FACULTY OF TEXTILE ENGINEERING TUL

COLOR APPEARANCE OF OPTICALLY BRIGHTENED TEXTILES

Azmary Akter Mukthy, M.Sc.

SUMMARY OF THE THESIS

Title of the thesis: **Color Appearance of Optically Brightened Textiles**
Author: **Azmary Akter Mukthy, M. Sc.**
Field of study: **Textile Engineering**
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Department: **Department of Material Engineering**
Supervisor: **doc. Ing. Martina Viková, Ph.D.**

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Ing. Pavel Valíček, Ph.D.	VSB – Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science

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Abstract

This research examines the appearance of optically brightened materials under different lighting conditions, focusing on how ultraviolet (UV) content influences perceived whiteness and color consistency. The aim of this study was to develop an interpolation-based technique for calculating luminescent spectral radiance factor of optically brightened textiles under altered lighting settings, addressing challenges posed by optical brightening agents and UV content in light sources. Both fluorescent and non-fluorescent samples were analyzed, consisting of metameric sample pairs, D-H Color Rule and optically brightened textiles. A series of controlled visual assessments and spectrophotometric measurements were conducted under multiple illuminants including D65, TL84, A, CWF and Light-Emitting Diodes (LEDs) with different correlated color temperatures. A measurement procedure was developed to quantify the fluorescent component of optically brightened materials under different calibrated UV content. The analysis focuses on metameric effects, color appearance variations, and the influence of fluorescence on sample matching and perception. The proposed method provides improved agreement between visual assessments and instrumental measurements and highlights more reliable evaluation of optically brightened materials. This contributes a practical and standardized approach for industries and color-critical applications where whiteness and consistent color rendering are essential.

Keywords: Metamerism, D-H Color Rule, Optical brightening agents, Light-Emitting Diodes, UV, Luminescent spectral radiance factor β_L

Anotace

Tato výzkumná práce zkoumá vzhled opticky zjasněných materiálů za různých světelných podmínek, přičemž se zaměřuje na to, jak obsah ultrafialového (UV) záření ovlivňuje vnímanou bělost a barevnou konzistenci. Cílem této studie bylo vyvinout interpolační techniku pro výpočet luminiscenčního spektrálního radiačního faktoru opticky zjasněných textilií za změněných světelných podmínek, která by řešila problémy s barevným vzhledem výrobků způsobené optickými zjasňujícími prostředky a různým obsahem UV záření ve světelných zdrojích. Byly analyzovány fluorescenční i nefluorescenční vzorky, které se skládaly z metamerních párů vzorků, D-H barevného pravítka a opticky zjasněných textilií. Byla provedena řada kontrolovaných vizuálních hodnocení a spektrofotometrických měření při použití různých světelných zdrojů, včetně D65, TL84, A, CWF a LED s různými korelovanými teplotami chromatičnosti. Byl vyvinut měřicí postup pro kvantifikaci fluorescenční složky opticky zjasněných materiálů při různých kalibrovaných hodnotách obsahu UV záření. Analýza se zaměřuje na metamerické efekty, variace vzhledu barev a vliv fluorescence na shodu a vnímání vzorků. Navrhovaná metoda poskytuje vyšší shodu mezi vizuálními hodnoceními a přístrojovými měřeními a zdůrazňuje spolehlivější hodnocení opticky zjasněných materiálů. To přispívá k praktickému a standardizovanému přístupu pro průmyslová odvětví a aplikace, kde je rozhodující bělost a konzistentní podání barev.

Klíčová slova: Metamerie, D-H barevné pravítko, Optické Zjasňující Prostředky, Světelné diody, UV záření, Činitel luminiscenční záře β_L

Summary

1. Introduction

The color rendering properties of textiles with optical brightening agents is critical due to its influence by UV-sensitive lighting conditions [1-3]. Also the difference between two metameric colors can come from the spectral power quality of different light sources [4-10]. The widespread use of optical brightening agents (OBAs) in textiles and the emerging market of lighting industries, make it crucial to study the visual perception of whiteness and color [11]. In the textile industry, there is the greatest need for optical brighteners when brightening cotton, silk, wool, nylon, polyester, acrylic and cellulose acetate, etc [12-13]. The concept of extreme whiteness is the main motive for achieving the brightest whiteness with OBAs. OBAs are chemical compounds that absorb light in the ultraviolet range of the electromagnetic spectrum and re-emit light in the blue to blue-violet range through fluorescence. The blue to blue-violet part of the spectrum that is visible to the human eye has a longer wavelength and ultraviolet light has a shorter wavelength and is invisible to humans. Thus, by adding more UV light, FWAs provide an excellent whiteness appearance.

The total appearance of optically brightened materials is a combination of two components: non-fluorescent reflection, known as reflected spectral radiance factor, β_R and the fluorescence emission, known as the luminescent spectral radiance factor, β_L. The summation of both quantities describes the total radiance factor, β_T of the material. However, it is important to consider the potential challenges for obtaining the total spectral radiance factor of a optically brightened textiles illuminated by a specified standard illuminant since the light emitted from a fluorescent sample is the sum of the reflected light and the fluoresced light. The addition of new light sources increases the complexity of the scenario for the colorimetric study of color and white textiles, specifically those contain OBAs [14-16].

2. Purpose and the aim of the thesis

- The aim of this study was to develop an interpolation-based technique for calculating luminescent spectral radiance factor of optically brightened textiles under altered lighting settings, addressing challenges posed by optical brightening agents and UV content in light sources. Both fluorescent and non-fluorescent samples were analyzed, consisting of metameric sample pairs, D-H Color Rule and optically brightened textiles to achieve the following objectives:

    - To develop and validate a measurement technique for calculating luminescent spectral radiance factor accurately. This method also aimed to understand the reliability of interpolation technique for predictive UV Impact. A detailed step-by-step procedure for calculating luminescent spectral radiance factor is presented to ensure clarity and reproducibility.
    - To achieve a more comprehensive and practical assessment of the color appearance of optically brightened textiles under different illumination conditions by combining conventional measurement with this interpolation based calculation
    - To investigate the influence of UV content on total spectral radiance and whiteness value of the optically brightened samples when exposed to light sources with varying UV content.
    - To understand the interaction between light source SPD, UV content and color perception of optically brightened textiles.
    - To evaluate the relation between whiteness indices and color differences (*ΔE*) under selected lighting conditions.

- The purposes of evaluation of matte colored metameric sample pairs under different lighting conditions are:

    - To determine metameric differences for diverse lighting settings
    - How color matching differs under different conditions

  - Performance of different metamerism index and color difference formula
  - How strong correlation between visual judgment and calculated value
  - Effects of illuminance on visual differences
  - To analyze the perceptual significance of different metameric indices

- The purposes of analyzing the appearance of two color scales of the D & H Color Rule under different lighting conditions are:

  - To investigate observer variability under varying lighting conditions
  - Identifying pairs with large ΔE to highlight significant color difference
  - Agreement analysis of observers matching pairs under each light sources
  - Influence of SPD on visual assessment
  - Relation between visual assessment and color difference across light sources

3. Overview of the current state of the problem

Recent progresses in illuminant technology, LED lights have taken the market by storm over the last few years, largely due to their high efficiency, affordability and extensive use in exterior and interior lighting. Each of these light sources has different spectral characteristics that strongly influence the human perception of whiteness and color [17-24]. Color scientists face challenges of accurately simulating CIE standard Illuminant D65, particularly for optically brightened materials and emphasize the importance of accurate measurements of ultraviolet content in illuminants [25-28].

Current methods explore the methodologies for spectrophotometric and spectroradiometric measurements of materials, particularly focusing on the effects of ultraviolet (UV) content on the whiteness of optically brightened materials [29-37]. There is still a need for standardized UV levels to ensure consistent evaluations of optically brightened materials. The interaction between spectral radiance factors, whiteness indices, and metamerism in optically brightened textiles remains underexplored.

4. Methods used, studied material

4.1. Experiment-1: Metameric sample evaluation

4.1.1. Samples used

Color samples contained 12 matte colored metameric sample pairs were used in experiment 1 as shown in Figure 1. Photo-paper was used as main materials for producing samples with HP DeskJet 2600 series printer.

Figure 1. Twelve matte colored metameric sample pairs under D65

4.1.2. Lighting conditions

For the visual assessment, two lighting setups were used: an LED-based setup, designated as LCAM LEDs and a setup containing standard illuminants, designated as GretagMacbeth (now X-Rite) Judge-II.

- **LCAM LEDs**

The viewing cabinet featured an interior coated with Munsell N7 spectrally neutral paint and had internal dimensions of 42 cm (width) × 74 cm (depth) × 74 cm (height). It was equipped with four LED light sources with nominal correlated color temperatures (CCTs) of 2700 K, 4000 K, 5000 K, and 6500 K. The illuminance level inside the cabinet was adjustable, ranging from 50 lx to 1500 lx. These light sources were solid-state LEDs utilizing a violet pump chip and a ternary phosphor. Figure 2 illustrates the physical layout of the cabinet equipped with four distinct LED channels and the spectral power distributions

(SPDs) of these LEDs, highlighting their differences in spectral shape and relative intensity across wavelengths. These variations directly influence the perceived color and illuminance delivered by each source.

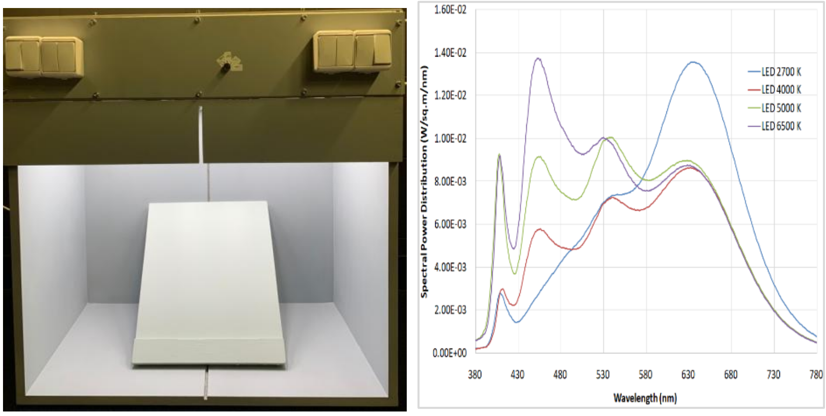


Figure 2. Left: LCAM LEDs viewing cabinet and Right: SPD of four LEDs

Although categorization by nominal CCT is common practice, the specific measured CCT values and other parameters for each LED type are provided in the corresponding Table 1.

Table 1. Parameters of the used LED lighting sources

Nominal CCT [K]	**Measured values**	**Illuminance level [lux]**					
		50	**100**	**200**	**500**	**1000**	**1500**
6500	*x*	0.3023	0.3015	0.3014	0.3016	0.3020	0.3036
	y	0.3116	0.3112	0.3111	0.3113	0.3117	0.3128
	CCT [K]	7225	7279	7406	7388	7351	7233
	Luminance [$\mathrm{cd/m^2}$]	6.64	11.98	7.53	17.06	29.48	178.41
	CRI	93	93	93	93	93	93
5000	*x*	0.3361	0.3357	0.3356	0.3359	0.3363	0.3387
	y	0.3537	0.3535	0.3534	0.3536	0.354	0.3550
	CCT [K]	5254	5370	5374	5363	5345	5258
	Luminance [$\mathrm{cd.m^{-2}}$]	8.18	14.47	8.97	19.92	33.67	198.22
	CRI	98	98	98	98	98	98
4000	*x*	0.3693	0.3677	0.3676	0.3678	0.3682	0.3712
	y	0.3678	0.3671	0.3671	0.3673	0.3676	0.3693
	CCT [K]	4176	4300	4304	4299	4290	4211
	Luminance [$\mathrm{cd.m^{-2}}$]	4.82	8.53	5.33	12.19	21.18	136.23
	CRI	97	97	97	97	97	97
2700	*x*	0.4361	0.4346	0.4344	0.4347	0.4355	0.4390
	y	0.4066	0.4067	0.4068	0.4071	0.4075	0.4082
	CCT [K]	3034	3061	3064	3061	3050	2998
	Luminance [$\mathrm{cd.m^{-2}}$]	4.72	10.34	6.53	14.78	25.67	157.56
	CRI	95	95	95	95	95	95

The visual assessment was performed under four LEDs and illuminance levels from dark to very bright (50lx, 100lx, 200lx, 500lx, 1000lx and 1500 lx). The spectral power distribution and the luminance of the different configurations were measured with a Photo Research PR-740 spectroradiometer over a plaque containing pressed Barium Sulphate white standard produced by Merck (according DIN 5033, s.n. K46044148) placed in the centre of the bottom surface of the lighting cabinet.

- **GretagMacbeth Judge-II:**

The visual assessment was conducted inside a viewing cabinet designated as GretagMacbeth (now X-Rite) Judge-II, which was equipped with the following standard lighting sources: JII_D65, JII_TL84, JII_CWF and JII_A. The cabinet features a unique seven-phosphor fluorescent daylight technology that enables highly accurate color rendering and ensures reliable visual color matching. It also includes an ultraviolet source that can be used independently or in combination with other light sources to detect and evaluate optical brighteners, whitening agents, and fluorescent dyes or pigments. The viewing cabinet and SPDs of light sources is shown in Figure 3.

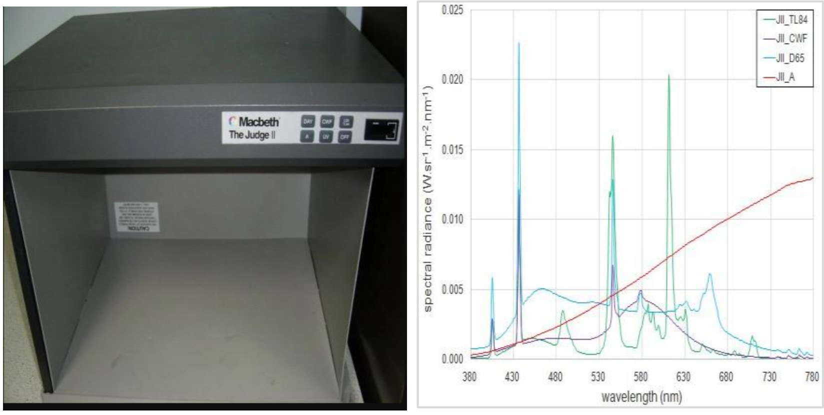


Figure 3. Left: GretagMacbeth Judge-II viewing cabinet and Right: SPDs of JII_D65, JII_TL84, JII_CWF and JII_A

The spectral power distribution and other optical properties of the light sources and samples' was measured with a Photo Research PR-740 spectroradiometer over a plaque containing pressed Barium Sulphate white standard produced by Merck (according DIN 5033, s.n. K46044148) placed in the centre of the bottom surface of the lighting cabinet. The parameters of the lighting sources employed in the experiment are summarized in Table 2.

Table 2. Parameters of the used lighting sources

Measured values	**Light source**			
	JII_D65	**JII_TL84**	**JII_CWF**	**JII_A**
x	0.3069	0.3941	0.3861	0.4573
y	0.3146	0.3793	0.3867	0.4104
CCT(K)	6986	3666	3924	2734
Luminance(cd.m^{-2})	295.8	215.1	210.4	380.3

The *L*a*b** values of the 12 metameric pairs were calculated. These values reflect the color coordinates of each sample, providing a quantitative basis for analyzing color differences and metamerism effects under the test lighting setups. Table 3 presents the *L*a*b** values of the twelve metameric pairs under light sources used in experiment 1.

Table 3. *L*a*b** values of the 12 metameric pairs under used lighting sources

	JII_D65			**JII_TL84**			**JII_A**			**JII_CWF**		
Sample	***L****	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****	***L****	***a****	***b****
1	63.2	14.1	-10.7	63.6	12.3	-10	63.8	12.8	-8.5	62.2	9.8	-12.5
2	63.8	9.7	-7.6	64	8.3	-7.4	64.2	9.3	-6.2	62.9	6.6	-9.1
3	63.1	4.3	-3.9	63.1	3.9	-4.0	63.3	2.7	-2.9	63.2	3.2	-3.7
4	63.7	1.0	0.1	63.7	1.1	0.6	63.7	2.7	-0.2	63.0	0.5	-0.8
5	64.2	-2.2	2.9	64.2	-1.0	2.5	64.2	-0.1	1.9	63.9	-1.3	2.6
6	63.6	-5.8	4.8	63.3	-4.4	4.4	63.3	-3.2	2.9	63.2	-3.8	4.3
7	64.1	-10.5	7.9	64.1	-10.4	7.8	63.4	-7.6	5.9	63.6	-7.7	6.9
8	45.5	24.7	-1.9	46.8	24.4	0.1	48.1	25.5	3.5	45.4	18.9	-2.4
9	82.6	18.5	0.9	83.5	19.9	2.6	84.9	18.2	5.3	83.9	15.1	3.5
10	81.7	-40.8	67.4	81.6	-31.9	68.3	80.8	-24.4	55.2	82.1	-26	67.9
11	82.6	18.5	1.03	83.5	19.9	2.7	84.9	18.2	5.4	83.9	15.1	3.6
12	81.7	-40.4	67.2	81.6	-31.5	68.1	80.8	-23.9	55.1	82.1	-25	67.7

4.1.3. Visual assessment

Seven observers under LEDs and ten observers under JII_D65, JII_TL84, JII_CWF and JII_A, were asked for the assessment. The observers were between 20 and 56 years of age. All 12 metameric pairs were presented to all observers in five consecutive sessions under the experimental light sources. The observers were asked to adapt to the mid-gray interior of the cabinet for 2 minutes after each new lighting condition and illuminance levels. After adaptation, they were provided with the grey scale and sample pairs. Due to the determination method used in the experiment; the participants were required to evaluate and compare the sample pair with grey scale. Each participant was asked to determine a closest grey scale value according to his/her own perception. After visual assessments, the grey scale number (GS) for each pair was transformed to the corresponding visual color difference (ΔV) in CIELAB unit by Equation (1) [38]:

$$\Delta V = 26.36\mathrm{e}^{-\mathrm{GS}/1.659} - 0.9532 \tag{1}$$

This exponential Equation (1) is used to predict CIELAB colour difference from grey scale rating as shown in Figure 4. Figure 4 also illustrates moments from the visual experiment.

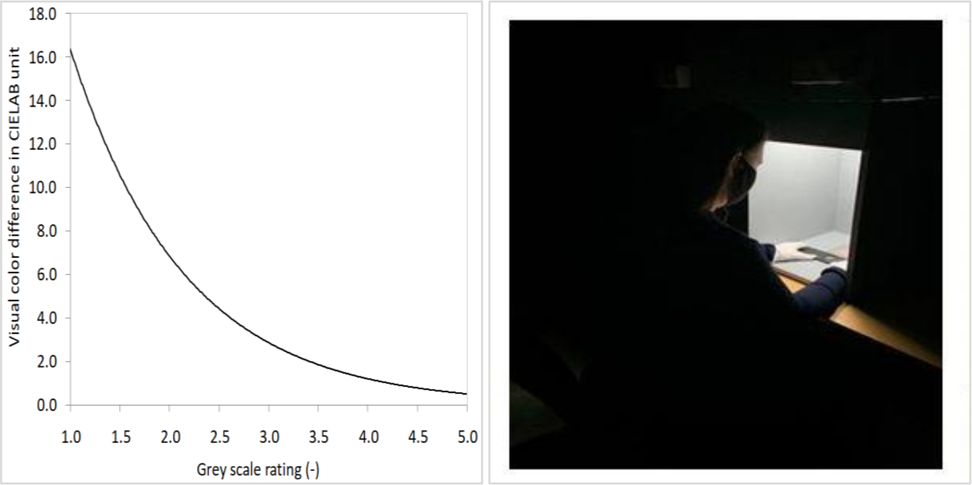


Figure 4. Left: Visual color difference in CIELAB unit as a function of grey scale rating and Right: Moment captured during visual experiment

The distance between observers and sample was 50cm. The illumination: viewing geometry was always approximately *0°*:*45°*. All observers had normal colour vision examined by Farnsworth-Munselll 100 Hue test.

4.2. Experiment-2: D&H Color Rule evaluation

4.2.1. Samples used

The D & H Color Rule consists of two color scales as shown in Figure 5. One scale gradually changes color from blue to brown and the steps are numbered 1 to 21 on the back. The other scale changes color from purple to green and the steps are numbered A to U on the back.

Figure 5. The D-H color rule: (Left) Top side and (Right) back side

The color rendering properties of D & H Color Rule were analysed under LEDs, SPLIII_D65, SPLIII_TL84, and SPLIII_A. The reflectance percentage (Metameric included) of each pairs of the both scales are showing in the Figure 6.

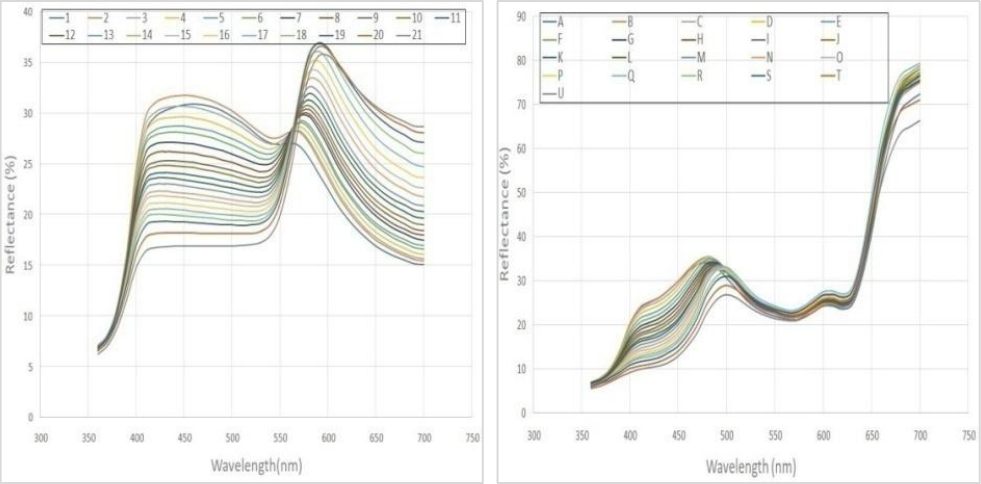


Figure 6. The reflectance percentage of each pair of the two scales of the D-H color rule

4.2.2. Lighting conditions

For the visual assessment, two lighting setups were used: an LED-based setup, designated as LCAM LEDs (described in section 4.1.2) and a setup containing standard illuminants, designated as GretagMacbeth Spectralight III.

- **GretagMacbeth Spectralight III**

GretagMacbeth Spectralight III had a visual color rating system equipped with two filtered tungsten halogen sources that simulate daylight at a correlated color temperature (CCT) of 6500K, equivalent to a D65 illuminant. The interior of the observation cabins were painted light gray, corresponding to Munsell N7. This system also features an ultraviolet source consisting of two F30T8 BLB and one F6T5 BLB, which can be used in conjunction with another source. The spectral power distribution and other optical properties of the light sources and samples' was measured with a Photo Research PR-740 spectroradiometer over a plaque containing pressed Barium Sulphate white standard produced by Merck (according DIN 5033, s.n. K46044148) placed in the centre of the bottom surface of the lighting cabinet. The viewing cabinet and spectral power distribution of lighting sources are shown in Figure 7.

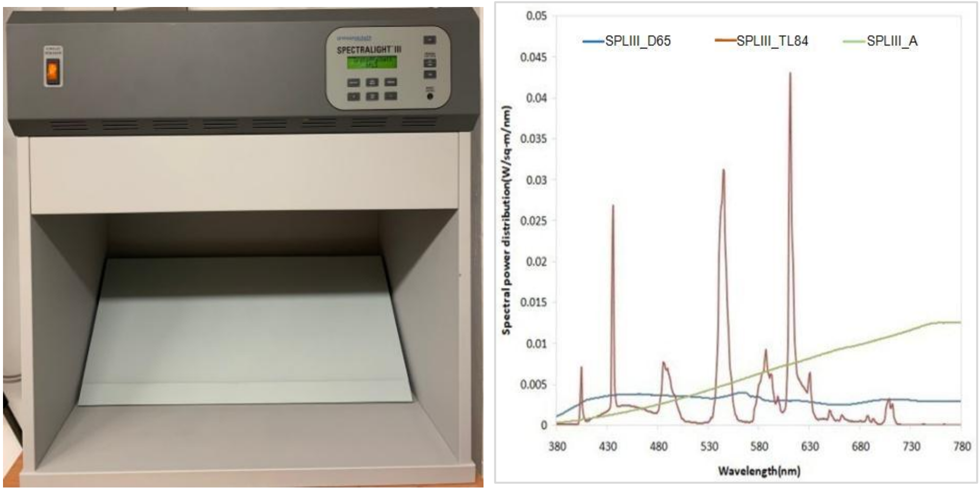


Figure 7. Left: GretagMacbeth Spectralight III viewing cabinet and Right: SPDs of SPLIII_D65, SPLIII_TL84 and SPLIII_A

Table 4 summarizes the colorimetric and color-quality characteristics of the tested light sources.

Table 4. Parameters of the used lighting sources

Parameters	**SPLIII_D65**	**SPLIII_TL84**	**SPLIII_A**	**LED65**	**LED50**	**LED40**	**LED27**
X	95.60	101.09	109.77	97.06	95.40	100.50	107.55
Y	100	100	100	100	100	100	100
Z	107.25	57.56	33.25	122.67	86.31	70.28	37.42
x	0.3157	0.3908	0.4517	0.3036	0.3387	0.3712	0.4390
y	0.3302	0.3866	0.4115	0.3128	0.3550	0.3693	0.4082
u´	0.199	0.228	0.257	0.198	0.206	0.222	0.250
v´	0.469	0.507	0.526	0.458	0.485	0.497	0.523
Duv	0.0022	0.0017	0.0011	-0.005	0.004	-0.001	0.0013
Tcp	6334	3805	2825	7233	5258	4211	2998
***CRI* (Ra)**	95	83	99	94	97	98	96
Rf	96	82	99	95	97	97	96
Rg	99	100	99	102	101	101	99

4.2.3. Visual assessment

All light sources were placed in the light box, the walls and sample holder of which were painted with an achromatic light grey paint N7 according to Munsell's nomenclature. A D&H Color Rule was placed in the sample holder. The observer made visual judgments in a *45°:0°* geometry at approximately 40 cm distance. Eight observers with normal color vision, superior and average color discrimination, respectively, participated in the visual assessment according to the FM 100 Hue color vision test. Visual assessments were performed repeatedly on different days, with each observer performing three baseline sessions for each light source, where they were asked with finding the position of the D&H Color Rule slides at which the samples appeared to be in color match. The observer then had to determine the maximum acceptable slide displacement in both the left and right directions to maintain an approximate color match in the viewing window. In principle, this produced 5 individual judgments of a single light source at each session, for a total of 480 individual judgments.

4.3. Experiment-3: Optically brightened textiles evaluation

4.3.1. Samples used

A set of ten optically brightened samples was prepared for this experiment. Pre-treated fabrics were treated with fluorescent whitening agents in different concentrations. The experiment was performed under D65 and D65UV conditions, highlighting the impact of ultraviolet radiation on their visual appearance.

Under D65, the samples reflect only the visible portion of the spectrum provided by D65, resulting in their inherent, non UV-activated color appearance. In contrast, in the presence of UV energy activates optical brightening agents causing noticeable changes in brightness, whiteness, and overall color tone. As a result, the samples appear visibly brighter and slightly bluish under D65+UV compared with the baseline D65 illumination. This comparison highlights the significant role of UV radiation in modifying the visual perception of materials, especially those containing fluorescent whitening agents. Figure 8 presents the optically brightened samples viewed under two different lighting conditions. The left image corresponds to illumination with D65, while the right image shows the same samples under D65 enhanced with UV.

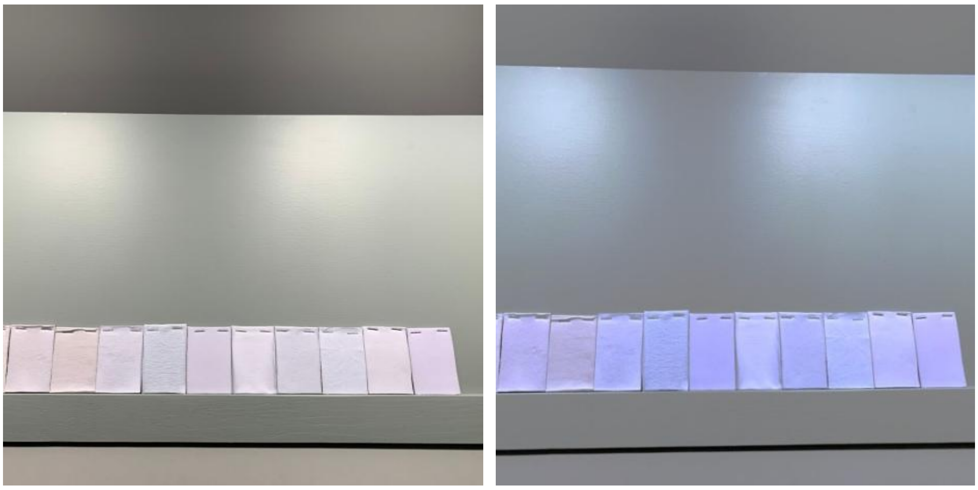


Figure 8. Optically brightened samples under (Left) D65 and (Right) D65+UV

4.3.2. Lighting conditions

GretagMacbeth Spectralight III was used (as shown in Figure 7), a visual color rating system equipped with two filtered tungsten halogen sources that simulate daylight at a correlated color temperature (CCT) of 6500K, equivalent to a D65 illuminant. The interior of the observation cabins were painted light gray, corresponding to Munsell N7. This system also features an ultraviolet source consisting of two F30T8 BLB and one F6T5 BLB, which can be used in conjunction with another source. Radiometric measurements of D65 simulator with source and D65+ UV were carried out using SpectraScan PR-740 Spectroradiometer. The spectroradiometric was calibrated with white standard.

It is designed for spectral based photometric and colorimetric precise light measurements. The spectral power distribution of the D65 and D65+UV and the position of white standard under Spectralight III are showing in the Figure 9.

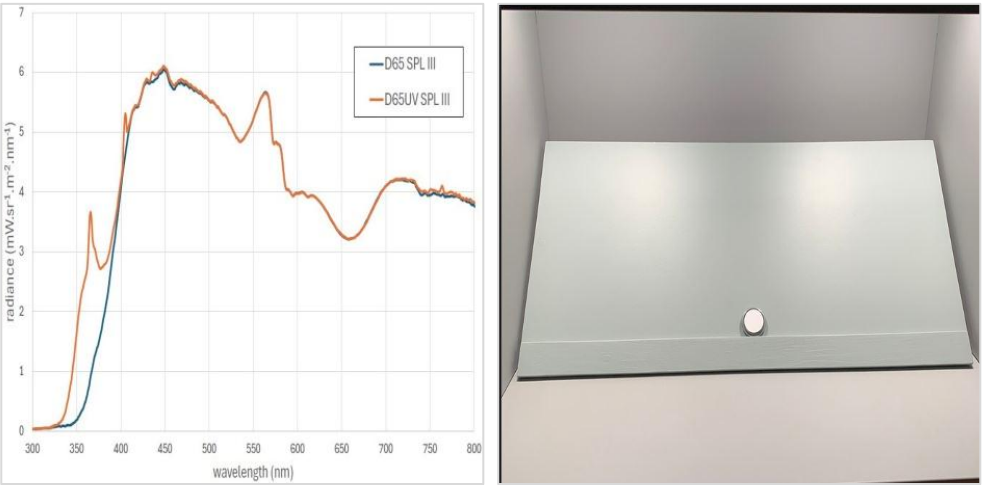


Figure 9. (Left) The spectral power distribution of the D65 and D65+UV under Spectralight III; (Right) the position of white standard under D65

4.3.3. Visual assessment

A pair comparison experiment was carried out with ten optically brightened samples in terms of the difference in whiteness between the pairs. The samples were labeled as sample 1, sample 2, etc. The number of possible unique pairs is calculated as in Equation (2):

$$\text{Number of pairs} = \frac{n\,(n-1)}{2} = \frac{10\,(10-1)}{2} = 45 \qquad (2)$$

So there were 45 unique pairs to compare. To avoid bias, pairs were randomly presented to observers by manual shuffling.

We asked observers to select the whiter sample of a pair as compared to gray scale for staining and repeated the process for all 45 pairs. Visual assessment was performed under the D65 and D65+ UV illumination conditions of the GretagMacbeth Spectralight III viewing booth. Four color-normal expert subjects (three females, one male) with an average age of 33 years and an average experience in color assessments of 8 years took part in the visual assessments. Each subject was adapted to the viewing conditions for at least two minutes before assessing the samples under each lighting condition.

4.4. Proposed method for measurement of luminescent spectral radiance factor

A detailed step-by-step procedure for calculating luminescent spectral radiance factor is presented below to ensure clarity and reproducibility.

Step-1: Ganz-Griesser Calibration (GG) of the spectrophotometer

The Ganz-Griesser calibration method (GG) is a technique used to standardize and control the ultraviolet (UV) content of light sources in instruments like spectrophotometers when measuring optical properties, particularly for color measurements. This method is often employed to simulate the effect of daylight (CIE D65) on samples, especially when dealing with materials containing Fluorescent Whitening Agents (FWAs), which are sensitive to UV light. Key Concepts of Ganz-Griesser Calibration:

- **CIE D65 Standard Illuminant:** CIE D65 is a standard illuminant that represents average daylight, including both visible and UV light components. It is used as a reference in color measurement to ensure consistency and comparability.

- **Need for UV Calibration:** In instruments like the Datacolor Int. Elrepho 450x, the light source may not perfectly match the CIE D65 spectrum, especially in the UV region. This discrepancy can lead to inaccurate color measurements, particularly for samples with FWAs. The Ganz-Griesser method is used to adjust or calibrate the UV content of the instrument's light source to closely match the CIE D65 illuminant.

Step-2: Total spectral radiance factor (β_T) measurement:

Spectrophotometric reflectance of the samples was measured by using Datacolor Int. Elrepho 450x device. Before measurement, the device was calibrated to a UV content close to CIE D65 using the Ganz-Griesser method. This step is crucial as it sets the baseline for the spectral measurements. The sample is illuminated diffusively due to the use of an integrating sphere and the detector measures the reflected light at 0° (perpendicular to the sample surface). The spectral data obtained from this measurement includes both the reflected light (from the surface) and any emitted light (from fluorescence), giving the total spectral radiance factor, β_T.

Step-3: Measurements of the samples with a 420 nm long-pass Filter:

With the goal to capture only the light that is reflected by the sample without any influence from UV-induced fluorescence, measurements were taken of the same samples with a 420 nm long-pass filter using Datacolor Int. Elrepho 450x. A 420 nm long-pass filter allows light with wavelengths longer than 420 nm to pass through while blocking shorter wavelengths (including most UV light). By filtering out light below 420 nm, this filter prevents the measurement device from capturing any fluorescence that might be triggered by UV light in the sample, isolating only the reflected light component. Since the UV light is filtered out, the measurement primarily represents the reflected spectral radiance factor β_R .

Step-4: Linear interpolation for data below 420 nm:

To interpolate the values linearly for the wavelengths 400 nm and 410 nm from the absorption to the luminescence portion of the FWA curve, the steps below were followed:

(a) Let's denote the absorption value at 390 nm as A_{390} and the luminescence value at 420 nm as L_{420}

(b) Also let's denote the unknown values we need to find at 400 nm as X_{400} and at 410 nm as X_{410} .

(c) Linear interpolation formula: (3-5)

The general formula for linear interpolation between two points (x_1, y_1) and (x_2, y_2) and to find a value y at a point x is:

$$y = y_1 + \frac{(x-x_1)}{(x_2-x_1)} * (y_2 - y_1) \tag{3}$$

For 400nm:

$$X_{400} = A_{390} + \frac{(400-390)}{(420-390)} * (L_{420} - A_{390}) \tag{4}$$

For 410nm:

$$X_{410} = A_{390} + \frac{(410-390)}{(420-390)} * (L_{420} - A_{390}) \tag{5}$$

Step-5: Calculation of Luminescent Spectral Radiance Factor (βL):

The luminescent spectral radiance factor β_L, was calculated by using the relationship $\beta_T = \beta_L + \beta_R$ from the data obtained from the steps 2, 3 and 4.

Step-6: Relative SPDs of (D65 + UV) illumination in the UV range

The International Commission on Illumination (CIE) provides several standard illuminants and spectral power distributions (SPDs) that serve as a reference for various lighting and color applications. However, these standard illuminants typically do not specify varying percentages of ultraviolet (UV) content within the same SPD. For a D65-like spectrum with more or less UV content, we used an Excel spreadsheet developed in the LCAM laboratory and this typically involves converting reflectance to color coordinates using a standard observer and illuminant (D65).

5. Summary of the results achieved

5.1. Experiment-1: Metameric sample evaluation

Summary of the results: In experiment 1, twelve metameric sample pairs were evaluated under multiple light sources.

- The observed decrease in the correlation between the Nimeroff Metamerism Index (MI) and the CIE Metamerism Index with increasing correlated color temperature (CCT) indicates a growing divergence between the two metrics under higher-CCT illuminants. As CCT increases, the spectral power distributions of the light sources tend to become more complex and spiky, particularly for LED-based illuminants. Under these conditions, the Nimeroff MI and the CIE MI differ more in their sensitivity to spectral shape and chromatic adaptation effects, resulting in reduced correlation as shown in Figure 10 (a). The correlation between the two indices decreases progressively when moving from illuminant JII_D65 to illuminant JII_A, indicating that their agreement depends strongly on the reference illuminant as shown in Figure 10 (b).

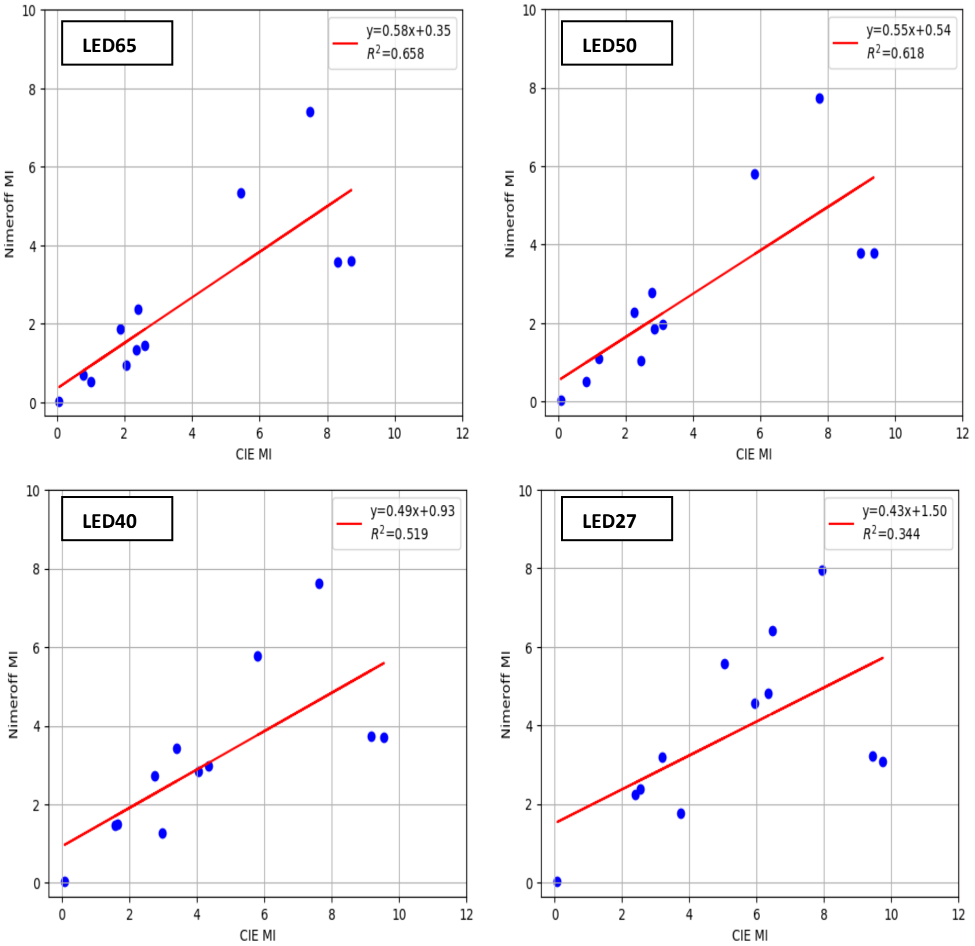


Figure 10 (a). Nimeroff MI vs. CIE MI under LEDs at 1000lx

This behavior reflects the fact that the two indices are based on different theoretical assumptions and computational formulations: the CIE MI relies primarily on color difference calculations in a standardized color space, whereas the Nimeroff MI incorporates different weighting of spectral mismatches. Consequently, changes in the illuminant SPD affect the two indices in different ways. Highest correlation value of JII_D65 can be attributed to its closely matched to reference D65. D65 is a well-balanced daylight illuminant with a relatively smooth spectral distribution and widely used as a reference in colorimetric modeling and visual experiments.

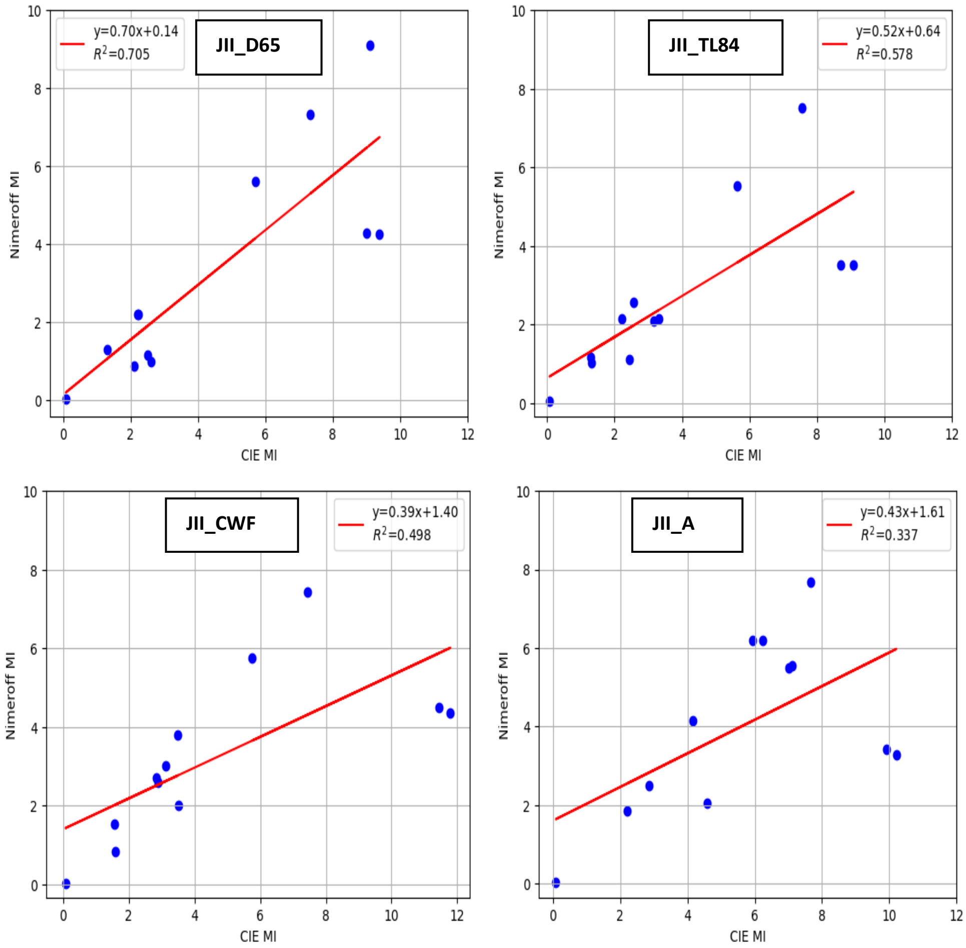
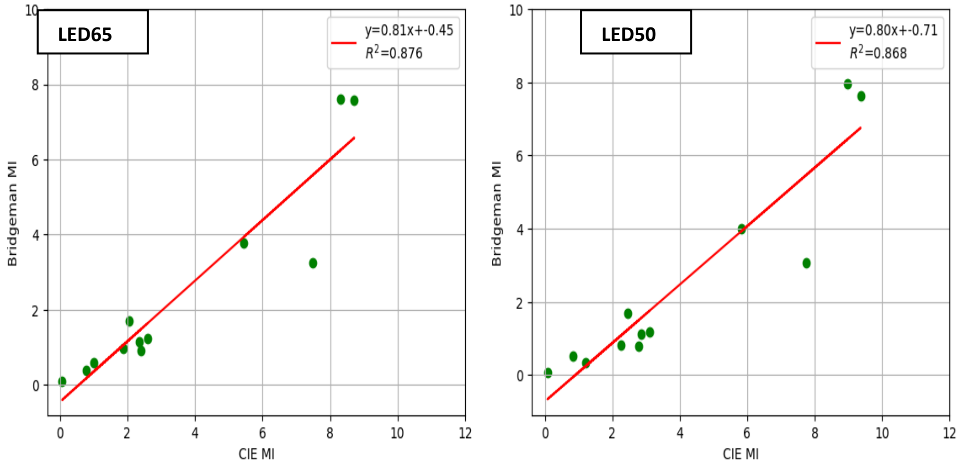


Figure 10 (b). Nimeroff MI vs. CIE MI under traditional light sources

- A similar trend as Nimeroff MI is observed for the relationship between Bridgman’s Metamerism Index and the CIE Metamerism Index, where the correlation decreases with changes in correlated color temperature as shown in Figure 11 (a).



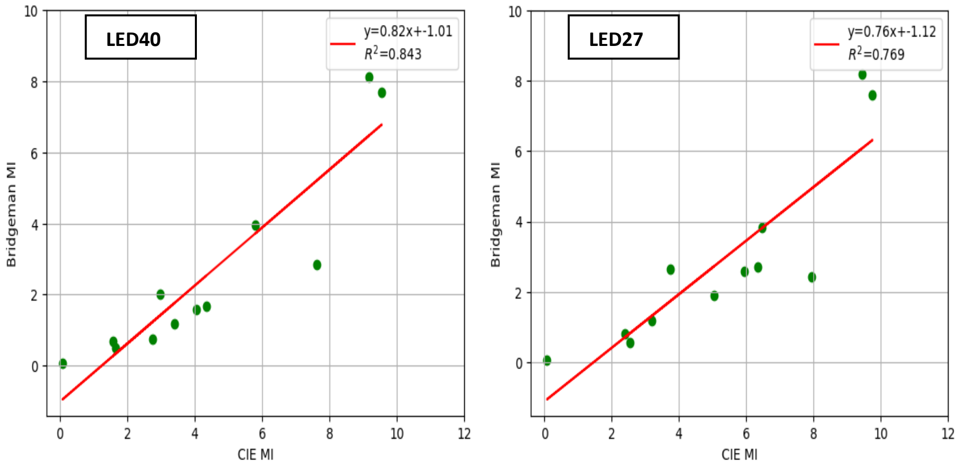


Figure 11 (a). Bridgman’s MI vs. CIE MI under LEDs at 1000lx

However, in contrast to the Nimeroff MI, the correlation between Bridgman’s MI and CIE MI remains consistently strong across all illuminants. The stronger and more stable correlation can be attributed to the closer conceptual alignment of Bridgman’s MI with the CIE framework.

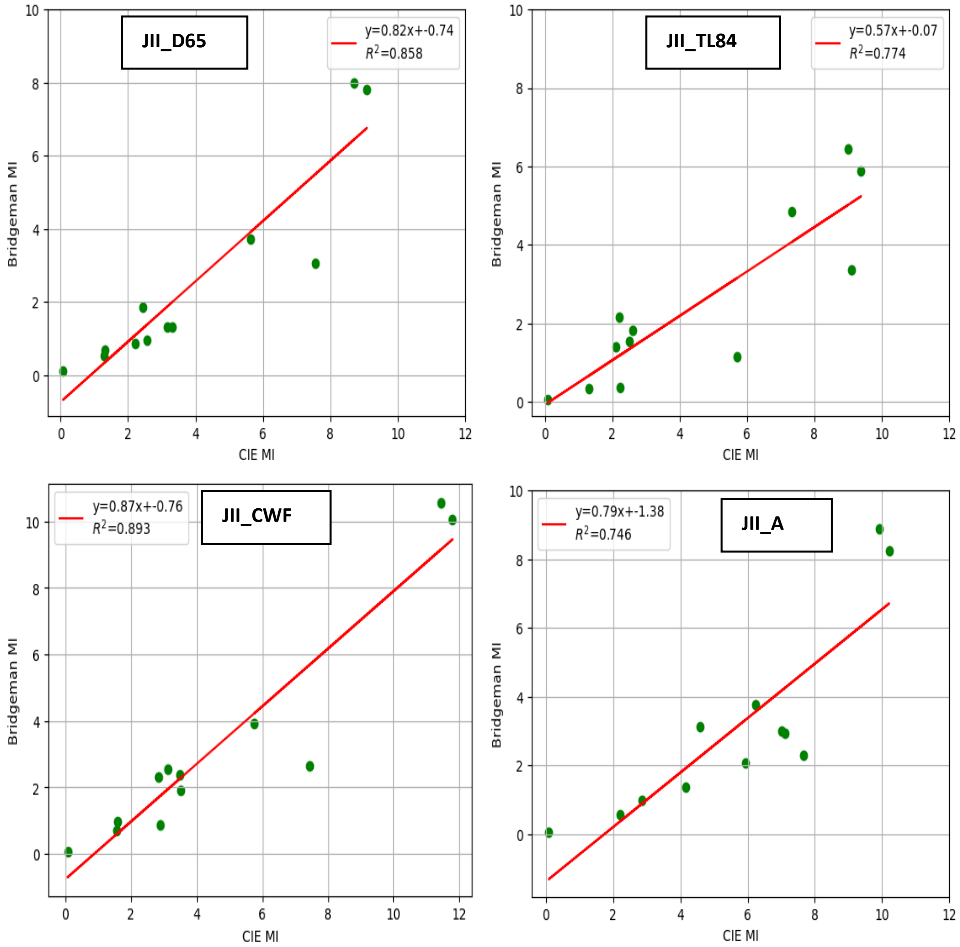


Figure 11 (b). Bridgman’s MI vs. CIE MI under traditional light sources

Both indices are fundamentally grounded in color difference based evaluations and respond in a similar manner to changes in perceived color under different illuminants. As a result, even when the spectral characteristics of the illuminant vary, Bridgman's MI tracks the changes in CIE MI more consistently than the Nimeroff MI, which places greater emphasis on spectral mismatch characteristics. Both LED65 and standard JII_D65 exhibit the highest correlations between Bridgman's MI and the CIE MI. This can be explained by their daylight-like spectral characteristics, which provide relatively smooth and well-distributed spectral power distributions compared to other illuminants.

- The comparison between visual assessment and the CIE Metamerism Index shows a broadly consistent level of agreement, with correlation values of approximately 0.6 for all LED light sources as shown in Figure 12 (a).

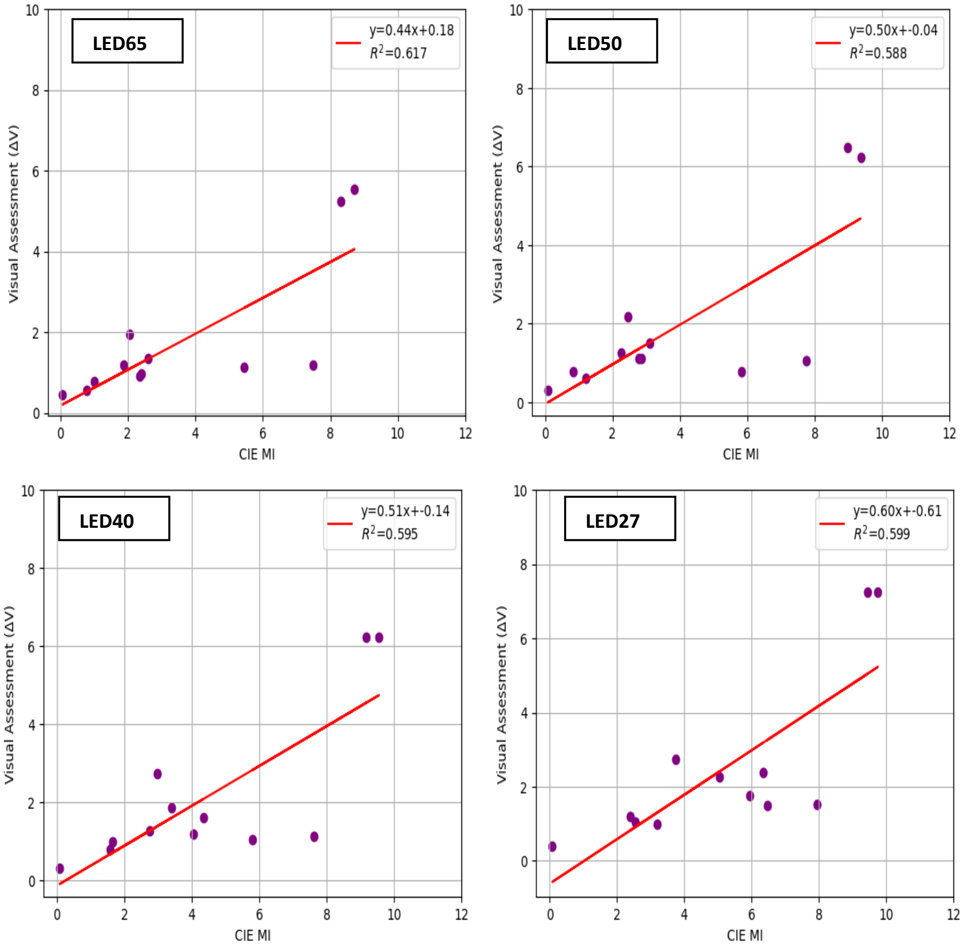


Figure 12 (a). Visual assessment vs. CIE MI under LEDs at 1000lx

This indicates a moderate correspondence between perceptual judgments and the colorimetric prediction provided by the CIE MI, suggesting that the CIE MI captures the main perceptual trends of metameric color shifts under LED illumination. The observed decrease in correlation when moving from JII_D65 to JII_A reflects the increasing deviation of the test illuminants from daylight conditions as shown in Figure 12 (b). JII_D65 exhibits the highest correlation because it closely matches the reference conditions under which both human visual adaptation and the CIE colorimetric framework are most stable.

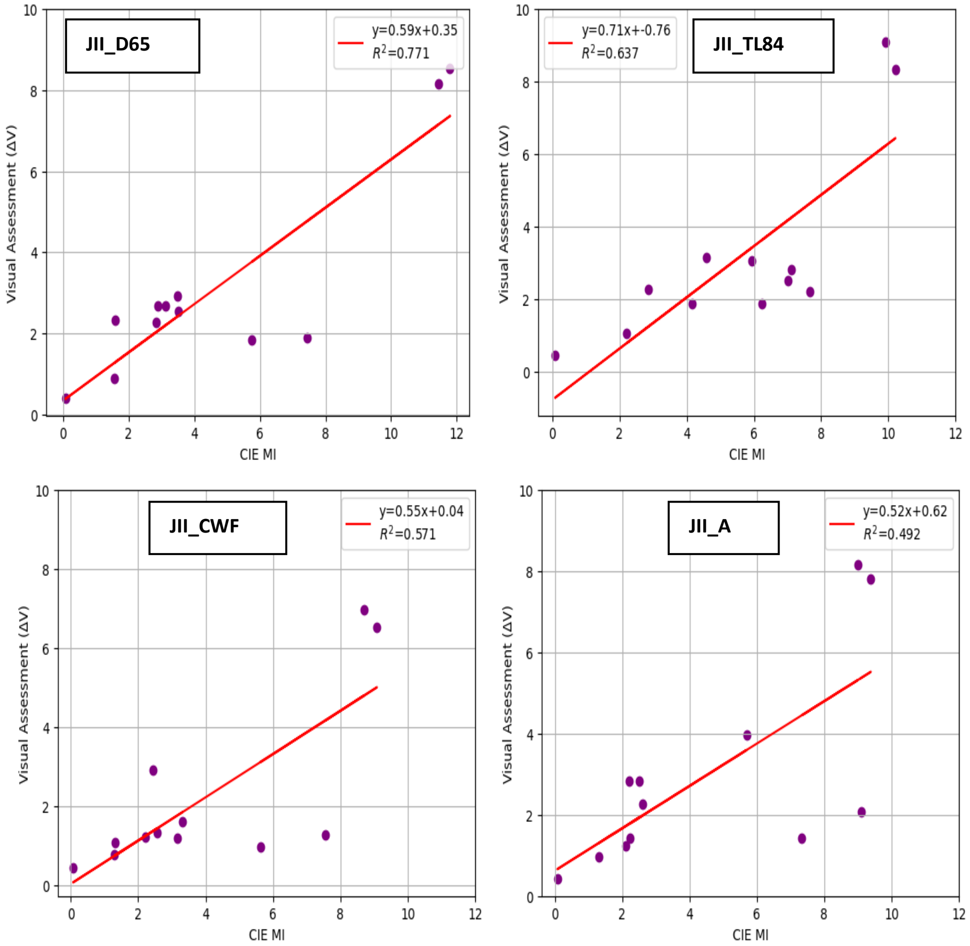


Figure 12 (b). Visual assessment vs. CIE MI under traditional light sources

- One-Factor ANOVA test (significance level, α= 0.05) using ΔE^*_{ab} MI revealed that the differences in MI values between the LEDs and traditional light sources were statistically significant, with a p-value < 0.05.
- The conformity test graphs obtained using CIELAB and *CAM02-UCS* show similar overall trends but differ noticeably in the degree of correlation observed between different light source combinations as shown in Figure

13 and 14. In both color models, high conformity is achieved when comparing LED light sources with each other; however, the performance diverges when LEDs are compared with traditional illuminants.

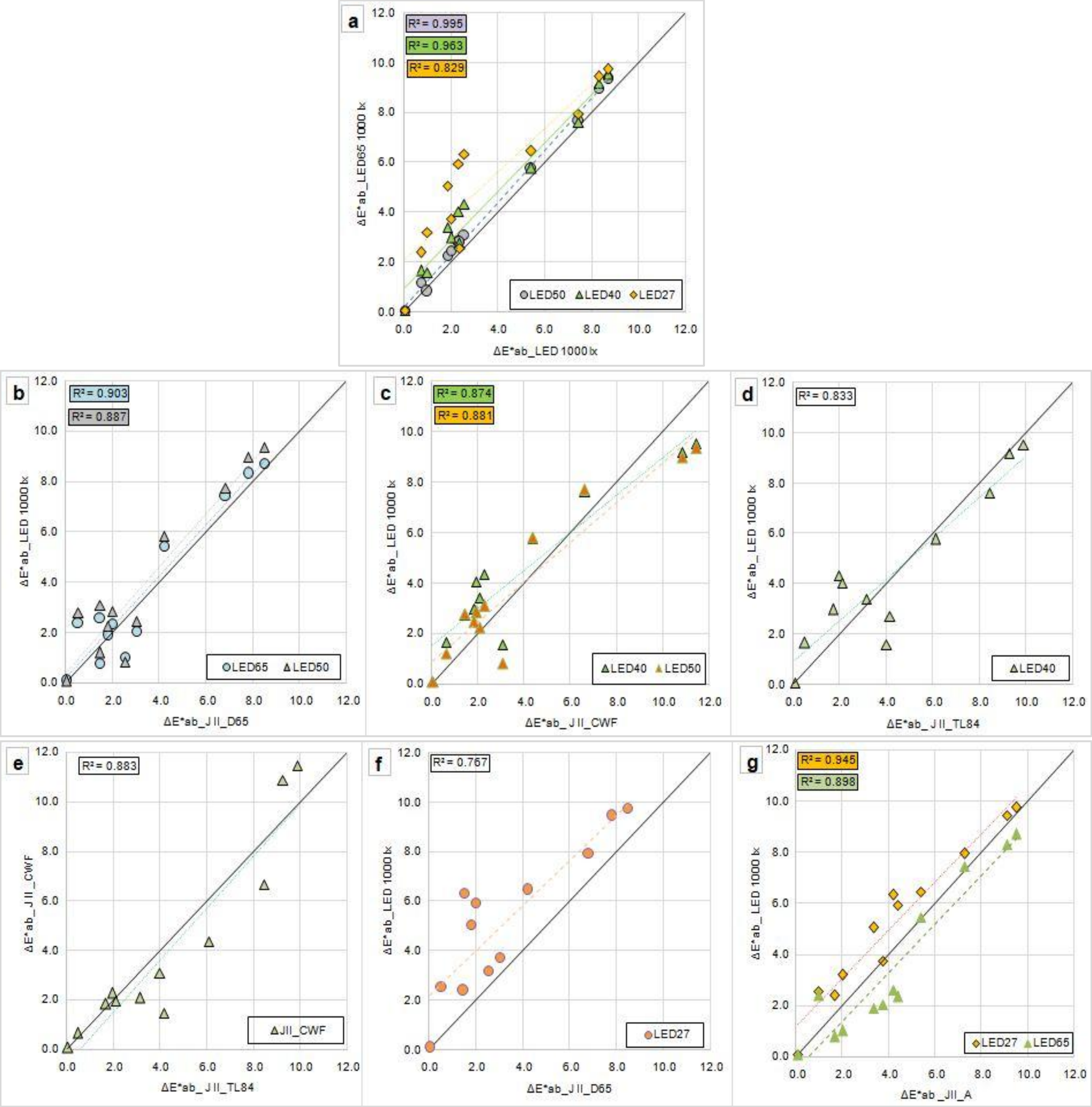


Figure 13. CIELAB conformity graphs for selected light-source pairings in (a) all LEDs at 1000lx, (b-d) LEDs at 1000lx – traditional light sources (JII_D65, JII_CWF, JII_TL84), (e) traditional fluorescent sources (JII_CWF, JII_TL84), and (f-g) Extreme cross-CCT comparisons (LED27– JII_D65 and LED65–JII_A)

The lowest conformity is observed for LED40–JII_TL84 and LED27–JII_D65 combinations, indicating substantial disagreement between the datasets. This behavior reflects the fact that *CAM02-UCS* explicitly models viewing conditions and chromatic adaptation, making it more responsive to differences in spectral power distribution and correlated color temperature between illuminants. In the CIELAB graph, data points are relatively symmetrically distributed around the correlation line implying mostly random deviations with limited systematic bias.

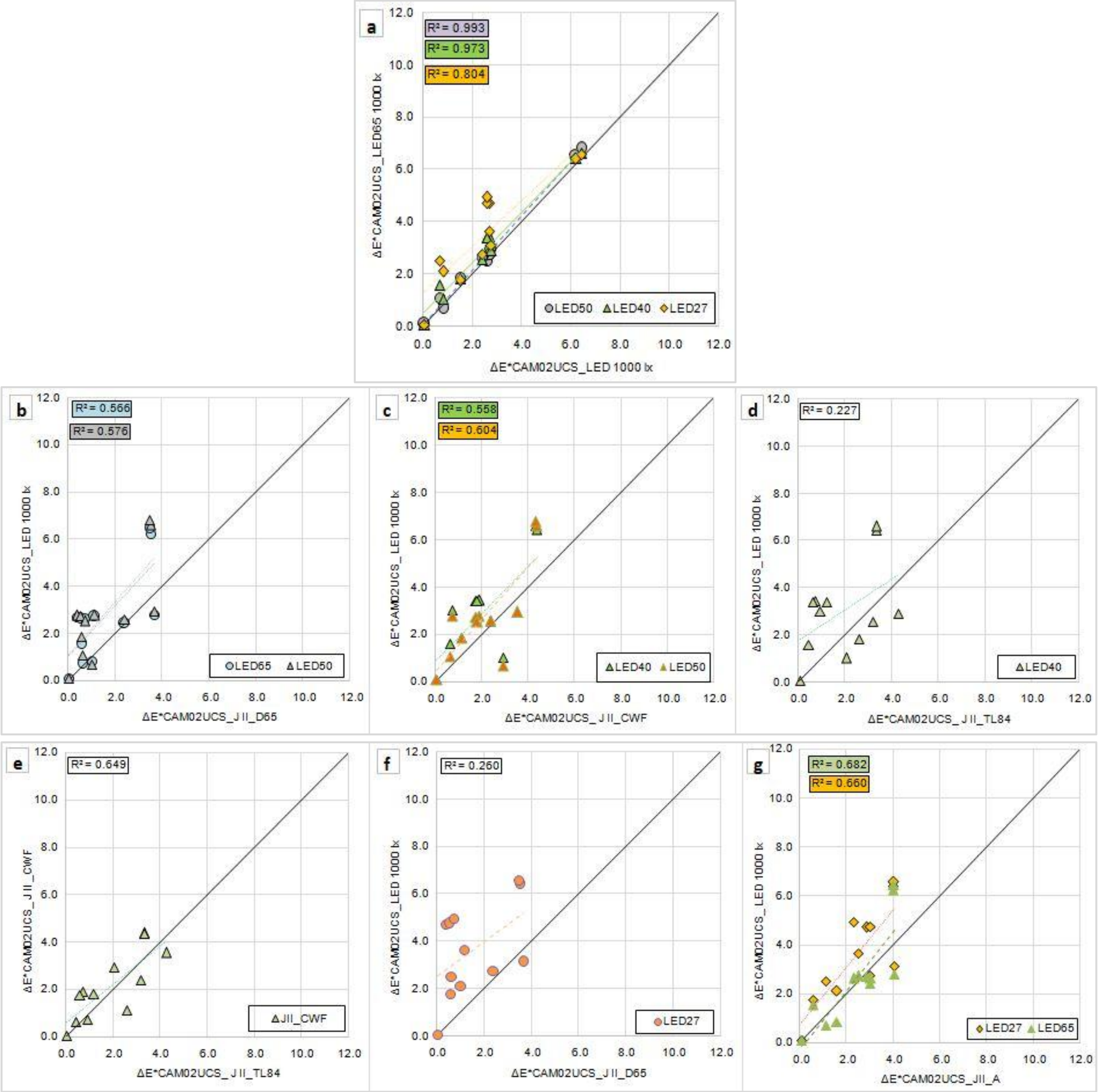


Figure 14. *CAM02-UCS* conformity graphs for selected light-source pairings in (a) all LEDs at 1000lx, (b-d) LEDs at 1000lx – traditional light sources (JII_D65, JII_CWF, JII_TL84), (e) traditional fluorescent sources (JII_CWF, JII_TL84), and (f-g) Extreme cross-CCT comparisons (LED27– JII_D65 and LED65– JII_A)

Conversely, in the *CAM02-UCS* graphs as shown in Figure 14, the deviations are larger and more structured for LED–traditional source pairs, revealing systematic over- or under- estimation of color differences depending on the illuminant combination. This indicates that *CAM02-UCS* amplifies illuminant-induced differences rather than averaging them out, as CIELAB tends to do. Based on the conformity analysis, reliable color-difference evaluation is achieved when measurements are performed under spectrally similar LED illuminants. Therefore, *CAM02-UCS* is more appropriate where illuminant-dependent perceptual effects are critical, while CIELAB is better suited for applications requiring cross-illuminant comparability.

- To evaluate the effect of CCT on the visual judgment, regression analysis (significance level, α= 0.05) revealed that CCT significantly affects mean visual assessment.
- The results obtained from *STRESS* values for CIELAB and *CAM02-UCS* revealed that across all illuminance levels, the overall *STRESS* values obtained using *CAM02-UCS* are consistently lower than those from CIELAB as shown in Figure 15 and 16, indicating that *CAM02-UCS* provides a closer agreement with the visual assessments.

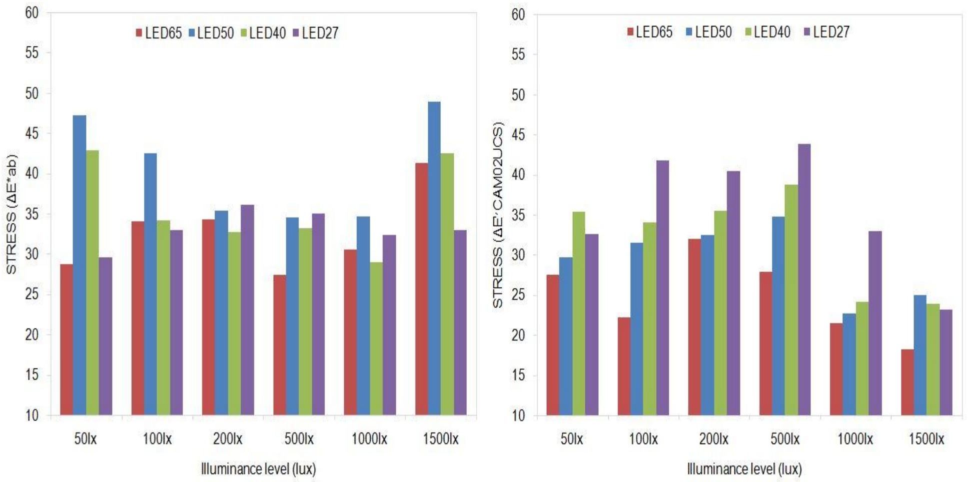


Figure 15. *STRESS* values showing the deviation between visual assessments and color-difference predictions in CIELAB (left) and *CAM02-UCS* (right) under LED lighting across different illuminance levels

For LED65, *CAM02-UCS* is more stable and consistent across higher illuminance levels, while CIELAB shows increased deviation at very high illuminance. The minimal variation indicates that LED27's spectral characteristics are largely independent of illuminance levels. In contrast, LED50 and LED40 demonstrate the strongest illuminance sensitivity. Their *STRESS* values start very high at 50 lx, drop at mid-range illuminances (500-1000lx), and then rise sharply again 1500lx. This pronounced fluctuation reflects a strong dependence of both LEDs' spectral rendering on illuminance. These results indicate that the color-rendering behavior of LED sources is highly dependent on illuminance, with medium illuminance levels (500-1000lx) providing the most reliable performance. Lower *STRESS* values of traditional light sources also revealed that *CAM02-UCS* better predicts visual assessments under different light sources than CIELAB.

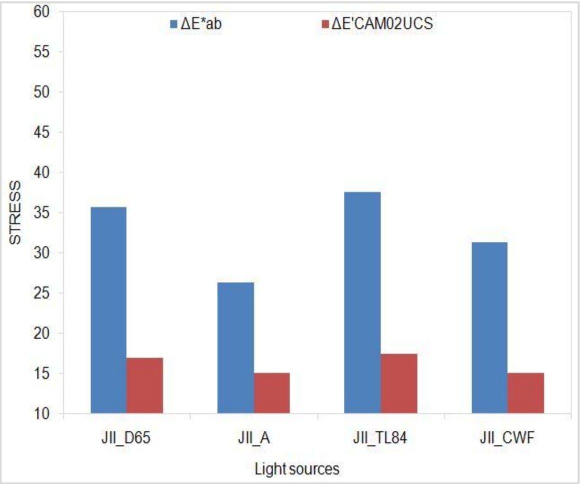


Figure 16. *STRESS* values showing the deviation between visual assessments and color-difference predictions in CIELAB and *CAM02-UCS* under JII_D65, JII_A, JII_TL84 and JII_CWF

- Results obtained from the relation between visual assessment value (ΔV) as a function of illuminance for different correlated color temperatures (CCTs) at 50lx, 100lx, 200lx, 500lx, 1000lx and 1500lx revealed inter-observer variability in visual perception as shown in Figure 17. Across all CCTs, the SD values fluctuates more at lower illuminance (50lx to 500lx) indicating significant inter-observer variability. But across all CCTs, the SD values remain relatively similar between 1000 lx and 1500 lx, implying that increasing illuminance modestly affects the mean visual score but does not significantly alter perceptual variability.

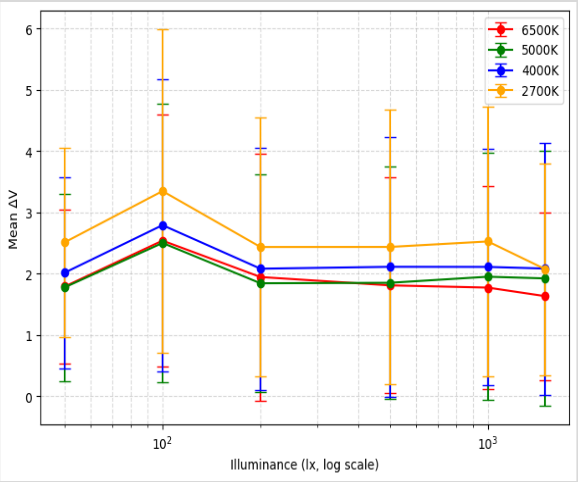


Figure 17. Mean visual assessment value (ΔV) as a function of illuminance for different correlated color temperatures (CCTs). Illuminance levels of 50lx, 100lx, 200lx, 500lx, 1000lx and 1500lx are shown on a logarithmic scale

The strong overlap of SD bars between illuminance levels, particularly for cooler CCTs, further suggests perceptual saturation, where additional illuminance yields limited perceived visual change, consistent with nonlinear human visual response characteristics described by magnitude based visual assessment methods.

- The boxplot revealed the distribution of visual assessment scores under different traditional light sources as shown in Figure 18. JII_D65 has lowest median and mean scores but a narrower spread, indicating more consistent visual assessments. JII_A exhibits highest median and mean visual assessment score, indicating most observers perceive better visual quality under that light source. However, the narrower box and shorter whiskers for JII_CWF indicate lower variability in the visual assessment scores, meaning observers or samples responded more uniformly under this light source. In contrast, the wider spread for JII_A suggests greater variability, implying that while some samples perform very well, others perform less consistently. Overall, JII_CWF offers more stable and predictable visual performance, whereas JII_A shows less consistency despite comparable average performance. The visual perception under JII_TL84 is less consistent across samples.

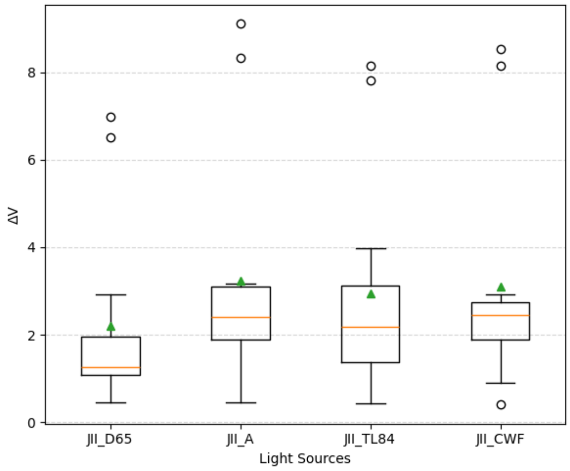


Figure 18. Boxplot showing the distribution of visual assessment scores under different light sources

Key findings:

1. The illuminant deviates from reference D65, either toward higher CCTs or toward the warm spectrum, the agreement between Nimeroff MI and CIE MI diminishes, leading to lower correlation
2. Bridgman's MI remains robust and largely consistent with the CIE MI, even under varying illuminant conditions
3. Since the CIE MI is fundamentally based on standardized color difference calculations referenced to daylight viewing conditions, its predictions align more closely with visual judgments under JII_D65
4. ΔE^*_{ab} MI significantly differs across light sources
5. High conformity when comparing LED light sources with each other but performance diverges when LEDs are compared with traditional illuminants
6. *CAM02-UCS* is more appropriate where illuminant-dependent perceptual effects are critical, while CIELAB is better suited for applications requiring cross-illuminant comparability
7. CCT significantly affects mean visual assessment
8. *STRESS* based on *CAM02-UCS* better predicts visual assessments under varying illuminance and lighting conditions, whereas CIELAB is less reliable at high illuminance levels
9. Significant inter-observer variability at lower illuminance (50lx to 500lx)
10. Increasing illuminance (1000lx to 1500lx) modestly affects the mean visual score but does not significantly alter perceptual variability

11. Some metameric pairs achieved exceptionally high visual performance under traditional light sources with lower CCT

Key Takeaway:

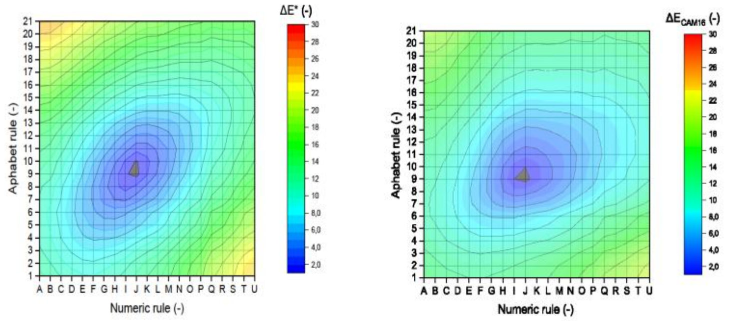
1. Both Bridgeman MI and Nimeroff MI provide complementary insight into spectral behavior but cannot replace color difference based metamerism measures
2. *CAM02-UCS* amplifies illuminant-induced differences rather than averaging them out, as CIELAB tends to do
3. Additional illuminance yields limited perceived visual change under cooler CCTs
4. Emphasizing appropriate selection of color difference metric based on the illuminant, particularly as industries increasingly adopt LED technologies
5. Traditional light sources resulting in better overall color rendering and lower metameric effects than LEDs

5.2. Experiment-2: D&H Color Rule evaluation

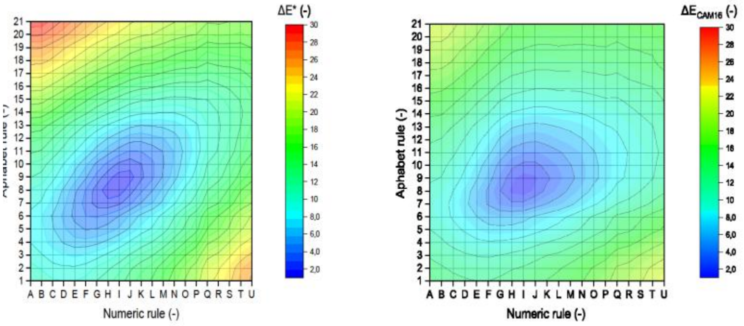
Summary of the results: In experiment 2, the color rendering properties of D & H Color Rule were analysed under LEDs, SPLIII_D65, SPLIII_TL84, SPLIII_CWF and SPLIII_A.

- To measure color shifts of the matched D-H pairs between light sources, color difference for both the CIELAB color space and CIECAM16 color space were calculated. Pairs J-9 and J-10 for SPLIII_D65, as well as I-9, J-9 for LED65, exhibited the exact matches ($\Delta E \leq 1$). Additionally, the pair K-10 for LED50, along with pairs L-11 & M-11 for LED40 and pairs P-13 & Q-14 for LED27 showed matches within this threshold. The results suggesting that these pairs exhibited low metameric effects under their respective lighting conditions. However, no matching pairs were observed for SPLIII_TL84 and SPLIII_A. The absence of matching pairs for SPLIII_TL84 and SPLIII_A indicates potential metameric effects in these cases, as their ΔE values likely exceeded the acceptable threshold for visual match. Across, all scenarios, ΔE values calculated using CIECAM16 were consistently higher than those obtained with the CIELAB color space as shown in Figure 19.

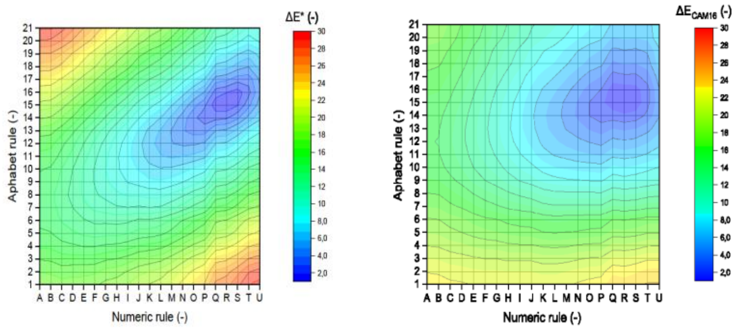
(a) SPLIII_D65



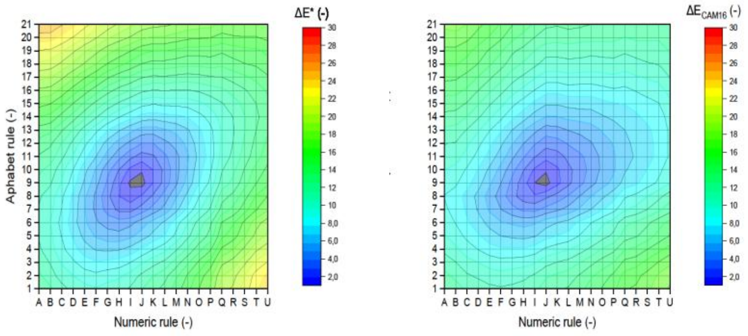
(b) SPLIII_TL84



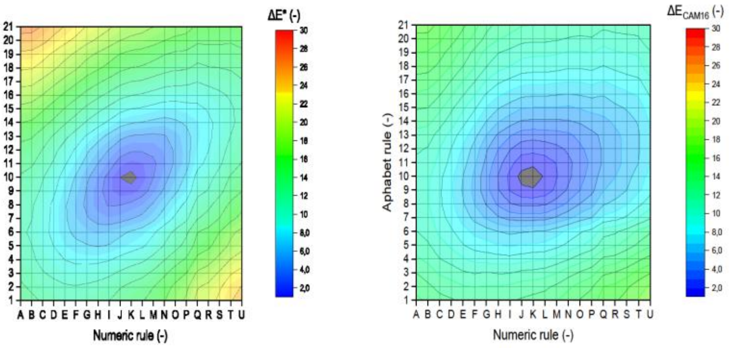
(c) SPLIII_ A



(d) LED65



(e) LED50



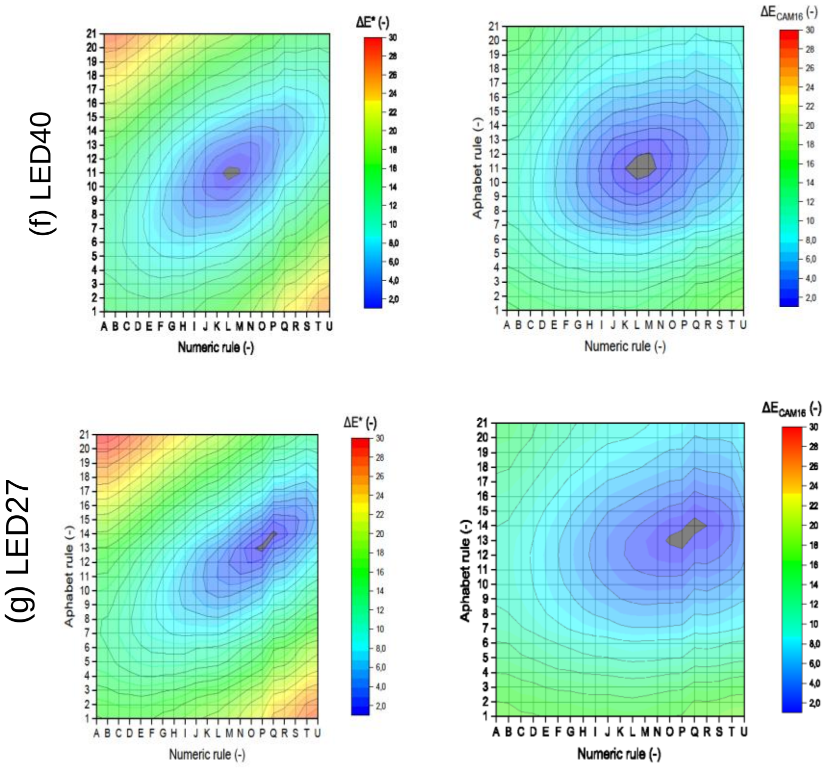
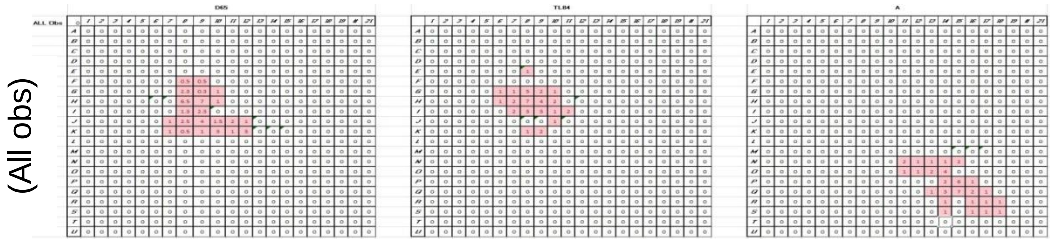


Figure 19. Map of color difference for (left) CIELAB and (right) CIECAM16 under SPLIII_D65, (b) SPLIII_TL84, (c) SPLIII_A, (d) LED65, (e) LED50, (f) LED40, and (g) LED27. The color bar on the right indicates *ΔE* values for CIELAB and CIECAM16

The higher *ΔE* values obtained using CIECAM16, compared to CIELAB; suggest that the von Kries chromatic adaptation in CIECAM16 may account for slight differences in perceived color, amplifying the perceptual discrepancy between samples.

- The observer-based metamerism comparison allowed direct visual comparison of observer consistency across different lighting conditions as shown in Figure 20, and showed that observers consistently matched the pairs G-8, H-8, H-9, J-9, K-10 & K-12 under SPLIII_D65, while pairs G-8, H-8, H-9, I-8 & I-9 were predominantly matched under SPLIII_TL84.



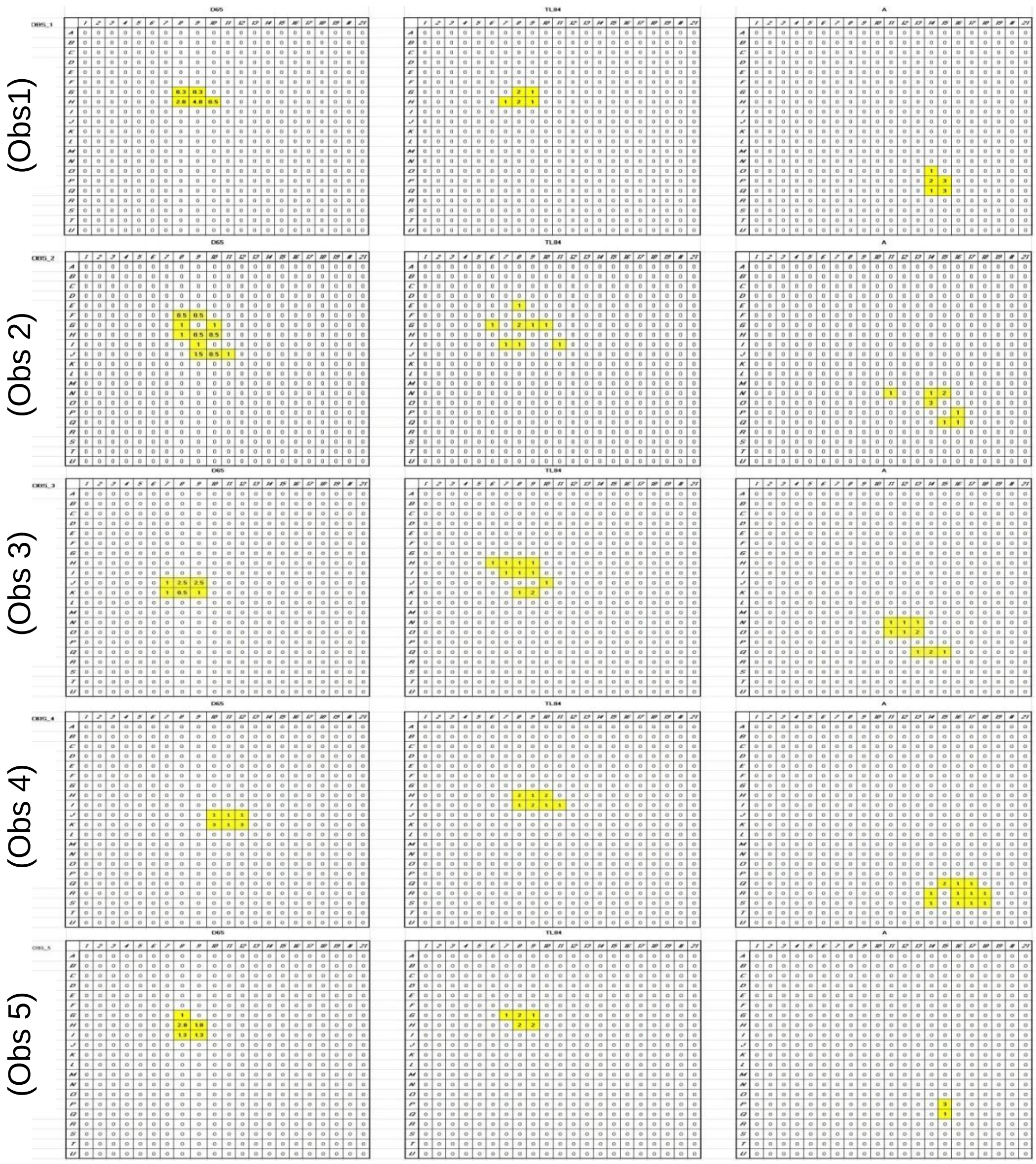


Figure 20. Observers’ variability maps for all observers together (red area) and for five individual observers (yellow area) under SPLIII_D65, SPLIII_TL84 and SPLIII_A

However, this pattern completely shifted to pairs O-14, P-15, Q-14 & Q-15 under light source SPLIII_A. Additionally, observers exhibited more uncertainty under these light sources compared to LEDs, as evidenced by the broader spread of the matching patterns in contrast to the more defined pattern observed under LEDs as shown in Figure 21.

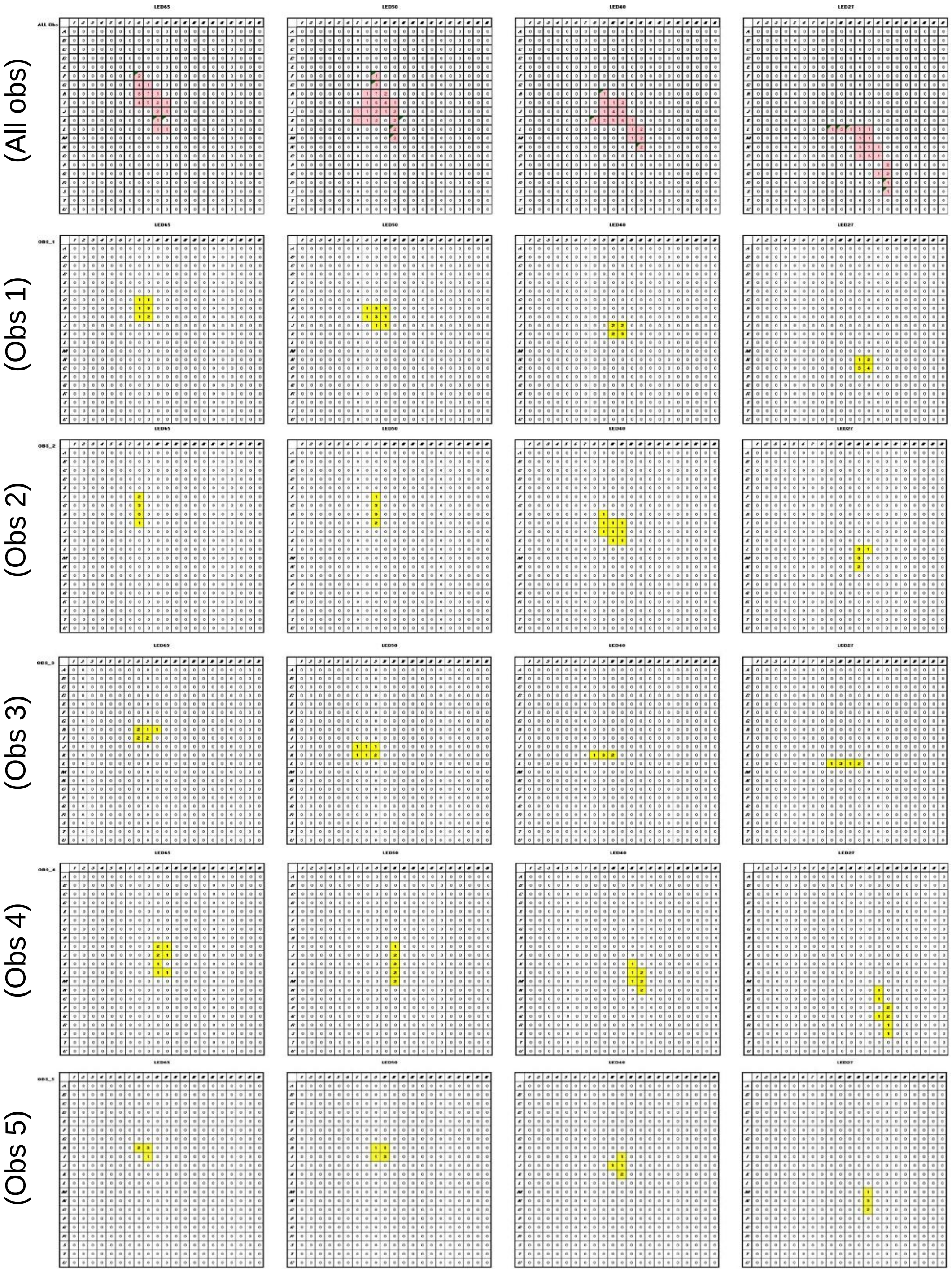
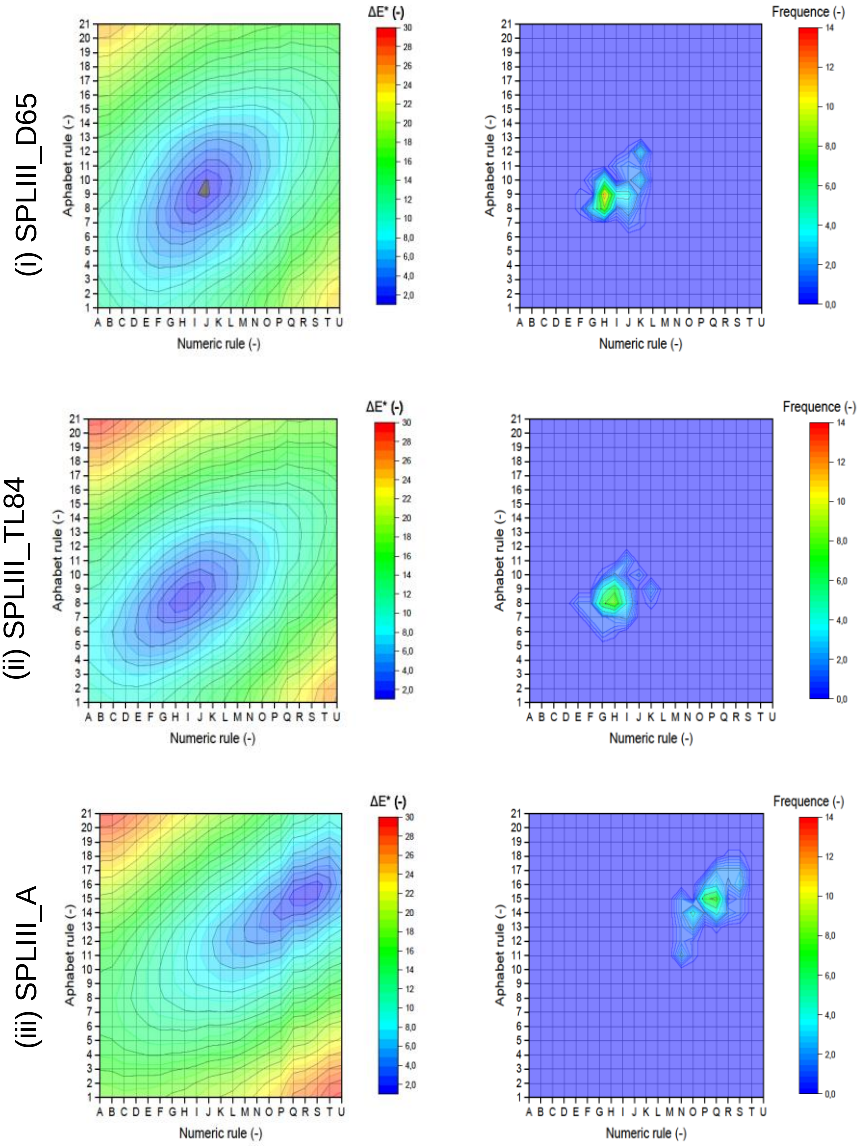


Figure 21. Observers' variability maps for all observers together (red area) and for five individual observers (yellow area) under LED65, LED50, LED40 & LED27

The preferred pairings under LED65 were G-8, H-8, H-9, I-8, & I-9; under LED50, pairings G-9, H-9, & I-9 were most frequently chosen; J-10, J-11, K-9, K-10 & K-11 were consistently matched under LED40 and L-10, L-12, N-13, & O-13 were predominantly matched under LED27. This variation in matching patterns emphasizes the complex nature of metamerism, where color perception changes under different illuminants, leading to potential challenges in achieving consistent color matching across various lighting environments.

- The cluster analysis as shown in Figure 22, helped to determine if some light sources are more effective at maintaining D-H color pair consistency. It has showed that all of the pairs had Delta E below 2.5. A Delta E of 2.5 suggests that while the colors may appear similar under certain light sources, there is enough of a difference for some observers to notice. This indicates that metameric effects are present, where the colors may match under one light source but appear different under another. The slight color difference reflected by a Delta E of 2.5 emphasizes how metamerism can cause subtle discrepancies in color perception across different lighting conditions.



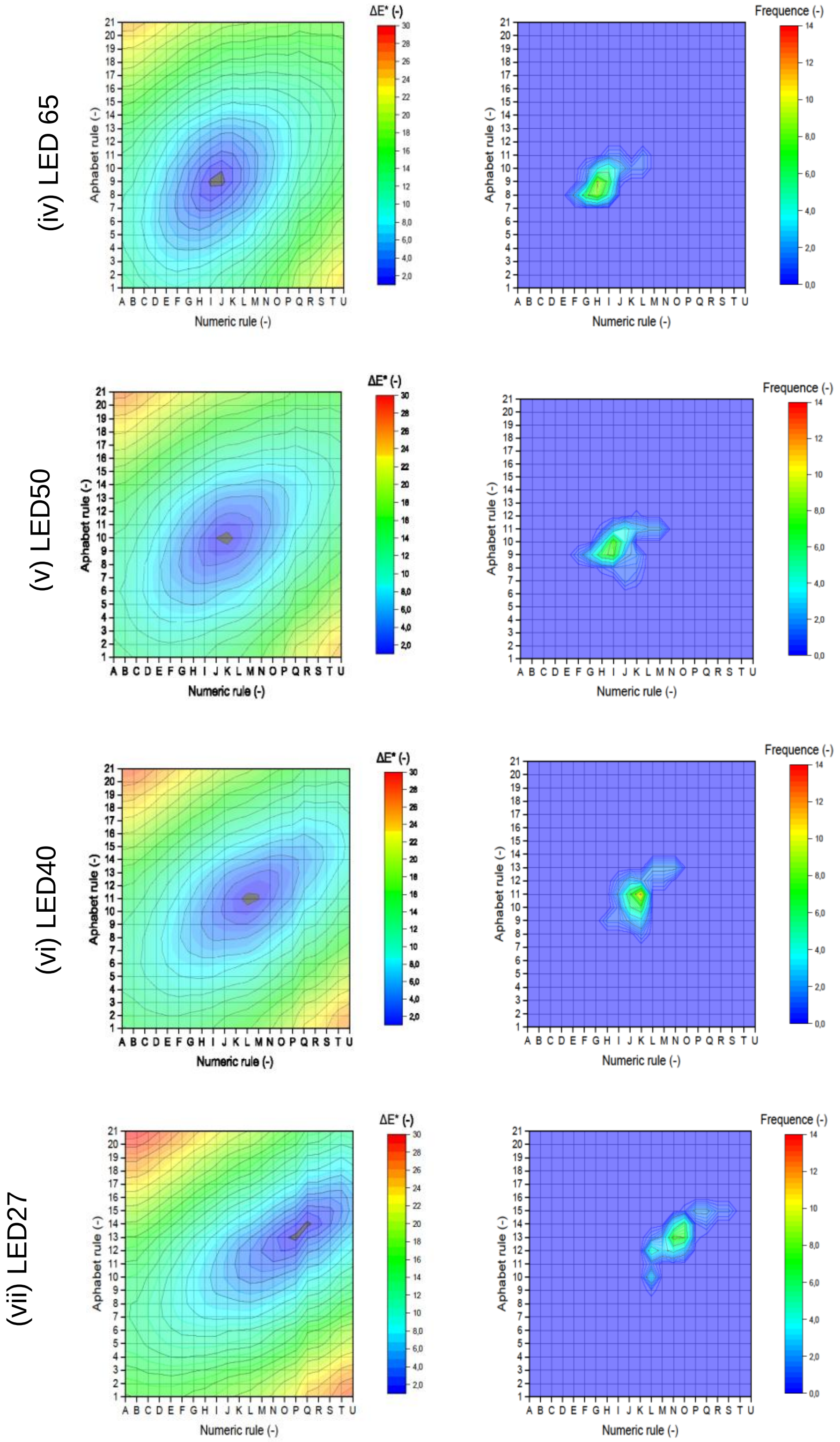


Figure 22. Left image: The color map shows the variation of color difference (*ΔE**) between alphabet rule and numeric rule under experimental lighting conditions. Right image: The color map shows the frequency of occurrences of the corresponding *ΔE** values

- To analyze the influence of delta E (color difference) by *CRI*, Rf and CCT, a multiple regression analysis was performed and CCT significantly affects Delta E. It highlights that higher CCT lighting sources may produce more consistent or stable color appearance, leading to lower perceptual color discrepancies. In contrast, a strong positive correlation was observed between *CRI* and Rf (r = 0.99), demonstrating that these two color-rendering metrics behave almost identically across the tested lighting sources.
- To represent the preferences of observers under different light sources, pie chart data were analysed as shown in Figure 23. Under SPLIII_D65, SPLIII_TL84, 6500K (LED65), and 5000K (LED50) light sources, the H series of D-H Color Rule dominates the chart. In contrast, under SPLIII_A (incandescent), 4000K (LED40), and 2700K (LED27) lighting, a different set of sample pairs takes precedence.

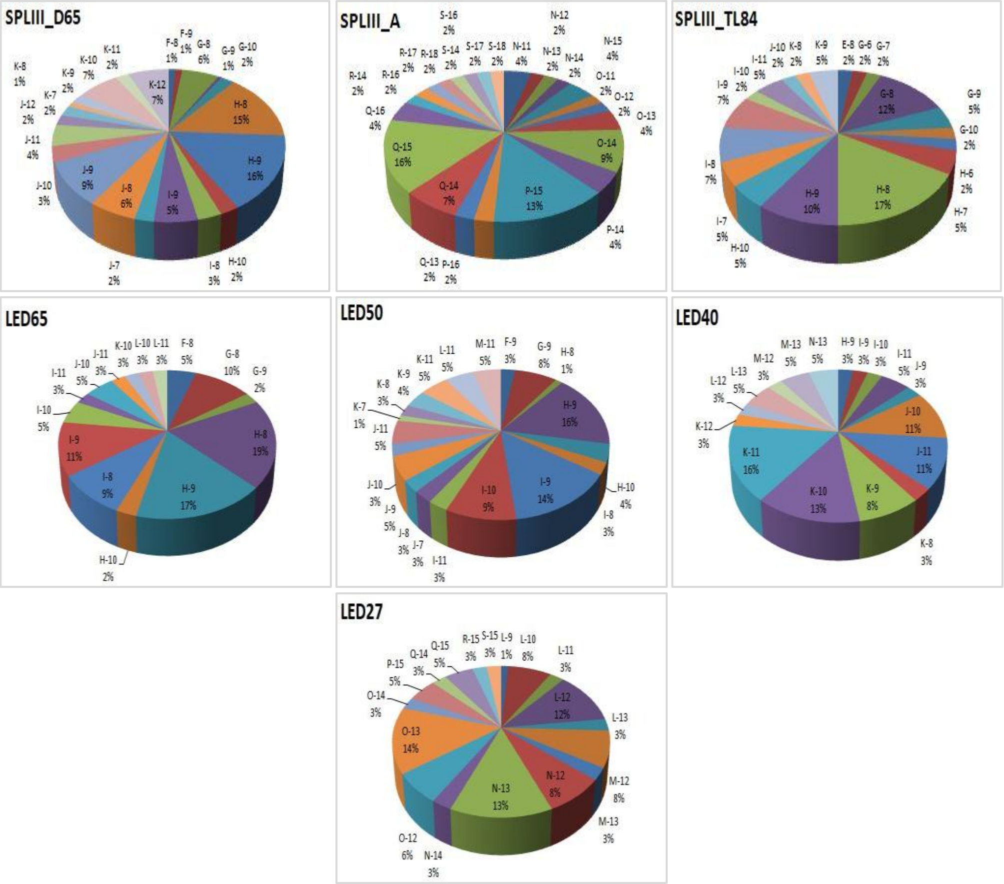


Figure 23. Pie chart distribution of sample pairs preferences across light sources

The differences in sample pair preferences under various light sources can be attributed to the spectral power distributions (SPDs) of these illuminants. The light sources like, SPLIII_A (incandescent), 4000K (LED40), and 2700K (LED27) are typically warmer light sources, with a higher proportion of red and yellow wavelengths. These enhance the appearance of colors in the red-yellow spectrum while potentially muting blues and greens. On the other side, light sources like SPLIII_D65, SPLIII_TL84, 6500K (LED65) and 5000K (LED50) are cooler or neutral light sources, closer to daylight, with more balanced SPDs that emphasize a wider range of colors evenly. It was concluded that the observed differences are primarily due to the variations in SPD, the color temperature of the light sources, and how they interact with the spectral properties of the sample pairs. This highlights the importance of context when interpreting color matches under different lighting conditions.

Key findings:

1. Low color difference under SPLIII_D65 and LEDs
2. Higher ΔE values obtained using CIECAM16, compared to CIELAB
3. Broader spread of the matching patterns for SPLIII_TL84 and SPLIII_A, in contrast to the more defined pattern under SPLIII_D65 and LEDs
4. Pairs having Delta E below 2.5, preferred under SPLIII_D65, LED65, LED50, LED40 & LED27
5. CCT significantly affects Delta E
6. *CRI* and Rf behave almost identically across the tested lighting sources

Key Takeaway:

1. Variations in matching patterns emphasizes the complex nature of color difference under varying lighting conditions
2. Emphasizing how a slight color difference (a Delta E of 2.5) cause discrepancies in color perception across different lighting conditions.
3. Possible to predict the factors that causing variations in Delta E for the sample set
4. The variations in SPD, CCT and how they interact with the spectral properties of the sample pairs, affect observer preferences

5.3. Experiment-3: Optically brightened textiles evaluation

Summary of the results: In experiment 3, a set of ten optically brightened samples were investigated under D65 and D65UV conditions to observe the actual behavior of optical brighteners.

- The results showed a noticeable increase in total spectral radiance in the blue region when UV was included, which led to higher perceived whiteness as shown in Figure 24.

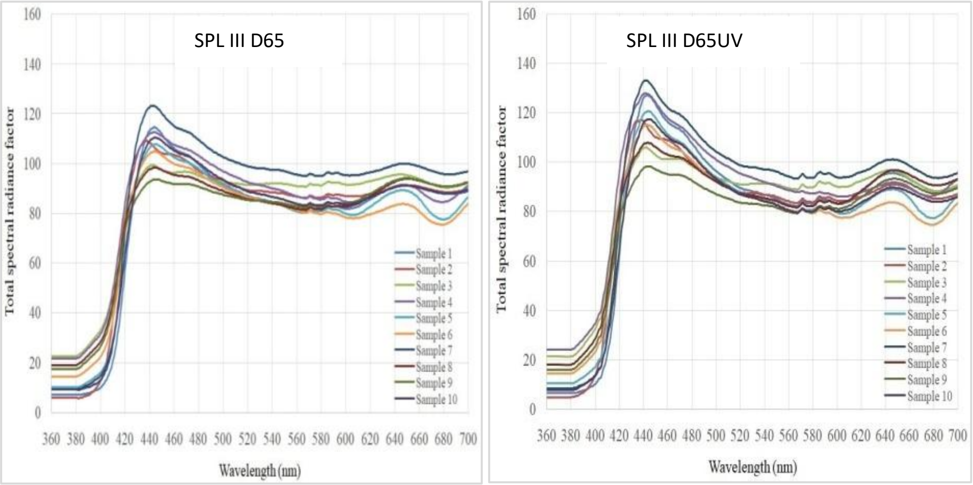


Figure 24. The complete spectrum under D65 and D65+UV lighting conditions of Spectralight III booth

In contrast, under D65, the radiance curve reflects only the intrinsic reflectance of the material, resulting in lower radiance in this region. Although the optical brightening agent (OBA) remains present and can still respond in the visible range (400nm-700nm), its fluorescence is significantly weaker because the UV radiation intensity is insufficient to properly excite the OBA. As a result, the fluorescence contribution becomes minimal and the measured radiance is dominated by the material’s inherent reflectance rather than by OBA-induced emission.

- When UV is included, fluorescence increases the luminance (L^*) and shifts the chromaticity toward the blue region (more negative b^*) as shown in Figure 25.

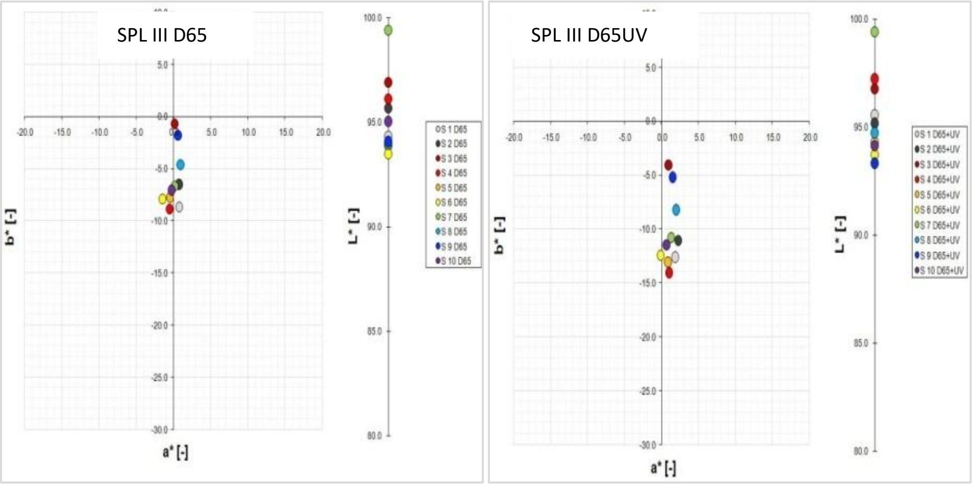


Figure 25. *CIEL*a*b** values of ten samples under D65 and D65+UV at SPLIII

- These changes result in a measurable rise in *ΔE* as shown in Figure 26.

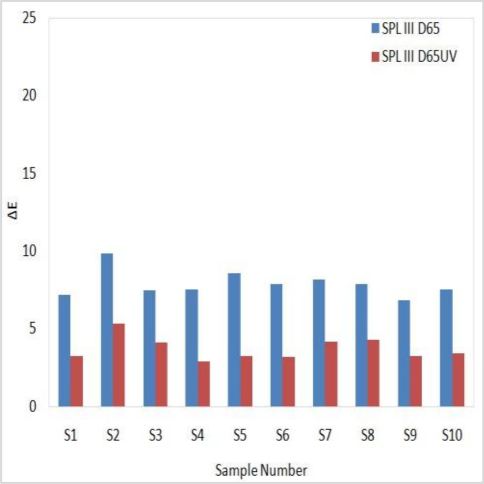


Figure 26. *ΔE* values of samples under D65 and D65+UV at SPLIII

Samples with highest *ΔE* values exhibit stronger UV sensitivity and greatest fluorescent contribution, whereas samples with lowest values show minimal or no response to UV excitation.

- The CIE whiteness index (WCIE) increased by approximately 14–26 units across samples, while the Ganz–Griesser whiteness index (WGG) showed an even larger enhancement of 30–52 units as shown in Figure 27, confirming its higher sensitivity to fluorescence-induced changes in luminance. The difference in mathematical structure explains why the two indices do not rank the samples identically. WCIE is dominated by the luminance component (*Y*) and responds moderately to chromatic shifts, whereas WGG strongly amplifies the blue–yellow tint factor and is therefore far more sensitive to UV-induced fluorescence.

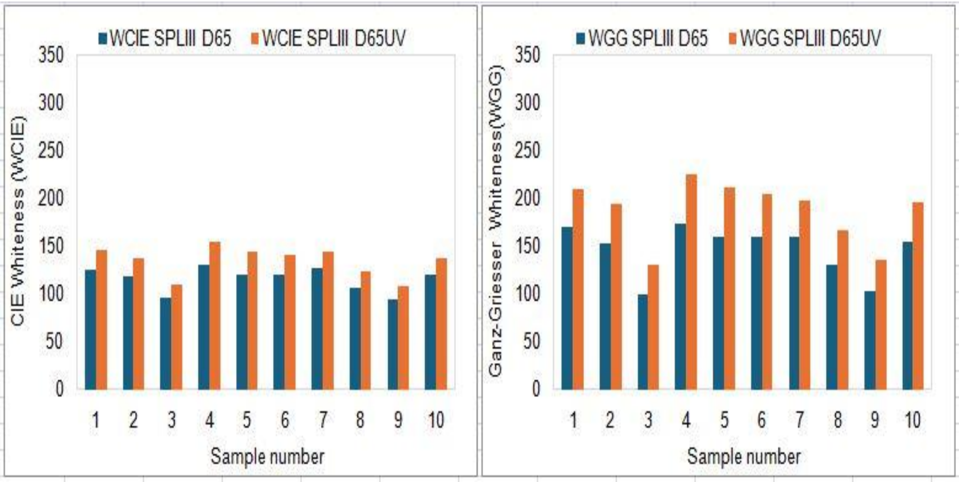


Figure 27. The CIE whiteness and the Ganz-Griesser whiteness (WGG) values for the ten samples under D65 and D65+UV at SPLIII

- Based on the Chi-Square tests' outputs, the null hypothesis (H_0) for both D65 and D65+UV conditions was confidently rejected. Both Table 5 and 6 summarizes the frequency counts for 45 unique pairs under D65 with UV and D65 without UV. The evidence suggests that UV content does have a measurable impact on the perceived whiteness. The extremely low p-values for both conditions suggest that the effect of UV on color appearance is not due to random chance and is statistically significant.

Table 5. Pair observed frequency and Chi-Square test's output for D65+UV

D65UV										
Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	5	7	3	12	12	7	10	1	0	10
2	5	7	1	11	6	5	12	1	0	10
3	9	11	3	10	9	7	12	7	6	10
4	0	1	2	12	3	3	9	0	0	4
5	0	6	3	9	12	8	9	3	0	8
6	5	7	5	9	4	7	9	5	2	9
7	2	0	0	3	3	3	10	0	0	3
8	11	11	5	12	9	7	12	1	2	11
9	12	12	6	12	12	10	12	10	0	12
10	2	2	2	4	3	9	1	0	12	10
Chi-Square = 552.53										
P-value = 4.10586E-89										

These outcomes demonstrated the strong role of fluorescence in color appearance but also highlighted practical limitations of conventional measurements, especially the need for repeated measurements at different UV levels.

Table 6. Pair observed frequency and Chi-Square test's output for D65

D65										
Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	5	7	2	11	10	5	11	1	0	12
2	5	7	0	8	3	3	11	0	0	10
3	10	12	2	11	12	8	11	6	4	12
4	1	4	1	11	2	3	9	0	0	3
5	2	9	0	10	10	8	8	1	0	8
6	7	9	4	9	4	5	9	4	1	9
7	1	1	1	3	4	3	11	0	1	4
8	11	12	6	12	11	8	12	1	3	11
9	12	12	8	12	12	11	11	9	0	12
10	0	2	0	4	3	8	1	0	12	12
Chi-Square = 552										
P-value = 4.1305E-89										

Key findings:

1. UV content has a direct and measurable influence on total spectral radiance factor, whiteness and *ΔE*
2. Samples with highest *ΔE* values exhibit stronger UV sensitivity
3. Ganz-Griesser whiteness better reflects fluorescence effects compared to CIE whiteness due to the difference in their mathematical structure
4. Fluorescence contribution is concentrated in the blue region (420–470 nm), increasing perceived whiteness

Key Takeaway:

The initial results offered a foundational understanding of the UV sensitivity of optically brightened textiles; however, since conventional evaluation reveals only the overall impact of UV without capturing how the response evolves across different UV percentages, a new method became essential to quantify the influence of varying UV proportions with greater precision and consistency.

5.4. Results from proposed interpolation method

Summary of the results: To address this, an interpolation-based method was developed to virtually calculate the fluorescent spectral radiance factor at varying UV percentage.

- Three graphs as in 28. (a), (b) and (c) illustrate how the reflectance changes across different wavelengths and how the luminescent properties contribute to the total spectral radiance factor for the ten optically brightened samples.

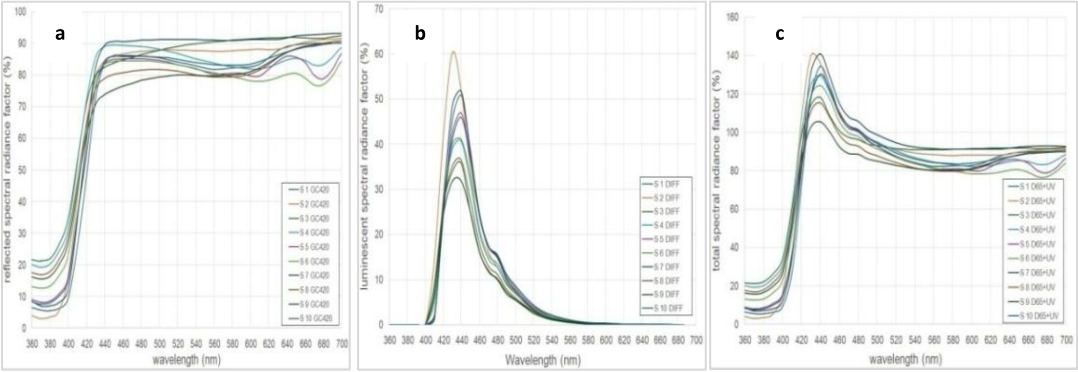


Figure 28. (a) Reflected spectral radiance factor, β_R (b) luminescent spectral radiance factor, β_L and (c) total spectral radiance factor, β_T of ten optically brightened white samples obtained by interpolation technique at 100% UV (equivalent to *CIED65*)

- Interpolated data for luminescent spectral radiance factors (β_L) agreed sufficiently with actual Spectralight III measurements, reinforcing the reliability of the interpolation technique as shown in Figure 29.

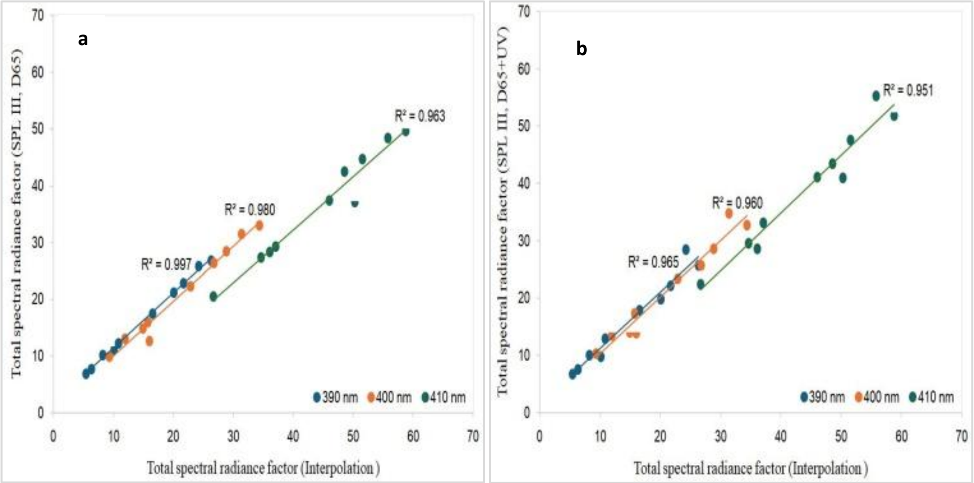


Figure 29. Correlation between total spectral radiance factor obtained from interpolation technique and actual data under the (a) D65 and (b) D65+UV provided by the Spectralight III

- Sample with highest β_R, β_L, and β_T values (Figure 28) shows clear shifts in its CIE *L*a*b** color values when UV is increased from 0% to 100% as shown in Figure 30. Sample appears progressively brighter as the UV intensity increases.

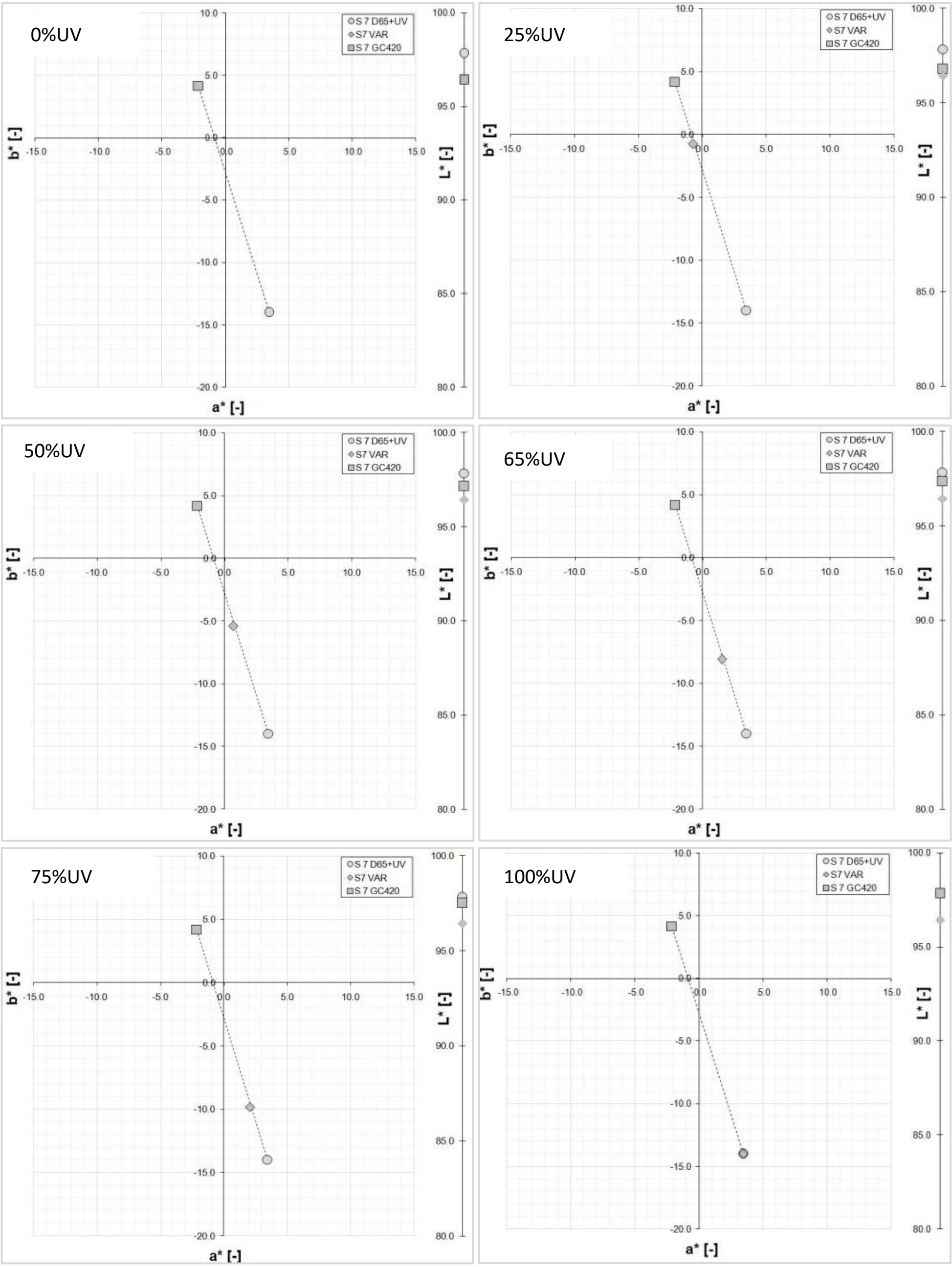


Figure 30. *CIEL*a*b** values of sample 7 under 0%UV, 25%UV, 50%UV, 65%UV, 75%UV and 100%UV. The circular markers (S4 D65+UV) represent measurements obtained under standard D65 illumination with full UV content. The diamond markers (S4 VAR) correspond to measurements made under variable UV excitation. The square markers (S4 GC420) represent the UV-

suppressed condition measured using the GC420 long-pass filter

- To quantify the impact of varying UV content on perceived color, the color difference (*ΔE*) for CIELAB color space was calculated as shown in Figure 31. By comparing the *ΔE* values across different UV percentages, it was observed that *ΔE* decreases with increasing UV percentage. At 0% UV, samples appeared dull or less bright compared to the CIED65 condition, resulting in a larger color difference (higher *ΔE*). As the UV percentage increases, the color appearance of the sample approaches that of the CIED65 reference condition. This reduces the perceived color difference, causing *ΔE* to decrease. At 75% UV, the sample is likely to be at its maximum brightness, which is close to the CIE D65 state or the 100% UV state, since we considered 100% UV to be CIED65. Therefore, *ΔE* becomes minimal, indicating a closer match between the sample under test and the reference illuminant.

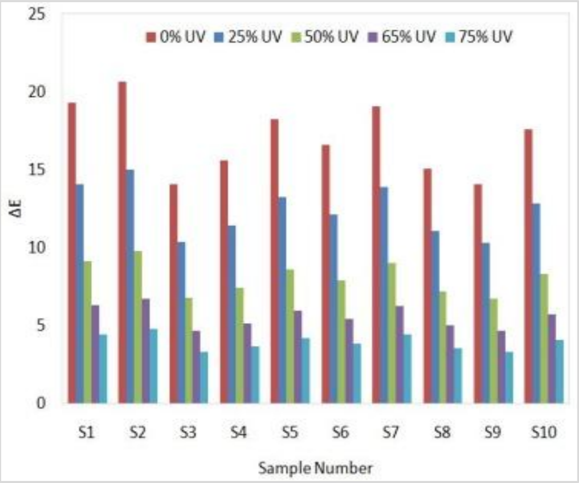


Figure 31. *ΔE* values for the ten samples under different UV conditions obtained from interpolation technique

It was shown that small UV fluctuations have a significant influence on the color of optically brightened textiles. The results show significant differences between D65 and D65+UV, and samples under D65+UV show very good agreement with 75% UV. Based on these findings, a recommendation is of using SPLIII's D65 simulator with 75% UV settings for accurate color evaluation of optically brightened textiles compared to the CIED65 illuminant.

- The smooth and monotonic nature of the Center of Gravity (CoG) trajectory suggests that all samples respond coherently to the increase of UV% from 0% to 100%, demonstrating a systematic and predictable color shift driven by the fluorescence of whitening agents as shown in Figure 32. Overall, the CoG path effectively represents the group-level chromatic evolution of the sample set under varying UV excitation.

- The Weighted Centers of Gravity plot shows the UV-induced chromatic response across the ten samples, ranging from weakly fluorescent yellowish materials to intensely blue-shifting fluorescent substrates. Figure 32 represents the Weighted Centers of Gravity of ten samples in the CIE a^*b^* plane reveals distinct colorimetric behaviors under UV excitation.

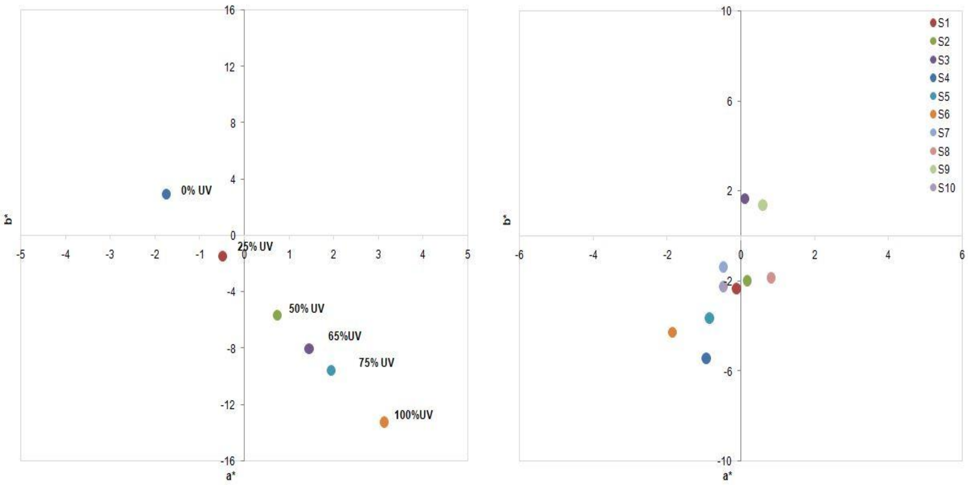


Figure 32. Left: The trajectory of the Center of Gravity (CoG) of the ten samples and Right: Weighted Centers of Gravity of all samples in the CIE a^*b^* chromaticity plane as the UV excitation was gradually increased from 0% to 100%

- The correlation between WCIE under D65 and WCIE under varying UV% showed a substantial increase, rising from 0.49 at 0% UV to 0.913 at 100% UV, reflecting WCIE’s strong sensitivity to UV-induced fluorescence as shown in Figure 33. In contrast, the correlations involving WGG (D65 and D65UV) and WGG under different UV% increased more moderately, rising from 0.58 to 0.94 and 0.66 to 0.95, respectively. It is due to the fact that WGG is less UV responsive by design. The correlation between WCIE under D65UV and WCIE under different UV% exhibited a smaller but still clear improvement, from 0.662 at 0% UV to 0.80 at 100% UV**.** Overall, the results show that higher UV excitation enhances predictive accuracy across all cases, but the degree of improvement depends on UV sensitivity of the whiteness metric. Results gave an impression of the precision of the SPLIII in replicating different UV conditions. For both methods, the D65+UV whiteness values are in the range of the highest UV% data points. This confirmed how well the SPLIII's D65+UV condition simulates natural daylight (which includes UV). The GG method is a special calibration specifically for optically brightened textiles.

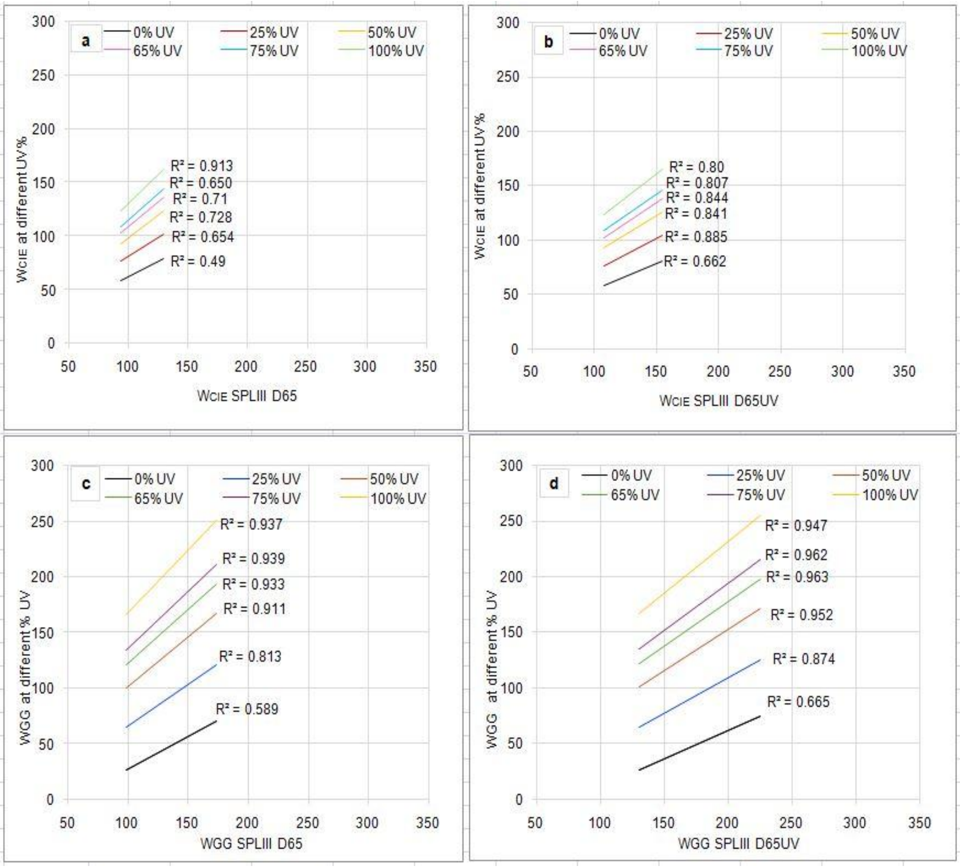


Figure 33. The CIE whiteness and the Ganz-Griesser whiteness (WGG) values for the ten samples under different UV conditions obtained from interpolation technique

This difference in whiteness values provides insight into how FWAs are perceived under different calibration methods. The GG represents a more reliable measure of optically brightened textiles as it gave the strongest correlation under the D65+UV condition of SPLIII and maximum UV changes.

Key findings:

1. Interpolated results agree sufficiently with the actual data obtained from SpectraLight III data
2. A strong correlation between CIE whiteness and Ganz-Griesser whiteness value
3. The GG represents a more reliable calibration method for optically brightened textiles
4. The SPLIII’s D65 with 75%UV condition simulates natural daylight (which includes UV) well

Key Takeaway:

1. Interpolation is a reliable technique for prediction UV impact
2. Continuous UV variation became possible instead of only discrete levels
3. The method reduced time, measurement load, and dependence on specific instrument UV calibration
4. By combining conventional measurement with interpolation based calculation, a more comprehensive and practical assessment of the color appearance of optically brightened textiles under different illumination conditions can be achieved.

Suggestions:

Based on the findings, the following recommendations are suggested:

- **Use Interpolation for predictive UV impact**

The interpolation method used to calculate luminescent spectral radiance factors (β_L) is a reliable technique for understanding how textiles will react under different UV conditions. It is recommended to apply this technique to predict the impact of UV content on the appearance of optically brightened textiles.

- **Use of SPLIII’s D65 simulator with 75% UV:**

For the most accurate color rendering of optically brightened textiles, it is recommended to use SpectraLight III's D65 simulator with 75% UV. This setting closely matches the CIE D65 illuminant, ensuring consistent and reliable color evaluations.

- **Application of Ganz-Griesser calibration:**

For evaluating optical brighteners, it is recommended to use Ganz-Griesser calibration (GG) in conjunction with SPLIII's D65 simulator. This combination provides a more reliable measure of whiteness and color by capturing both reflected and luminescent spectral radiance factors.

6. Evaluation of results and new findings

The proposed interpolation-based method introduces a more practical and efficient alternative to conventional measurement approaches for evaluating luminance spectral radiance factor and perceived whiteness of optically brightened textiles under varying UV percentage. By enabling continuous adjustment of UV percentage rather than requiring repeated physical measurements at discrete UV levels, the method substantially reduces measurement time, effort, and reliance on specialized UV-calibrated equipment.

The close agreement between interpolated and experimentally obtained spectral radiance and colorimetric values ensures its validity and robustness, offering a significant improvement in accuracy over conventional luminance measurement methods. It demonstrates that fluorescence-related optical behavior can be accurately predicted without exhaustive laboratory measurement. The methodology accounts for the spectral characteristics of both visible and UV light, addressing a critical gap in existing models by providing a more precise estimation of luminance and whiteness in materials that respond to UV radiation. This allows for a more reliable prediction of how materials will appear under diverse UV conditions, which is essential for quality control and color management in color-sensitive industries. Additionally, the methodology has the potential to serve as a standard for luminance measurements, offering consistency and reproducibility across research studies and industrial applications. This improves the reliability and flexibility of whiteness, *ΔE* and *CRI* evaluations and supports more realistic modeling of visual appearance under different illuminants, including modern LEDs where UV content varies widely. Therefore, the method not only strengthens the analytical understanding of fluorescence effects but also facilitates the development of more accurate tools for predicting the optical behavior of materials in real-world lighting environments, ultimately enhancing the design and manufacturing processes in industries that rely on precise color rendering and luminance control.

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8. List of papers published by the author

Publications in journals

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[2] Mukthy, A.A., Vik, M., Viková, M. Color perception estimations of metameric pairs under different illuminance levels, Vlakna a Textil 2022, 29(1), 36-45. https://doi.org/10.15240/TUL/008/2022-1-005. *[Impact factor= 0.52]*

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Contribution in conference proceeding

[1] Vik, M., Mukthy, A. A., Viková, M. Whiteness Perception under LED Source with High Content of UV Radiation, AUTEX-2021, Gumaraes, Portugal.

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9. Curriculum Vitae

Azmary Akter Mukthy

Address: Rampura, Dhaka, Bangladesh
Phone: +8801618991207
Email address: azmaryamukthy27@yahoo.com

Professional Experience

09/2013-10/2017	Lecturer, Primeasia University, Dhaka, Bangladesh • Teaching and research in the field of textile dyeing, printing, and quality testing

Education

10/2019 - Present	Ph.D. in Material Engineering, Technical University of Liberec, Czech Republic • Research field: Color appearance of optically brightened textiles; metameric properties of colored and white samples
07/2017	M.Sc. in Textile Engineering, Bangladesh University of Textiles, Dhaka, Bangladesh • Activities: Advanced dyeing, printing, finishing & coloration, technical textiles, textile materials & properties, and chemistry of fiber-forming polymers
06/2013	B.Sc. in Textile Engineering, Bangladesh University of Textiles, Dhaka, Bangladesh • Activities: Textile wet processing, textile finishing, textile raw materials, fabric processing, polymer Science, and textile physics

Skills

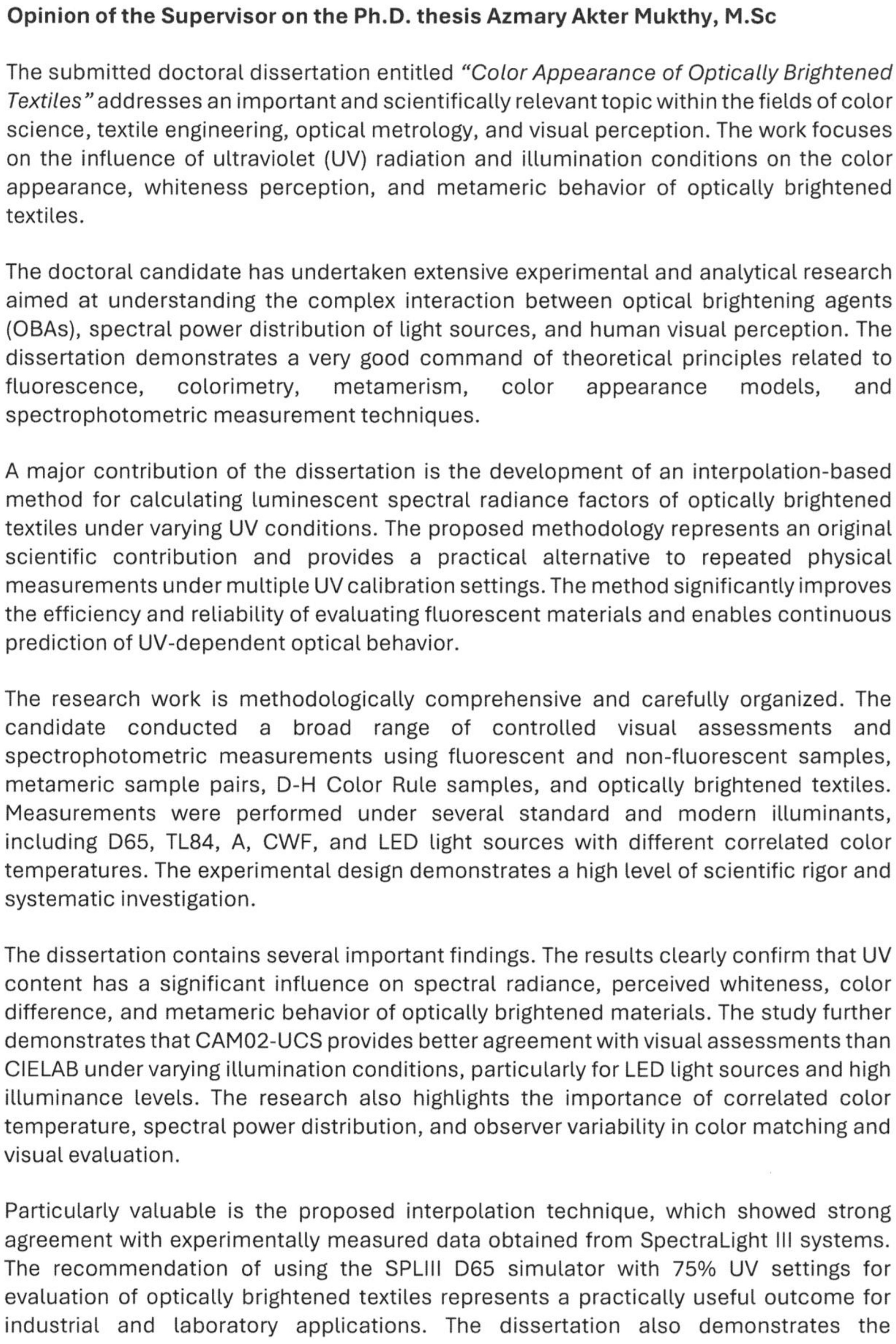
Digital competence	• Microsoft office • Windows, and Linux OS • EM Modeling using ABAQUS Software
Language	• German (Level B1)

10. Brief description of the current expertise, research and scientificactivities

Doctoral studies

Studies:	Full-time student at the Faculty of Textile Engineering, Department of Material Engineering. Specialization: Material Engineering
Exams:	1) Structure and properties of textile fibre (13-12-19) 2) Mathematical Statistics (04-06-20) 3) Optics of Solids (04-02-21) 4) Sensorical Textile Materials (20-12-23) 5) Experimental technique of the textile (24-10-24)
SDE:	State Doctoral Exam completed on 28-03-25 with the overall result passed.
Research projects:	**Project title: Color appearance of products under different light Sources** Role in Project: Team leader Project number: SGS-2020-6038 Project duration: 2 years (2020 and 2021)

11. Recommendation of the supervisor



Opinion of the Supervisor on the Ph.D. thesis Azmary Akter Mukthy, M.Sc

The submitted doctoral dissertation entitled *“Color Appearance of Optically Brightened Textiles”* addresses an important and scientifically relevant topic within the fields of color science, textile engineering, optical metrology, and visual perception. The work focuses on the influence of ultraviolet (UV) radiation and illumination conditions on the color appearance, whiteness perception, and metameric behavior of optically brightened textiles.

The doctoral candidate has undertaken extensive experimental and analytical research aimed at understanding the complex interaction between optical brightening agents (OBAs), spectral power distribution of light sources, and human visual perception. The dissertation demonstrates a very good command of theoretical principles related to fluorescence, colorimetry, metamerism, color appearance models, and spectrophotometric measurement techniques.

A major contribution of the dissertation is the development of an interpolation-based method for calculating luminescent spectral radiance factors of optically brightened textiles under varying UV conditions. The proposed methodology represents an original scientific contribution and provides a practical alternative to repeated physical measurements under multiple UV calibration settings. The method significantly improves the efficiency and reliability of evaluating fluorescent materials and enables continuous prediction of UV-dependent optical behavior.

The research work is methodologically comprehensive and carefully organized. The candidate conducted a broad range of controlled visual assessments and spectrophotometric measurements using fluorescent and non-fluorescent samples, metameric sample pairs, D-H Color Rule samples, and optically brightened textiles. Measurements were performed under several standard and modern illuminants, including D65, TL84, A, CWF, and LED light sources with different correlated color temperatures. The experimental design demonstrates a high level of scientific rigor and systematic investigation.

The dissertation contains several important findings. The results clearly confirm that UV content has a significant influence on spectral radiance, perceived whiteness, color difference, and metameric behavior of optically brightened materials. The study further demonstrates that CAM02-UCS provides better agreement with visual assessments than CIELAB under varying illumination conditions, particularly for LED light sources and high illuminance levels. The research also highlights the importance of correlated color temperature, spectral power distribution, and observer variability in color matching and visual evaluation.

Particularly valuable is the proposed interpolation technique, which showed strong agreement with experimentally measured data obtained from SpectraLight III systems. The recommendation of using the SPLIII D65 simulator with 75% UV settings for evaluation of optically brightened textiles represents a practically useful outcome for industrial and laboratory applications. The dissertation also demonstrates the advantages of Ganz-Griesser calibration for fluorescence-sensitive whiteness evaluation.

The thesis is written in a clear and logically structured manner. Experimental results are thoroughly analyzed, statistically evaluated, and critically discussed. The conclusions are well supported by the presented data and demonstrate the candidate's ability to independently conduct scientific research, interpret complex experimental findings, and formulate meaningful scientific conclusions.

From both theoretical and practical perspectives, the dissertation contributes valuable knowledge to the understanding of fluorescence-driven color appearance and illumination-dependent visual perception. The outcomes have direct relevance for textile manufacturing, quality control, color management, printing, retail lighting, and other color-critical industries where accurate whiteness and color consistency are essential.

The candidate has demonstrated the ability to work independently, apply advanced measurement techniques, perform statistical analyses, and develop innovative methodological solutions. The dissertation fulfills the requirements expected of a doctoral thesis in terms of originality, scientific contribution, methodological quality, and scope of research.

Based on the scientific quality of the dissertation and the significance of the achieved results, I fully recommend the submitted thesis for defense and recommend awarding the candidate the degree of Doctor of Philosophy (Ph.D.).

Supervisor:
doc. Ing. Martina Viková, Ph.D.
LCAM KMI FT, Technická univerzita v Liberci
7. 5. 2026

12. Opponents' reviews

Reviewer Report on a Doctoral Thesis

Candidate: **Azmary Akter Mukthy, M.Sc.**

Thesis Title: **"Color Appearance of Optically Brightened Textiles"**

Reviewer: **prof. Ing. Aleš Richter, CSc.**

Field of Study: **Textile Engineering**

The main goal of the thesis is examining the appearance of optically brightened materials under different lighting conditions, focusing on how ultraviolet (UV) spectrum influences perceived whiteness and colour consistency. The aim of this study was to develop an interpolation-based technique for calculating luminescent spectral radiance factor of optically brightened textiles under altered lighting settings.

The dissertation covers two areas that are influenced by the spectral distribution of light sources used during visual assessment and subsequent measurement.

In the introduction, the author discusses how color appearance depends on viewing conditions. She then provides a detailed analysis of material whiteness evaluation, including basic information on methods to enhance whiteness through chemical and physical processes.

The author clearly outlines current measurement methods and discusses their advantages and disadvantages, including their applicability in industrial practice.

The section on materials and methods describes individual experimental setups, characterizes the light sources used, and details the selected sets of samples. The range of light sources and samples used constitutes a unique dataset suitable for further analysis.

In the Results and Discussion, they are analysed the tested parameters individually and compares the visual assessments with the measured values of the indices. Candite tests and verifies hypotheses, critically compares individual light sources, and evaluates the quality of visual assessments using a statistical metric known as STRESS (standardized residual sum of squares).

I have to note that the author does not discuss this fundamental metric anywhere in her paper, so the reader must look up its exact description.

In Chapter 4.2, "Results of Experiment 2: D & H Colour Rule Evaluation," the author presents a series of graphical maps. On the one hand, she characterizes the criteria for the coloration of individual isolines in the graph in the case of an objective evaluation using measurements.

However, she does not specify how frequency is calculated in the case of a visual assessment.

Figure 74 shows the central points of occurrence of the tested samples in the CIELAB colour space. It is unclear what significance these points have based on the information provided.

I think, it is more important to discuss the position intervals of these samples in the case of a light source with variable UV radiation spectrum.

In the Conclusions candidate Azmary Akter Mukthy, M.Sc**.** summarizes the partial results of her experiments, including significant findings for evaluating the quality of light sources and measured materials, such as optically brightened textiles, in industrial practice.

I recommend this thesis for defense because the author offers own perspective on a long-standing issue. I am attaching 3 questions that candidate prepares responses in your defense.

The language level of the thesis is acceptable. It is a mixture of American and British grammar. Spelling mistakes are few and rare.

The author demonstrates a very good understanding of the current state of knowledge. The thesis meets the standard requirements for a doctoral thesis."

Questions:
1) Describe the STRESS statistical metric exactly and, if possible, briefly.
2) Explain the frequency calculation for the graphs in Figure 63.
3) Can the author provide examples of cases in which the general color rendering index (Ra) yields a significantly misleading evaluation compared to other metrics?

I recommend the thesis for defence.

Prof. Ing. Aleš Richter, CSc.,

EXTERNAL EXAMINER´S OPINION OF DISSERTATION THESIS

External examiner: doc. Ing. Tomáš Novák, Ph.D., VŠB-TU Ostrava
Author: Azmary Akter Mukthy, M.Sc.
Title of dissertation thesis: Color Appearance of Optically Brightened Textiles
Study programme: P0723D270003 Textile Engineering
Thesis supervisor: doc. Ing. Martina Viková, Ph.D.
University: Technical University of Liberec, Faculty of Textile Engineering
Year: 2026

1. Relevance of the topic

This dissertation addresses the highly relevant issue of how textiles with optical brighteners appear under different lighting conditions, with a particular focus on the effect of ultraviolet radiation on the perceived whiteness, colour consistency and metamerism of materials. This topic is significant in terms of both basic research in colorimetry and textile engineering and industrial practice, where accurately assessing the whiteness and colour of textiles is essential for quality control, colour communication and reproducible production. The work addresses the increasing use of modern LED light sources, which have significantly different spectral power distribution to traditional standard light sources.

The focus on optical brighteners, whose fluorescence is strongly dependent on the UV content of the source of radiation, is particularly valuable. The author correctly identifies the fact that conventional methods of evaluating whiteness and colour differences may be inadequate for fluorescent materials as they cannot fully capture luminescence and its changes under varying UV excitation.

2. Objectives of the thesis and their achievement

The main objective of this dissertation was to develop an interpolation method for calculating the luminescent spectral radiance factor of optically brightened textiles under light sources with varying UV content. This objective was supplemented by sub-objectives focusing on analysing metameric differences, investigating the relationship between visual and instrumental evaluation, examining the influence of correlated colour temperature, colour rendering index and spectral power distribution of light sources, and evaluating whiteness using various indices.

Based on the results presented, it can be concluded that the thesis objectives were achieved. The author conducted an extensive series of experiments involving metameric samples and optically brightened textiles. The proposed interpolation method enabled the prediction of the luminescent component at various levels of UV radiation, achieving good agreement with actual measurements performed using "Gretag Macbeth SpectraLight III".

3. Methodological quality of the work

The work's methodology is comprehensive and well-structured. The author applies spectrophotometric measurements with controlled visual evaluation to create a suitable basis for comparing instrumental and perceptual data. Various lighting conditions are utilised in the study, including D65, TL84, A, CWF and LED sources with different correlated colour temperatures. Different illuminance levels are also taken into account. Combining multiple evaluation approaches is also beneficial.

4. Results and scientific contribution

This dissertation provides a thorough analysis of how the UV component, affect the colour appearance, whiteness and metameric behaviour of textile materials. Experiments were conducted to evaluate metameric samples, the D-H colour rule and optically brightened textiles under various illuminants and LED light sources. The results revealed that the spectral power distribution has a significant impact on both instrumentally measured colour differences and observers' visual assessments.

Most valuable outcome is that the CAM02-UCS model more closely aligns with visual assessments than the traditional CIELAB model. Next significant contribution of this work is the proposal of an interpolation method for calculating the luminescent spectral radiation factor at varying UV levels. This method enables more efficient prediction of the behaviour of optically brightened textiles, eliminating the need for repeated measurements at each UV radiation level. The results show good matching with experimental data and demonstrate clear potential for use in the textile industry.

5. Formal and linguistic quality

The thesis is logically structured and contains all needed sections (detailed methodology, results, conclusions) includes very extensive literature review. The author effectively combines theoretical knowledge with experimental verification by drawing on current scholarly literature. A large number of graphs, tables and diagrams complement the text

While the thesis's formal quality is good, some sections are relatively lengthy and repetitive. The clarity could be improved by placing a greater emphasis on the key contribution of the proposed method.

The linguistic quality is generally acceptable, though minor phrasing and grammatical inaccuracies appear in the text. However, these do not diminish the thesis's scientific value.

6. Overall evaluation

This dissertation is a valuable academic contribution to the field of evaluating the colour appearance and whiteness of optically brightened textiles. The author demonstrates an excellent understanding of colorimetry, metamerism, fluorescence and optical brighteners. The experimental section is extensive and methodologically diverse, and the results are supported by statistical analysis.

The top contribution is the proposal and validation of an interpolation method for predicting the luminance spectral radiance factor at various levels of UV radiation. This method has the potential to simplify and refine the evaluation of optically brightened textiles in laboratory and industrial settings.

The author's publication record, including articles in peer-reviewed journals and conference papers, further supports the thesis.

This dissertation meets the requirements for doctoral study. It presents original scientific findings and offers new methodological insights with clear practical implications for textile engineering, colorimetry and the evaluation of whiteness in optically brightened materials.

I recommend this thesis for defence.

In Ostrava

5.5.2026 doc. Ing. Tomáš Novák, Ph.D.

7. Questions for the defence

1. How would the proposed method perform on samples with very high concentrations of optical brighteners, where a non-linear fluorescent response?

2. Could the proposed interpolation method be integrated with modern machine learning models to predict the appearance of textiles under various lighting conditions?

3. Do you see an opportunity to add a small UV component to LED lighting systems?