SOLAR & THERMAL 2A COLOUR

When colour is being considered, it is photopic vision and the sensitivity of the cone cells that defines what we perceive. Colour is typically defined by three properties; hue, chroma and lightness;

Hue represents the colour, so red, green or blue, etc at any point on a colour wheel, as below;

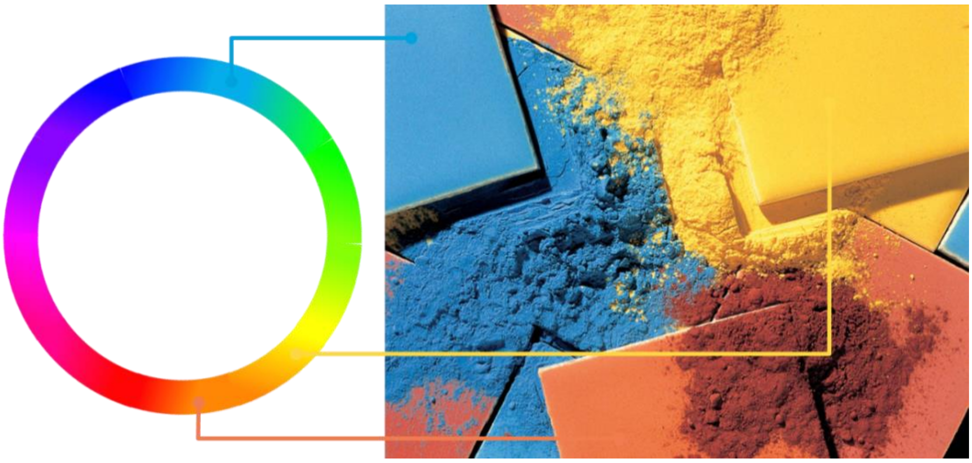


Figure 1 - Representation of hue

Chroma is the colour relative to grey or the pure hue, so how vivid it is. This parameter is also termed saturation;

Figure 2 - Representation of chroma

Lightness, or value, defines the colour from dark to light, so essentially, black to white;

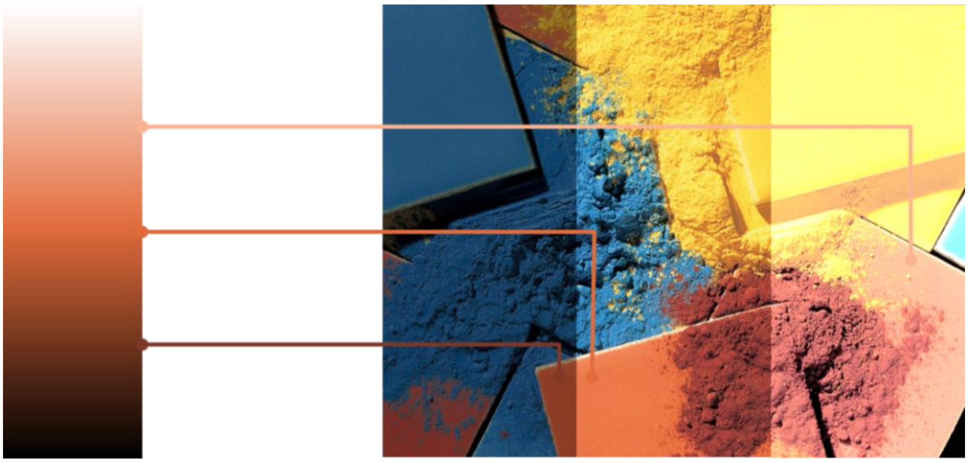


Figure 3 - Representation of lightness

THE MUNSELL COLOUR SYSTEM

The aforementioned 3 factors can best be observed in a 3-dimensional colour space. Albert H. Munsell published his first colour space in 1905 [1], based on human perception of colours, and with reference to hue, chroma and lightness.

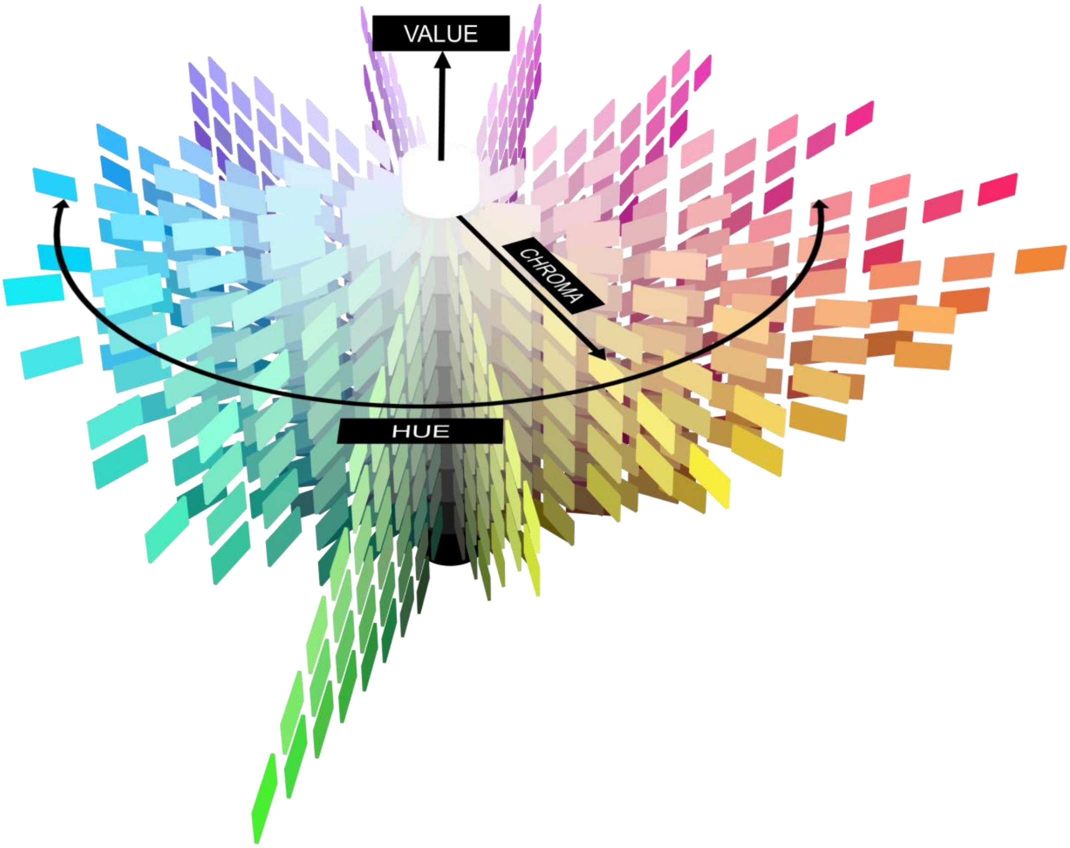


Figure 4 - Munsell Colour System

The Munsell system evolved over time, and this is considered the foundation for many of the current colour models and standards used today, including CIELAB.

COLOUR PERCEPTION

Technical Document Solar & Thermal 1-A discusses photopic vision, and the cone cells, with sensitivities as below, with data adapted from work by Sharpe and Stockman [2];

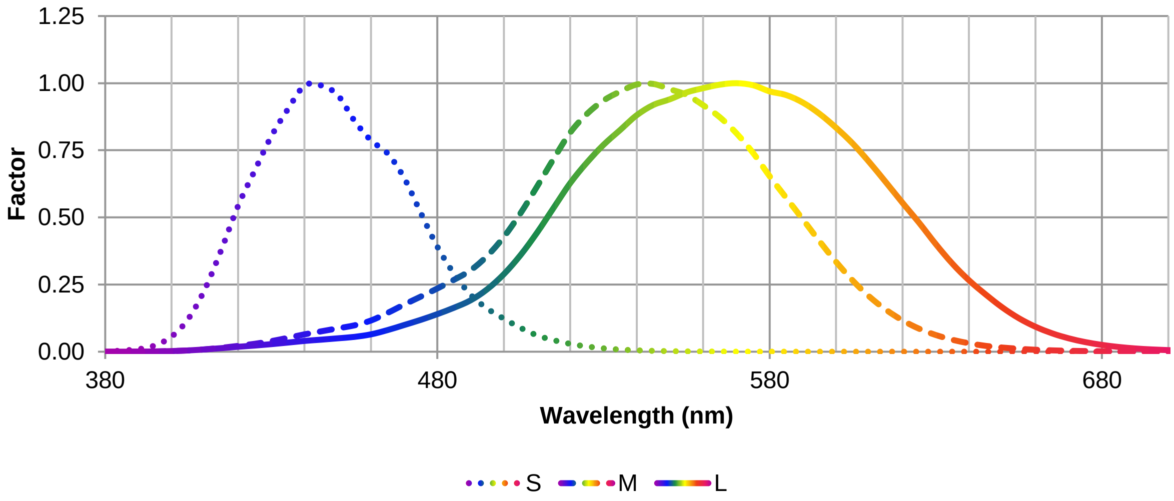


Figure 5 - Spectral sensitivity of S, M and L Cone Cells in Human Vision

Humans will perceive colour based on the relative intensities of the incident light, which will be influenced not only by the spectral properties of the object being observed, but also by the spectral distribution of the light source illuminating said object. If we consider viewing an object, with the below spectral properties, under daylight, we can consider this alongside the spectral efficiency of daylight in the visible region. This will result in a spectrum for the incident light to the observer.

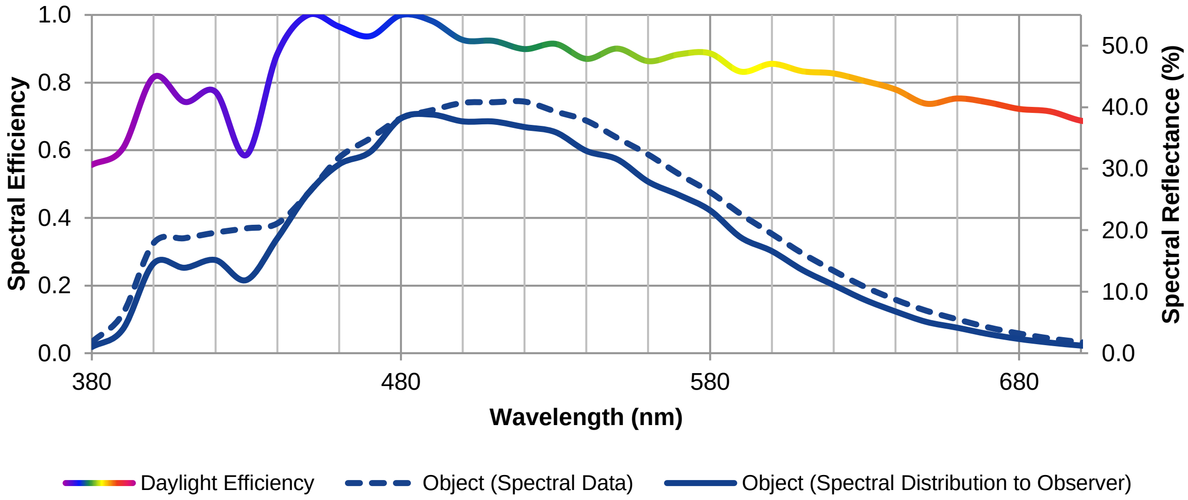


Figure 6 – Spectral Influence on an Object for Incident Dayight

Based on this, it can be observed that there is a high level of incident light in the blue (S cones) and green (M cones) wavelength regions, and relatively low in the red (L cones) region. As such, the object will appear blue-green.

INFLUENCE OF LIGHT SOURCES

As stated, the light source will also influence the colour. If we take the previous example, and illuminate using an incandescent bulb, with the below spectra, the incident light to the observer will also shift;

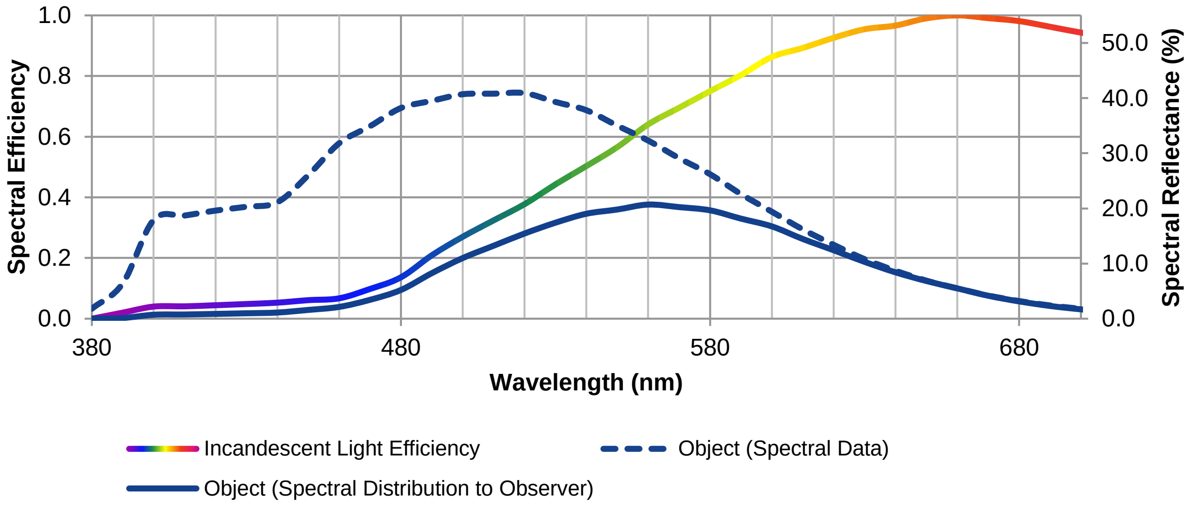


Figure 7 – Spectral Influence on an Object for Incident Artificial Light

There is now a relatively higher level of incident light in the yellow and red regions of the visible light spectrum, changing the perceived colour of the object.

MEASURING COLOUR

When measuring colour, consideration is often given to the CIE (Commission internationale de l'Eclairage) 1931 colour space, which relates spectrophotometric data to perceived colour. Spectrophotometric is obtained from UV/vis reflectance and transmittance measurements.

Measured data can be considered against the efficiency of the S, M and L cone cells, by using the CIE tristimulus values ($\bar{x}$, $\bar{y}$, $\bar{z}$), which are mathematical constructs representing associated colour components and spectral sensitivity of a standard observer.

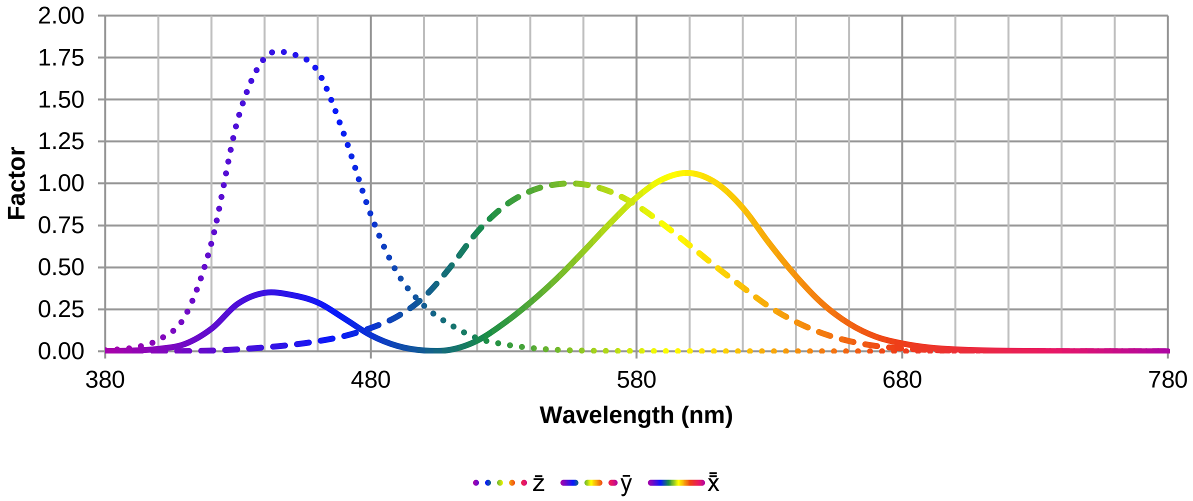


Figure 8 - Tristimulus Values

The tristimulus values, when used in conjunction with spectrophotometric data, and a spectral model for a light source, allow colour to be determined as three components, X, Y and Z.

$$X = 100 \cdot \frac{\int_{380}^{780} I_\lambda S_\lambda \bar{x}_\lambda . d\lambda}{\int_{380}^{780} I_\lambda \bar{y}_\lambda . d\lambda}$$

$$Y = 100 \cdot \frac{\int_{380}^{780} I_\lambda S_\lambda \bar{y}_\lambda . d\lambda}{\int_{380}^{780} I_\lambda \bar{y}_\lambda . d\lambda}$$

$$Z = 100 \cdot \frac{\int_{380}^{780} I_\lambda S_\lambda \bar{z}_\lambda . d\lambda}{\int_{380}^{780} I_\lambda \bar{y}_\lambda . d\lambda}$$

Where;	I_λ	Illuminant Function
	S_λ	Sample Reflectance or Transmittance
	λ	Wavelength

These values can be plotted on the CIE 1931 or CIE 1976 colour space chromaticity diagrams, when converted into *x* and *y* co-ordinates;

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

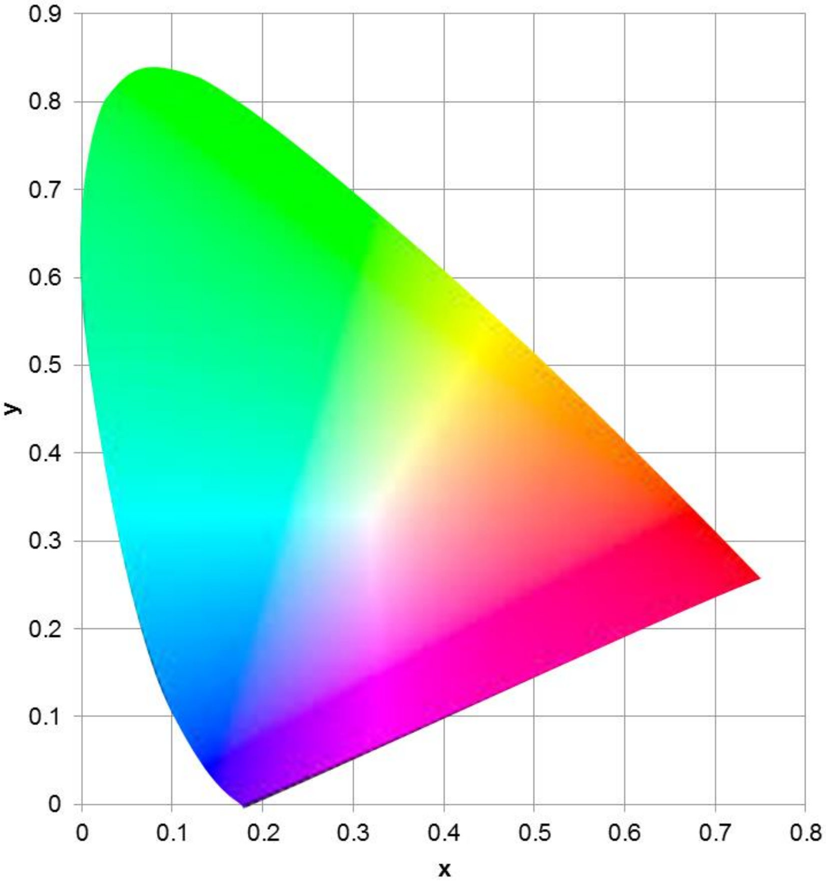


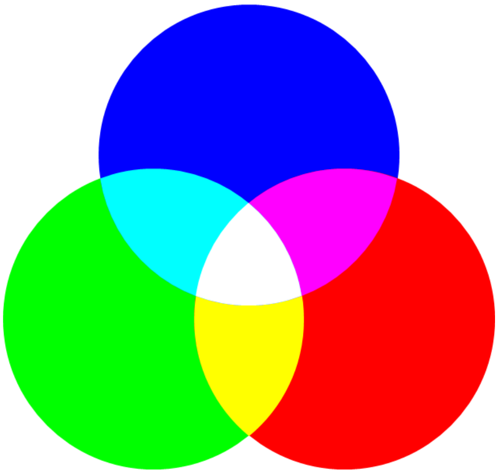
Figure 9 - Chromaticity Diagram

These components can also be used to generate values used for representation of colour, such as sRGB or L*a*b*.

COLOUR SPACES & MODELS

Various colour spaces exist when communicating colour values, with the most common summarised within this section

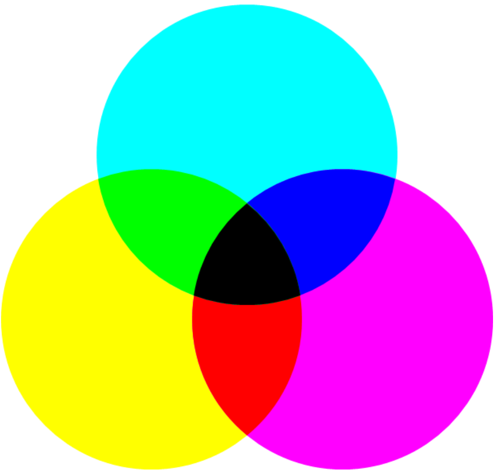
RGB



The RGB colour model uses addition of red, green and blue primary colours in order to generate colours over the visible spectrum. This relates to the response of the cone cells, where spectral sensitivity relates to the blue (S-cones), green (M-cones), and red (L-cones) wavelengths.

The RGB colour model doesn't become an absolute colour space until the individual chromacity of the R, G and B are defined. For example; s-RGB and CIE-RGB. s-RGB refers to the colour space created by Microsoft and Hewlett-Packard and was incorporated into IEC 61966-2-1:1999 [3].

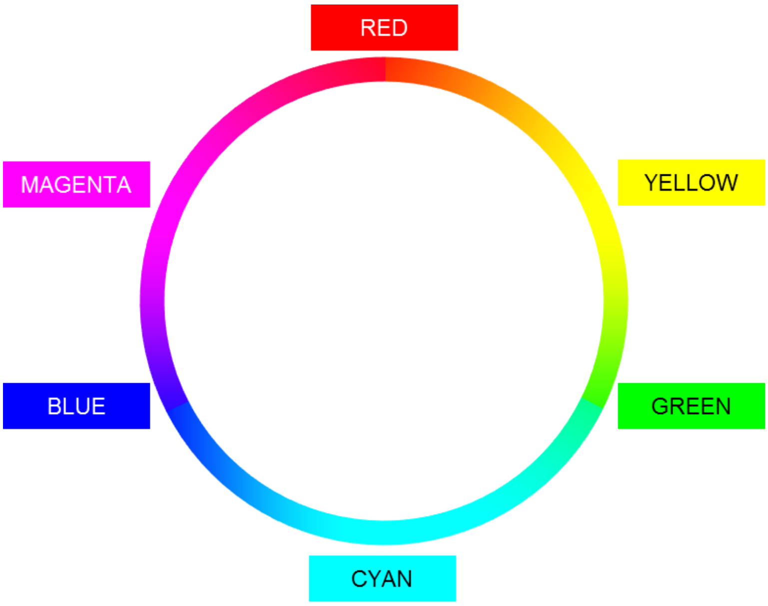
CMYK



CMYK is a subtractive colour model, using cyan, magenta, yellow and key (black). This colour model is often used for printing.

As with RGB colour spaces, the CMYK colour space doesn't become absolute until the C, M and Y values are defined.

CYLINDRICAL CO-ORDINATE REPRESENTATIONS (HSL, HSV)

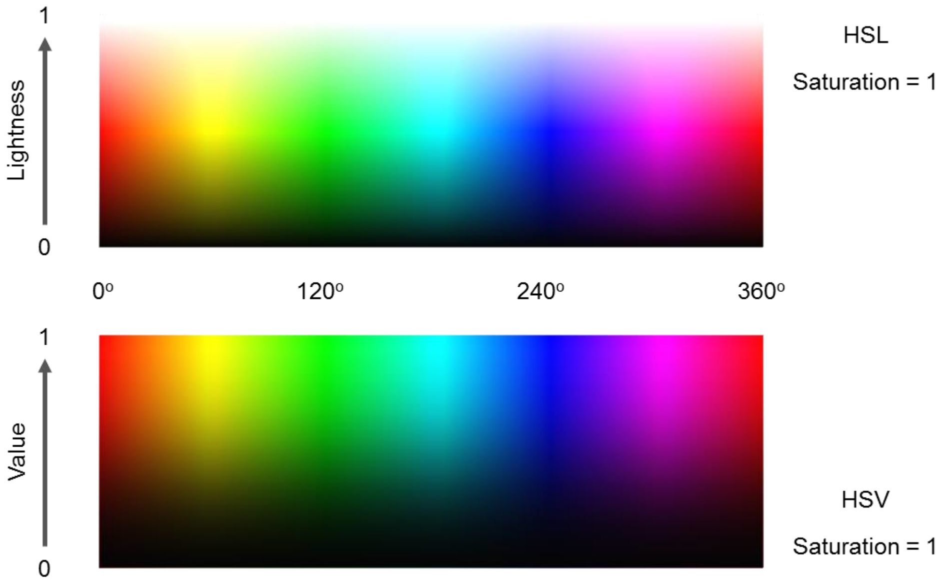


Colour wheels represent colour hues based on cylindrical coordinates. These values can then be applied to colour models, such as HSL (Hue, Saturation and Lightness) and HSV (Hue, Saturation and Value.

HSL and HSV can be directly translated into RGB, and allow better user perceived selection of colour compared with an RGB model.

Hue, refers to the angle on the colour wheel, so effectively, the pure colour. Saturation refers to the intensity of colour. The difference between these two models then comes from the lightness and value. Lightness is effectively the amount of white, whilst value is the brightness, or amount of light.

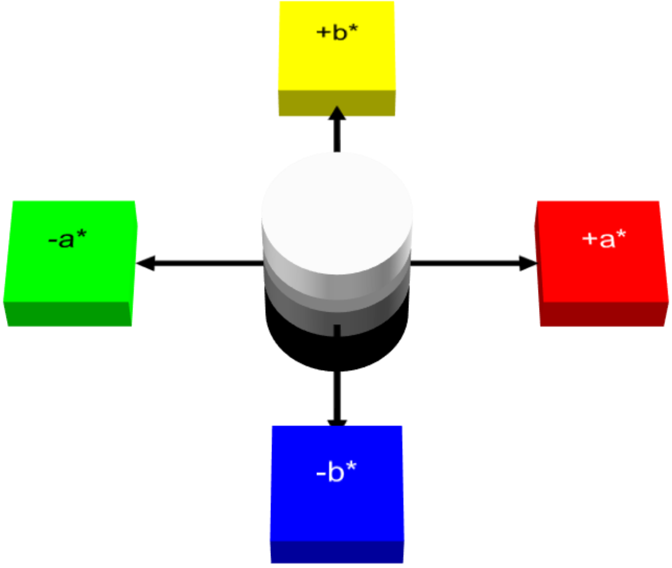
Therefore, in a HSL colour model, a white can be achieved from high lightness, whilst in a HSV colour model, white is achieved with low saturation.



CIE L*a*b*

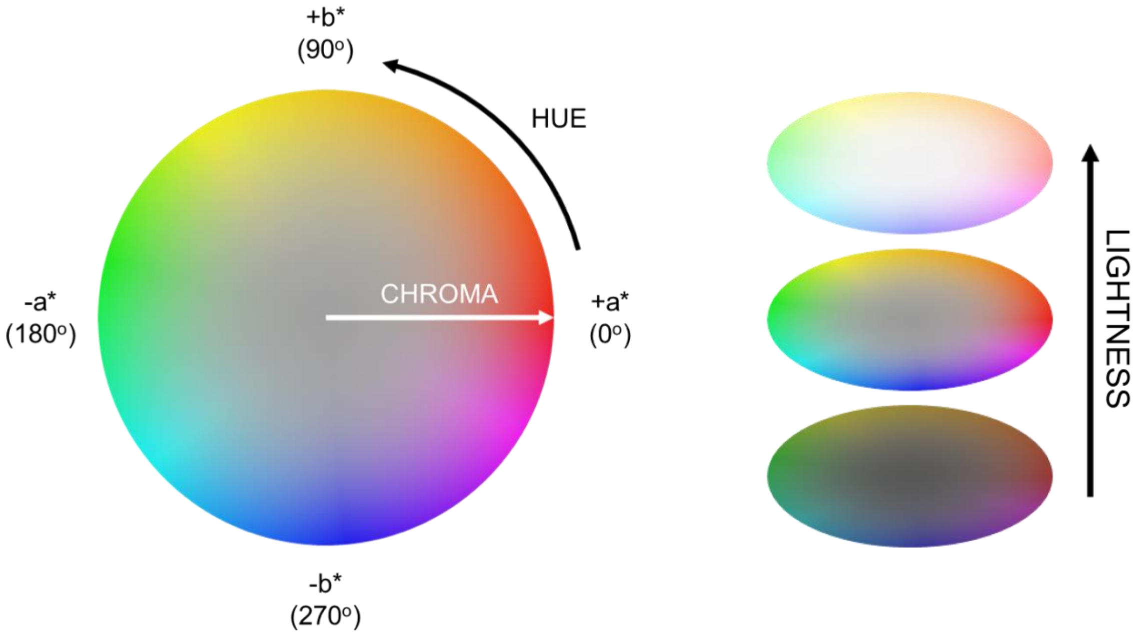
L*a*b* coordinates, defined by CIE, are commonly used in the paint and textile industries, but also when describing the colour, or tint, of glass and coated glass. L refers to lightness, with a and b, the opposite colour components of green to red (a*) and blue to yellow (b*).

Because L*a*b* coordinates are related to human perception of colour, and perceptual uniformity, they can be readily applied to the determination of colour difference, ΔE*.



CIE L*c*h*

The L*c*h* colour space is similar to the L*a*b* colour space, but uses cylindrical co-ordinates for the hue, as opposed to rectangular co-ordinates.



COLOUR DIFFERENCES

In order to assess colour and colour differences, it will typically be spectrophotometric measurements that will be taken, as this allows a less subjective analysis. For colour difference, it is the CIE L*a*b* or CIE L*c*h* values that can be most readily translated into a perceptual difference.

Colour difference is termed delta E*, or ΔE*, and has developed over several decades from the CIE 1976 formula that first calculated difference based on L*a*b* co-ordinates, to CIEDE2000, which compensates for perceptual uniformity across the colour space, and is based on the CIE 1976 L*c*h* values.

With regards glass, there are no predetermined limits in current regulations for colour uniformity, and if colour tolerances are introduced, they are often defined by the architect. A values of ΔE* ≤ 2.9, based on spectrophotometric measurement, is often used when no tolerance has been specified.

It is worth noting, that for glass, as a ΔE*, based on L*a*b* values, is typically used, this won't account as accurately for perceptual uniformity. As such, some shifts in colour, with a similar ΔE*, may in fact appear less or more dissimilar, depending on the original colour;

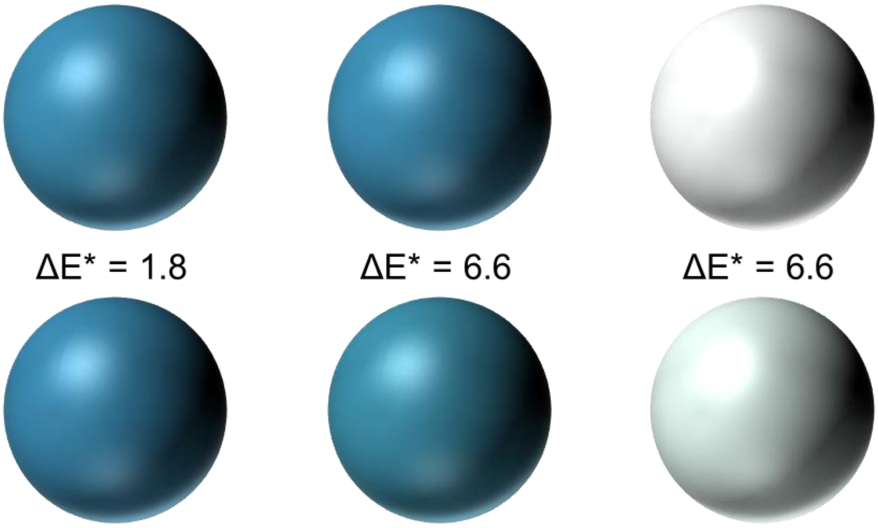


Figure 10 - Rendered Colour Differences

From the above, a ΔE* of 6.6 for the blue, may appear less noticeable than the same ΔE* for the white.

COLOUR RENDERING INDEX

The colour rendering index (CRI) is a measure of how accurate a colour is reproduced under certain lighting conditions, relative to natural light.

For glass, the colour rendering index in transmission is defined by EN 410 [4] as the "*change in colour of an object as a result of the light being transmitted by the glass*". Effectively, this will describe the colour difference between an object under natural daylight, and behind glazing, and so the light through the glazing is the lighting condition.

The calculation is based on the CIE 1964 U*V*W* system, and this allows colour differences to be determined with regards hue and saturation, and so without the influence of lightness. As such, even though a dark purely neutral glass would reduce how light an object appears, it won't specifically change the hue and saturation.

OVERALL CRI

Using 6 mm SGG PLANICLEAR float glass as an example, this has a relatively flat spectrophotometric profile across the visible light wavelength, and so will offer a high colour rendering index, calculated to be 99.2%.

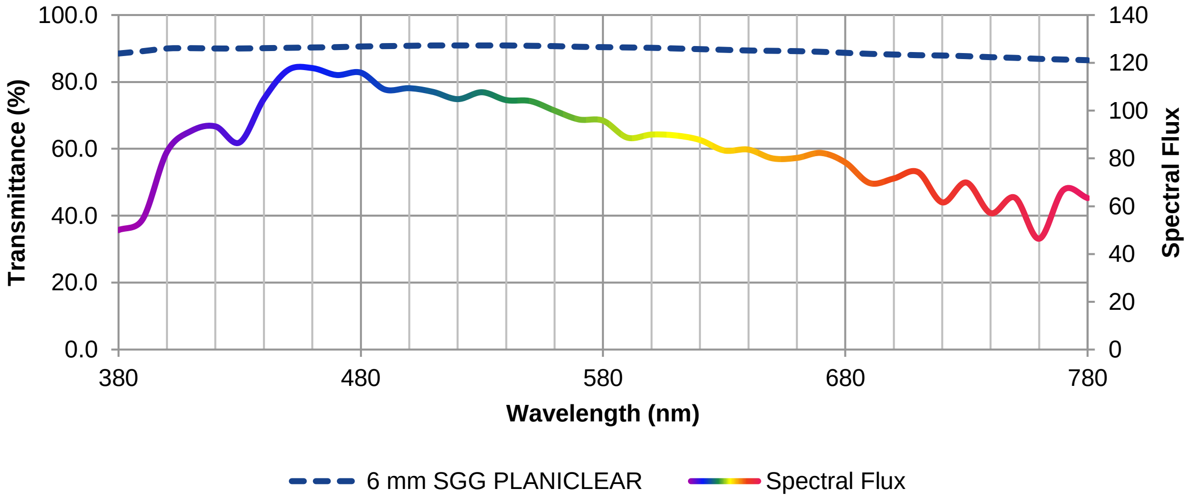


Figure 11 - SGG PLANICLEAR Spectral Transmittance

Replacing the 6 mm SGG PLANICLEAR with 6 mm SGG PARSOL GREEN, then the variance of the transmittance over the visible wavelength range will more greatly influence the perceived colours of objects. As this glass type will absorb more red wavelength light, the objects will appear less red, and so more toward greens and blues. Compared with 6 mm SGG PLANICLEAR, the 6 mm SGG PARSOL GREEN will offer a CRI of 88.4%.

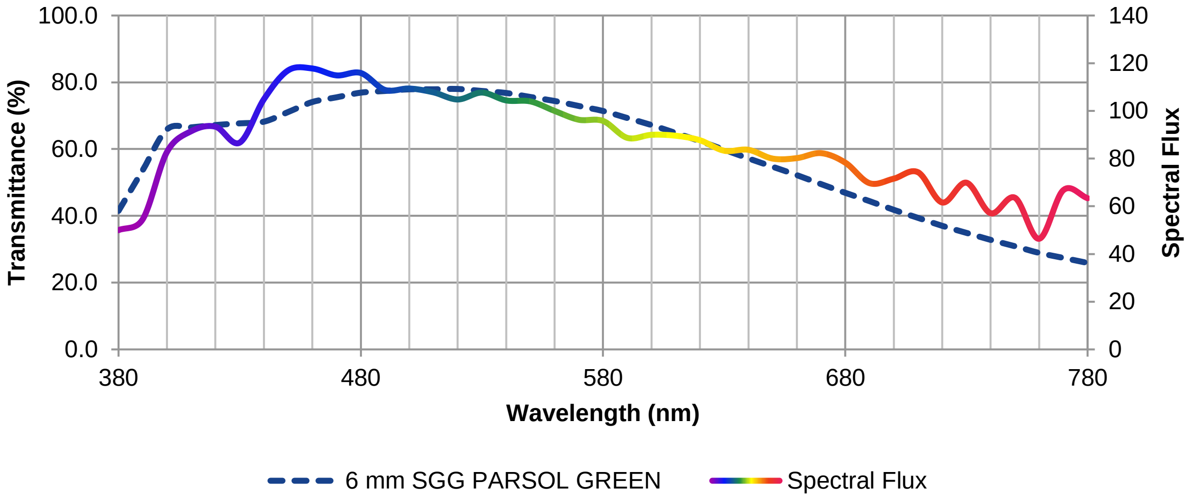


Figure 12 - SGG PARSOL GREEN Spectral Transmittance

If we take a third example, this time a laminated glass with a red interlayer, the CRI is extremely low, as the majority of the blue and green wavelength regions of light are blocked out. As a result every test colour will take on a red hue, as this becomes dominant region of the spectral distribution of the light source.

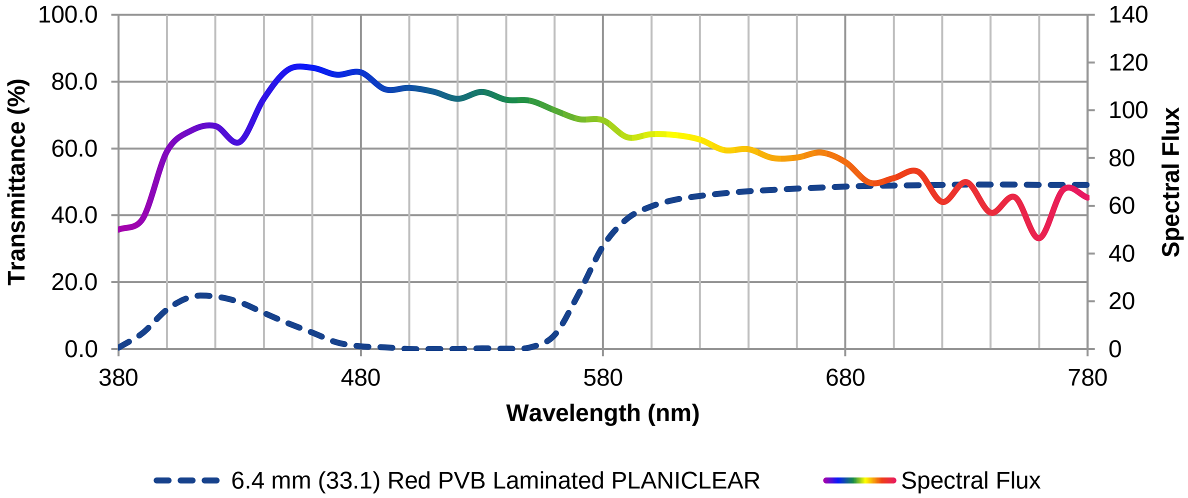


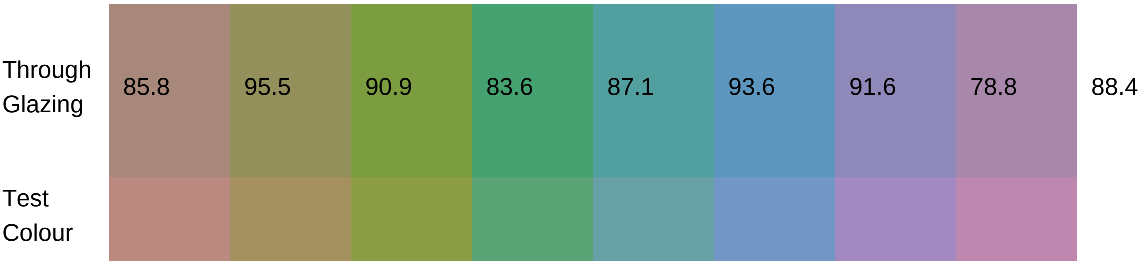
Figure 13 – Red PVB Laminate Spectral Transmittance

SPECTRAL DEPENDENCE FOR CRI

The CRI is an overall performance, and is calculated from the CRI of 8 test colours. As such, this won't take into account any influence of spectral selectivity of the glass with regards colour rendition. Taking the previous two examples, the 6 mm SGG PLANICLEAR, being relatively neutral, will offer good colour rendering for all 8 test colours assessed in calculation;

Through Glazing	99.4	99.1	99.1	98.9	99.1	99.1	99.8	99.3	99.2
Test Colour									

The 6 mm SGG PARSOL GREEN will offer higher CRI in some regions, where the spectral efficiency is least affected.



Through Glazing	85.8	95.5	90.9	83.6	87.1	93.6	91.6	78.8	88.4
Test Colour									

In order to understand this, it's best to look at the glazed vs. unglazed spectral efficiency of the test colours with regards the tristimulus values. If we calculate based on normalised light levels, and transmittance for the SGG PARSOL GREEN, the following applies for test colour 2;

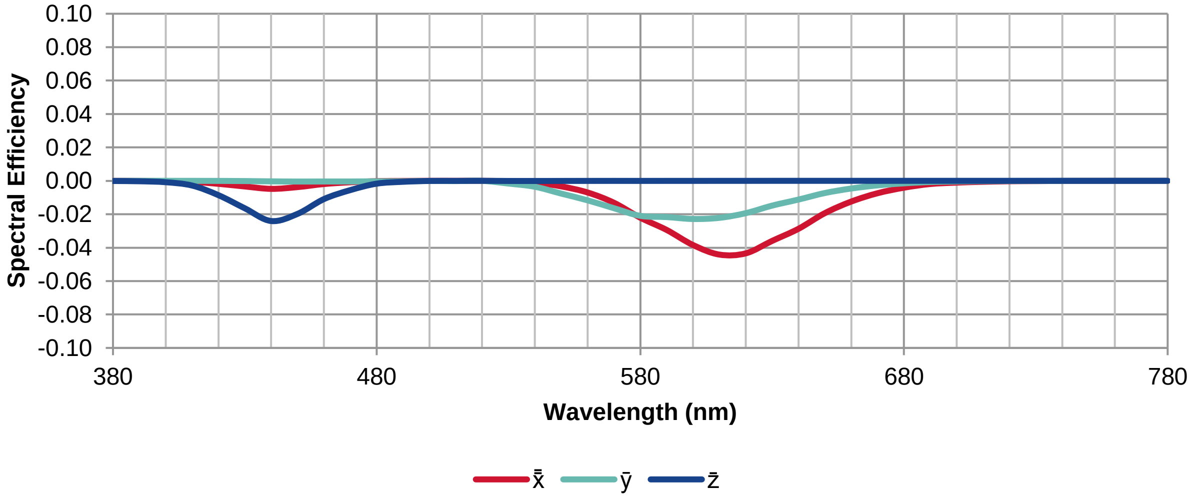


Figure 14 - Test Colour 2 Tristimulus Variance (SGG PARSOL GREEN)

The same applied to test colour 8, where the CRI is lower, shows a greater shift, as below;

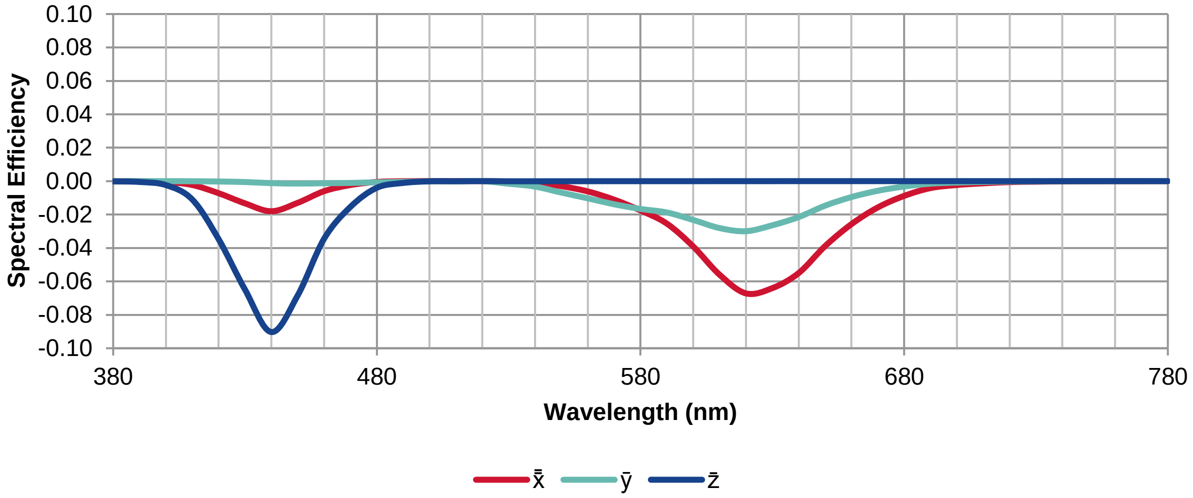
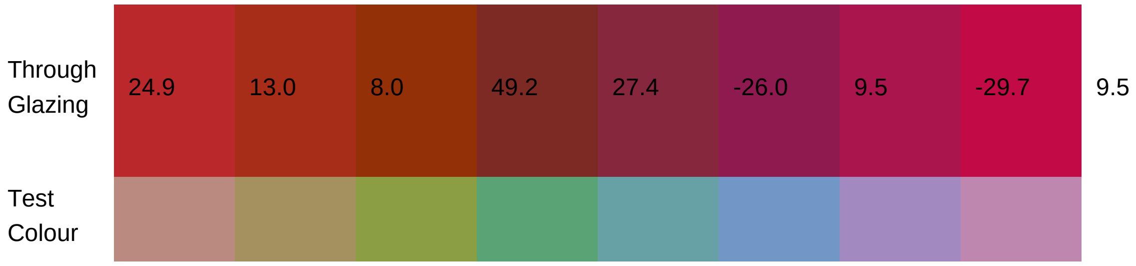


Figure 15 - Test Colour 8 Tristimulus Variance (SGG PARSOL GREEN)

The red interlayer sample, as per previous, will show a much greater spectral shift due to the significant change to the distribution of the incident light. As such, the CRI is lower across all test colours.



Through Glazing	24.9	13.0	8.0	49.2	27.4	-26.0	9.5	-29.7	9.5
Test Colour									

In comparison to the 6 mm SGG PARSOL GREEN, test colour 8 shows a much more significant spectral shift, where almost all the z̄ tristimulus response is lost;

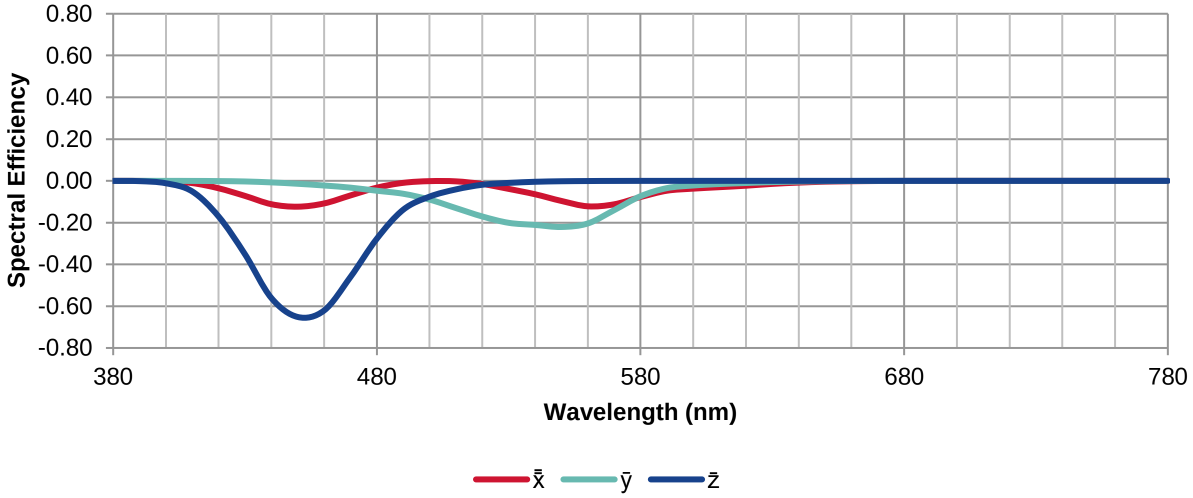


Figure 16 - Test Colour 8 Tristimulus Variance (Red PVB)

METAMERIC FAILURE

Metameric failure is a term used to describe colour differences arising from changes from samples viewed under different light sources (illuminant metameric failure), or when viewed by different observers (observer metameric failure).

Illuminant metameric failure will occur when colour are matched by under a specific light source, and then when viewed under a different light source the colours appear different. This would occur due to spectral mismatch between the two objects, in conjunction with the influence of the spectral efficiency of the light source.

For example, if you matched an SGG COOL-LITE SKN 176 II and an SGG COOL-LITE XTREME 70/33 II under an incandescent light source, such as in an office, you would achieve theoretical ΔE* of 3.2.

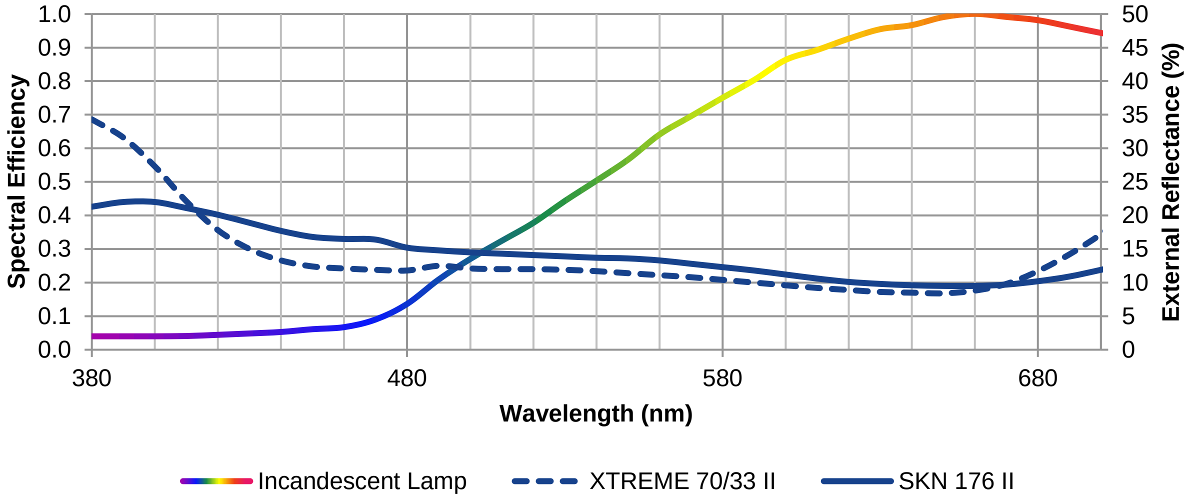


Figure 17 - Spectral Output for SKN 176 II and XTREME 70/33 II Under Incandescent Light

Moving both samples into daylight would give a spectrally more evenly distributed light source, with a greater level of blue wavelength light. This would increase the relative difference in the b* value by highlighting this region of spectral difference, and so increase the theoretical colour difference to a ΔE* of 4.7.

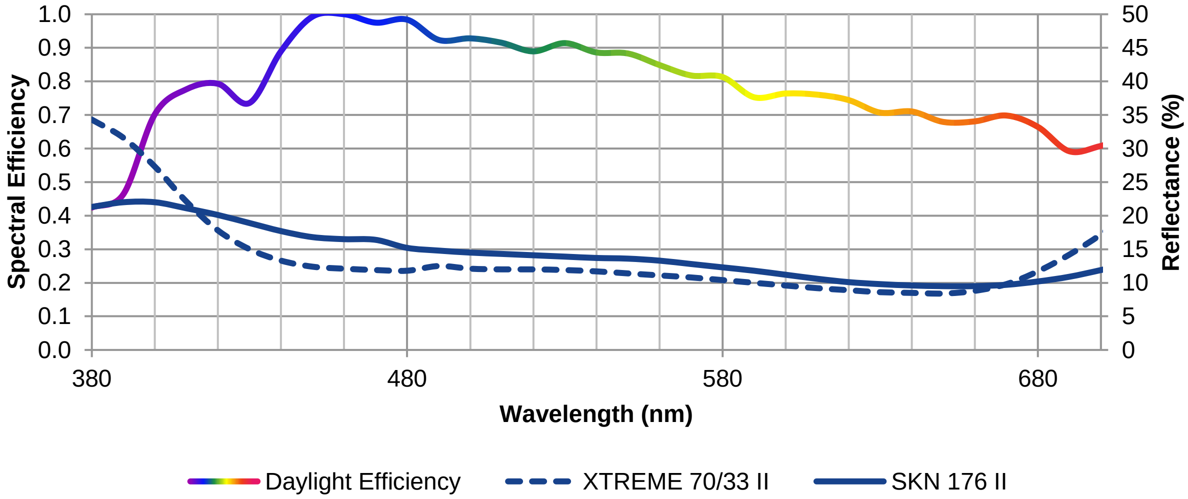


Figure 18 - Spectral Output for SKN 176 II and XTREME 70/33 II Under Daylight

Observer metameric failure would occur where one individual with a different relative proportion of S, M and L cone cells, compared to another, would therefore have a greater, or lesser, degree of sensitivity to different wavelength regions of light. This would then result in the potential for one observer to colour match two objects, whilst another observer may see a greater difference.

Fundamentally, in order to achieve a true colour match, it is the spectral properties of the object that need to be assessed.

REFERENCES

[1] A. H. Munsell, *A Color Notation,* G.H.Ellis Company, 1905.

[2] L. T. Sharpe and A. Stockman, “The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype,” *Vision Research,* vol. 40, no. 13, pp. 1711-1737, 2000.

[3] International Electrotechnical Commission, *IEC 61966-2-1:1999 - Part 2-1: Colour management - Default RGB colour space - sRGB,* IEC, 1999.

[4] European Committee for Standardization, *EN 410:2011 - Glass in building. Determination of luminous and solar characteristics of glazing,* CEN, 2011.