshop (Table 3, column 8). The steps of this process are outlined below:

1. The XYZ values of the surface colours were calculated using the computed xyY values through Equation 4.

$$X=xY/y; Y=Y; Z=(1-x-y)Y/y \tag{4}$$

2. The RGB equivalents of the XYZ values were determined using the Munsell Conversion Software (WallkillColor, n.d.).
3. The colour arrangement of same-hues was visualized in Photoshop using the RGB values of the surface colours.

The visual representation of the colour arrangement of same-hues under ten distinct light sources is provided in Figure 4. The specific regions within the arrangement, where the six colours from the composition are applied, are identified by their corresponding colour numbers, as detailed in Table 4.

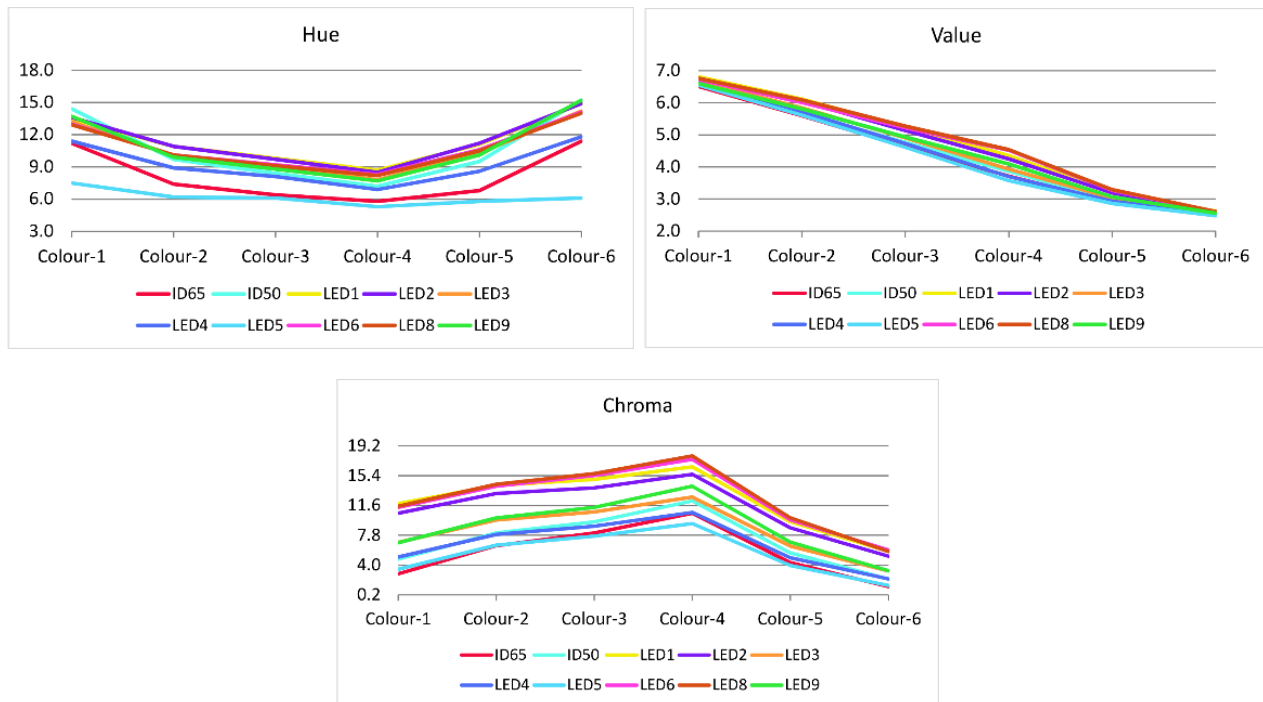


**Figure 4.** The Appearances of the Colour Arrangement 7 Under Different Light Sources.

### 7. The Evaluation of the Results

The visual appearance of the colour composition, and consequently its perceptual impact, is influenced by the spectral power distribution of the illuminating light. The extent of this variation is contingent upon the colour temperature of the light emitted by the respective light source. To quantitatively characterize the alterations in the perceived colours induced by different light sources, it was essential to establish the Munsell Color System notations for the apparent colours. To achieve this, the RGB values of the perceived colours under each light source were converted into their corresponding Munsell Color System notations using the Munsell Conversion Software. The resulting data are presented in Figure 5. These results can be further analyzed across the three colour attributes as follows:

- **Hue:** All six surface colours displayed shifts in hue across the various light sources, with the red surfaces shifting towards the orange direction on the hue circle. In other words, the red hues transitioned into orangish-red tones. It can be concluded that hue shifts were most pronounced under warm lights and least noticeable under cool lights. The extent of the hue shift is also influenced by the chroma component. Specifically, colours with lower chroma exhibited more pronounced hue shifts, while those with higher chroma displayed less significant changes in hue.
- **Value:** The perceived value of the surface colours was darker under cool lights, while the surface colours became lighter as the colour of light became warmer.
- **Chroma:** The chroma of surface colours decreased under two cool lights (ID65 and LED5), while it increased under four warm lights (LED1, LED2, LED6, LED8) and one neutral light (LED9). For the remaining neutral lights (ID50, LED3, LED4), chroma increased on some surfaces while it decreased on others. The variation in chroma was less pronounced for colours with low chroma and more noticeable for colours with high chroma. This trend demonstrates an inverse relationship with hue shifts induced by chroma, showing a counteracting pattern.



**Figure 5.** The Variation in Surface Colour Attributes According to the Light Source.

## 8. Conclusions

In this study, the perceived colours in various surface-light combinations were computed within the xyY colour space, employing two daylight and nine LED light sources. To facilitate digital visualization of the perceived colours, their corresponding RGB values were derived. The obtained data were subsequently visualized through a composition of geometric forms, effectively illustrating how surface colours are altered under different lighting conditions. The results of this study are anticipated to make a significant contribution to the field of lighting design, particularly in spaces where artworks are exhibited, and can also serve as a reference for the selection of light sources in other functional environments containing coloured objects. Furthermore, the findings presented herein offer valuable insights not only for the disciplines of architecture and art but also for other fields in which colour measurement is employed as a fundamental data parameter. Specifically, in studies where the assessment of materials' or products' performance, quality, or visual characteristics is based on colour analysis, the impact of the lighting conditions under which the tests are conducted is an indispensable factor that must be carefully considered.

Expanding on this approach, which effectively illustrates the influence of light sources on colour perception, the study will be extended to encompass yellow, green, blue, and purple hues. In addition to colour compositions in which these four hues are individually applied, the study will also incorporate colour arrangements that combine different hues, thereby enhancing the comprehensiveness and depth of the study's findings.

## Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Conflict of Interests

The Author(s) declare(s) that there is no conflict of interest.

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