Abstract

Noor, Kashif. Effect of lighting variability on the color difference assessment (under the supervision of Dr. David Hinks.)

The purpose of this study was twofold: a) to quantify the degree of lighting variability in selected large and medium retail stores, and to compare the measured area lighting to the quality of lights used in selected standard light booths, and b) to assess the performance of the current ISO and AATCC recommended color difference formula, DE_{CMC}, to a new formula, CIEDE2000 (or DE_{00}), recently recommended by the Commission Illumination de l'Eclairage (CIE).

The effect of lighting variability was assessed using two pairs of metameric dyed cotton samples. Spectroradiometric measurements of several large department stores were taken at various locations around the store, including areas in which clothing was displayed, changing areas, in front of full length mirrors, at the check-out counter, etc. Similar measurements were made at several medium sized retail chain stores. The lighting variability was assessed using key factors, including illuminance (lx), correlated color temperature, metamerism index and color inconstancy index. Using the measured spectral data at each location in the store, and the reflectance factors of the two metameric pairs, the variability in key colorimetric data was calculated and compared to standard illuminant data. Also, as a new color difference formula has been recently adopted by the CIE, the performance of the new formula was assessed using 19 color difference sample

pairs (100% polyester) around 5 color centers. The colors of four of the color centers were selected to be in regions of color space that the new formula is reported to perform better than DE_{CMC}, namely blues, dark, and near neutral colors. The performance of each color difference formula was assessed against visual pass/fail data for thirty one expert shade matchers were using each color difference pair.

Considerable variability was found within each store measured, and between stores, for each of the colorimetric and radiometric variables studied. For instance, the illumination levels varied from 50 Lux to approximately 1800 Lux and very often did not comply with the levels recommended by the Illuminating Engineering Society (IES). DE_{cmc} values ranged from .4 to 7.5. In general, the lighting variability at the point-of-sale indicates strongly that protocols for selecting dye recipes should be developed to minimize color inconstancy between the light sources used in the store in order to insure that the color perceived by the consumer is close to that intended by the product designer.

Using the limited set of color difference pairs, the performance of CIEDE2000 was found to be the same as DE_{cmc} with optimum correlations of 87%. It was also demonstrated that the performance of CIEDE2000 will likely vary significantly as a function of the selected illuminant. This factor brings into question the prudence of the textile industry recommending the new formula as a result of the significant variability in lighting that exists: a) at the point-of-sale for garments, b) between the store lighting and in standard light booths, and c) that the performance of the new formula does not appear to be significantly better than DE_{cmc}.

Effect of Lighting Variability on the Color Difference Assessment

By

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Biography

Kashif Noor was born on September 28, 1977 in Toba Tek Singh, Pakistan. He started his elementary education in Bern (Switzlerland) and completed Primary School in Pakistan, he was in Kuwait City for Middle School and finished his High School from Tehran.. He got his Bachelors in Textile Engineering with concentration in Dyeing & Finishing Operations from the University of Engineering and Technology, Lahore, Pakistan. After graduating in November 2001, he joined College of Textiles, North Carolina State University as a Masters student in the Textile Chemistry program.

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Finally, the author is extremely grateful to his parents for all their love and support - who gave up there dreams, so that ours could come true. My brothers – for we inspire each other.

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1. Radiometry

1.1 Electromagnetic Spectrum

Electromagnetic radiation is one type of several forms of energy. The prime source for the radiation is from the sun and the cosmic rays entering the atmosphere. The spectrum is made up of different levels of radiation varying in frequency and wavelength consisting of UV, infra-red, visible light, γ-rays, etc. Radiation can also be produced by oscillating electrical circuits, which can range from several thousand meters to less than a millimeter. The visible spectrum is comprises only a small region of the electromagnetic spectrum as indicated in the diagram below:

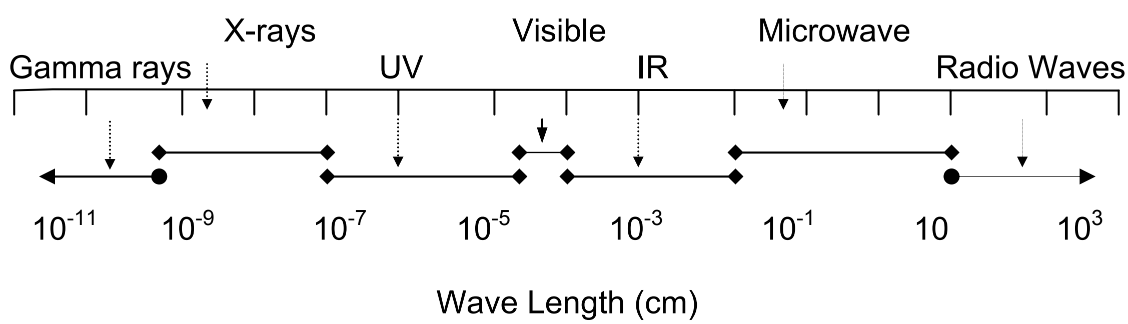


Figure 1. Simplified diagram of the electromagnetic spectrum.

1.2. Light

Electromagnetic radiation travels in the form of a transverse wave and can be characterized by wavelength and frequency[2]. The number of waves passing through one point in one second will be the frequency denoted by *v*, and it can also be given as the reciprocal of time, *t*,

$$v = 1 / t \qquad (1)$$

The propagation of light can be well explained by the electromagnetic theory of light but fails to explain the emission and absorption of light. The exchange between the light and matter takes place in discontinuous process as compared to continuous process proposed by earlier theories. Max Plank (1905) demonstrated this exchange of energy takes place in form of quanta. The total amount of energy is given by

$$\epsilon = h.\ v \qquad (2)$$

where v is the frequency of the radiation and h is a constant ($h = 6.624 \times 10^{-27}$ erg. sec). The idea of continuity in waves has been discarded because the kinetic translation of energy takes place in jumps. According to Einstein's law[3] (1905), the quantum energy (hv) is equal to the sum of energy W_O, to free the electron from the atom of the metal surface and W (kinetic energy) of the electron outside the atom.

$$W_O + W = hv \qquad (3)$$

The wavelength in terms of quantum energy can be given by

$$\epsilon = 1240 / \lambda \text{ electron-volts} \qquad (4)$$

In 1924, through Louis De Broglie's work, a relationship was recognized between waves and photons. Wave mechanics has been able to explain the wave-particle duality of light.

Light is known to have a fixed[1] speed in vacuum independent of intensity, given by:

$c = 2.99790 \times 10^{10}$ cm per second or

c= 186,000 miles per second

Whenever light travels through a medium of refractive index η, the speed of the light is altered according to the following relationship:

$$\textit{Speed of light in a medium} = c / \eta \qquad (5)$$

1.3. Measurement of Light

Radiometric measurements refer to the energy of the radiation while *photometric* measurements are weighted by the visual sensitivity (the so-called V_f function) of the average visual observer at 555 nm. A *point source* is one which produces its own radiation and is the same in all directions.   A *Lambertian source* is one in which light travels through a transparent medium and is highly diffuse or is reflected from a surface.

1.3.1 Radiance Flux (Φ_ϵ)

Radiance flux (Φ_ϵ) is the energy per unit time (dQ/dt) that is radiated from a source with the range of .01 to 1000 μm[4], which includes the visible, infra-red and U.V regions. A radiant flux of 1 watt means that the source produces 1 joule of energy per second.

1.3.5 Luminous flux (Φ_v)

Radiant flux when factored by the sensitivity of the human eye (CIE Photopic Curve) is called luminous flux[33] (Φ_v), whereas isotopic flux is weighted to the sensitivity of the human eye in the dark adapted state. The unit used is the lumen, which equals luminous flux emitted into unit solid angle by an isotropic point having a luminous intensity of one candela

$$1 \text{ lumen} = \text{radiant power} \times 1/683 \text{ watt} \times \text{luminous efficacy} \quad (6)$$

From quantum mechanics[5], photon energy at 555 nm

$$Є = hv = 3.582 \times 10^{-15} J \quad (7)$$

$$\text{and } 1 \text{ lumen} = 1.464 \times 10^{-3} J/s \quad (8)$$

$$N = 1.464 \times 10^{-3} / 3.582 \times 10^{-15} \quad (9)$$

$$1 \text{ lumen} = 1.4087 \times 10^{15} \text{ photons/second}^{5} \quad (10)$$

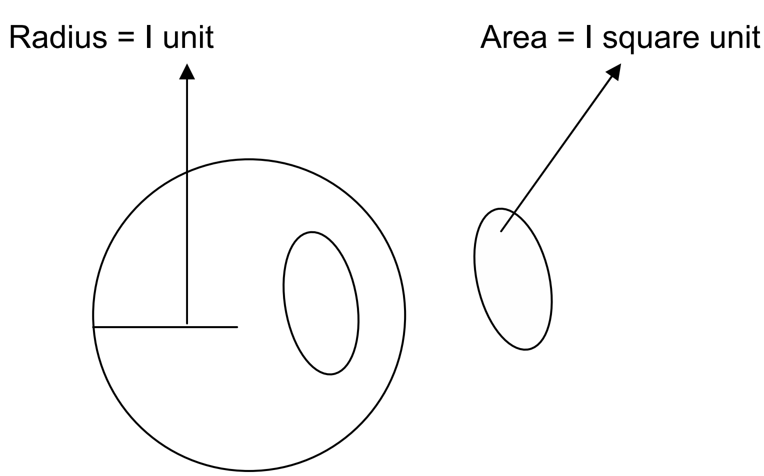
1.3.3 Luminous efficacy

Luminous efficacy is defined as the ratio of photometric flux to the total radiometric flux:

$$K = \Phi_v / \Phi_Є \quad (11)$$

1.3.4 Steradian angle

The steradian is the SI unit of solid angular measure. A steradian is conical in shape and has a unit of 1 if the subtended 'area' is equal to the square root of radius.



The numerical value of solid angle, Ω, is given by:

$$\Omega = A / r^2 \qquad (12)$$

1.3.5 Radiant and luminous intensity (I)

The radiant and luminous flux per unit solid angle is called as radiant and luminous intensity, respectively. For luminous intensity we will get:

$$I = d\Phi/d\omega \text{ (candela)} \qquad (13)$$

Hence, candela is defined as the luminous intensity in a given direction of a source that emits a monochromatic radiation of frequency 540 x 10^{12} Hz and that has a radiant intensity in that direction of 1/683 watt per steradian. Hence, by this measure intensity falls as the distance increases by square of the distance and is called as inverse square law

1.3.6 Irradiance and illuminance (lx)

Irradiance is the measure of radiant flux per unit area (W/m^2), whereas illuminance is the measure of luminous flux per unit area, as shown in Figure 2.

Foot-candle = lm / ft^2

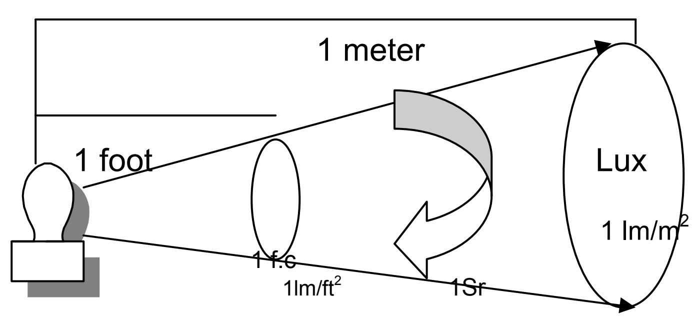


Figure 2. Diagram of how illuminance is defined

Irradiance from an extended source is related to the radiance of the source by the following equation:

$$E = \pi L \sin^2 (\theta/2) \tag{14}$$

This shows that the irradiance primarily depends on the central angle of viewing of the detector.

1.3.7 Radiance and luminance (L)

Both radiance and luminance can be defined as the flux density per unit solid angle. Radiance is independent of distance for an extended area source, because the sampled area increases with distance, canceling inverse square losses.

$$\text{Luminance} = 1\ \text{lm/m}^2\text{/sr or} \quad (15)$$

$$\text{Candela / m}^2$$

1.3.8 Troland

A troland is the "unit of retinal illuminance equal to that produced by viewing a surface having a luminance of 1 candle per square meter through a pupil having an area of 1 square millimeter" [34]

1.4 Black Body Radiation

A black body radiator has n enclosed cavity, with a heated enclosure and walls maintained at uniform temperature. There is a small opening through which the radiation escapes. The small opening will modify the radiation in such a way that it will depend on the size and shape of the opening and on the emissivity of the walls but this is a very small factor which does not really contribute significantly to the black body radiation curve[6]. In 1879, Josef Stefan showed that the radiation emitted is independent of the material. The black body radiation curves obtained by Max Plank were the advent of quantum theory, because the mathematical derivation assumes that energy is in discrete packets called quanta. The curves obtained are called black body (or Plankian) curves since they represents an idealized body that does not reflect or transmit light. The Plankian equation used is shown below:

$$M_e = \frac{c_1}{\lambda^5[\exp(c_2/\lambda T) - 1]} \qquad (16)$$

where,

M_e = emittance per wave length interval (Wm^{-3})

T = absolute temperature if the source (K)

λ = wave length of the radiation band (m)

c_1 = 3.74 x 10^{-16} Wm^{-2}

c_2 =0

1.5 Mechanisms by which radiation is produced

1.10.1 Incandescent

Incandescence is a term used for *temperature radiation* in that radiation is emitted from a heated object. Tungsten filament lamps filled with inert gas are the most common incandescent light sources, followed by quartz-halogen light bulbs. Typical incandescent bulbs operate at ab out 2850 K which operate at higher permits to be operated at higher temperature and giving light close to be being white. This part is heated again and the emitted photon might have a higher or lower energy[7].The energy emitted by an incandescent solid is less than the black body at the same temperature. Emissitivity (ε) is the ratio of radiant excitance. This part is heated again and the emitted photon might have a higher or lower energy[7].The energy emitted by the incandescent radiator to that of the black body. The emissivity of tungsten is not quite constant but decreases with increase in wavelength.

Characteristics:

Light of different wavelengths is emitted from different parts of the filament. When a part of the filament emits photons, it looses energy in the process and cools down.

1.5.2 Electric Discharge Lamps

When an electric current is passed through a gas or vapor, gas molecules get excited by the collision with the electrons. When the electrons come back to their normal state, they will emit radiation. They emit line spectrum instead of continuous spectrum by incandescent lamps.

Following are a few kinds of discharge lamps.

1.5.2.1 Sodium and Mercury Vapor Lamps

Sodium lamps have neon gas mixed in the lamps as sodium is a solid metal at room temperature. The neon helps to vaporize the sodium and in the mean time the lamp with give a pinkish color until the electrons from the sodium start emitting light which will have a yellowish color. A light closer to white color can be obtained by increasing the temperature and pressure in the presence of aluminum oxide tubes. Mercury lamps exhibit a bluish color to the light they emit. One half of the radiant power emitted is in the ultraviolet region and by coating the inside of the lamps by phosphors can convert this U.V part into visible region. These lamps are very efficient in converting electrical power into energy and thus being widely used for out door lighting. The kinetic energy of the electrons produced in the low pressure discharge is characterized by Maxwell-Boltzmann function:

$$F(\epsilon)\, d\epsilon = \frac{2\pi}{\pi K_B\, T^{1/2}} \times \epsilon 1^{/2} \exp(-\epsilon / K_B T)\, D\epsilon \qquad (17)$$

1.5.2.2 Fluorescent lamps

In the presence of mercury liquid and a rare gas, radiation is produced which is rich in U.V content. With the help of different phosphors, different kinds of spectral power distribution can be obtained. Calcium tungstate can be used as a phosphor for cool fluorescent lighting with lead as an activator to improve the efficiency of the phosphor. Warm fluorescent lamps which include the long wavelength phosphors (Magnesium flouro-germanate) to improve the color rendering properties. A tri-band fluorescent lamp has become very popular which has a ‘white’ light with good color rendering properties. The line emission takes place at 435nm, 545 nm and at 610 nm. These have a higher lamp efficacy but because the spectral power distribution is not broad, they fail to simulate day light and a metameric pair may not be a match under these lamps.

1.5.3 Xenon Arc Lamps

A high voltage pulse is used to ionize a high pressure xenon gas which produces a continuous spectrum over the U.V and visible region except for line emission at 450 nm and 500 nm. At low pressure, a bluish-green hue is obtained with a greater number of line emissions at the lower wavelength.

The line emission can be controlled by varying the intensity of the applied current and the vapor pressure. This lamp is currently used for light fastness tests and as a day light simulator by measuring instruments like spectrophotometers.

1.5.4 Lasers

A coherent and monochromatic radiant energy of high intensity is obtained by the Laser (light amplification of stimulated radiation).Its a process in which an excited molecule is striked by a photon. They can in a range of a few milliwatts to hundreds of kilowatts. Lasers are extremely important as monochromators and for aligning optical instruments.

6. Color Temperature

The temperature of a plankian radiator whose radiation has the same chromaticity as that of a given stimulus. The term is specifically used for discharge lamps because for incandescent the filament temperature is always 40 K lower not the same as that of the black body. The color temperature is $T_{c,}$ is expressed on reciprocal scale and the unit is called as reciprocal “megaKelvin. For tungsten, the relationship between the color temperature and logarithm of the luminous power *P*, is given by[8]

$$Log\ P = a_o - 11350 / T_c \qquad (18)$$

where a_o is a constant depending on the size of the filament

7. Correlated Color Temperature

It is the temperature of the Plankian radiator whose perceived color resembles that of a given stimulus under the same brightness and specific conditions.

However, suggestions have been made to change the above definition as follows: "The temperature of Plankian radiator whose chromaticity is the nearest to the chromaticity of the given stimulus on a diagram where the CIE 1931 standard observer based on *u'*, 2/3*v'* co-ordinates of the Plankian locus and the test stimulus are depicted" [9].

8. Lamp Efficacy

Human observer is very sensitive to the light at 555 nm (yellow-green) as compared to blue and red which appear dimmer even if they are of the same radiant flux. The term photopic curve describes the sensitivity of the eye to the radiation through out the visible spectrum. The total luminous flux F, can be calculated from

$$F = K_m \int P_\lambda V_\lambda d_\lambda \qquad (19)$$

Where P_λ is the radiant flux and K_m is the luminous efficacy

9. Color Rendering Index

Color rendering is the evaluation of how the color looks in a given light source as compared to a reference source. The spectral composition of different lamps is different and the sample may reflect different wave lengths and look different. Most of the lamps developed today emit light that is concentrated at three or four wave lengths having a higher lamp efficacy and a source which has a broader spectrum usually has good color rendering properties and lower lamp efficacy. Plankian radiator is used as a reference for lamps with CCT less than 5000K; and Illuminant D where the CCT is greater than 5000K.

Incandescent lighting has been a source of lighting for quite some time now.. Fluorescent lighting has a higher lamp efficacy and longer lamp life but initial cost is high. Some problems might be seen in textiles under this lighting due to the presence of FBA's. Color rendering index can be measured by either by CIE special color rendering index

$$R_i = 100 - 4.6d_i \qquad (20)$$

The CIE general color rendering index is given by

$$R_a = 100 - [4.6/8 \times (d_1 + d_2 + \ldots d_8)] \qquad (21)$$

where d_i is the distance in the CIE U*V*U* between color coordinates of the test source and the nearest D source and d_1 to d_8 are the R_i values for the Munsell color circle at value 6.

10. Spectroradiometry

A spectroradiometer measures radiometric quantities as a function of wavelength. Following characteristics can be known through the instrument:

I. Spectral Power Distribution
II. Tristimulus values and chromaticity (CIE 1931 & CIE1964)
III. CIE color rendering indices

IV. Correlated Color Temperature

V. Luminance, illuminance etc

i. Monochromator

The radiation enters the monochromator where it is dispersed and transmitted via a narrow band of wavelengths through the exit slit which connected to the detector. Photoelectric response by the detector takes place which is analyzed by the computer. The measurement of the spectral radiometric quantity also involves the comparison of the test source with a reference source whose spectral power distribution is known. The wave length band transmitted by the monochromator is the same as used in the calculation of the tristimulus vales. F

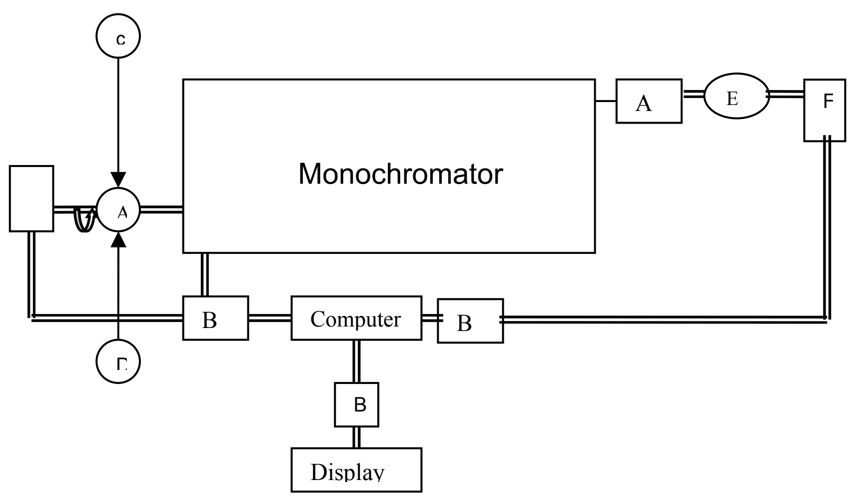


Figure3. Schematic diagram of a monochromatic spectroradiometer

A = Optical Coupler

B = Electronic Interface

C = Reference Source

D = Test Source

E = Detector

F = Power supply and measuring instrument

ii. Polychromator

In this case the dispersion of spectral power is done by a polychromator. It measures the flux at wavelengths at the same time which is done by the dispersing element onto a silicon detector. An array of 256 elements is spread out uniformly over the visible region. Such instruments can take a measure in fraction of a second but the accuracy is compromised because of the poor signal to noise ratio of the silicon detector.

The selection of the wavelength interval depends on the complexity of radiant power. For, incandescent light an interval of 10 nm will be sufficient because of the continuous nature of the spectrum. For discharge lamps the spectral power distribution is a mixture of continuous and line spectrum, a wavelength of 2 nm is considered to be adequate.

2. Color Space and Color Order Systems

2.1 Tristimulus values

The colors of objects are specified by the CIE according to a numerical theory based on trichromacy theory[35] . Color specification necessarily requires specification of the light source spectral power distribution, S, reflectance spectrum of the object, and the response of the eye of the observer, known as color matching functions. The CIE has defined two standard observers: the 2 degree standard observer and the 10 degree supplemental standard observer[36].

Owing to the presence of three receptors in the eye [ref] for the average color normal observer, three numbers are required to define the color matching functions. Hence, three numbers are required to specify any object color according to the equations shown below. XYZ are known as tristimulus values.

$$X = \sum_{380}^{750} S.R.\overline{x} \qquad (22)$$

$$Y = \sum_{380}^{750} S.R.\overline{y} \qquad (23)$$

$$Z = \sum_{380}^{750} S.R.\overline{z} \qquad (24)$$

Where

S = Spectral Power Distribution.

R = Reflactance (or Transmittance) of sample.

$\overline{x}$, $\overline{y}$, $\overline{z}$ = Color matching functions of standard Observer (2^0 or 10^0)

2.2 The chromaticity diagram

A convenient way to represent the tristimulus values of object colors in a mathematical space is by using a two dimensional scale, known as chromaticity coordinates, defined according to the relationship:

$$x = X / X + Y + Z \tag{25}$$

$$y = Y / X + Y + Z \tag{26}$$

$$z = Z / X + Y + Z \tag{27}$$

From the above equations we know that x + y + z = 1, so if we know any two of the variables the third can be found out.

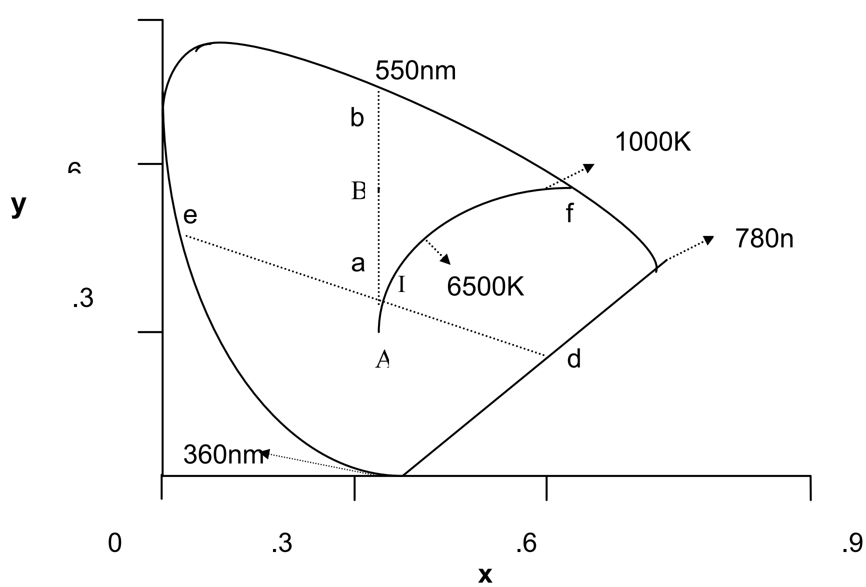


Figure 4. The CIE 1931 chromaticity diagram.

Some of the key features of the chromaticity diagram are:

- The smooth curve a-f is known as Plankian or black body locus. The CIE illuminants are plotted along this line. The color temperature of the black body increases from f to a.
- The dominant wavelength of a color will be the point of a straight line extended through the sample and the illuminant meeting the spectrum boundary, known as the spectrum locus.
- The excitation purity is defined as the distance of the sample point to the illuminant divided by the total distance from the illuminant to the spectral boundary. (Excitation Purity = a / a+b).
- If the sample lies between the points I and d, and the line is extended in the opposite direction to meet the spectral boundary, then the wave length given by that boundary is known as complimentary wavelength.
- CIE tristimulus system is not based on equal steps of visual perception, and hence is not perceptually uniform color space.
- The lighter the color, the more restricted it is in the chromaticity diagram.

While the x,y chromaticity diagram is valuable for defining the colors of objects, it is particularly useful in specifying the color of lights, e.g., the red, green and blue lights emitted from a cathode ray tube for color monitors. This is because the color displayed by monitors is achieved using an additive combination of primary lights, and x,y space maintains the additivity law .A more useful color space for object colors, however, is one based on a more perceptually uniform specification, in which the magnitude of distance between two objects in the space correlates with the magnitude of color difference visually perceived.

2.3 Color-order systems

A color-order system is a set of principles for the ordering of colors according to defined scales. More than 400 color order systems have been developed[11]. Almost all these systems comprise three dimensional attributes corresponding to a three dimensional space. The most prominent color-order systems are as follows:

- Munsell system
- Natural Color System
- DIN System (Deusches Institut Fur Normung)
- Optical Society of America System
- McAdam rectangular UCS diagram
- Adams chromatic Value Color Space
- Hunter Lab color space
- Adams-Nickerson (ANLAB) color space
- CIE 1960 UCS diagram
- CIE 1976 CIELAB color space

2.4 CIELAB Color Space

The CIELAB (or CIE L*a*b*) color space has three perpendicular opponent-color axes, where L* is the lightness scale (0-100), a* is the red-green axis and b* is the yellow-blue axis. These attributes are mathematically defined as nonlinear transformations of XYZ tristimulus space:

$$L^* = 116(Y/\ Y_n)\ 1/3 - 16 \qquad \text{for } Y/\ Y_n > .008856 \qquad (28)$$

$$L^* = 903.3\ (Y/\ Y_n) \qquad \text{for } Y/\ Y_n < .008856 \qquad (29)$$

$$a^* = 500\ [(X/X_n) - (Y/Y_n)] \qquad (30)$$

$$b^* = .4 \times 500[(Y/Y_n) - (Z/Z_n)] \qquad (31)$$

The three attributes are based on Herring's color opponent theory with complimentary colors on the opposite end of the axis. The color space can be shown as:

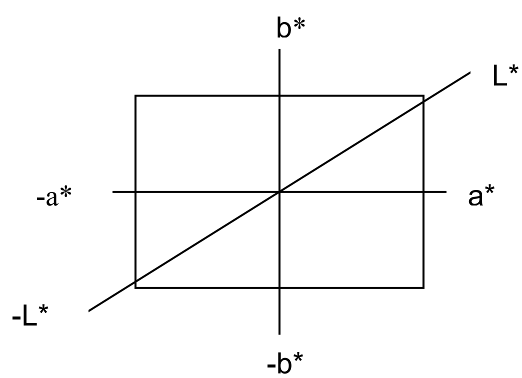


Figure 5. Plot of CIE L*a*b* space.

Where

L*= varies from 0 to 100(L*= 100; prefect diffuser)

a*= redness (+) or greenness (-)

b*= yellowness (+) or blueness (-)

Alternatively, the space can be defined in polar coordinates, known as CIELCH, in which chroma, C*, represents how far from gray an object is when compared to a neutral gray of equal lightness, and hue angle, h^o, varies from 0-360. The equation for chroma and and hue is:

$$C^* = (a^{*2} + b^{*2})^{0.5} \tag{32}$$

$$H_{ab} = tan^{-1}\ (b^*/a^*) \tag{33}$$

2.5 Single Number Pass/Fail Criteria

For decades, significant effort has been made to develop a single mathematical scale that correlates with visual pass/fail acceptability criteria between two objects, often referred to as a standard and a batch or trial. It was shown that for a Euclidian color space, the total color difference ΔE_σ between the batch and standard would be the Pythagorean sum of differences between any of the three attributes (Ai = 1, 2, 3)[12].

$$\Delta E_\sigma = [\sum_{I=1} (\Delta Ai)^{2}]^{1/2} \tag{34}$$

Where $\Delta Ai = \Delta A_{i,B} - \Delta Ai_{i,s.}$

This approach was not successful when applied to the XYZ system as there was no relation between visual magnitude of color difference and differences in XYZ between two objects; that is, perceptually the trichromacy system is highly nonuniform.

2.5.1 CIELAB color difference formula

The simple color difference formula based on CIELAB color space that assumes Euclidean geometry correlates with perceived visual magnitude of color difference is given by:

$$\Delta E^{*}_{ab} = [(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}]^{1/2} \tag{35}$$

Where

$\Delta L^{*} = L^{*}_{B} - L^{*}_{S}$

$\Delta a^{*} = \Delta a^{*}_{B} - \Delta a^{*}_{S}$

$\Delta b^{*} = \Delta b^{*}_{B} - \Delta b_{S}$

and, B = batch and S = standard

In this case, the DE formula produces a tolerance sphere around a given object color, in which pass/fail tolerance is the same in all directions in the space.

2.5.2 The JPC79 color difference formula

In 1979, a color difference formula by McDonald was introduced based on extensive visual data for 600 polyester thread pairs around 55 color centers[11].

$$\Delta E_{t} = [(\Delta L/L_{t})^{2} + (\Delta C/C_{t})^{2} + (\Delta H/H_{t})^{2}]^{1/2} \tag{36}$$

Where

$L_t = .081L_1/(1+.017L_1)$

$C_t = .063C_1/(1+.013C_1)+.638$

$H_t = TC_t$

$T = 1$ if $C_1 < .638$, otherwise

$T = .36 + [.4\cos(\theta_1 + 35]$

unless, θ_1 is between 164^o and 345^o when

$T = .56 + [.2\cos(\theta_1 + 168)]$

The subscript 1, denotes the standard of a pair of samples.

This formula was used by JP Coats as an internal instrumental pass/fail tolerance, but was later revised by the Colour Measurement Committee (CMC) of the Society of Dyers and Colourists in the U.K.

2.5.3 CMC (l: c) Color Difference Formula

It was discovered that the JPC79 formula produced erroneous data related to the chromatic differences near the neutral axis; that is, the calculated color differences correlated poorly with visual assessments for neutral colors. Also, a discontinuity in lightness differences near the lower values of L* was also observed. Hence, the JPC79 formula was modified to give a new formula, now known as CMC (l: c) [12], which is now a standard for the American Association of Textile Chemists and Colorists (AATCC), the American Standards and Test Methods (ASTM), and the International Standards Organization (ISO). Hence, it is used throughout at the global textile industry as the primary method of instrumental pass/fail assessment. The formula is defined as follows:

$$\Delta E_{cmc} = [\Delta L^*/ l\, S_L)^2 + (\Delta C^*_{ab}/c\, S_c)^2 + (\Delta H^*_{ab}/S_H)^2]^2 \qquad (37)$$

where,

$$S_L = 0.040975\ L^*_{ab,\,1} / (1+ 0.01765\ L^*_{ab,\,1})$$

unless

$$L^*ab,\ 1 < 16 \text{ when } S_L= 0.511$$

$$S_c = 0.638 + 0.638\ C^*_{ab,\,1} / (1+0.0131\ C^*_{ab,\,1})$$

$$S_H= S_c\,(Tf + 1\text{-}f)$$

$$\text{Where } f = [C^{*}_{ab,\,1}{}^{4} / (C^{*}_{ab,\,1}{}^{4} + 1900)]^{½}$$

$$T = .36 + [.4 \cos (h_{ab,\,1} + 35^0)] \text{ unless hab, 1 is between } 164^o \text{ and } 345^o \text{ then}$$

$$T = .56 + [.2 \cos (h_{ab,\,1} + 168^o)]$$

and where

$L^*_{ab,\,1,}\ C^*_{ab,\,1}{}^{4,}\ h_{ab,\,1}$ is that standard of the pair samples.

The scalars, S_L, S_C, and S_H, produce an ellipsoid tolerance, the size and shape of which is dependent on the location of the standard in space. The variables, l and c, can be manipulated to define the ellipsoid for a given application. In textiles, since the dependence of lightness on overall color difference is less than other attributes due to texture properties (unlike, for example, paint chips) the recommended value for *l* is 2 and for *c* is 1[13].

While this equation is commonly used in the textile, and other, industries, it has been shown to exhibit significant error against various visual datasets, with correlations between 60-70% being common[37]. Hence, a number of other formulae have been investigated over the last two decades.

2.5.4 BFD (l: c) Color Difference Equation

Two extensive sets of data, containing both textile and nontextile samples, were used by Luo and Rigg to develop a new formula known as BFD (l:c)[14]. When visual chromaticity ellipses, obtained from various visual experiments, are plotted in the CIELAB a*b* diagram, they do not point towards the axis in the blue region, and this effect was taken into account in the following formula in and attempt to improve the correlation.

$$\Delta E_{BFD} = [\Delta L_{BFD}/l)^{2} + (\Delta C^{*}ab/cD_{c})^{2} + (\Delta H^{*}ab/D_{H})^{2} + R_{T}\,(\Delta C^{*}_{ab}\,\Delta H^{*}_{ab}/D_{c}D_{H}]^{1/2} \qquad (38)$$

Where

$$L_{BFD} = 54.6\log 10(Y + 1.5) - 9.6$$
$$DC = .521 + 0.035C * ab/(1 + 0.00365C * ab)$$
$$DH = DC(GT' + 1 - G)$$
$$G = [C * ab4/(C * ab4 + 14000)]1/2$$

Depending on the dataset, the performance of the BFD formula correlates as well or better then the CMC formula. In the 1990s, several new formulae were developed in an attempt to further improve the performance. The most notable formulae were from Nobbs, ΔE_{LDS}, CIE94, and CIEDE2000. The latter was recently formally adopted by the CIE as a general recommended color difference formula.

2.5.5 CIEDE2000 (k_L: k_C: k_H) Color Difference Formula

Different weighting functions for hue, chroma and lightness have been added to color difference equations over time. In 2000, a new color difference formula was introduced by Luo, Cui and Rigg[15]. What differentiates this formula from all others is that the equation was optimized by incorporating four separate, but generally considered reliable, color discrimination datasets corresponding to thousands of color difference samples. The equation is an attempt to overcome limitations of previous formulas, and is especially designed to improve the correlation with visual assessment for blues, dark colors and near neutral colors. The equation is specified as follows:

Step 1:

L*, a*, b* and C* are calculated as usual

$$L^* = 116(Y/ Y_n)\ 1/3 - 16$$

$$a^* = 500\ [(X/X_n) - (Y/Y_n)]$$

$$b^* = .4 \times 500[(Y/Y_n) - (Z/Z_n)]$$

Step2: L', a', C' and h" are calculated

$$L' = L^*$$

$$a' = (1+G)\ a^* \qquad \text{where } G = .5(\ 1- \ \overline{C^*_{ab}}^7 / \overline{C^*_{ab}}^7 + 25^7)$$

$$b' = b^*$$

$$C' = (a'^2 + b'^2)^{1/2}$$

$$h' = \tan^{-1}(b'/a')$$

$\overline{C^*_{ab}}^7$ is the arithmetic mean for $C^*_{ab,}$ values for a sample pair.

Step3: $\Delta L'$, $\Delta C'$,$\Delta H'$ are calculated:

$$\Delta L' = L'_b - L'_s$$

$$\Delta C' = C'_b - C'_s$$

$$\Delta H' = 2(C'_b C'_s)^{1/2} \sin(\Delta h'/2)$$

where $\Delta h' = h'_b - h'_s$

Step 4. Calculating CIEDE2000:

$$\Delta E_{00} = [\,(\Delta L'/K_L.S_L)^2 + (\Delta C'/K_C.S_C)^2 + (\Delta H'/K_H.S_H)^2 + R_T\,[(\Delta C'/K_C.S_C)\,(\Delta H'/K_H.S_H)^2]^{1/2}$$

S_L Function:

A set of visual experimental data was generated by Chou *et al.*[16] which accommodated samples with different lightness values. Different lightness equations were tested against the data and it was seen that Nobbs equation performed best against the visual data.

$$S_L = 1 + .015(L^* - 50)^2 / [20 + (L^* - 50)]^2$$

S_H Function:

A new S_H was developed by Berns[17] to fit 5 data-sets:

$$S_H = 1 + 0.015\overline{C}^*T$$

where

$$T = 1 - 0.17\cos(h - 30^0) + .24\cos(2h) + .32\cos(3h + 6^0) - .20\cos(4h - 63^0)$$

R_T Function:

As the orientation of ellipsoids points away from the achromatic axis in the blue region, the rotational function, R_T, was been developed to correlate for pass/fail performance of blue object colors. The reason for the tilt is not known.

a* Function:

Most of the modern color difference equations assume that the ellipses near the achromatic axis are circle which is not the case and therefore, we get poor fit. Rescaling of a*-axis was done so that the extra stretch would make the chromatic ellipses as circles. The a*-axis was also rescaled in such a way that there was a large effect for neutral colors and almost no effect for high chroma colors. The rescaling of a* has given better fit as compared to previous equations.

The CIEDE2000 formula was adopted as a recommended standard in 2002. However, no independent assessment has been reported by any industry to date. The AATCC color measurement and test methods committee, RA36, has stated in a recent press release that industries should not adopt this formula until it has been independently validated using new visual and instrumental data. Furthermore, RA36 insists that for the textile industry to adopt the new formula the industry must show that is exhibits significantly better performance than the current industry standard formula, DE_{CMC}.

2.6 Color Perception Phenomena

2.6.1 Color inconstancy

When an object (e.g. a garment) is removed from under one light source and placed under a different lamp with a different spectral power distribution, the human eye is able to compensate for the lighting differences so that the color would look approximately the same. Hence, a red object looks red under significantly differing light sources such as incandescent and daylight. This phenomenon is known as color constancy and is achieved through the process of chromatic and lightness adaptation[38]. The actual mechanism(s) by which the brain is able to adapt to the changes in illumination are not fully understood.

Complete adaptation generally takes up to three minutes. Also, it is known that color constancy does not only depend on the illuminant used but also on the geometry of viewing.

Color constancy can be grouped in to two classes: surface color perception and apparent color perception. The former is an attribute of the object and the latter simply as apparent color. For a polychromatic illuminant, surface color constancy will generally hold but not for mono-chromatic illuminants. Visual sensitivity has a non-linear correlation with the change in illuminant chromaticity. The calculation of color inconstancy from one illuminant to another can be done by computation of the XYZ values of an object such that the appearance remains the same under both lamps. Chromatic adaptation transform tells us as to which extent the observer is able to adapt to the change in lighting conditions. A new chromatic adaptation transform CMCCAT2000[31] has been introduced which is an improved and simplified version of CMCCAT97[32]. A forward and reverse mode was used in CMCCat97 (forward mode is the transformation of the trisitimulus values of a sample under non-daylight illuminant to the corresponding color under daylight and vice versa for reverse mode).The reversibility causes problems in CAT97 which has been removed in CAT2000 which also fits better with the experimental method.

2.6.2 Metamerism

The phenomena of metamerism occurs when two object colors have the same tristimulus values but different spectral stimuli. In these cases, the two objects will match under one condition but not another, e.g., under one light source but not another. For metamerism to occur, the reflectance spectra of the two objects should intersect each other at least at three points. Previous studies suggested that the three intersections were fixed but Wyszecki[10] showed that the location of intersection depends on the method of generating a metamer and it should have at least three intersections. There are four different types of metamerism:

2.6.2.1. Iluminant metamerism

The degree of metamerism of two objects that match under a specific light is given as the color difference ΔE between the two objects under a different illuminants, and this is defined by the CIE as Metamerism Index:

[give]

$$MI = ((DL_1^{*2}-DL^*{}_2^{\,2})+ (Da_1^{*2}-Da^*{}_2^{\,2})+ (Db_1^{*2}-Db^*{}_2^{\,2}))^{0.5}$$

Where subscripts 1 and 2 denote illuminant 1 and illuminant 2, respectively.

2.6.2.2. Observer Metamerism

As the color matching functions of two people will vary to differing extents, a pair of metamers may match for one person while it might be a mismatch for another person, all other conditions remaining the same. This is known as observer metamerism. Importantly, even if a color difference formula predicts a match between two objects, it might not be a match to any real observer as the color matching functions of the observer may be significantly different to that of the standard observer.

2.6.2.3. Field Size Metamerism

The angle of viewing and object has an effect on the color perception. A pair that seems a match at a distance might not be match when brought closer.

2.6.2.4. Geometric Metamerism

If the angle of viewing an object is changed, the pair of objects might not be a match any more.

3 Retail Lighting

A key component of color control in the textile supply chain is the lighting used in the area in which a textile product is displayed to a consumer. While many products are purchased via the internet, or via mail order, most products are purchased from retail stores. Hence, the lighting conditions, such as type of lamp, brightness, color rendering properties, are critical variables that influence the perception of the colors of garments.

In general, the retail color managers, which provide a critical and growing function in the specification and control of the textile supply chain, do not today become heavily involved in the lighting specifications developed by retail stores. This section provides an overview of the key factors that lead to variability in retail lighting as well as some recommended 'best practices' from the point of view of lighting engineers [ref].

3.1 Lighting design

3.1.1. Lamp selection

One of the preliminary processes in the design of a retail store is the selection of the lamps. The most commonly used lamps can be considered to apply to two broad areas:

a) For merchandizing areas: most lamps used are fluorescent cool white lamps, deluxe warm white, incandescent and so-called tri-band lamps (e.g., commercial lamps such as Ultralume U3000, U4100 and U5000).
b) For store and mall lobbies: most lamps used in lobbies consist of mercury vapor and mercury halide lamps[39].

In general, lamps are selected based on the store design, merchandize, space and economic considerations. Other criteria selecting the lamps involve lumen rating, life expectancy, chromaticity, color rendering, luminous efficacy, maintenance, ventilation, and even acoustics[40]. [A number of different categories can be considered for the use of different lamps, as indicated below.

3.1.1 Luminaire

A luminaire[19] is a lighting system that is an apparatus to enable the control and electrical distribution of the lamps in a cluster. According to the application and utilization of lamps, the CIE has classified luminaires into six main categories: direct, semi-direct, direct-indirect, diffuse, semi-indirect and indirect. In general lamps by without modification are a source of high glare, but these can be controlled by use of diffusers.

3.1.2 Light diffusing methods

Diffusers are clear translucent sheets or prismatic lenses. They are placed at the bottom of the luminairs to redirect or scatter light within 45^0 to 90^0 zone. In addition, baffles or louvers are used to enhance the diffusion. A baffle is a partition that is placed parallel to the direction of the (usually fluorescent) lamps and between two lamps, whereas a louver is a group of baffles of an egg crate arrangement that are placed below the lamps. Louvers are usually used where low ceiling brightness is required.

Materials that reflect the light into a given direction are also commonly used. Reflectors are of two types: specular and semi-specular which are mounted above the lamps to redirect the upward component of the flux; in general reflectors are used with incandescent and HID sources. For fluorescent lighting, diffuse reflectors are also used.

3.1.3 Lighting variability

Even if a store is designed to provide a specific illuminance level and particular color rendering properties, there are many factors that over time will affect the quality of light that illuminates products. These variables must be adequately controlled to prevent loss of illumination quality. Even redecorating a store with no change in lighting design can affect lighting quality significiantly. For instance, dark walls will absorb more light than pale colored walls. If the reflectance of the wall is increased, the inter-reflected light within the room increases and higher percentage of light will reach the illuminated space. Hence, the surrounding environment will therefore influence the perception of the color of objects, notwithstanding the effects of simultaneous contrast and lightness and chromatic crispening. According to IES[41]in general retail stores should be decorated so that wall reflectance should be in the 50% to 70% range, preferably with Munsell values of 7.5 to 8.5

3.1.3.1 Light loss and non-uniformity factors

To maintain average uniform illumination within a store, the initial lumens emitted from the lamp should be higher to compensate for the rapid light loss in the first few hours of burning. However, there is a loss in lumens with the passage of time. Some of the lighting variability is recoverable, whereas others factors lead to nonrecoverable changes.

Recoverable Factors included lamp burn-outs, lamp lumen depreciation, and dirt build-up on surfaces. Lamp burn-outs (LBO) should be replaced, preferably on a regular schedule to prevent excessive loss of illuminance. It is possible to calculate a LBO factor which is the ratio of the remaining lamps lighted to the total number of lamps and develop a protocol to replace lamps when the LBO reaches a predetermined level.

The illuminance of most lamps decreases with use; an exception is low pressure sodium lamps. Most lamps should be replaced at 70% of the rated life of the lamp to ensure minimum illumination level.

Dust and dirt accumulation on lamps is a surprising significant factor in reducing the reflectance of luminaires as well as reducing transmittance through lenses. In addition, dirt on general surfaces in the lit area reduces light reflection.

Additional, non-recoverable factors related to lamp brightness depreciation include: pressure and temperature changes in fluorescent lamps, voltage variability,

3.1.4. General considerations for illuminance

Illuminance at a given point can be calculated by the inverse square law[20] is given as

$$E = I / D^2$$

where E= Illumiannce …, I= luminous Internsity

When illuminance is calculated at a point that is not normal to the source, and the area over which the flux is distributed is greater than 1 sq.feet, a correction should be made .For a retail store, the reflection for walls and surfaces can be taken into account[4]:

$$E = \frac{\text{(lumens per luminaire) (RRC) (LLF)}}{\text{Area per Luminaire}}$$

where, RRC = reflected radiation co-efficient, LLF = Light loss factor

For retail stores that are designed to have highly variable illuminance levels, an observer's eyes become adapted to the illumination levels when moving from one area to another. In some cases there will be a sudden loss of ability to see the details of the object. Hence, it is recommended that the ratio of illumination for an illuminated area to the general area lighting should not be more than 5:1 at any place in the store and should not be less than 3:1[22].   In addition, diffuse lighting should be used throughout the store to remove shadows and harshness of direct lighting.

The recommended illumination levels for merchandizing, including showcases, is in the range 750-1000 lx[23]. For areas not expected to be visited often 300 lx is sufficient. However, displays should be illuminated between 2000 and 5000 lx.

3.1.5 Factors affecting an observer's visual comfort in a retail store

There are, of course, many factors that affect visual comfort of observers in a store. Some of the more important factors are described below.

Transient adaptation

Significant illuminance variability when an observer scans different merchandise leads to fluctuating (transient) adaptation transient adaptation, which causes visual fatigue.

Viewing angles

The size of merchandise is fixed, but the angle of illumination and viewing can be controlled to maximize visual acuity.

Contrast

Visual comfort depends to a large degree on the contrast between the merchandize and immediate background. Less contrast means significantly more time is required to differentiate the details of a given object.

Glare

Glare[24] is the excessive brightness in the field of view that causes loss in visual performance and visibility. It is caused by the reflected light from a surface leading to significant discomfort. One of the forms of reflected glare is called *veiling reflections*, which is the reflection of large windows and fluorescent luminaries on the surface being viewed. The effect of lighting variability on visual comfort has been modeled[25].

3.5.1.1 Psychological factors

It is well-known that the luminance and color of lighting plays a very important psychological role in the visual comfort[43] of an observer including for example:

a) observers can be made to feel relaxed using warm (yellow-orange) lights in addition to general fluorescent lighting.
b) light at longer wavelengths such as red increases intensity and anxiety in some people[27].
c) lamps with different spectral power effect the perception of strangers[28] and therefore comfort level is influenced.

4. Research Proposal

The effective control of color throughout the textile supply chain is of significant importance. Considerable management and control of the color variables is maintained during the design, manufacturing and approval process through standard lighting and viewing conditions. When the merchandize is placed in the retail stores, the standard conditions are not maintained any more and hence there is a possibility that the color of the merchandize might look different in the retail stores. For this purpose, lighting measurements were carried out in departmental stores and in different stores of the same retailer. There are various factors that can contribute to the visibility and a different perceived color of an object as compared to its reference. This can be due to the design of the store, lamp accessories, color of the walls, color of the merchandize placed in the viewing area and the quality of the lamps. The various factors have already been discussed in the introduction but only the effect of quality of lighting has been studied in this project. The spectral power distribution of the lamps in various parts of the store were measured and compared to other stores. The lighting quality in different light booths is also measured to see if there is any significant variability.

A color difference equation is used to test as to how much there is a difference between a trial and a reference pair. The performance of DEcmc and CIEDE2000 was seen using 850 samples under three different lamps and the shift of the same samples in the color space was seen which provides further evidence that since the equations are made based on D65, a form of chromatic adaptation should be introduced in these color difference equations. The widely used CMC equation was again evaluated against the newly introduced CIEDE2000 with a new experimental design using both visual and spectrophotometric equations to see if there is a considerable improvement in visual and instrumental measurements which could justify the replacement of the DEcmc.

II. EXPERIMENTAL

1. Equipment

Spectroradiometric measurements were made using a calibrated handheld LightSpex spectroradiometer by GretagMacbeth. The spectroradiometer was equipped with a 256 photodiode array and cosine receptor that collected all incident light over a 180 angle. In all cases, two measurements were made at each location and the data averaged.

Ahiba Texomat (1000 control unit) was used for dyeing the metameric pairs.Spectrophotometric measurements were made using a diffuse integrating sphere geometry spectrophotometer, Datacolor Spectraflash SX. Reflectance measurements were made in the following set up: specular included, UV included, and three measurements were made with 90 rotation of the sample each time, and the data averaged. Colorimetric data were calculated using various standard illuminants (and 'custom illuminants', as described below) and the CIE 10 degree supplemental standard observer.

2. Retail store measurements

A large global retail company was selected for the purpose of this study. The branded products of the retail company were not only displayed in its own stores but also in large department stores that carried merchandize of different brands. Hence, both the retail company's own stores as well as department stores were assessed.

The lighting in four of the retail company owned stores were measured along with three different departmental stores that carried the company's merchandize. The size of the store ranged from a very small to a very large store with four levels of retail floor space. Two (Store D & B)stores had large entrance/exit areas exposed to external daylight. Two (Store A & c) stores were a part of a mall and the entrance of the store was exposed to indoor lighting of a mall

.

Retail Company's Own Stores	**Departmental Stores**
Store D (Expose to Day Light)	Store A
Store E	Store B (Expose to Day Light)
Store F	Store C
Store G	

A map of each store was generated and areas selected for measurement were recorded. In general, areas that were measured included changing areas, check-out counters, key display areas, in front of full length mirrors, and entrance/exit areas. Unless otherwise stated, spectroradiometric measurements were taken 4 feet from ground level.

2.1 Data evaluation

The irradiance data collected for each measurement in the store was converted to standard ASTM tristimulus weighting functions (table 5 data) for a 10^0 observer [using a custom program developed by GretagMacbeth[48] .Metamerism indices, color inconstancy indices and $DE_{cmc\ (2:1)}$ was calculated for each custom illuminant for the metameric textile sample pair [which one??] described below. The CIE 1964 Supplemental (10^0) standard observer was used for the calculations. The Correlated Color Temperature, Lux and Color Rendering Index were directly calculated from the spectroradiometer using the GretagMacbeth LightSoft software. The illuminance values (lx) were calculated for the CIE photometric 10^0 observer.

Statistical analysis of key colorimetric data for each store was calculated .The distribution of data was seen to be not normal therefore non-parametric tests[44]were applied to analyze it.A non-parametric test is a hypothesis test that does not require any specific conditions about the shape of the population. The Wilcoxon signed rank test is used to see if the two dependent variables were selected from the same population where as in Kruskal-Wallis test three or more variables can be shown if they are from the same population or not.One-way Chi-Sqaure tells us if there is a significant difference between the variables. Other statistical methods such as S.D, upper and lower limit were also calculated.

3. Light Box Measurements

Spectroradiometric measurement of seven different standard light boxes were taken. All the light booths were in practical use on a regular basis and were intended to be representative of the majority of light boxes used by the textile industry. Three of of the light boxes were fluorescent based daylight simulators, and four were based on filtered tungsten lamps. The light boxes used were:

A = GretagMacBeth SpectraLight III	E = GretagMacBeth Judge-II
B = GIT/Datacolor International	F = GretagMacBeth SpectraLight III
C= GretagMacbeth Spectra Light Jr.	G= Unknown
D = GretagMacBeth Judge-II	H= Unknown

4. Preparation of Metameric Pairs

Two standard and batch metamers were dyed on 100% cotton twill using reactive dyes, as described below.

Sample Pair A

A 'standard' khaki sample was prepared by dyeing 100% cotton twill fabric using vinylsulofone-based reactive dyes with the standard recommended procedure by the dyestuff manufacturer at 60 ^{o}C .A sample size of 10.0 g was used with a liquor ratio of 20:1. The dyes and auxiliaries used for the dyeing were as follows:

Remazol B Blue RSP	.0396 g
Remazol G ORG F2GS	.01192g
Remazol Yellow RR	.04389 g
Na_2CO_3	4g/L
NaOH (100%)	2ml/L

Glauber's salt	35g/L

An identical procedure was used to dye a 'batch' sample, but using a different set of dyes to obtain a metameric match. The dyes and auxiliaries used were:

Remazol Br Yellow 3GL	.1896 g
Remazol Red RR	.0211g
Remazol Blue RR	.0258 g
Na_2CO_3	4g/L
NaOH (100%)	2ml/L
Glauber's salt	35g/L

Sample Pair B

A second blue standard and batch pair was prepared was prepared in the same method described for sample pair A above. The recipe for the standard is as follows:

Remazol TURQ GA	.9581g
Remazol B Red 3BS	.1936 g
Remazol Orange F2GS Liq 25%	.7702g
Na_2CO_3	4g/L
NaOH (100%)	2ml/L
Glauber's salt	45g/L

The recipe for the batch was as follows:

Remazol Br Yellow 4Gl 150%	.1190g
Remazol Red RR	.0151g
Remazol Blue RR	.2152g
Na_2CO_3	4g/L
NaOH	2ml/L
Glauber's salt	45g/L

The standard used for sample pair B was found to be significantly color inconstant, and was therefore used to find the variation of color inconstant indices with different custom illuminants.

5. Comparison of the performance of CIEDE2000 and DEcmc via visual assessment.

About 60 woven polyester fabric samples were dyed to light gray, medium gray, navy, blue, and red hues[47]. From this set, five color centers (Table 2.1) and a further 17 samples (Table 2.2) were selected to make up a series of sample pairs for visual assessment. Each sample pair was visually assessed by 31 expert observers using the same calibrated light box. Twenty one males and 10 females with normal color vision, and ages 24-65, were used. The observers were asked to rate the pairs as 'obvious pass', 'marginal pass', 'marginal fail', or 'obvious fail', based on the following criteria: The samples were to be made into separate high quality garments and were to be hung on a clothing rack and sold together.

AATCC Evaluation Procedure 9 was used for visual assessment with the following set up: $0/45^0$ geometry was maintained using a GretagMacbeth Spectra Light III with a calibrated filtered tungsten daylight simulator. The fabric sample size was about 4" by 6". In order to obtain enough expert observers, the experiment was executed during three separate color science conferences/symposia over the course of seven months. At each stage, the light source was calibrated prior to use and spectroradiometric measurements taken, using a calibrated GretagMacbeth Lightspex spectroradiometer, to ascertain that no significant variability was observed in the viewing environment between locations.

Prior to visual assessment, each sample was measured on a Datacolor International Spectraflash 600 plus CT spectrophotometer. Colorimetric values were calculated using D65, CIE 1964 Supplemental Observer (10 degree observer), specular included, large area view, and three averaged measurements on fabric folded four times. The samples were also measured after completion of the visual experiment. In addition, two l:c ratios for CMC were used, 2:1 and 1:1, and the equivalent ratios were used for DE_{00} where the ratios correspond to the parametric factors, k_L and k_C.

Table 1. Colorimetric data of color centers (CIELAB, $D_{65}/10^{o}$ observer)

	L*	**a***	**b***	**C***	**hº**
LG Std	63.20	-1.43	-0.36	1.48	194.28
MG Std	58.99	-1.65	-0.83	1.85	206.57
Navy Std	25.11	-7.25	-9.37	11.85	232.25
Blue Std	58.00	-5.09	-34.67	35.04	261.65
Red Std	36.42	48.37	17.81	51.55	20.21

Table 2. Colorimetric data of sample pairs (CIELAB, $D_{65}/10^o$ observer).

	L*	A*	b*	C*	hº	ΔE*	ΔL*	Δa*	Δb*	ΔC*	ΔH*
LG#2	64.13	-1.03	0.22	1.05	167.98	1.17	0.92	0.41	0.58	-0.43	-0.57
MG#5	58.93	-1.57	-0.66	1.7	202.86	0.19	-0.05	0.09	0.17	-0.15	-0.11
Navy A	25.35	-7.09	-10.41	12.6	235.76	1.08	0.24	0.17	-1.04	0.75	0.75
Navy B	24.63	-6.51	-8.17	10.45	231.44	1.48	-0.48	0.74	1.19	-1.4	-0.16
Navy G	25.38	-7.47	-8.77	11.52	229.58	0.69	0.27	-0.22	0.6	-0.33	-0.54
Navy J	24.59	-7.24	-8.8	11.39	230.56	0.78	-0.53	0.02	0.57	-0.46	-0.34
Blue D	58.97	-5.92	-33.31	33.83	259.92	1.87	0.97	-0.83	1.36	-1.21	-1.04
Blue E	58.32	-5.59	-33.09	33.55	260.41	1.69	0.32	-0.5	1.58	-1.49	-0.74
Blue G	58.53	-7.36	-31.57	32.42	256.87	3.88	0.53	-2.28	3.1	-2.62	-2.81
Blue I	58.41	-6.75	-32.19	32.89	258.17	3.01	0.41	-1.66	2.48	-2.15	-2.06
Blue J	60.16	-5.95	-31.37	31.93	259.27	4.04	2.17	-0.86	3.3	-3.11	-1.39
Blue O	58.56	-5.53	-33.77	34.22	260.71	1.15	0.56	-0.44	0.9	-0.82	-0.57
Red D	37.22	48.17	17.51	51.26	19.98	0.87	0.79	-0.2	-0.29	-0.29	-0.21
Red E	37.29	49.26	18.11	52.49	20.19	1.28	0.87	0.89	0.31	0.94	-0.02
Red G	38.19	50.63	16.74	53.33	18.3	3.06	1.77	2.26	-1.06	1.78	-1.75
Red H	38.27	49.76	17.76	52.83	19.64	2.31	1.84	1.39	-0.04	1.29	-0.51
Red M	37.35	48.72	17.87	51.9	20.14	1	0.93	0.35	0.07	0.35	-0.06
Red N	38.27	49.85	18.01	53	19.86	2.37	1.85	1.47	0.2	1.45	-0.31

6. Performance of CIEDE2000 and DE_{cmc} under different illuminants

Approximately 850 production matches to a 155 color standards were obtained from a global retail company. The same dyes were used in each group and the same fiber fabric construction was used. The sample size averaged about 2 ½ x 5 inches. Three spectrophotometric readings were taken for each sample using a Datacolor Spectra Flash SF 600 X. An aperture of 30 mm was used and specular component was included for matt samples but excluded for glossy materials. For the purposes of this study one standard and batch pair was selected for each of the 155 centers. The standard and batch pair was selected that represented the greatest difference between calculated DE_{cmc} and DE_{00} within each group.

III. RESULTS AND DISCUSSION

1. Metameric Pairs

Figure 6 shows the reflectance spectrum of the turquoise standard and batch pair. The pair is highly metameric owing to the reflectance curves intersecting at four distinct points. Table 3 shows key colorimetric data for the metamers.

Table 3. Colorimetric data for the standard and the trial metamers.

	L*	a*	b*	**DEcmc**	**C.I**	**M.I**
Standard	57.02	-6.19	-6.92			
Trial						
D65	57.17	-6.5	-7	**0.32**	**Ref**	**Ref**
A-10	55.95	-4.92	-9.84	**6.23**	**3.4**	**7.17**
CWF	55.58	-4.67	-9.26	**1.72**	**3.47**	**2.33**

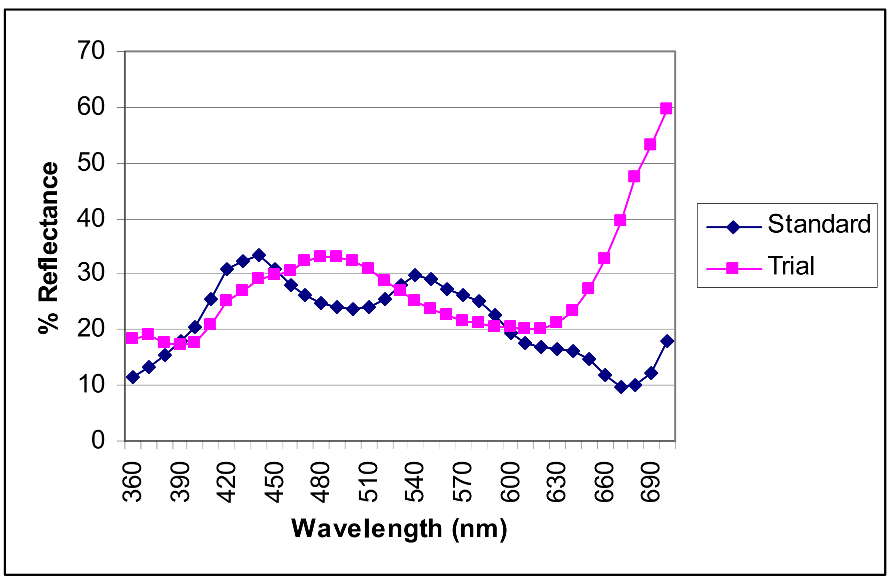


Figure 6. Reflectance spectrum of the standard and the trial

2. Light Booth Measurements

There are two kinds of lamps used to simulate daylight in standard light booths: filtered tungsten (as used solely by GretagMacbeth Spectralite III light boxes) and various fluorescent light sources with varying spectral power distribution (SPD). AATCC Evaluation Procedure 6 [ref] allows for various simulators to be used, although the quality of the simulator is defined based on color rendering index. It is not known, however, how significant the variability in actual daylight simulators will affect practical visual color difference assessment.

Figure 7 shows the variability in the SPD for the daylight simulators used in this study. Clearly the large SPD variability will likely produce significant variability in visual assessment of color difference pairs, particularly metamers. Furthermore, color inconstant samples may also appear to be significantly different colors when viewed under different daylight simulators with different SPD.

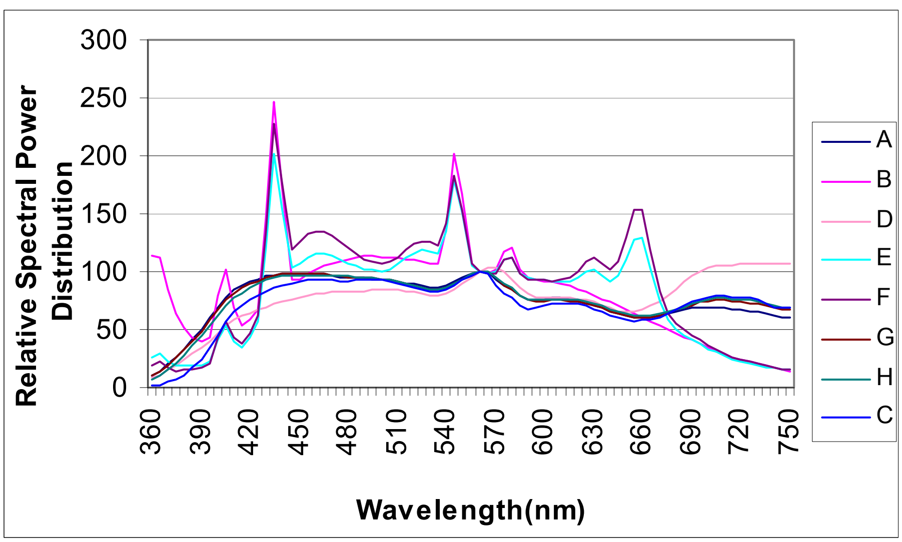


Figure 7. Relative spectral power distribution of daylight simulators in lighting booths

Table 4 shows a summary of colorimetric data for the turquoise metamers when calculated using each of the SPD data for the standard light booths. Clearly the variability in DE_{CMC} is high.

Table 4. Summary of colorimetric data for turquoise metamers using SPD data of standard light booths.

	DEcmc	C.I	M.I	CCT	CRI	Lux
A	0.86	1.07	1.06	5428	92	256
B	1.25	0.64	0.95	6802	87	1457
C	0.87	0.2	0.48	6595	96	1612
D	0.87	1.3	1.25	6255	93	1671
E	0.88	1.18	1.32	6695	93	583
F	0.63	0.33	0.3	6559	95	1434
G	0.67	0.27	0.3	6479	96	1470
H	0.89	0.21	0.48	6640	96	1234
I	0.86	0.22	0.45	6617	96	1086

3. Measurement of Stores

The lighting in four of the retail company owned stores were measured along with three different departmental stores that carried the company's merchandize. The size of each store ranged from a small (ca. 2000 sq.ft) to a very large store with four levels of retail floor space. A few stores had significant exposure to external daylight, while other stores were exposed to indoor lighting of a mall area.

3.1 Store A

Store A was a part of a departmental store that contained merchandize of the retailer along with many other brands. It had indoor lighting used in mall hall-way coming in the store.   Figure 8 shows the variability in spectral power distribution for the xx measurements at various locations. Figure 9 shows calculated DE_{CMC} data and indicates the location of each measurement.

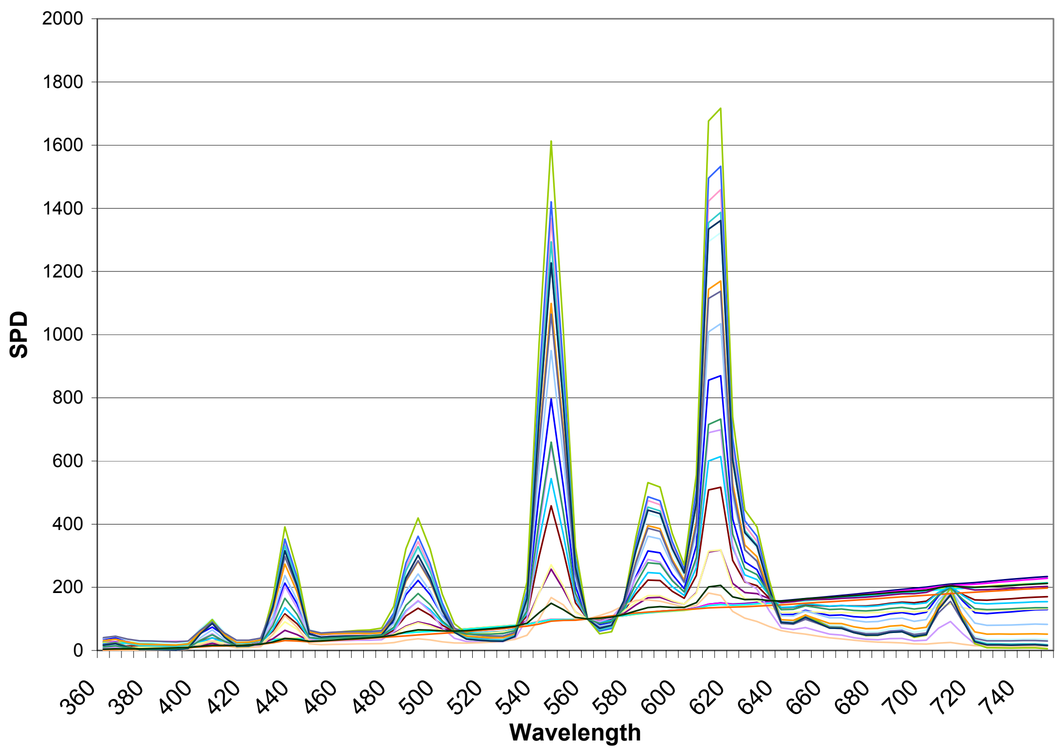


Figure 8. Normalized spectral power distribution data for measurement taken at store A.

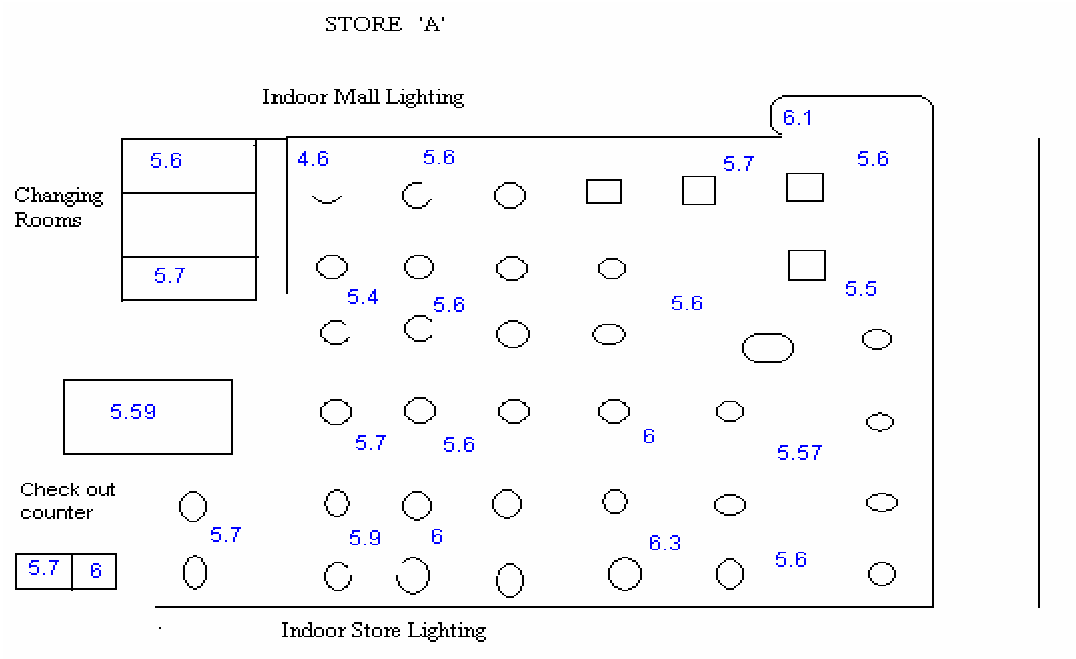


Figure 9. DE_{CMC} data calculated using SPD data and blue metamers for Store A.

From the spectral power distribution data in Figure 8, it is clear that the type of lighting used is generally quite consistent, with fluorescent sources in use with some use of incandescent lamps. Further, the DE_{cmc} values mapped out on the store lay out show that the color difference for the metamers is very consistent. From the point of view of the textile color managers, this scenario can be considered to be ideal.

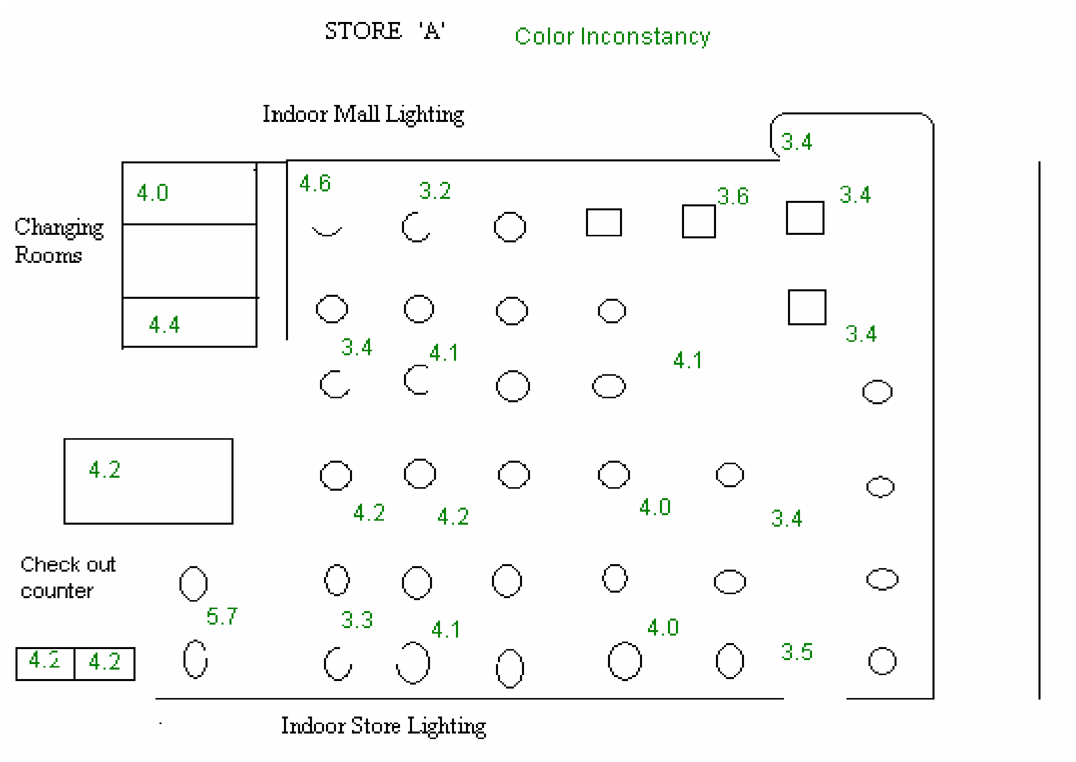


Figure 10. Color inconstancy index for standard blue metamer for store A.

The blue standard is considerably color inconstant under standard illuminants, and although Figure 10 shows a high color inconstancy index value for all locations in the store, the value is relatively consistent, ranging from 3.2 - 5.7. One possibility for further research is to devise an experiment to determine the significance of the color inconstancy index values on visual assessment. To date, this has not been demonstrated for practical (industrial) color assessment.

Figure 11 shows the variability in illuminance (lx) at the measured locations in store A. Clearly, since the brightness in the store can vary between approximately 250 lx and over 1000 lx, significant variability exists that could impact significantly the viewing experience for a consumer. For instance, the details of very dark samples viewed under low illuminance conditions (e.g., 300lx) will not be easily discerned.

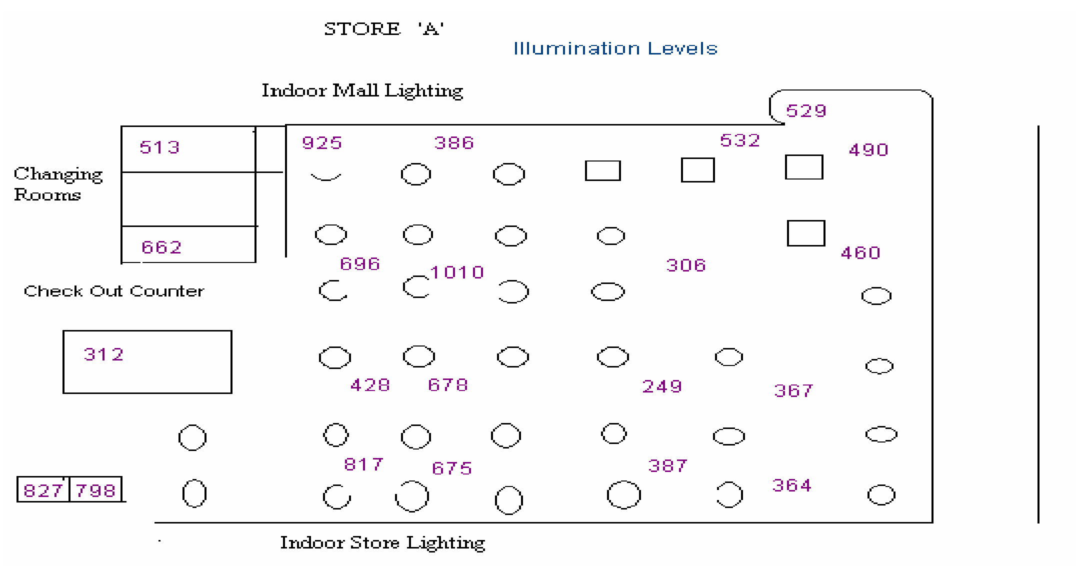


Figure 11. Illuminance values for the various locations of store A.

3.2 Store B

One of the problems that is often experience in stores exists in the over-lapping 'zones' between two different display areas.   Store designers produce different experiences by creating different background environments and, often, by using different lamps.   This is the case for store B, as indicated in Figures 12 and 13, which shows that at least two different lamps are used in this store.

In such a case, the merchandize placed in the border zone will be affected. In the figure below, we can see that in the men's section the DEcmc values vary significantly across the boundary. These values also vary significantly across the store from .59 to 5.45, indicating the variability of lighting and its impact.

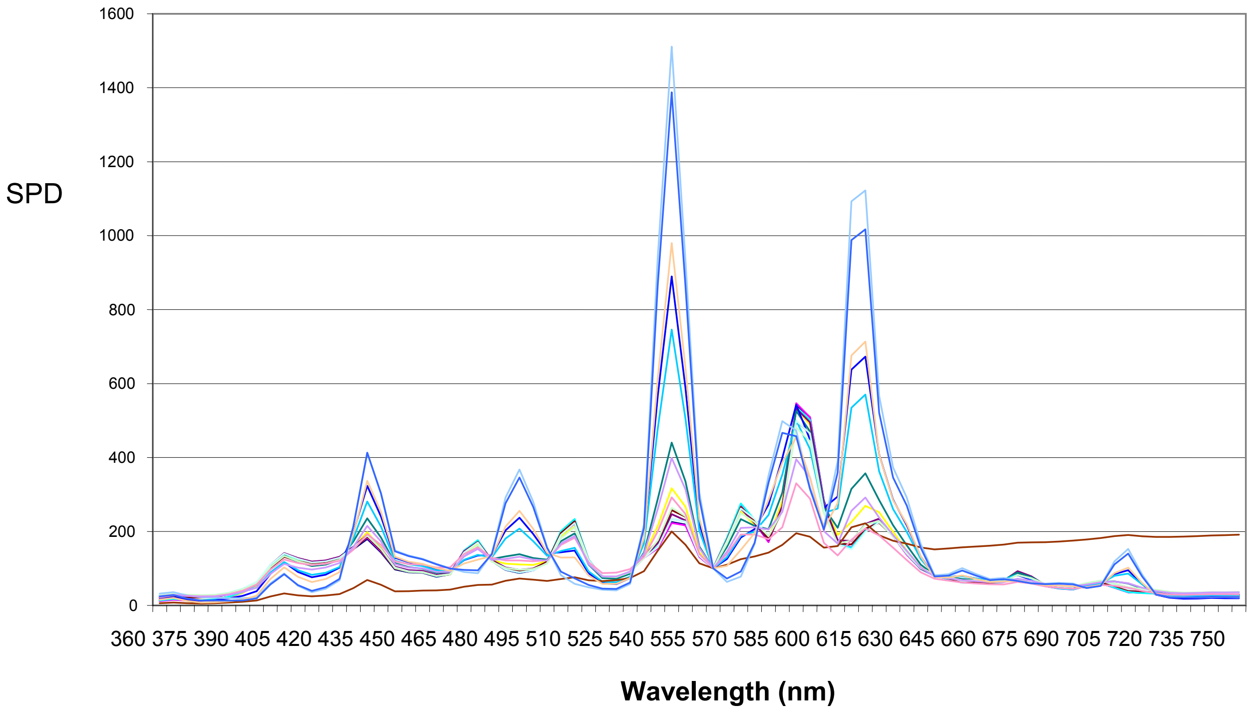


Figure 12. Normalized spectral power distribution data for measurement taken at store B.

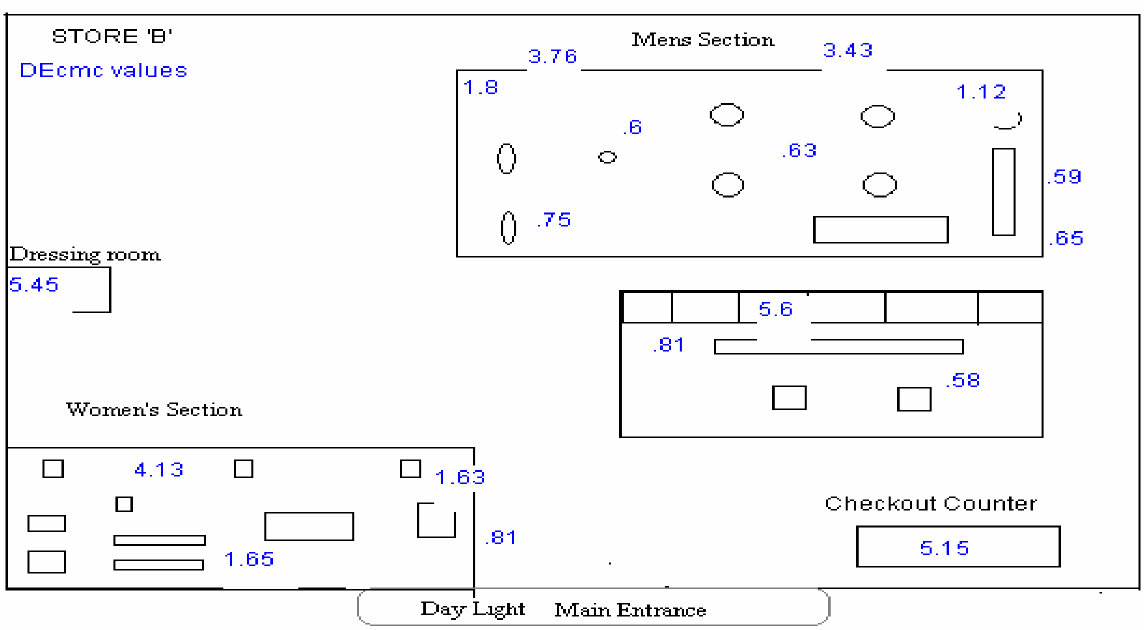


Figure 13. DE_{CMC} data calculated using SPD data and blue metamers for Store B.

In general, as shown in Figure 13, the color inconstancy values calculated for store B are very consistent, again indicating that the stores lighting variability is consistent. In addition, Figure 14 shows low but consistent illuminance for this store.

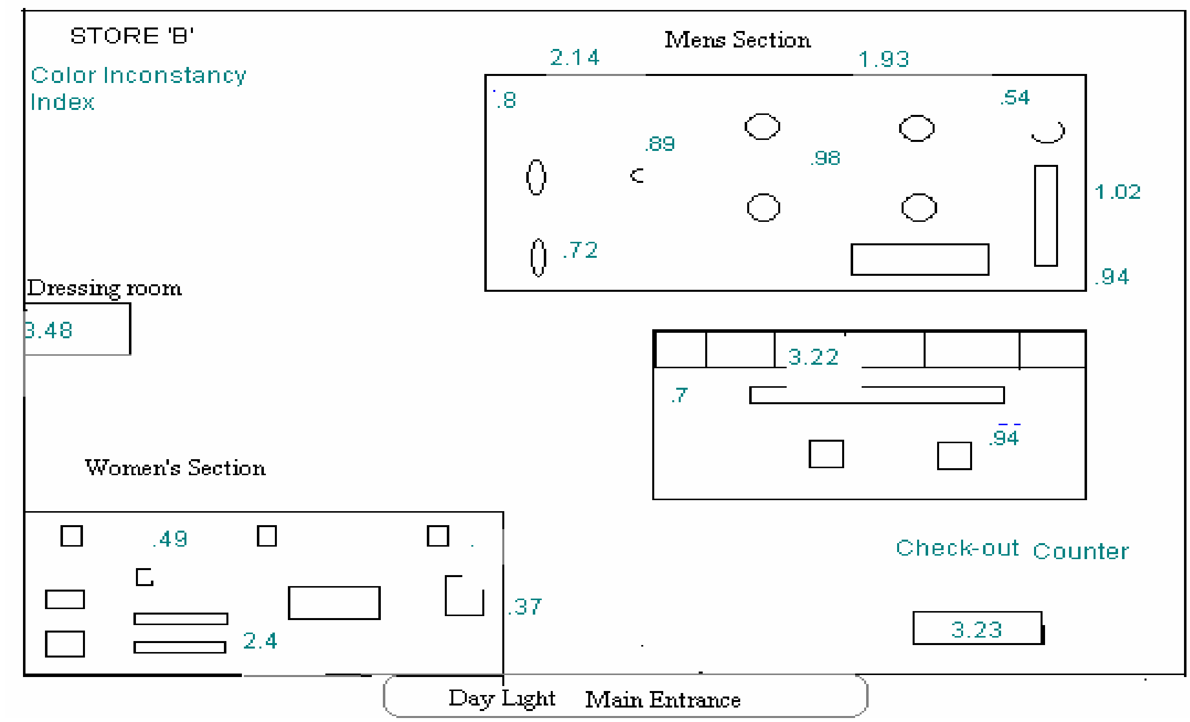


Figure 14. Color inconstancy index for standard blue metamer for store B.

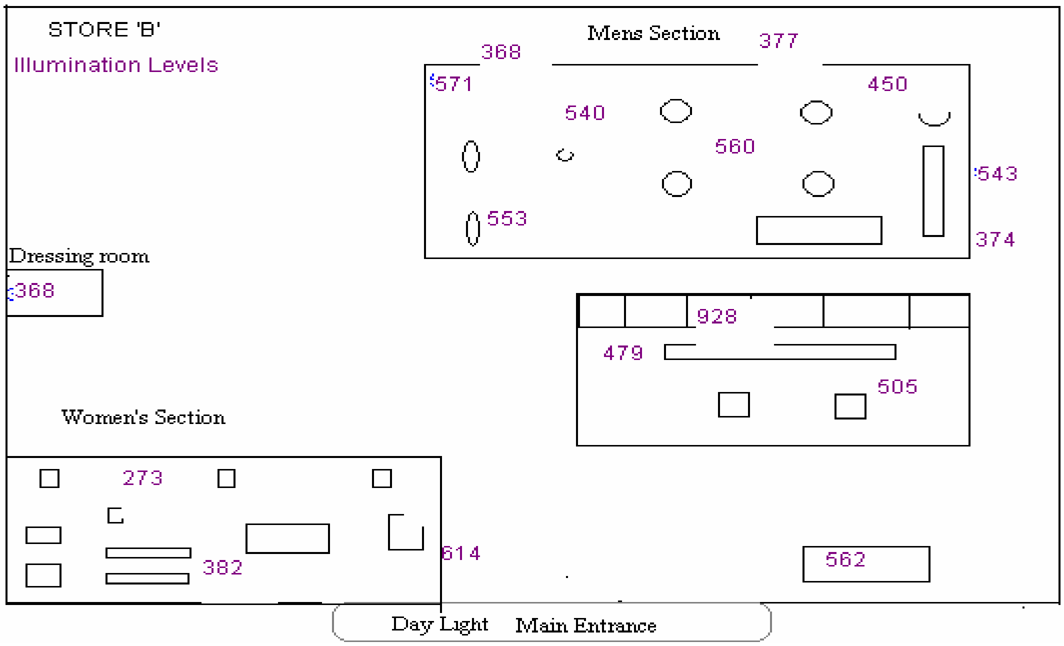


Figure 15. Illuminance values for the various locations of store B.

3.3 Store C

Similar data to store B were observed for store C. In fact, store C had very consistent lighting, with little variation in SPD, color difference and color inconstancy. However, the illuminance variability within the store was high, and was greater than the recommended limit ratio of 1:5. It is possible, therefore, that a loss of adaptation would occur, depending on the time period spent in these areas of the store.

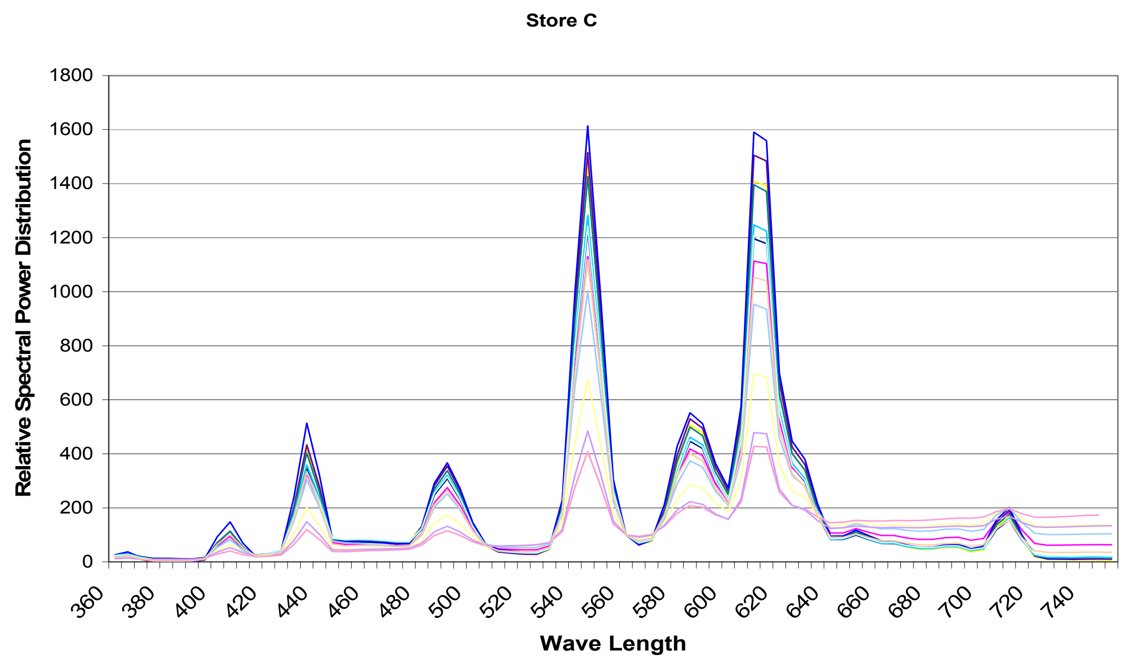


Figure 16. Normalized spectral power distribution data for measurements taken at store C.

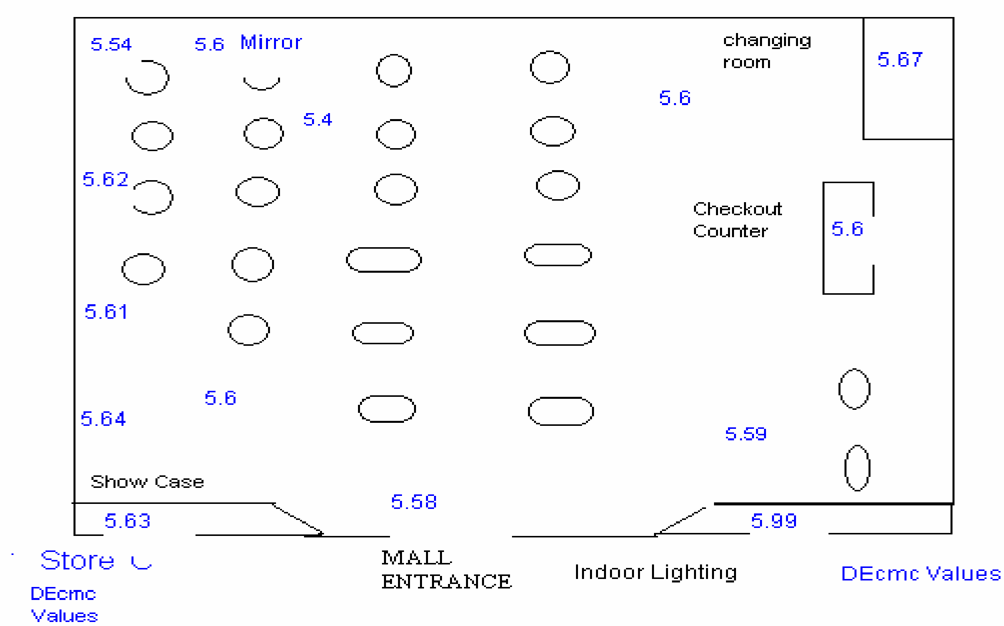


Figure 17. DE_{CMC} data calculated for blue metamers using SPD data and blue metamers for Store C.

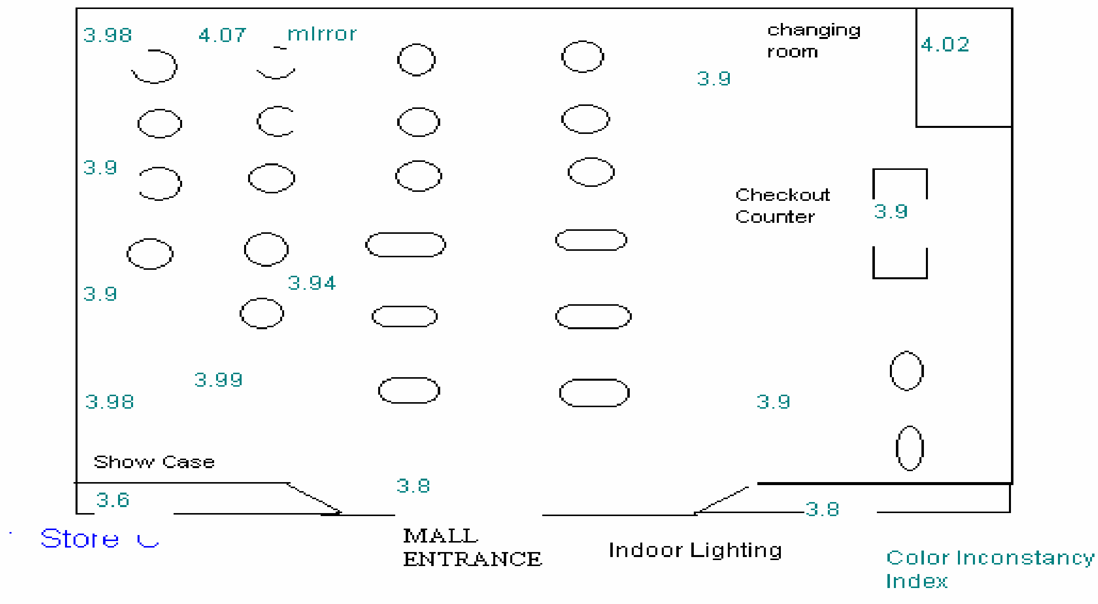


Figure 18. Color inconstancy index for standard blue metamer for store C.

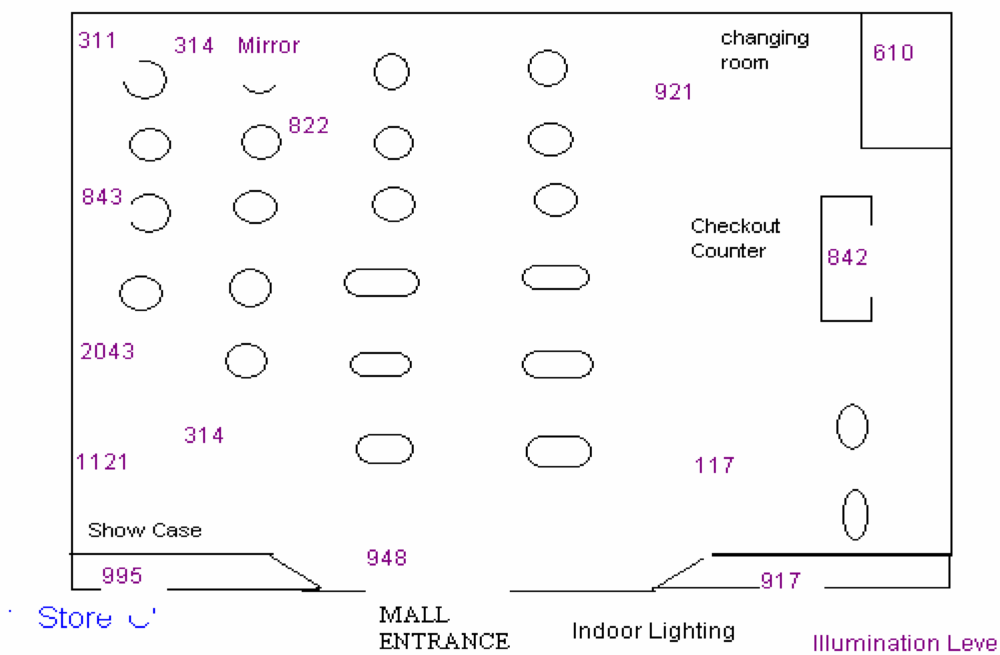


Figure 19. Illuminance values for the various locations of store C.

3.4 Store D

The quality of light varied greatly in store D. Not only were both incandescent and fluorescent lamps used interchangeably in the store, but the store had considerable exposure to external windows, which of course greatly affects SPD measurements. Figure 19 shows SPD data of all the measurements taken, and Figure 20 shows just those measurements taken near the external windows.

It was expected that the lighting variability of three different sources would lead to significant color difference, color inconstancy, and also illuminance variability. However, as shown in Figures 21-24, except for illuminance, surprisingly good consistency was observed in this store

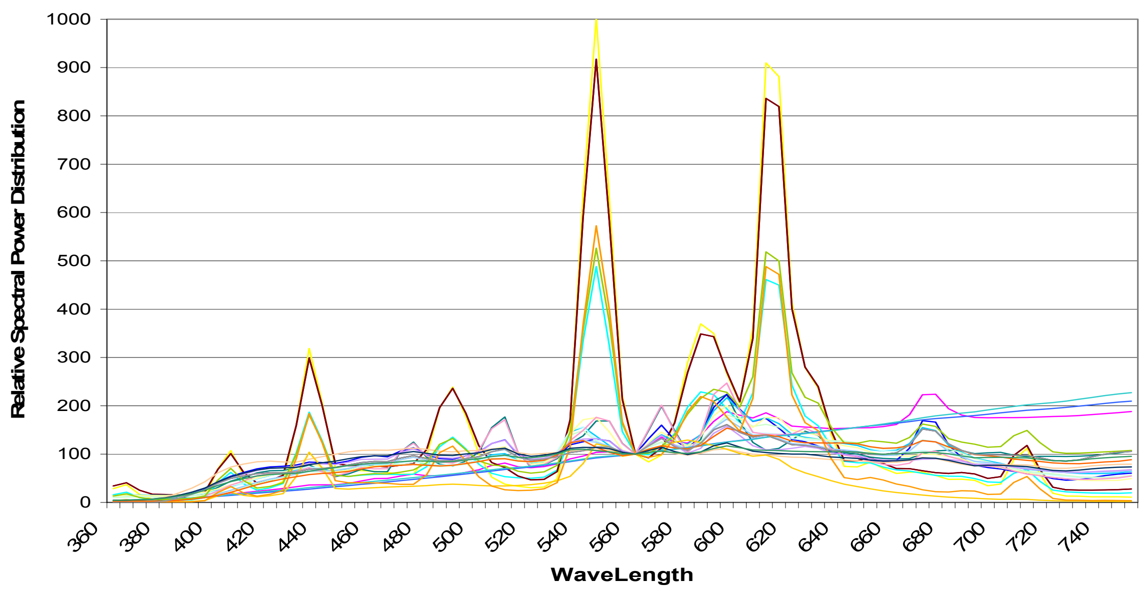


Figure 20. Normalized spectral power distribution data for measurements taken at store D.

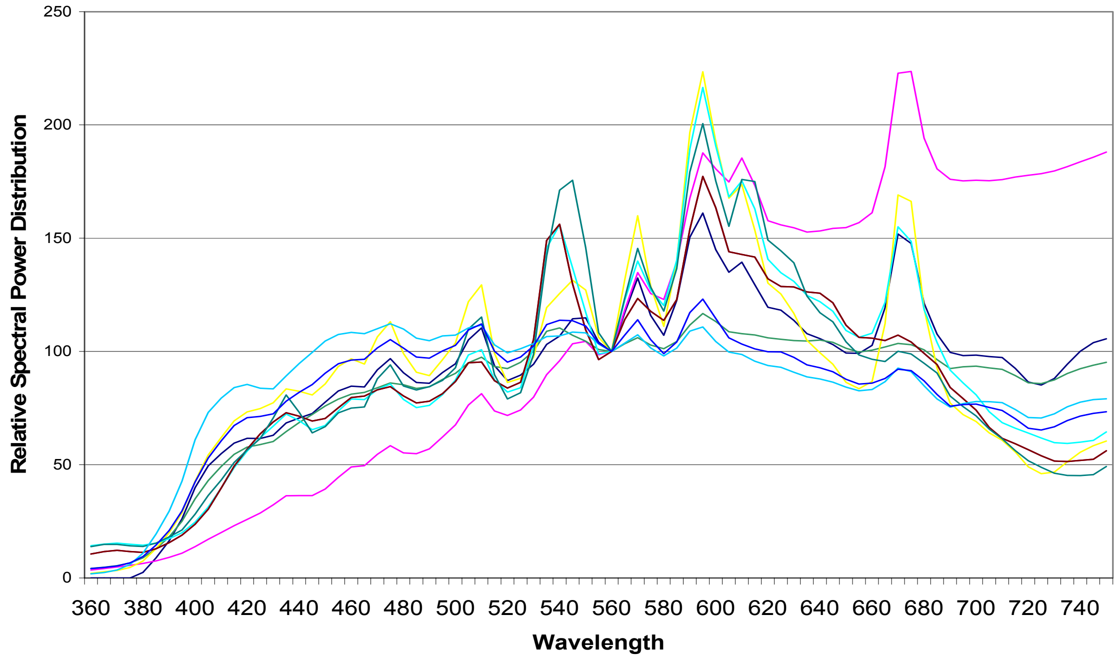


Figure 21. Normalized spectral power distribution data for measurements taken at store D near the external windows (measurements taken during the day).

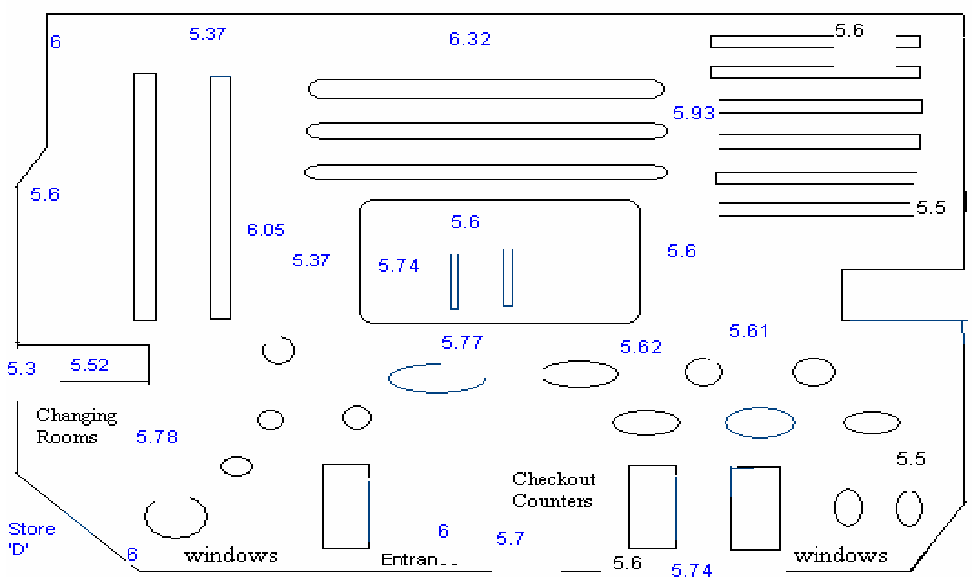


Figure 22. DE_{CMC} data calculated for blue metamers using SPD data and blue metamers for Store D.

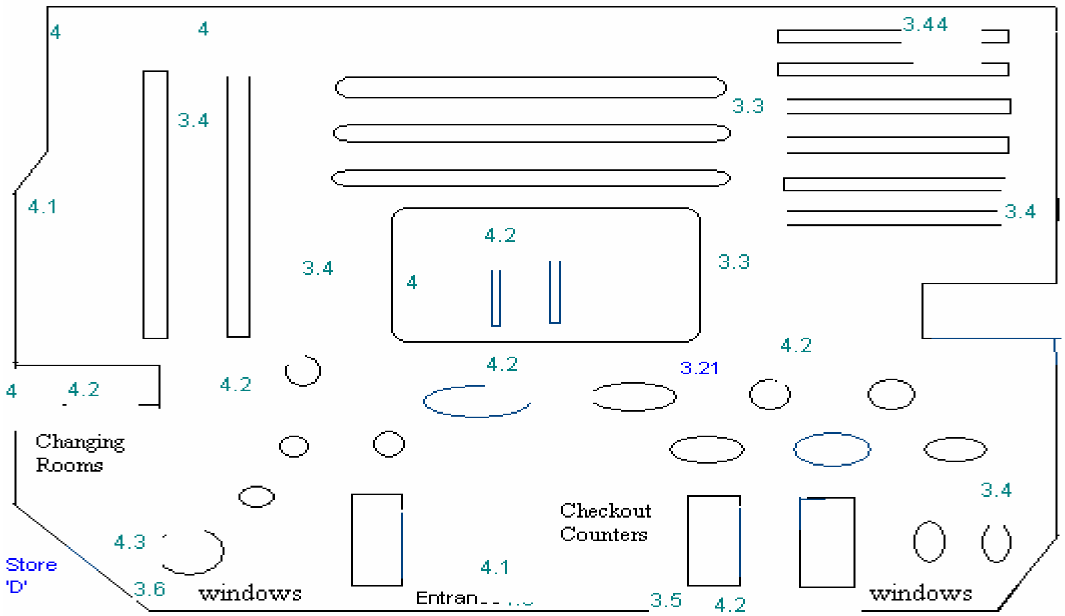


Figure 23. Color inconstancy index values for standard blue metamer for store D.

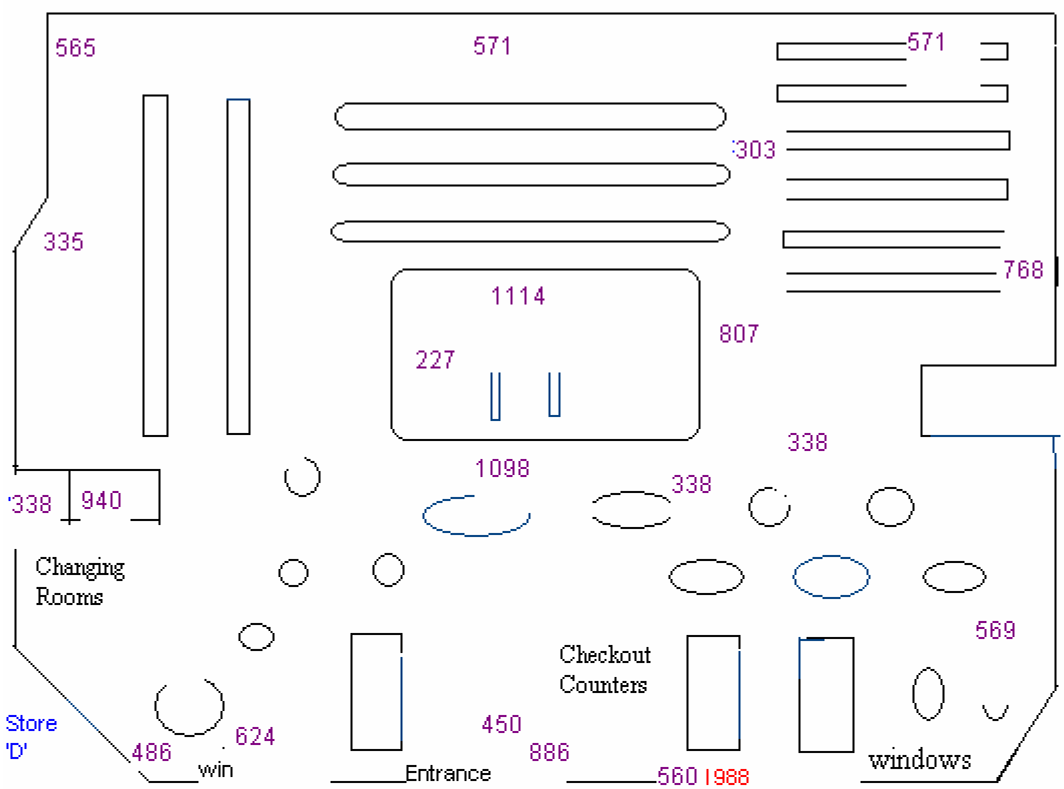


Figure 24. Illuminance values for the various locations of store D.

3.5 Store E

Figure 24 shows that at least three kinds of lamps were used, which led to a wide range of DE_{CMC} and color inconstancy values. Moreover, the illumination levels in this store varied greatly and in some areas the illuminance was so low that it was below the minimum level required by the spectroradiometer.

The stores is a large department store on four levels, although Figures 24-27 only show data for the first floor, which is where the merchandize from the retail company were displayed. Interestingly, near the entrance to the store the color inconstancy index varied from approximately 3 to 8 in only about a 5 feet distance. Clearly, therefore, color inconstant products will likely appear very different at different locations in this store.

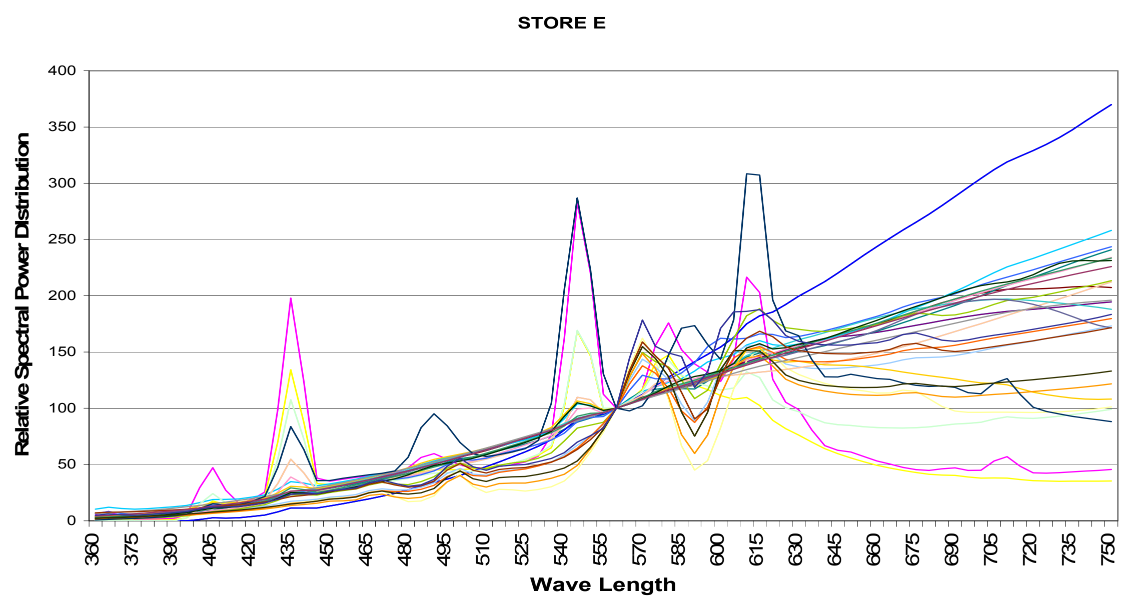


Figure 25. Normalized spectral power distribution data for measurements taken at store E.

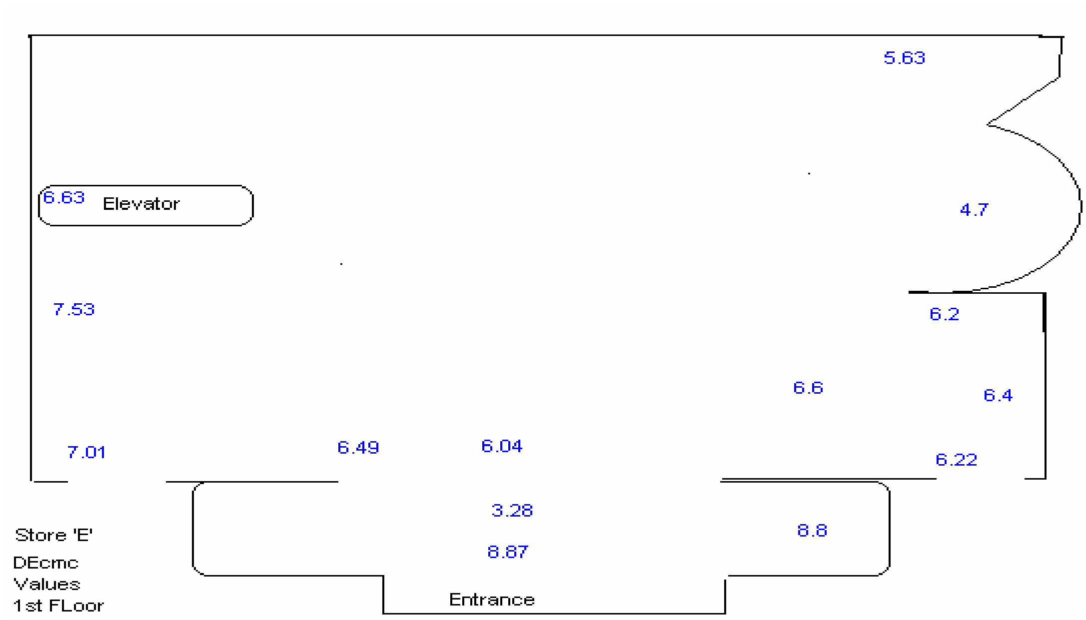


Figure 26. DE$_{CMC}$ data calculated for blue metamers using SPD data and blue metamers for Store E.

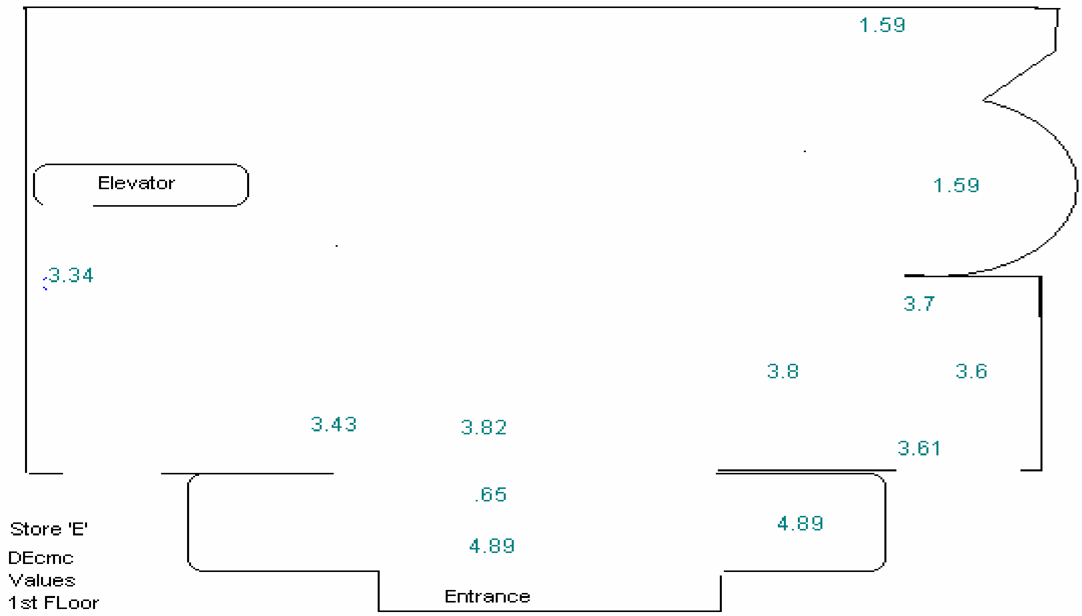


Figure 27. Color inconstancy index values for standard blue metamer for store E.

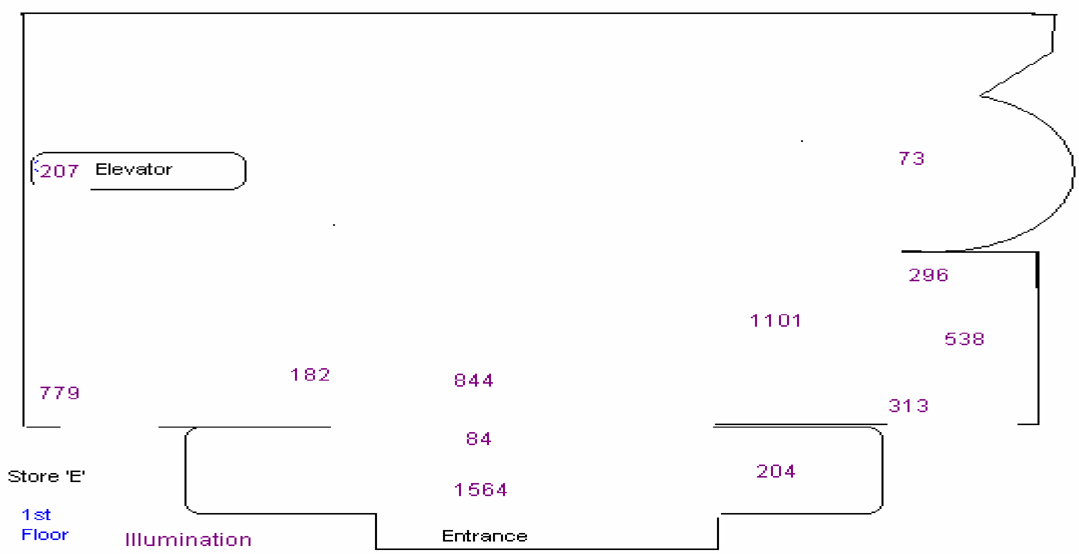


Figure 28. Illuminance values for the various locations of store E.

3.6 Store F

Figures 28-31 show that store F has relatively consistent lighting, although the illumiunance levels are generally low as compared to that recommended by IES[23] . The lighting consistency generally leads to consistent DE and color inconstancy values.

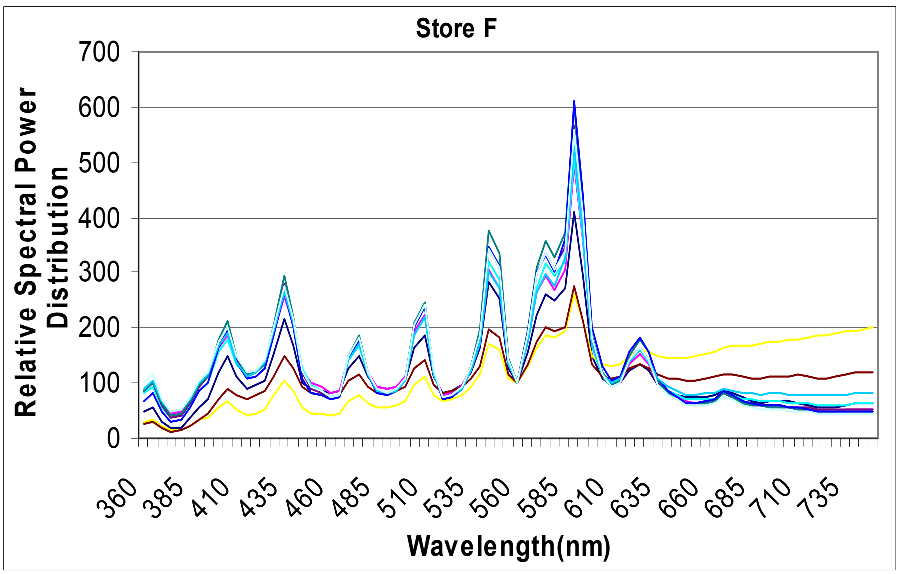


Figure 29. Normalized spectral power distribution data for measurements taken at store F.

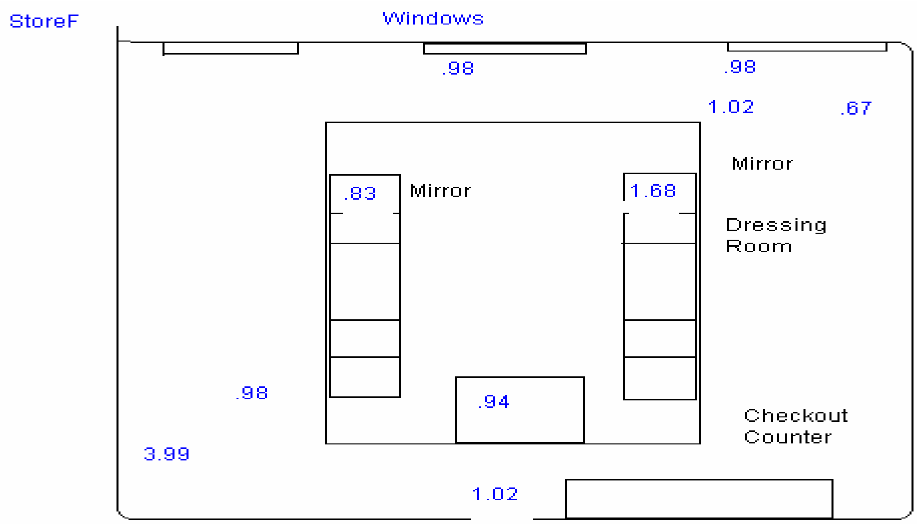


Figure 30. DE_{CMC} data calculated for blue metamers using SPD data and blue metamers for Store F.

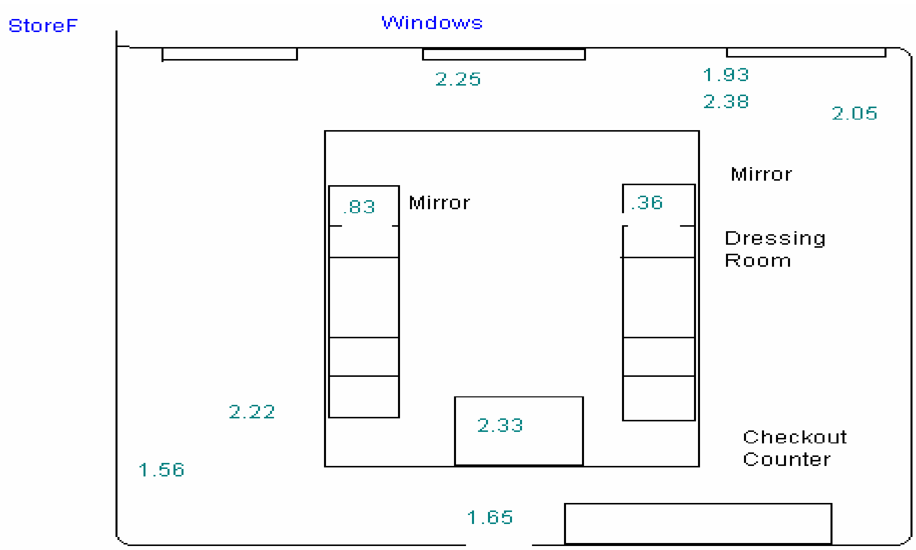


Figure 31. Color inconstancy index values for standard blue metamer for store F.

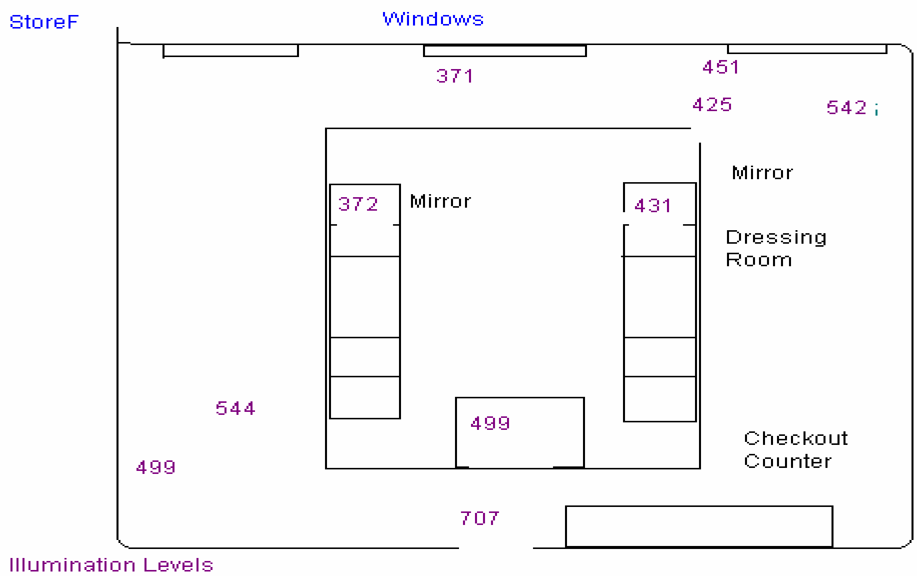


Figure 32. Illuminance values for the various locations of store F.

3.7 Store G

Store G contained mostly incandescent lighting, with only minor areas exhibiting fluorescent lighting data. The illumination ratio has not been maintained in this store, with the highest ratio being 1:9.

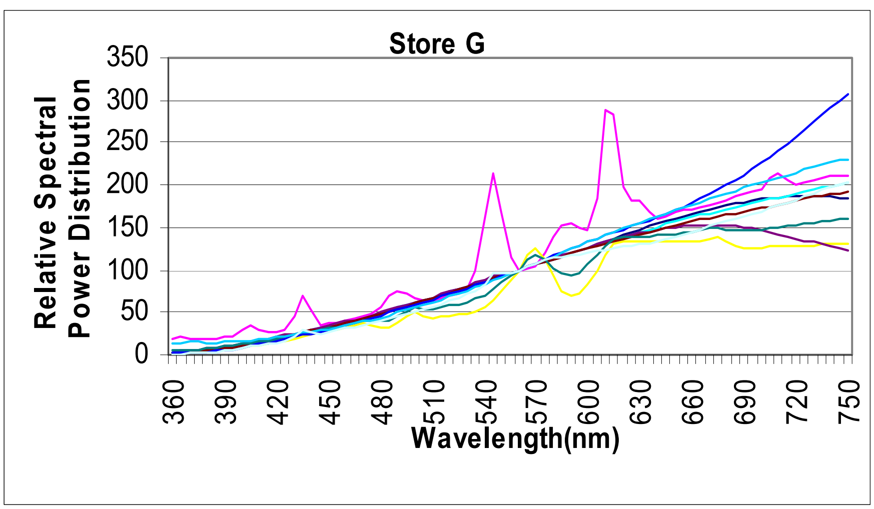


Figure 33. Normalized spectral power distribution data for measurements taken at store G.

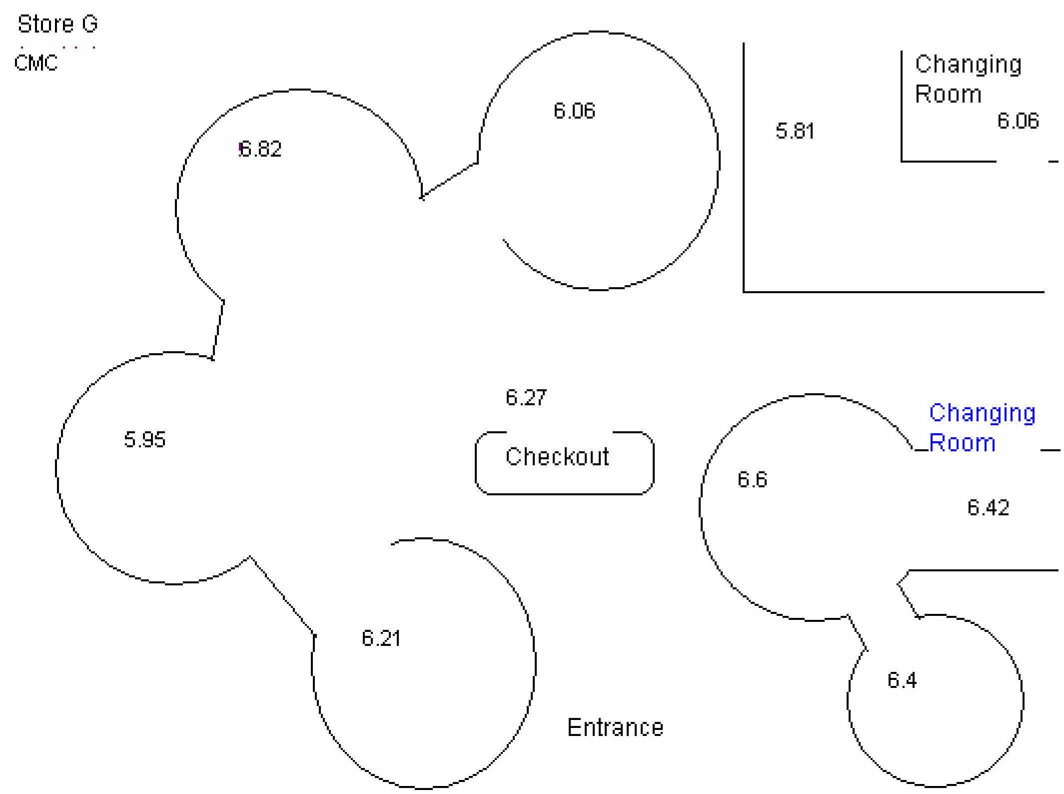


Figure 34. DE_{CMC} data calculated for blue metamers using SPD data and blue metamers for Store G.

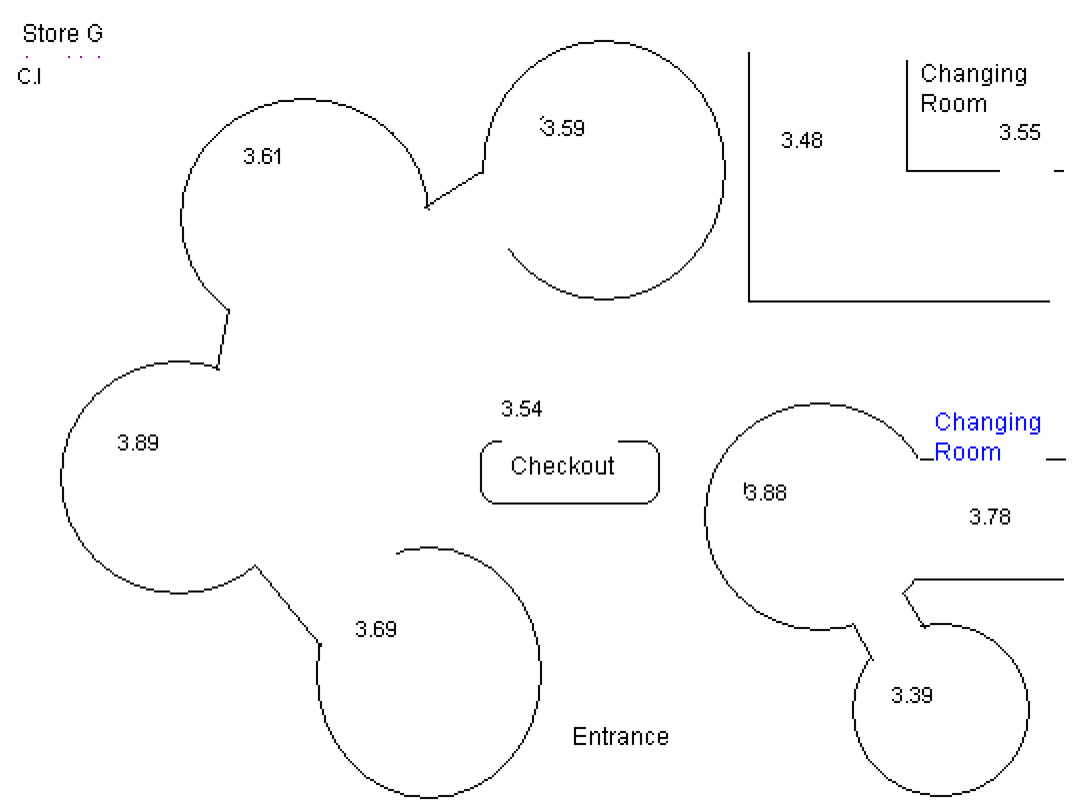


Figure 35. Color inconstancy index values for standard blue metamer for Store G.

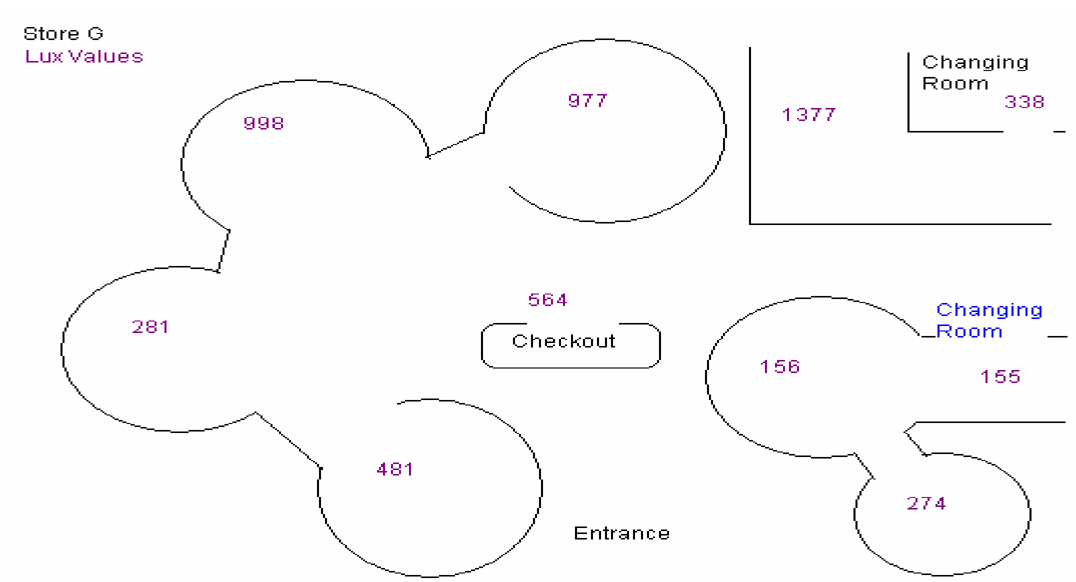


Figure 36. Illuminance values for the various locations of Store G.

3.8 Comparison of photometric and colorimetric data between stores

There are a number of common critical areas between stores that a retail company would probably desire to have similar lighting. Areas such as changing facilities, where clothing is displayed, at check-out counters, and entrance/exit areas. The colorimetric and photometric differences between stores for the check-out counters are described below to exemplify the kind of differences observed between the stores.

3.8.1 Check-out counters

Despite significant variability in SPD data within most of the stores studied as well as between stores, the color difference calculated using the average SPD data for each store for the turquoise metamers was found to be similar at all the check-out counters, as shown in Figure 36. However, the illuminance levels (Figure 37) at these locations varied significantly, from around 250-800 lx. Recommended levels are 3:1 to the general area of merchandize lighting which is often not the case. CIE metamerism indices and color inconstancy values for the turquoise metamers was found to be relative constant at that check-out counters. However, the color rendering index (Figure 39) values at these locations varied significantly from approximately mid sixties to upper nineties.

Figure 37. DEcmc values at the check out counters in different stores.

Figure 38. Comparison of illuminance (lx) values at the check-out counters in the six stores studied.

Figure 39. Comparison of metamerism index (M.I.) and color inconstancy index (C.I.) values at check-out counters in the six stores studied.

Figure 40 Comparison of CIE color rendering index C.R.I values at check out counters in the six different stores studied.

3.8.2 Statistical analysis

Clearly, there are many variables that lead to differences in perceived color differences of products within and between retail stores. Hence, meaningful statistical analysis is likely to be difficult, except in very specific circumstances, such as for a given type of metamer, or a given standard observer. However, the level of standard deviation as compared to a variability in, for example, color difference assessment resulting from different lighting conditions in standard light booths can be an effective means of determining the effectiveness of critical color difference assessment during wet processing of the textile goods on the perceived quality of the final garment by the consumer. In this section, statistical methods (see Experimental section) were used to assess the variability in data between stores and these were compared to the variability obtained in the standard light booths measured. Full statistical data is provided in the Appendix.

3.8.2.1 Color Difference (DEcmc $_{(2:1)}$)

Considerable variability in color difference measurement was found for the turquoise metamers under standardized lighting (light booths) compared to the retail lighting measured in this study. Using the standard daylight simulators used in the light booths, an average DE_{CMC} of 0.86 as compared to an average of DE 6.6 in retail lighting. While the difference in DE_{CMC} for the light booths and retail stores is not surprising, because the samples were made to match to illuminant D_{65}, the deviation within the stores is more telling on the kind of color control that is likely for a given store. For instance Figure 40 shows that the variability for Store C is lower than that of light booths, which shows that lighting is very consistent for this particular store. However, very high deviation was observed for store B.

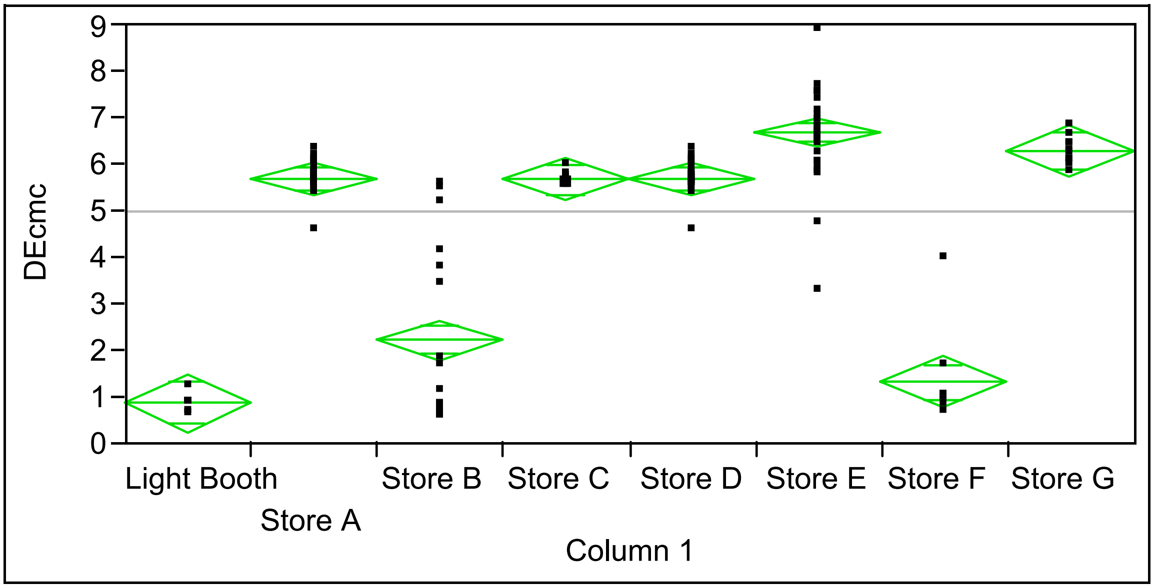


Figure 41. Comparison deviation among light booths with deviation among the retail stores using one way analysis of DEcmc.

3.8.2.2 Color Inconstancy

In general, the variability in color inconstancy for the standard light boxes is relatively small, as indicated in Figure 41. However, much higher variability is evident in most of the retail stores studied, particularly stores D and E.

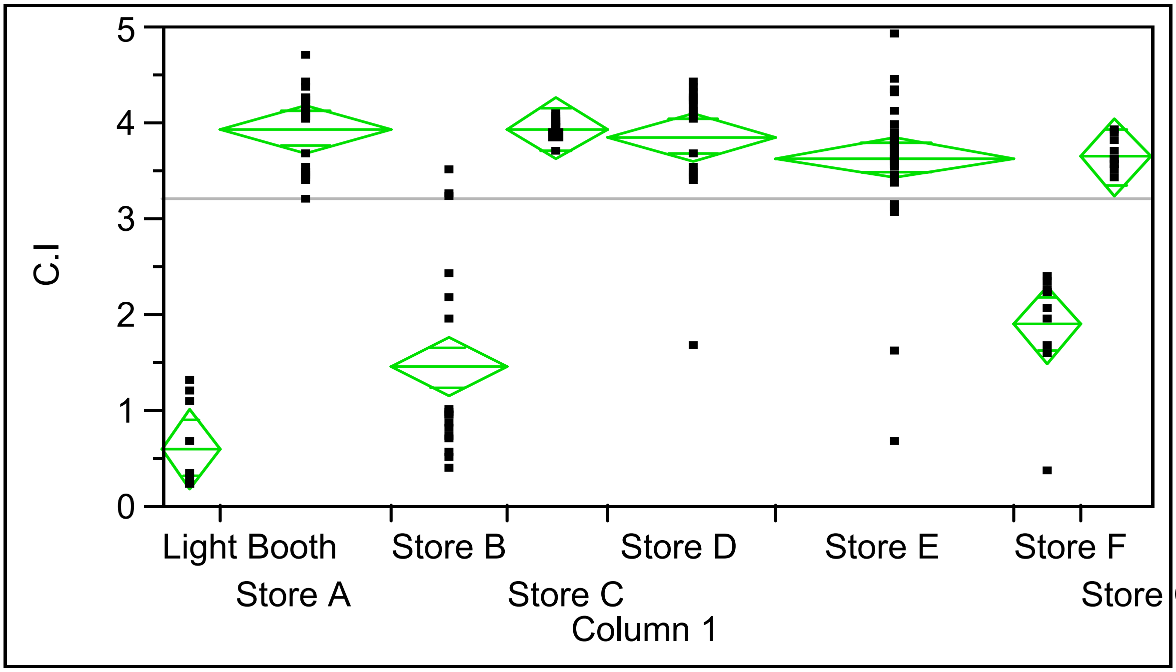


Figure 421. Comparison deviation among light booths with deviation among the retail stores using one way analysis of color Inconstancy Index

3.8.2.3 Metamerism Indices

As indicated in Figure 43, the variability in metamerism index is quite low for the standard light booths, and is also low for a number of the retail stores. However, a higher degree of variability in metamerism is seen in stores G and E.

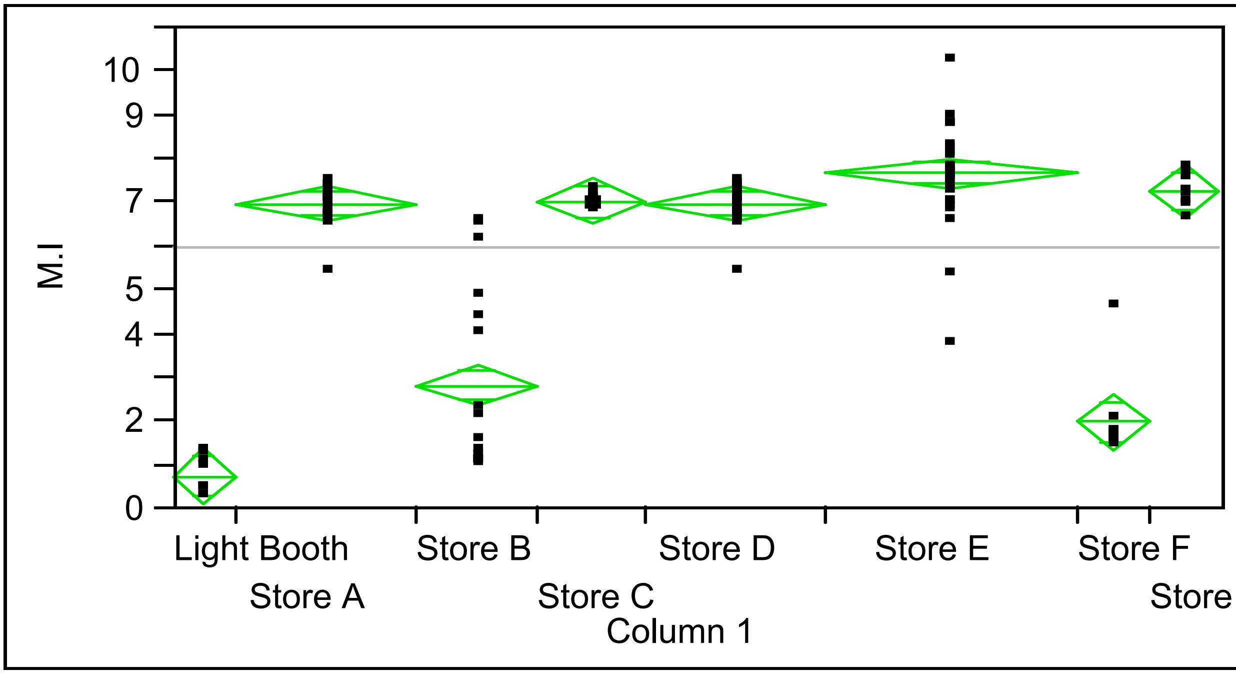


Figure 43. Comparison deviation among light booths with deviation among the retail stores using one way analysis of metamerism index.

4. Comparison of the performance of CIEDE2000 and DE_{CMC} by visual assessment.

Analysis of the effect of lighting variability on perceived color difference is critically dependent on the performance of the color difference formula used with respect to visual assessment of the magnitude of perceived color difference. The current ISO and AATCC recommended color difference formula for textile materials is DE_{CMC}. Recently, however, the CIE adopted a new color difference formula, CIEDE2000 or DE_{00}, that has been reported to correlate with visual discrimination datasets better than DE_{CMC}[14].

In view of the need to validate the new formula independently from the research groups that developed the formula, and in view of the need to obtain the validation data in advance of other textile institutions from adopting the new formula, an experiment was devised as part of this research to assess the performance of DE_{00} against a new, independent visual dataset and compare the performance to DE_{CMC}.

Hence, a new set of color difference samples were prepared for five color centers (standards). As shown in the experimental section (Table 1), most of the color centers (grays, blues and a navy) were selected based on the intended performance improvement of ΔE_{00} over other formulas such as ΔE_{CMC} and CIE94. The performance of DE_{CMC} is known to correlate poorly with visual pass/fail data for near neutral colors, blues and dark colors. Also, the 'batch samples' shown in Table 2 were selected because there was a significant difference between ΔE_{CMC} and $\Delta E_{00,}$ except for MG2, which was included in the set as a test case in which all observers should have responded to the match as an obvious pass. Hence, the samples represented areas of color space that were biased toward showing an improvement in ΔE_{00} when compared to ΔE_{CMC}.

The fabric samples from Tables 1 and 2 were measured before and after the visual observer experiment, and very little difference in colorimetric data was observed (a change of less than 0.1 in ΔL^*, Δa^*, Δb^*, etc). Hence, it can be assumed that the appearance of the samples did not change during the experiment.

In determining pass/fail decisions, there will always be variation in subjective judgments, which makes it necessary to obtain data from a sufficiently large set of observers. The number of observers used in this experiment, 31, constitutes significantly more than has been used for most visual color difference datasets, from 8 to 24 in most cases (except the RIT-DuPont dataset with 50 observers)[14]. A key criterion for this experiment was to use expert shade matchers, i.e., observers that are trained in making visual judgments, to help minimize observer variability and to correlate maximally with practical industrial color assessments. Most of the observers for this study make visual judgments as their main job function. Observers were asked to rate each sample pair as obvious pass, marginal pass, marginal fail or obvious fail. The observers were also asked to identify the principle attributes by which the samples differed (lighter/darker, redder/greener, yellower/bluer, brighter/duller). Using this visual data, two approaches were used to assess the performance of the color difference formulas, ΔE_{CMC} and ΔE_{00}, against the visual data:

i) Using Three Ranges: Pass, Marginal (pass or fail), and Fail.

The three ranges were defined as follows: an obvious colorimetric pass if $\Delta E<0.8$, a marginal colorimetric pass if $0.8\leq\Delta E<1.2$, and an obvious colorimetric fail if $\Delta E\geq1.2$. The marginal pass and marginal fail visual data were combined into one group, ‘marginal’. A consensus was assumed if >60% of the observers gave the same decision (pass, marginal, or fail).

As shown in Table 4, based on the criteria described above for pass, marginal, fail for the formulas, the % agreement between the consensus decision of the 31 observers (when consensus is defined as >60% agreement amongst observers) was found to be 67% in the case of $\Delta E_{CMC(1:1)}$, $\Delta E_{00(1:1)}$, and $\Delta E_{00(2:1)}$, whereas 57% agreement was found for $\Delta E_{CMC(2:1)}$. These data indicate that the two ΔE formulas perform approximately equivalently, depending on the l:c ratio employed.

By incorporating a marginal category, while requiring at the same time a pass or fail decision (i.e., marginal pass or marginal fail), it was believed that maximum information could be obtained from the experiment. For instance, data could be obtained pertaining to observer variability when samples were deemed borderline pass/fail. Unfortunately, it is difficult to obtain meaningful statistical data with three ranges, and it is to be expected that significantly larger variance would be obtained by including the marginal category.

Table 5. Observer Pass/Fail Data versus ΔE_{CMC} & ΔE_{00}.

	1:1		2:1		Overall	
	ΔECMC	ΔE00	ΔECMC	ΔE00	Observer results	% Consensus
LG#2	1.24	1.11	1.05	.89	No Consensus	50
MG#5	**.25**	**.2**	**.25**	**.19**	**Obvious Pass**	**65**
Navy A	**1.04**	**.79**	**1.0**	**.78**	**Obvious Fail**	**81**
Navy B	**1.28**	**1.07**	**1.14**	**1.03**	**Obvious Fail**	**81**
Navy G	**.74**	**.55**	**.66**	**.52**	**Marginal (Pass)**	**61**
Navy J	.89	.55	.63	.44	No Consensus	41
Blue D	1.25	1.02	1.03	.68	Marginal (Pass)	55
Blue E	**.92**	**.54**	**.88**	**.48**	**Obvious Pass**	**61**
Blue G	**2.43**	**1.56**	**2.3**	**1.5**	**Obvious Fail**	**68**
Blue I	1.84	1.13	1.82	1.09	Marginal (Fail)	52
Blue J	**2.55**	**2.16**	**1.99**	**1.37**	**Obvious Fail**	**61**
Blue O	**.74**	**.59**	**.61**	**.39**	**Obvious Pass**	**62**
Red D	.89	.68	.47	.37	No consensus	50
Red E	1.02	.79	.6	.46	No consensus	52
Red G	**2.36**	**1.88**	**1.65**	**1.35**	**Obvious Fail**	**83**
Red H	2.12	1.64	1.18	.92	Obvious Fail	56
Red M	1.03	.79	.53	.41	Marginal (Pass)	52
% agreement with consensus*	67%	67%	57%	67%		

*consensus = >60% agreement amongst observers (shown in **bold**)

Clearly, during the analysis stage, it is possible to simply assess pass/fail criteria by combining, for instance, obvious pass and marginal pass.

ii) Using Pass/Fail Only

In 1995, Oglesby predicted and compared the performance of ΔE_{CMC} and CIE94 using several statistical methods and a large set of production samples[46]. The discrimination method employed by Olgesby (Equation 1) was employed with this dataset to show % discrimination (% agreement) for ΔE_{CMC} and ΔE_{00}:

$$D = (W_1(P_c-P_x)+W_2(F_c-F_x)/N)100 \qquad (1)$$

where, D = % discrimination, W_1 = N/2P and W_2 = N/2F, in which the symbols are defined in Table 4.

Table 6. Summary of symbols used in discrimination equation 1.

	Formula Passed	Formula Failed	Total
Visual Passed	P_c	P_x	P
Visual Failed	F_x	F_c	F
Total	P_c+F_x	P_x+F_c	N

The higher the discrimination, the better is the performance of the color difference formula. Furthermore, this formula allows for optimization of the pass/fail number. Figures 43 and 44 show the % Discrimination for ΔE_{CMC} and ΔE_{00}, as well as CIELAB ΔE for comparison, at three pass/fail tolerance levels (0.8, 0.9 and 1.0) for both 2:1 and 1:1 l:c ratio, respectively.

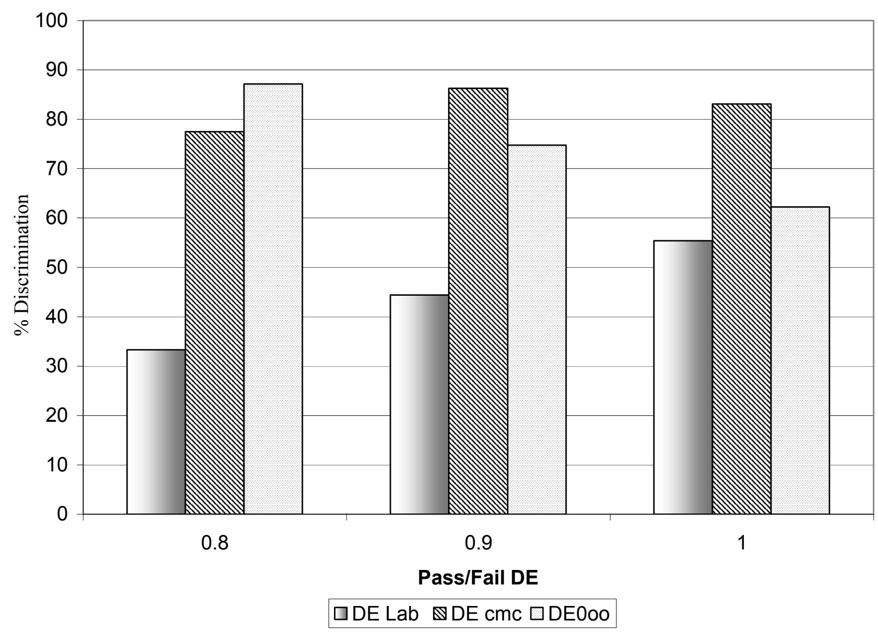


Figure 44. Percent discrimination for $\Delta E_{CMC(2:1)}$ $\Delta E_{00(2:1)}$ and CIELAB ΔE at three pass/fail values.

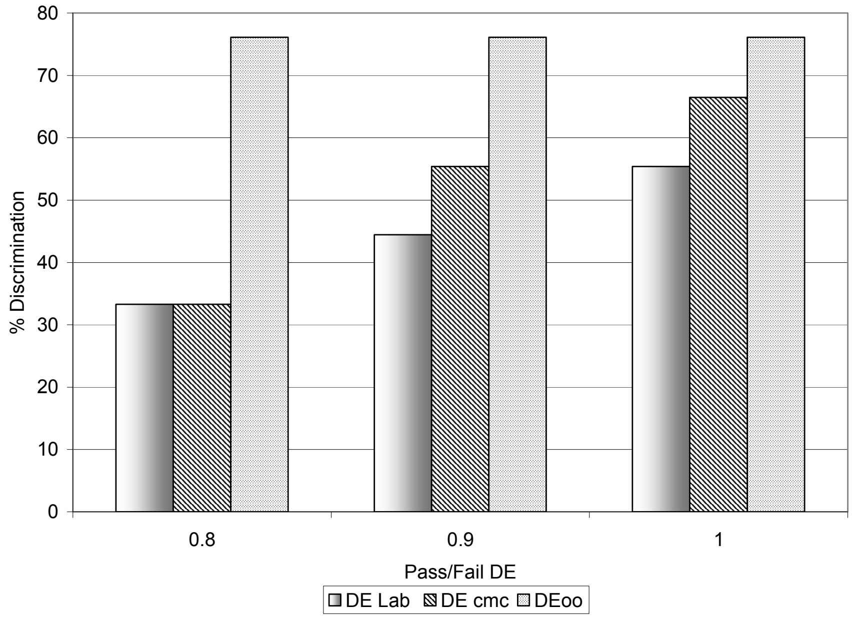


Figure 45. Percent discrimination for $\Delta E_{CMC(1:1)}$ $\Delta E_{00(1:1)}$ and CIELAB □E at three pass/fail values.

The data show that, at l:c ratio 2:1 (Figure 42), both ΔE_{CMC} and ΔE_{00} perform significantly better than CIELAB ΔE. Furthermore, the maximum % discrimination observed for ΔE_{CMC} was 87% (at ΔE pass/fail of 0.9), and for ΔE_{00} was also 87% (at ΔE pass/fail of 0.8). Calculation of % discrimination at other ΔE tolerance values did not improve the maximum % discrimination. At l:c ratio of 1:1 (Figure 42), ΔE_{00} clearly outperformed the other formulas, although the % discrimination was never higher than 80%. It is clear that an l:c ratio of 2:1 provides better agreement with the visual observer set than 1:1. It is also clear that ΔE_{CMC} and ΔE_{00} perform similarly.

From the discrimination factor analysis we have seen that both CMC and CIEDE2000 have almost the same agreement with the visual judgments used for this study. These results are similar to analysis by Kuehni [29] for the Witt and BFD dataset which range around 61.6 % to 65.9%.

5. Analysis of variation in CIEDE2000 and DEcmc as a function of illuminant.

All the major color difference formulae to date have been developed for standard conditions which include illuminant D_{65}. In industrial practice, these formulae are used commonly to predict color differences under many different illuminants, such as illuminant A, F2, and F11. It is assumed that the simple chromatic adaptation transform incorporated into L*a*b* formulae, i.e., normalizing the data using X_n Y_n Z_n tristimulus values of the selected illuminant, ensures that the performance of the formulae against visual assessment will be equivalent for any illuminant. However, no published data appears to be available that validates this assumption.

Therefore, in this section, the variability in calculated DE values for both DE_{00} and DE_{CMC} was assessed using a large set (155 pairs) of industrial color difference textile samples that represented almost all significant attributes of color space. The color difference pairs were supplied by a leading textile retail company. Importantly, all samples were selected to have minimum metamerism (the samples were prepared using the same dye combinations), so that changes in performance of color difference formula as a function of the illuminant were likely due to formula differences and not due to metamerism.

The goal of this assessment was to determine if the performance of the formulae are likely to vary significantly as a function of the illuminant, thereby demonstrating whether a detailed assessment of the performance of these formulae is required using different illuminants.

5.1 Variation as a function of hue angle, h^o

Colorimetric data were calculated for L^*,a^*,b^*,C^*,h^o for illuminants D_{65}, A, and F2 for each sample pair, and color differences were calculated using $DE_{CMC(2:1)}$ and $DE_{00(2:1)}$. The effect of varying l:c ratio was not investigated.

It is well-known that no general agreement exists for hue angle regions that correspond to particular hue names. For the purposes of this study the following ranges were used to describe specific hue names: Blue 170^o to 255^o; Purple 256^o to 313^o; Red 0^o to 25^o and 314^o to 360^o; Orange 26^o to 51^o ; Yellow 52^o to 73^o; Green 74^o to 170^o. The number of samples lying within each of these hue categories was determined under each illuminant as seen in Table7. Figure 56 shows a plot calculated color difference as a function of h^o for both CMC and CIEDE2000.

Table 7. Distribution of samples under different illuminants through out the hue region

	DAY	A-10	CWF
Blue	29	33	30
Green	23	14	31
Yellow	22	31	25
Orange	21	33	17
Red	42	25	32
Purple	18	19	20

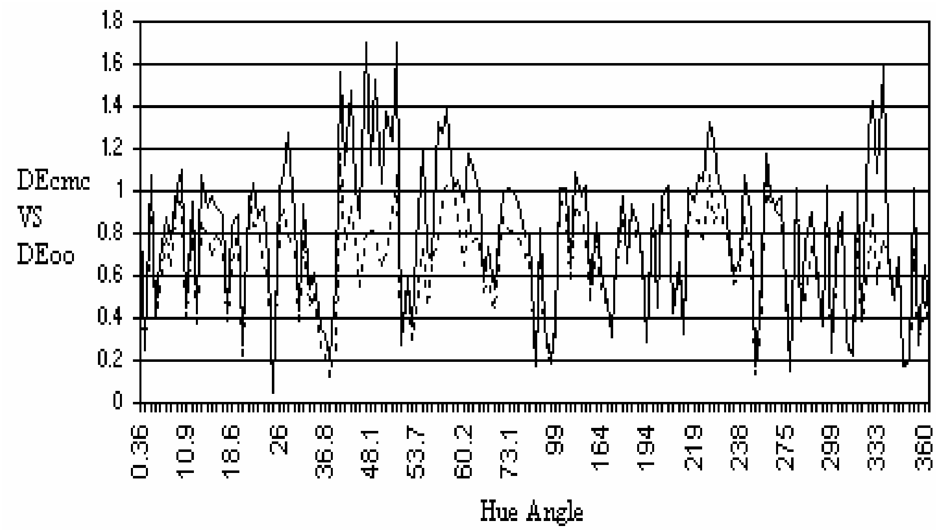


Figure 46. Calculated values of DE_{CMC} (solid) and DE_{00} (dashed) plotted against h^o for D_{65}.

It is clear from the data that significant differences do exist in certain regions of the space. In section 4, it was shown that the performance of the two formulae were equivalent for the sample set studied, even though the samples were selected were biased toward showing and improvement in the performance of DE_{00}.

To assess the significance of the differences in DE values for the two formulae, statistical methods were applied to determine the amount and region of maximum difference. The Friedman Test[45] was applied, which is a non-parametric analysis of randomized block experiment; using this test statistical significance was found spread through the full hue range for all three illuminants as well as the different hue ranges. The data were also treated by a One Sample Wilcoxon Test to determine the range of the difference in which it would lie (e.g. .15 to .5).

Figures 57-59 show the different patterns in differences between the two formulae (DE_{CMC} - DE_{00}) for three illuminants. Clearly the variation appears considerable, indicating that the performance of each formula is likely to vary significantly as a function of illuminant.

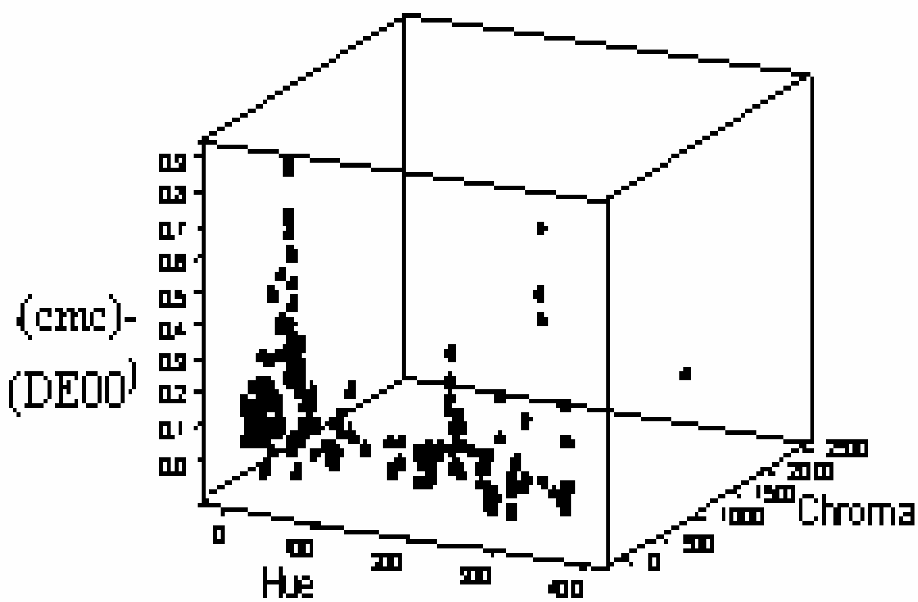


Figure 47. Plot of DE_{CMC} - DE_{00} against h^o and C* for D_{65}.

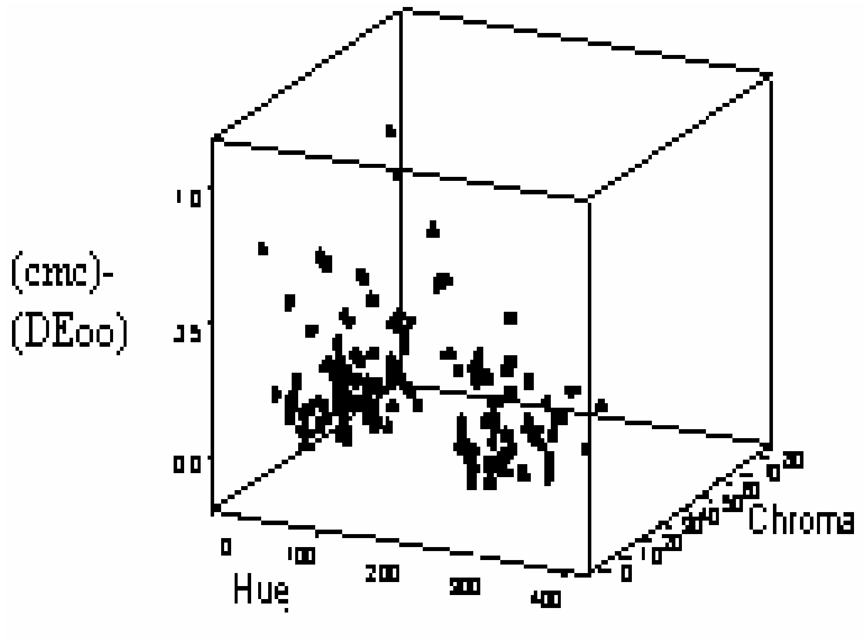


Figure 48. Plot of DE_{CMC} - DE_{00} against h^o and C* for illuminant A.

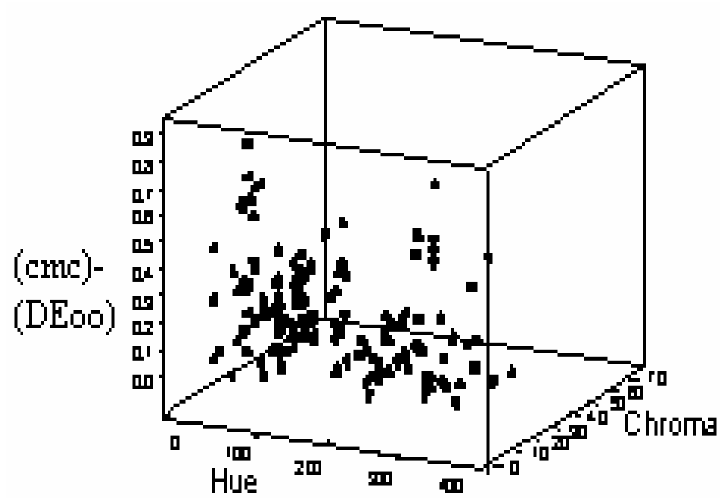


Figure 49. Plot of DE_{CMC} - DE_{00} against h^o and C* for illuminant F2.

Interestingly, as CIEDE2000 is intended to perform better than CMC in the blue region, very little variation in the blue area is observed for D_{65}; in fact larger differences are observed in the orange-red region. Under illuminant A the main differences in the calculate DE values appear in the green and red region, as indicated in Table 6. Under illuminant F2, maximum difference in the two formulae is observed in the yellow-orange region.

The above discussion can be confirmed by simple arithmetic operations such as mean. The over all mean for the two formulae is the same for all three illuminants but vary considerable within various hue regions (Table 8)

Table 8. Comparison of arithmetic mean of color difference data for all samples across entire hue range.

Mean		**Blue**	**Green**	**Yellow**	**Orange**	**Red**	**Purple**	**Sum**
D65	cmc	0.81	0.72	0.92	0.95	0.76	0.67	0.8
	exp	0.71	0.63	0.69	0.63	0.61	0.62	0.65
A-10	cmc	0.75	0.78	0.8	0.87	0.75	0.73	0.78
	exp	0.65	0.68	0.61	0.65	0.58	0.69	0.64
CWF	cmc	0.81	0.7	0.97	0.82	0.82	0.68	0.8
	exp	0.68	0.61	0.67	0.65	0.63	0.62	0.64

Statistical analysis of the two formulas showed a significant difference existed throughout the hue range under all three illuminants, as shown in the calculations below:

D_{65}

S = 107.36 DF = 1 P = 0.000

S = 108.76 DF = 1 P = 0.000 (adjusted for ties)

	N	Est Median	Sum of Ranks
CMC_DAY	155	0.85500	297.0
EXP_DAY	155	0.75500	168.0

Grand median = 0.80500

A S = 95.41 DF = 1 P = 0.000

S = 99.23 DF = 1 P = 0.000 (adjusted for ties) Grand median = 0.75500

F2 S = 105.70 DF = 1 P = 0.000

S = 112.22 DF = 1 P = 0.000 (adjusted for ties) Grand median = 0.77000

Similarly, a significant difference was shown for each hue region, except for the purple region:

D65 S = 3.56 DF = 1 P = **0.059**

A-10 S = 0.47 DF = 1 P = **0.491**

CWF S = 1.80 DF = 1 P = **0.180**

The range of difference that would lie between the minimum and maximum values has been shown by Wilcoxon One Sample Test. For the whole hue range the following was calculated:

	N	Median	Estimated Confidence	Achieved Confidence Interval
DAY	155	0.1250	95.0	(0.1000, 0.1500)
A-10	155	0.1250	95.0	(0.1050, 0.1450)
CWF	155	0.1300	95.0	(0.1100, 0.1500)

Hence, when the entire hue range is considered similar variation between the two equations is observed. However, variation exists between the specific hue names, as shown in Table 9.

Table 9. The predicted range of difference by Wilcoxon Test based for each hue name.

	D65		A		F2	
	Achieved Confidence	Confidence Interval	Achieved Confidence	Confidence Interval	Achieved Confidence	Confidence Interval
Blue	95.1	0.05, 0.13	95.1	0.05, 0.12	94.9	0.08, 0.17
Green	95.0	0.06, 0.12	94.8	0.07, 0.13	95.1	0.06, 0.11
Yellow	94.9	0.15, 0.31	95.1	0.14, 0.23	95.0	0.17, 0.41
Orange	94.8	0.2, 0.41	95.1	0.14, 0.25	94.8	0.11, 0.21
Red	95.0	0.08, 0.16	94.9	0.06, 0.25	94.9	0.09, 0.25
Purple	95.0	0.005, 0.09	95.0	0.005, .09	95.0	0.00, 0.12

As stated above, differences in the two formulae for samples in blue hue range (Tables 10 and 11) are statistically insignificant.

Table 10. Colorimetric data for blue samples with hue angle in the range 265-285°.

Hue Angle	DE_{cmc}	DE_{00}	DE*	L*	C*	H*	a*	b*	DL*	Da*	Db*
270^0 to 280^0	0.98	0.88	2.02	78.7	13.4	272.1	0.5	-13.4	1.8	0.2	-0.8
	0.54	0.58	0.5	58.2	16.9	274.5	1.34	-16.9	-0.1	0.47	-0.8
	0.15	0.16	0.34	57.4	17.3	274.5	1.37	-17.3	0.34	-0.03	0.05
	0.39	0.42	0.51	73.6	19.2	278.6	2.89	2.89	-0.19	-0.21	-0.4
	1	1.01	1.93	58.7	17.2	278.9	2.68	2.68	-1.7	0.57	-0.4
265^0 to 270^0	0.99	0.93	1.5	64.84	17.2	265.3	-1.4	-17.1	1.2	-0.6	0.7
+	0.9	0.91	2.16	63.14	18.8	266.4	-1.1	-18.8	-2.1	0.15	-0.3
280^0 to 285^0	0.76	0.48	1.51	40.4	43.1	281.3	8.45	-42.2	-0.96	0.7	-0.94
	0.9	0.74	1.61	71.9	21.4	282.31	4.58	-20.9	1.14	-0.74	0.87

Table 11. Arithmetic and statistical calculations for the critical Blue area

Hue angle	Mean	Friedman's Test	Wilcoxon Test
270^0 to 80^0	0	P = 0.180	(-0.030, 0.235)
265^0 to 285^0	0.05	P = 0.739	(-0.025, 0.180)

Differences in the calculated values for the two formulae were observed as a function of C* and L*, although no consistent pattern was evident. It is likely that the hue differences exhibit the most significant difference between the two formulae, with chroma and then lightness being secondary.

From the 155 nonmetameric sample pairs studied it is evident that a statistically designed experiment is required to test the performance of the current ISO and AATCC recommended formula, DE_{CMC} with the new CIE formula, CIEDE2000, as a function of illuminant.

IV. SUMMARY AND CONCLUSIONS

1. Lighting variability in retail stores

Textile products are commonly sold in two types of retail store; one in which the retail company developing products owns and sells its own products, and the other type is departments stores which sell the products of many merchandizers. In the former situation, the retailer has control over the store design, including lighting. For a branded retail company, the latter situation presents problems, as the retailer does not necessarily have control over the lighting used in the department store.

In view of the above situation, it is important for retail companies to assess the level of lighting variability within and between stores in which products are sold. Assessment of the variability can then be used to improve color inconstancy of the products between the different lighting environments that are most likely to be used to display the products. Assessment of the lighting variability also enables action to be taken to improve the uniformity in lighting from within and between stores.

The data reported here is for one retail company that has both stores within its control and department stores that display its goods. For the six stores assessed, the following conclusions can be drawn:

1. There is a wide variety of lamps being used in the retail stores, which are significantly different from common standard illuminants against which the pairs are matched.

2. The lighting in the departmental stores is generally more consistent than in the stores under the control of the retail company.

3. The illumination levels within the store were found to be generally lower than those recommended by IES, and in one case illuminance was below the minimum level required for spectroradiometric measurement. Furthermore, in some cases, the illumination ratio exceeded the recommended ratio range of 3:1-5:1.

4. External (day) uncontrolled daylight leads to significant variability in color difference of metamers.

5. For optimum color control for textile merchandize it is clear that assessment and optmization of the level of color inconstancy for key lighting areas in which the product will be displayed/used is required.

2. Performance of DE_{CMC} and DE_{00} against a new visual dataset

For a limited set of data (5 color centers and 17 sample pairs), the proposed new CIE color difference formula, CIEDE2000, cannot be considered an improvement over the current AATCC recommended formula, $\Delta E_{CMC(2:1)}$. A statistical assessment method showed the % descrimination between calculated and experimental pass/fail assessment for both formulae was 87%. This result is surprising as the color centers selected were in the regions of color space in which improvements in performance for CIEDE2000 were reported. Importantly, however, it cannot be concluded that the new formula is not an improvement of the currently recommended formula for all parts of color space. Hence, a more detailed independent assessment of the new formula is warranted. This may be achieved by conducting a highly controlled visual color difference study that is replicated in different areas of the world. Once the error in visual assessment is quantified through replication, the optimum performance possible for a color difference formula should be obtainable.

3. Analysis of variation in CIEDE2000 and DEcmc as a function of illuminant

From the 155 nonmetameric sample pairs studied it is evident that the differences in the performance of the current ISO and AATCC recommended formula, DE_{CMC}, and the new CIE formula, CIEDE2000, vary as a function of illuminant. Moreover, it was expected that the largest differences would be observed in the areas of color space that CIEDE2000 was optimized, such as the blue region. The sample set used did not validate this expectation. Clearly a statistically designed experiment is required to test the performance of the formulae as a function of illuminant.

For this experiment, visual observers will be required to assess (e.g. pass/fail) a large set of color differences samples in which color centers vary throughout CIELAB color space for all the common illuminants. The descrimination datasets would then be used to assess the predictive performance of the formulae for each illuminant/light source. From this data, chromatic adaptation transforms (CAT) can be optimized. It is possible that different CATs may be required for different textured substrates.

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VI. APPENDIX

1. Statistical analysis between retail stores studied.

Table VI.1 Standard deviation, mean and confidence intervals for DEcmc $_{(2:1)}$

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Light Booth	8	0.86	0.18	0.70	1.01
Store A	25	5.68	0.31	5.55	5.81
Store B	17	2.20	1.91	1.22	3.19
Store C	15	5.65	0.10	5.59	5.71
Store D	25	5.68	0.31	5.55	5.81
Store E	35	6.66	0.99	6.32	7.00
Store F	10	1.30	0.97	0.61	2.00
Store G	10	6.26	0.30	6.03	6.48

Table VI.2 Wilcoxon / Kruskal-Wallis Tests (Rank Sums) for DEcmc $_{(2:1)}$

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
Light Booth	8	112	14.000	-4.084
Store A	25	1797.5	71.900	-0.141
Store B	17	351	20.647	-5.468
Store C	15	1014.5	67.633	-0.519
Store D	25	1797.5	71.900	-0.141
Store E	35	4197	119.914	7.586
Store F	10	201.5	20.150	-4.121
Store G	10	1114	111.400	2.993

Table VI.3 One way Test, ChiSquare Approximation for DEcmc $_{(2:1)}$

ChiSquare	DF	Prob>ChiSq
110.3728	7	<.0001

Table VI.4 Standard deviation, mean and confidence intervals for Color Inconstancy.

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Light Booth	9	0.60	0.45	0.2492	0.95
Store A	25	3.93	0.41	3.76	4.10
Store B	17	1.45	1.0	0.90	1.99
Store C	15	3.93	0.09	3.88	3.99
Store D	25	3.85	0.58	3.61	4.09
Store E	35	3.63	0.76	3.37	3.89
Store F	10	1.89	0.60	1.46	2.3

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Store G	10	3.64	0.16	3.52	3.75

Table VI.5 Wilcoxon / Kruskal-Wallis Tests (Rank Sums) for color inconstancy.

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
Light Booth	9	88	9.7	-4.663
Store A	25	2480	99.2	3.335
Store B	17	384	22.5	-5.278
Store C	15	1481.5	98.7	2.440
Store D	25	2456.5	98.2	3.213
Store E	35	2840	81.1	1.224
Store F	10	276.5	27.6	-3.549
Store G	10	724.5	72.4	-0.077

Table VI.6 One way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
81.1463	7	<.0001

Color Rendering Index

One way analysis shows us that the variation in the plot is not the same as for other parameters which is pretty consistent. We have the highest deviation in the parameter within the same store.

Table VI.7 Standard deviation, mean and confidence intervals for Color Rendering Indices.

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Light Booth	9	93.7	2.99	91.4	96.0
Store A	25	88.8	7.41	85.7	91.8
Store B	17	77.2	5.14	74.5	79.8
Store C	15	85.3	2.99	83.6	86.9
Store D	25	89.2	9.28	85.4	93.1
Store E	35	90.9	9.24	87.7	94.1
Store F	10	67.5	7.54	62.1	72.8

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Store G	10	97.3	2.05	95.8	98.7

Table VI.8 Wilcoxon / Kruskal-Wallis Tests (Rank Sums) for Color Rendering Indices.

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
Light Booth	9	885	98.333	1.817
Store A	25	1977	79.0	0.723
Store B	17	442	26.0	-4.929
Store C	15	842	56.1	-1.678
Store D	25	2026.5	81.0	0.980
Store E	35	3198.5	91.3	2.870
Store F	10	120.5	12.050	-4.762
Store G	10	1239.5	123.9	3.909

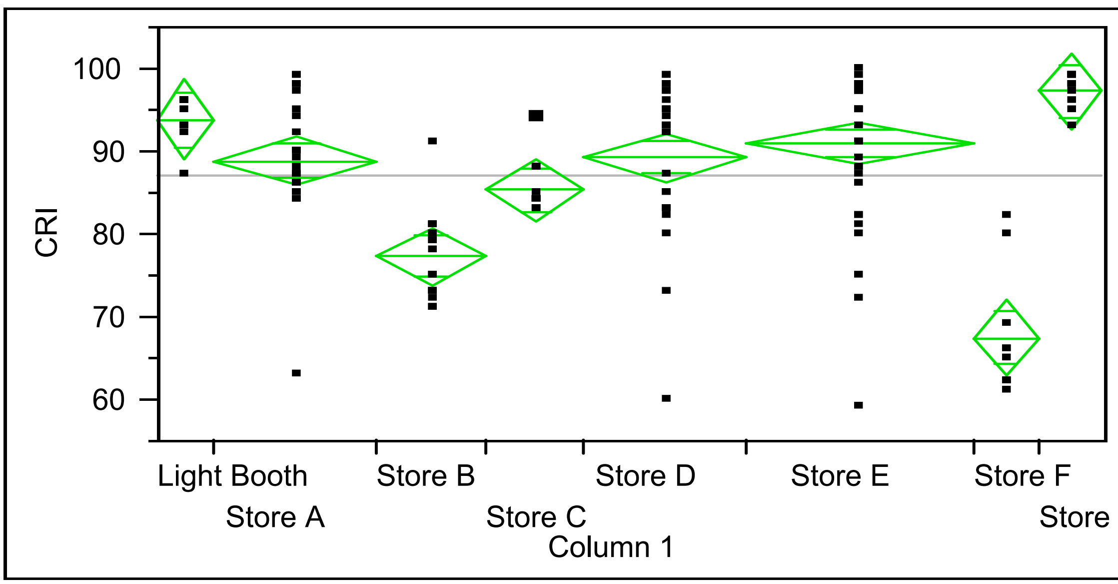

Figure VI.9 One-Way Analysis of Color Rendering Index.

Correlated Color Temperature

Only the light booths have a color temperature of around 6500K, mostly the stores are using lamps with color temperature of 3800 K.

Table VI.10 Standard deviation, mean and confidence intervals for CCT.

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Light Booth	9	6452.22	412.94	6134.8	6769.6
Store A	25	2887.40	55.37	2864.5	2910.3
Store B	17	3668.06	310.06	3508.6	3827.5
Store C	15	3032.13	54.32	3002.0	3062.2
Store D	25	3803.12	765.05	3487.3	4118.9
Store E	35	2722.40	342.83	2604.6	2840.2
Store F	10	3744.30	1208.47	2879.8	4608.8
Store G	10	2853.90	95.83	2785.3	2922.5

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
Light Booth	9	1276	141.778	4.996
Store A	25	1248.5	49.940	-3.057
Store B	17	1789	105.235	3.289
Store C	15	1165	77.667	0.400
Store D	25	2626	105.040	4.094
Store E	35	1070.5	30.586	-6.883
Store F	10	1109	110.900	2.894
Store G	10	447	44.700	-2.227

Table VI.11 One way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
103.3424	7	<.0001

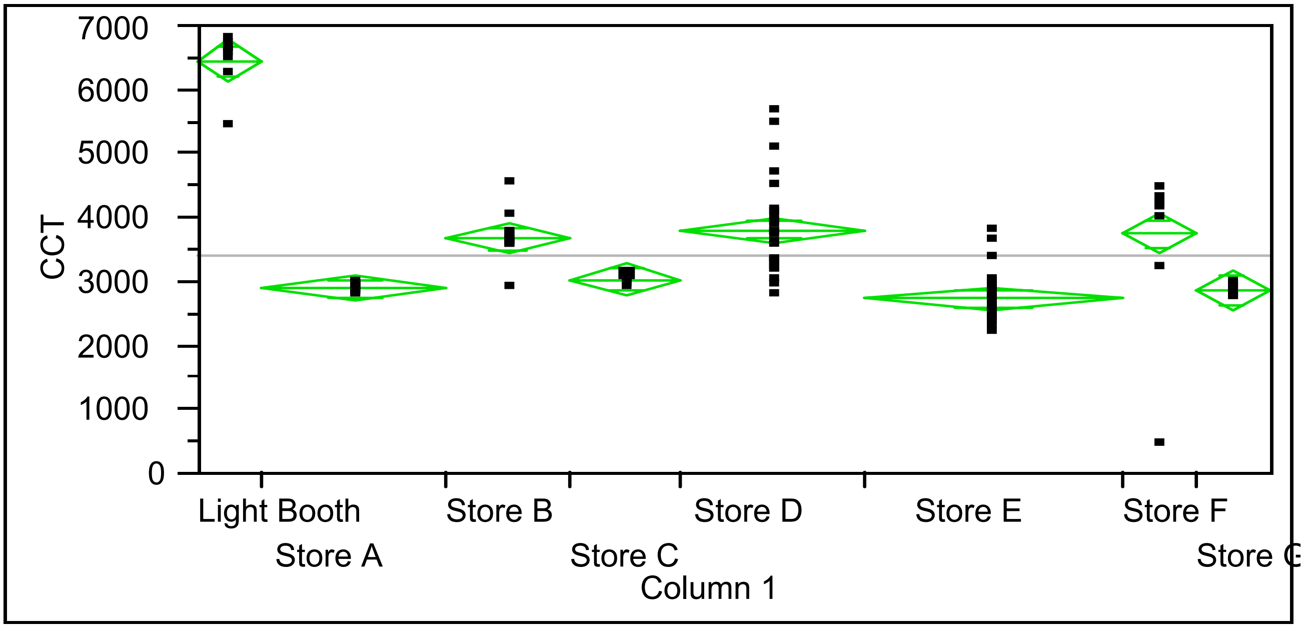

Figure VI.12 One-way Analysis of Color Correlated Temperature.

Table VI. 13 Standard deviation, mean and confidence intervals for Metamerism Indices.

Level	Number	Mean	Std Dev	Lower 95%	Upper 95%
Light Booth	9	0.73	0.41	0.41	1.04
Store A	25	6.94	0.42	6.76	7.11
Store B	17	2.79	2.11	1.70	3.88
Store C	15	7.01	0.11	6.94	7.07
Store D	25	6.95	0.43	6.77	7.13
Store E	35	7.66	1.13	7.26	8.05
Store F	10	1.95	0.94	1.28	2.63
Store G	10	7.24	0.33	7.00	7.48

Table VI.14 Wilcoxon / Kruskal-Wallis Tests (Rank Sums) for Metamerism Indices

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
Light Booth	9	60.5	6.7	-4.887
Store A	25	1938.5	77.5	0.522
Store B	17	388.5	22.8	-5.251
Store C	15	1160.5	77.3	0.371
Store D	25	1964	78.5	0.655
Store E	35	4010	114.5	6.588
Store F	10	237	23.7	-3.855
Store G	10	972	97.2	1.833

Table VI.15 One way Test, ChiSquare Approximation for Metamerism Indices

ChiSquare	DF	Prob>ChiSq
97.5814	7	<.0001