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TM-30: The future of measuring colour in lighting

White Paper

unios.com/tm-30

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EMAIL SALES@UNIOS.COM

PHONE +61 8 9248 1888

This white paper will enable you to:

- Identify the four fundamental considerations of colour quality
- Understand the TM-30 standard along with the advantages over its predecessor CRI
- The importance of colour reproduction and how the knowledge can be used to enhance a space

1. Snapshot

The vast array of colours we see is known as visible light, only a tiny band within the electromagnetic spectrum. Indoors, what we perceive as an object's colour is strongly correlated to the qualities of the artificial light source illuminating the object.

A term commonly used within the lighting industry is colour rendering index (CRI) which is a metric used to analyse a light sources colour reproduction qualities. However, the metric does have a few limitations as highlighted in figure 1.1.

TM-30 was first introduced in 2015 to overcome the limitations in CRI. The purpose of TM-30 is to provide a more accurate measure of a light source to provide designers the data to enhance all spaces.

Comparing CRI to TM-30

CRI	TM-30
1 Value Ra - Fidelity index calculated using the average value of 8 colour samples	**2 Values** R_f and R_g - Fidelity index and gamut index calculated using 99 colour samples
Core Colour Samples (8) Secondary Colour Samples (7)	Core Colour Samples (99)
Metrics (17) • R1-R15 • Ra (avg of R1-R8) • Re (avg of R1-R15)	**Metrics (50)** • R_f – Fidelity index • R_g – Gamut area index • 48 hue-specific measurements • +1 colour vector graphic
✓ Well established industry standard	✓ Two index values more fairly indicate colour performance
✗ Limited to 8 pastel tones penalising saturated colours	✗ Not fully adopted by the industry as it is relatively new

Figure 1.1: A comparison of metrics and features between CRI and TM-30 colour measurement

2. Introduction

In a world that has been taken away by a new energy efficient light source over the last decade – light emitting diodes (LEDs), a primary focus and demand within the industry has revolved around efficacy.

THAT IS, HOW EFFICIENT CAN WE MAKE a lamp source to maximise brightness per watt consumed. And rightly so, studies show that when considering electricity consumption in commercial buildings alone, lighting accounted for 17% of electricity consumption in 2012, substantially down from 38% in 2003[1]. This was predominantly due to a large shift away from incandescent lamps to fluorescent lamps, as well as the increase usage of building automation technology but the driver behind LEDs is to continue this "trend in energy consumption reduction" and minimising maintenance.

As the efficacy growth rate of LEDs begin to decline, there has been a shift in focus towards the quality of light, namely colour. The IES define colour as "the characteristic of light by which a human observer can distinguish between two structure-free patches of light of the same size, shape and brightness[2].

Another important term is colour rendition or colour rendering, which is a general term used for the ability of a light source to provide accurate colour information to a human observer when objects are illuminated by that source[3]. In layman's terms, colour rendition is the ability of a light source to reproduce an object's colours as if it was outside in natural daylight.

In a world filled with artificial light, not only is the purpose to provide visibility for humans when there is insufficient natural daylight for practical use, but there should be an ongoing awareness of the quality of artificial light to reproduce colours for quality of living, especially in human-occupied spaces. This paper is to provide insight on the importance of colour and its key metrics that are used to measure the quality of a light source's colour, with a primary focus on colour rendition characteristics.

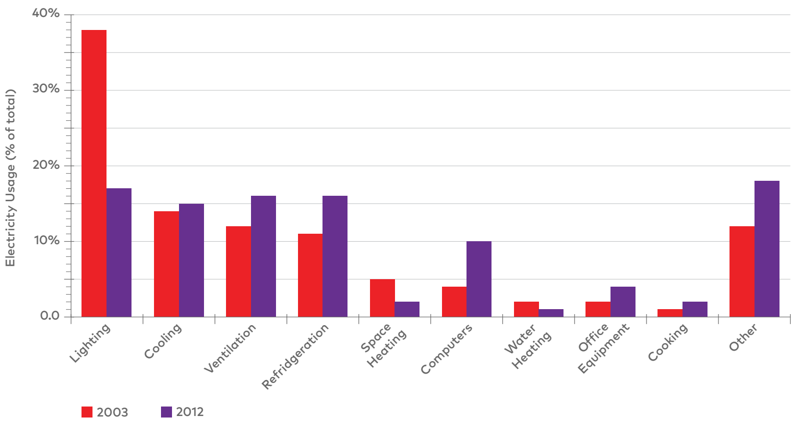


Figure 2.1: Electricity consumption in the commercial sector 2003 vs 2012[1]

3. The Importance Of Colour

The visible light spectrum is a small segment of the electromagnetic radiation spectrum that can be seen by the human eye[4]. The visible light spectrum is between the wavelengths of ~380nm (violet) to ~740nm (deep red) and commonly referred to as the rainbow.

Artificial lighting is versatile in its purpose from:

- Illuminating spaces with insufficient natural daylight for humans to carry out tasks
- Create moods for the observer by showcasing a particular set of colours
- Correctly illuminating art in dark spaces as per the artists' intention e.g. museums
- Art pieces themselves via the application of decorative lighting
- Safety and safe movement

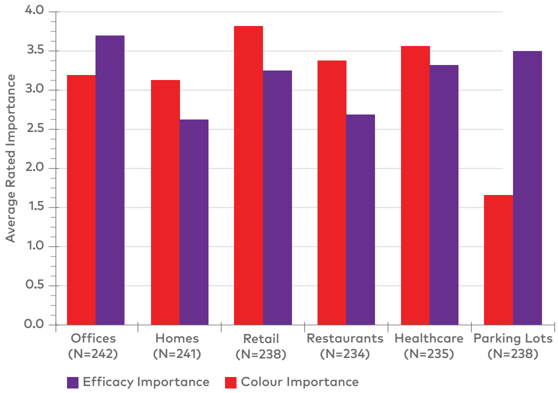


Figure 3.1: The importance of colour and efficacy per industry[5]

In 2004, a survey conducted with lighting professionals requested them to rank the importance of lamp colour and the importance of lamp efficacy within certain environments, with 4 being the most important and 0 being the least. The survey concluded that colour is a critical consideration in most lighting applications and is thought of as a more important characteristic than lighting efficacy[5]. Figure 3.1 shows that out of six categories, four of them ranked higher in colour importance rather than efficacy importance.

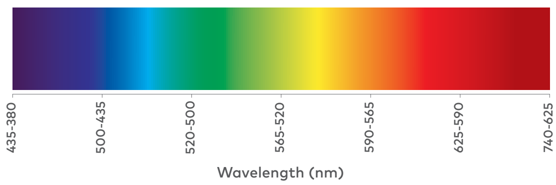


Figure 3.2: The visible light spectrum

Colour Perception and Interpretations

Colour is a key characteristic in how it can transform a space, as well as how it plays on a human psychological level. When a space is lit correctly, there can be a number of benefits including increased productivity, attractiveness of a space, realistic representations of objects and creating particular emotional experiences.

For example, cooler or "bluer" light is generally used for areas that require productivity as the blue wave light spectrum tends to suppress the creation of melatonin, making occupants feel more awake and alert[6].

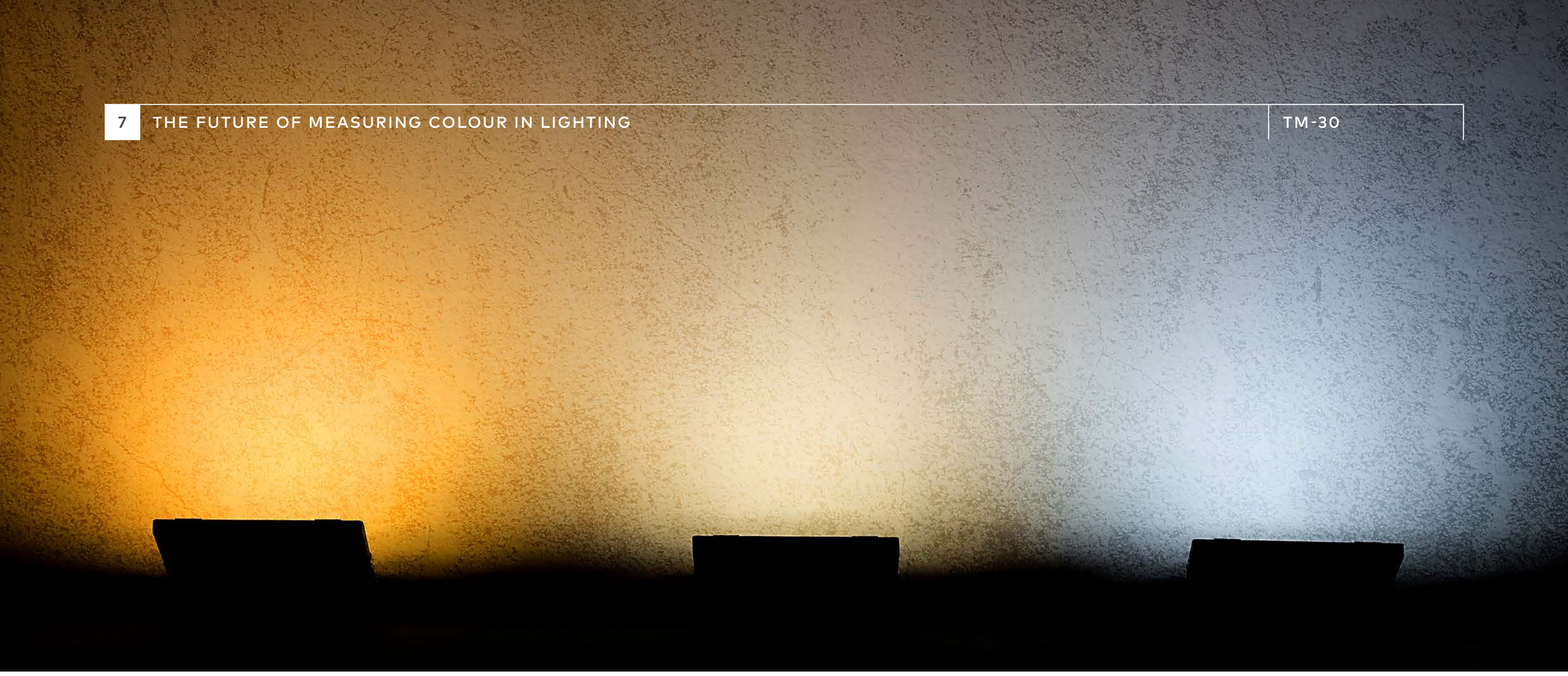
Whereas warm coloured tones, such as yellow and orange tend to create a more relaxing and inviting atmosphere thus are generally used in intimate or hospitality spaces.

With the exception of tetrachromats, people who are more sensitive to colour, most humans would perceive colour similarly. Although there is no correct meaning of colours, there is a general consensus that particular colours invoke similar perceptions and interpretations, as shown in figure 3.3. This allows artists and designers to create exhibits and architecture using these common colour interpretations.

Common colour interpretations

WHITE Purity / Innocence / Soothing	BLACK Fear / Power / Unhappiness	BROWN Secure / Full / Disagreeable
RED Anger / Intensity / Passion	ORANGE Exciting / Unique / Warm	YELLOW Cheerful / Stimulating / Serene
GREEN Fresh / Natural / Wealth	BLUE Cool / Sad / Social	PURPLE Melancholy / Prideful / Regal

Figure 3.3: Common colour interpretations[5]



4. Main Metric Considerations

There are many different factors when considering colour, starting from the source of where light comes from, to what we see as objects in the real world.

↑ *Figure 4.2: Respective Correlated Colour Temperature of light sources[7]*

WITHIN THE SURVEY OF LIGHTING professionals introduced in section 3, a second question was asked to determine what influences a lighting professional's decision when colour is of importance, scoring the characteristics from 0 (not useful at all) to 4 (very useful). The results are shown in figure 4.1.

Characteristics	Average Usefulness Rating	Standard Deviation	Number of Responses
Color Rendering Index (CRI)	3.5	0.7	237
Correlated Color Temperature (CCT)	3.2	1.0	233
Color Stability	3.2	1.0	232
Lamp Type	3.1	1.0	235
Color Consistency	3.1	1.0	228
Spectral Power Distribution (SPD)	2.4	1.2	226
Full-Spectrum Index (FSI)	2.0	1.3	204
Brand Name	1.9	1.2	226
Gamut Area	1.5	1.2	189

Figure 4.1: Most useful light source colour characteristic

Excluding lamp type, the top four ranked metrics were:

1. Colour Rendering Index (CRI)
2. Correlated Colour Temperature (CCT)
3. Colour Stability
4. Colour Consistency

Correlated Colour Temperature (CCT)

For white light, correlated colour temperature (commonly abbreviated as CCT) is a term used to measure a lamp source's perceived colour using the units Kelvin (K). The basis of the terminology stems from the absolute temperature of a planckian radiator, also known as blackbody. That is, as a Planckian radiator increases in temperature, the colour of the radiator changes. The market tends to use a mixture of terminology to describe the colours seen in Figure 4.2, which are summarised below:

- Orange/yellow colours tend to be lower temperatures which the market commonly refers to as "warmer" colour temperatures.

  1800K-2200K – amber

  2700K-3000K – warm white

- As the temperature increases, we start to observe the shift towards a whiter colour which the market commonly refers to as "natural or neutral" white.

  4000K-5000K – natural/neutral white

- As temperatures increase from 5000K, the term "cool daylight" is generally used to describe the colour that begins to introduce hints of blue.

  6500K – 8000K – cool daylight

As discussed in section 3, different colour temperatures have advantages over one another thus selecting the appropriate colour temperature can impact the space, and occupants within. Correlated colour temperature generally refers to a white light source only, thus does not cover all colours that fall within the colour space. The blackbody locus (or Planckian locus) is plotted on a colour space created in 1976 by the International Commission on Illumination (CIE) in figure 4.3.

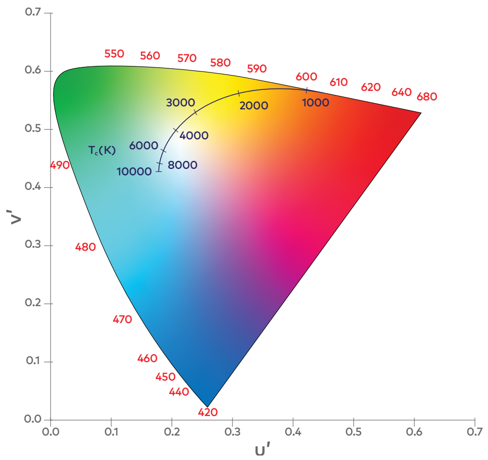


Figure 4.3: CIE 1976 colour space with Blackbody Locus[8]

Colour Stability

For most light sources, the colour output will tend to change over its lifetime even when they are all manufactured to the same CCT. Colour stability is the ability to maintain its original colour over time[3]. This term is also commonly known as colour shift or chromaticity coordinate shift.

The importance of colour stability is not noticed on initial installation, but rather over time. Too often we measure the lumen maintenance (brightness depreciation over time), but in certain applications, colour stability can be just as important. For example, where colours are paramount to be maintained are in museums, hospitals, retail stores, and in most hospitality spaces. Figure 4.4 shows an example of poor colour stability over time.

LEDs tend to shift in either four directions, a blue shift, a green shift, a yellow shift or a red shift as shown in Figure 4.5. The initial colour shift of an LED may not always be the same as its long-term colour shift[9].

There are numerous factors for the causes of colour shift but a commonality amongst components is the quality of materials used. Some causes are listed below but are not limited to[10]:

- LED packages – quality of materials and manufacturing can contribute to colour shift over time, but a primary factor that contributes to a faster shift is higher operating temperature.
- Luminaire construction – the selection of materials and methods used to create luminaires can affect how they change over time, overall affecting the colour shift of the luminaire itself. For example, reflectors, lenses, diffusers are all materials and components that light bounces/refracts from within a luminaire.
- Thermal management – for a target output, if an LED is selected that operates on its maximum electrical limits or an LED is paired with an inadequate heat sink, incapable of dissipating heat sufficiently away, this would lead to an increase in operating temperature thus causing an acceleration in shift.
- Application – where the luminaire is situated, the external environment can play a factor in the speed of how fast a luminaire's colour shifts. For example, contaminants in the air such as sulfur can attack the components of a luminaire causing changes in its properties thus resulting in colour shift.

↑ Figure 4.4: Example of a room with a downlight of poor colour stability[11]

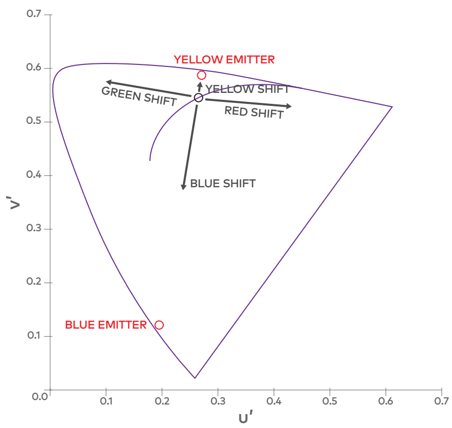


Figure 4.5: Colour shift directions for LED devices using the CIE 1976 color space[9]

Without physically testing for extremely long periods of time, there are methods within the industry that help predict colour shift against time. In 2019, the IES published a technical memorandum; TM-35-19 – Projecting Long-Term Chromaticity Coordinate Shift of LED Packages, Arrays and Modules.

TM-35-19 references another well-known technical memorandum used throughout the industry in creating datasets used for projecting lumen maintenance (brightness depreciation) and colour maintenance (colour stability); LM-80-15 – Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays and Modules.

Further information can be read in TM-35-19.

Colour Consistency

Colour consistency refers to the amount of variation in chromaticity (colour coordinates) among a batch of identical light sources[3]. That is, how consistent is the colour of the light source during a production run of LEDs at its initial output. With predecessor technologies, this was particularly difficult to maintain due to a different method of ignition and colour creation, but with LEDs, although easier to reproduce consistently, still is an important characteristic to measure.

An example of poor colour consistency can also be found in figure 4.4 that demonstrates the variation of luminaire colour when first installed.

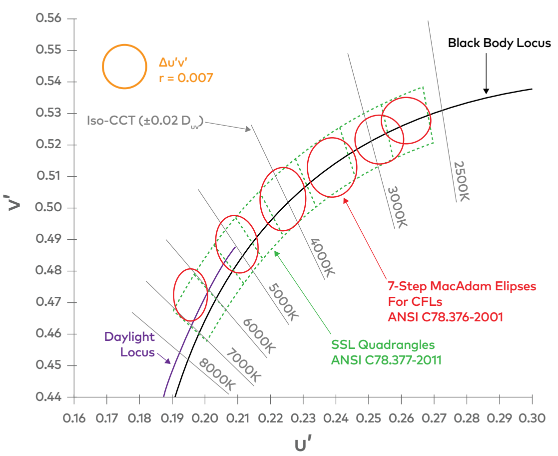


Figure 4.6: ANSI Tolerance for SSL and CFL sources in the CIE 1976 Color Space Diagram[12]

To limit this variation in colour, the industry uses a measurement known as Standard Deviation Colour Matching (SDCM) or also known as MacAdam ellipses. Along the blackbody-locus diagram introduced in section 4, ellipses are plotted for commonly produced CCTs to show the realm of colour variance which LEDs can be within for each "step". MacAdam ellipses are often reported with a step size which is in reference to the multiple of the original standard deviation ellipse (1-step). Figure 4.6 shows the same colour space diagram as figure 4.3 but with a 7-step ellipse drawn for common CCTs. The smaller the step number, the tighter the colour consistency of an LED batch as shown in figure 4.7. There is a misconception that points A and B on figure 4.7 – both points on the edge of an ellipse are 1-step apart. "1-step" refers to the centre point to any point along the edge, thus in this example, A and B are 2-steps apart. Studies determined a 3-step difference is just noticeable to the human eye, but is difficult to extrapolate outside of the testing field given the number of factors the research was conducted within[12].

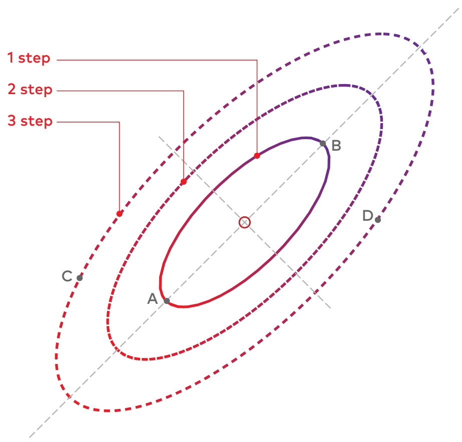
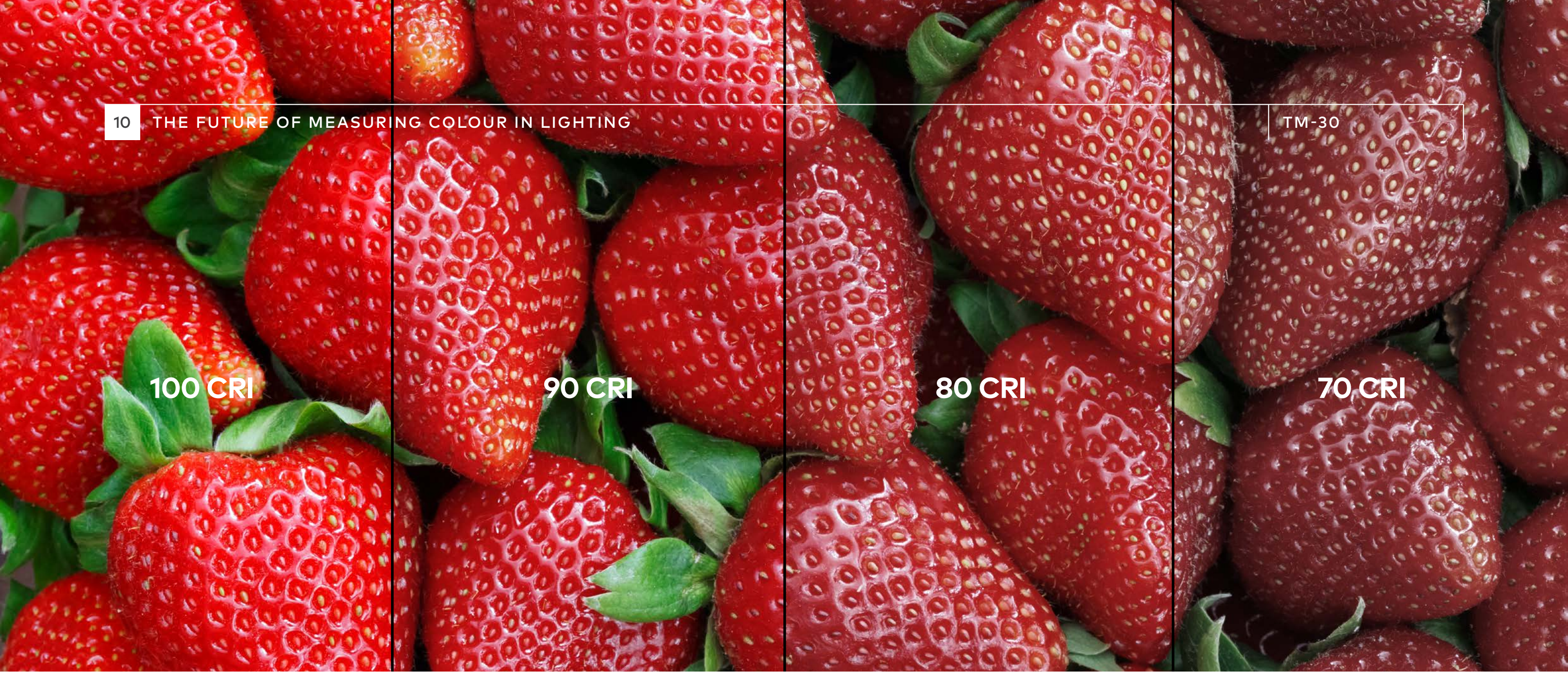


Figure 4.7: 1, 2 and 3-step MacAdam ellipse example for a given CCT [12]

Most white light source manufacturers generally offer "bins" of LED which reference a certain area within the colour space diagram for a given CCT along with the number of steps this bin may cover. Depending on the preference of the luminaire manufacturer, they have the ability to select particular bins to suit what they may deem to be a more suitable colour for their products. This paper will not go into the intricacies of colour mixing to obtain a colour in-between two bins.

This means luminaire manufacturers generally offer a step of colour matching with their luminaires. For example, if a luminaire manufacturer offers a product with a 3-step MacAdam (or ≤3 SDCM), they are offering a batch of products that should all be within three deviations of the original CCT.



Colour Rendering Index (CRI)

Deemed the most important criteria when colour is important, CRI is a measure of a light source's ability to illuminate object colours "realistically" compared to a familiar reference source, daylight or natural light[3]. The measurement is a scale metric from 1-100, with 100 being closest to natural light. The measured light source is referenced against eight moderately saturated test-colour samples in comparison to the reference source of the same CCT. The average of these eight results form the basis of the general CRI, or Ra. Figure 4.10 gives a rough guide of a range of CRI and their respective quality of colour rendering properties.

Code	CRI Range	Colour Rendering Properties
6	57-66	Poor
7	67-76	Moderate
8	77-86	Good
9	87-100	Excellent

Figure 4.10: CRI and colour rendering qualities

However, there is one major flaw with the CRI method when measuring the quality of colour rendering properties of a light source. There are 15 colour test samples within the CRI metric as per figure 4.11, however only eight are used to determine the general CRI. The first eight reference colours are pastel, while deeper reds, blues and greens are omitted from the general CRI measurement. This means there theoretically could be light sources that are of a high CRI, yet reproduce red colours poorly. This explains why lighting professionals often want to know the R9 value as well as the CRI value. An uncommon metric CRI (Re) is the average amongst all 15 colours, but is rarely referenced within the industry.

In practice, there is a general guide that LED manufacturers do use which include reference to R9 (reds) which are listed below[13]. Figure 4.9 represents a visual representation of red strawberries, with the general rule applied of an increase in CRI results in an increase in R9.

- CRI80+ generally has an R9 value >0
- CRI90+ generally has an R9 value >50
- CRI97+ generally has an R9 value >90

With this knowledge, lighting professionals and industry bodies have strongly expressed the need for an additional metric that can supplement CRI (Ra)[14].

↑ *Figure 4.9: The effect of how the human eye perceives red strawberries in relation to CRI*

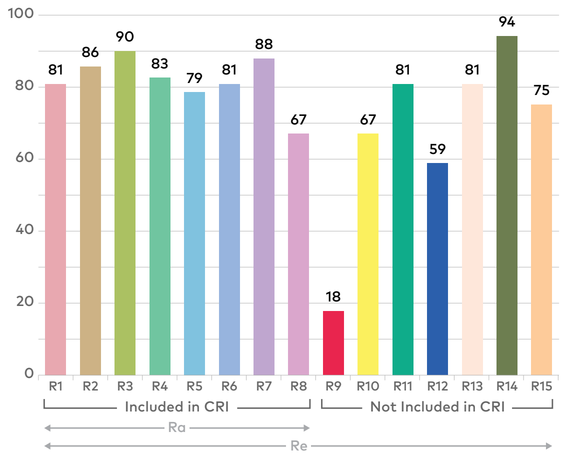


Figure 4.11: Example of a CRI80+ LED's individual R1-R15 performance

5. TM-30: A new method of evaluating light source colour rendition

In 2015, the IES published a new technical memorandum TM-30-15, IES Method for Evaluating Light Source Color Rendition. In 2018, an updated publication was released to the industry (TM-30-18) which has been formally recognised as an approved American National Standard (ANSI) to evaluate light source colour rendition[15].

COLOUR RENDITION AFFECTS MANY perceptual attributes of a space including naturalness, vividness, preference, normalness and clarity[15]. TM-30 is a method which evaluates 50 numerical measures and one graphic of a light source's colour rendition properties:

- Average colour fidelity (R_f) – 1 measure
- Gamut area (R_g) – 1 measure
- Hue-specific fidelity (16 measures), chroma shift (16 measures), hue shift (16 measures)

R_f and R_g measures are averages, while the other 48 measures are hue specific. The evaluation method is applicable generally to white light sources used for general illumination within indoor spaces and some outdoor environments. It is noted that these measures do not take into any consideration any colour perception or memory specific to individual humans.

Colour Evaluation Samples (CES)

In section 4 it was discussed that CRI was limited due to the number of test colour reference samples within the metric and thus was not a sufficient metric to determine a light source's colour rendition properties.

In TM-30, the colour rendition of the test source and reference illuminant are compared using a set of 99 colour evaluation samples. Thirty-three of the CES were extrapolated from the original measured range of 400-700nm to include up to 380-780nm, however does not greatly impact results within the 400-700nm spectrum. Figure 5.1 showcases the approximate 99 colours.

The 99 colours were mathematically selected from 105,000 spectral reflectance factors which were deemed by the authors to best represent the range of all possible colours in real world objects including textiles, plastics, skin tones and colour systems.

The original set was reduced to 65,000 colours following the Natural Colour System (NCS)[16] that was typically found in most interior rooms. From the NCS range, a set of 4,880 samples with desirable properties such that no specific wavelengths of colour were penalised nor favoured. To generate a practical sample set, 99 colours were selected such that it best represented the larger set and were relatively uniform across the colour space. As shown in figure 5.2, no particular spectrum is favoured heavily in comparison to the eight test colour samples (TCS) in CRI.

Figure 5.1: Approximate colours for the 99 CES[15]

Fidelity Index (R_f)

The fidelity index is an average measure of all 99 individual CES in reference of the tested light source in comparison to a reference illuminant. The equation to calculate the fidelity index is below:

$$R_f = 10ln\left[\exp\left(\frac{R'_f}{10}\right) + 1\right]$$

where;

$$R'_f = 100 - 6.73\left[\frac{1}{99}\sum_{i=1}^{99}(\Delta E_{Jab,i})\right]$$

The fidelity index is generally compared against CRI, which addresses many of the concerns with the previous metric as discussed in section 4. Similarly, to CRI, the fidelity index uses a scale of 0-100 with 100 being the best representation of the 99 CES. However, due to the fidelity index having a much larger colour sample set, CRI and R_f may not be directly compared (as a high performing CRI light source may have a poor R_f).

As the value is of an average, except for 100, two light sources that have the same fidelity index value of <100 and same CCT may not exhibit the same colour appearance of objects. The logarithmic function of the fidelity index means that it won't exactly equal the mean of each individual fidelity value, unlike CRI.

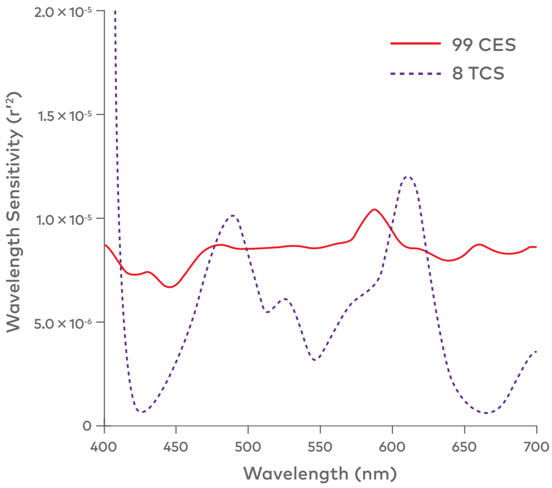


Figure 5.2: Spectral sensitivity comparison between the 99 CES and 8 TCS in CRI[15]

Hue Angle Bins

The remaining 49 measures must first categorise the 99 CES into hue-angle bins which divide the CIE Colour Appearance Model (CAM02-UCS) colour space into 16 equal parts as shown in figure 5.3. A reference illuminant (black) and test source (red) can be plotted against the 99 CES as shown in figure 5.4. The average in each bin is then taken, and all 16 averages are connected to form a polygon. The diagram on the right in figure 5.4 shows the clear graphical difference between the reference illuminant and test source in each respective hue bin. These 16 pairs now form the basis of the other 49 measures. It is noted that the 99 CES points of each CCT vary and thus each reference illuminant CCTs polygon does not look the same.

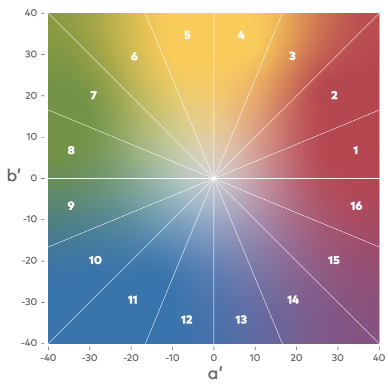


Figure 5.3: Equally divided Hue angle bins in the CAM02-UCS

Gamut Index (R_g)

The gamut index is a measure of the area spanned by the average coordinates of the CES in each hue-angle bin comparing between the reference illuminant and the test source[15]. Once the polygons are drawn as per figure 5.4, the gamut index can be calculated by the ratio of the area between the two polygons as per the equation below:

$$R_g = 100 \times \frac{A_t}{A_r}$$

Where;

A_t = the area of the test source

A_r = the area of the reference illuminant

The R_g value can have three different results:

- R_g = 100: indicates that on average, test source does not decrease or increase in chroma in comparison to the reference illuminant.
- R_g > 100: indicates that the test source has a larger polygon area and thus an increase in chroma on average.
- R_g < 100: indicates that the test source has a smaller polygon area and thus a decrease in chroma on average.

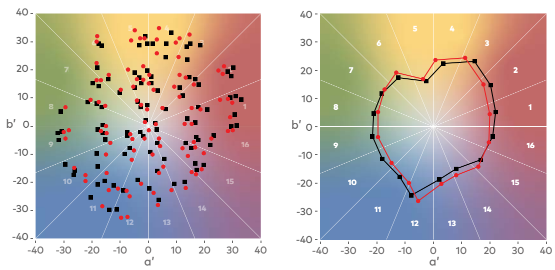


Figure 5.4: Example of a reference illuminant and test source plotted on the CAM02-UCS, and average coordinates in each hue bin connected together to make polygons[15]

Chroma as a term is often substituted with colour saturation. R_g as a numerical value does not describe which hues may have an increase or decrease in chroma in comparison to the reference illuminant. Therefore, it is best to compare by visually analysing the polygon diagrams and determining where there may be a relative increase or decrease in chroma. As a guide, the gamut index generally ranges from 60-140. It is noted that both average indexes – gamut and fidelity, cannot be maximised simultaneously. Logically, as there is an increase (or decrease) in chroma in comparison to the reference illuminant, they no longer represent a "perfect" match with all 99 CES and thus cannot achieve a fidelity index of 100. Figure 5.5 best represents the relationship between R_f and R_g, and is generally used to quickly compare two light sources of the same CCT against one another.

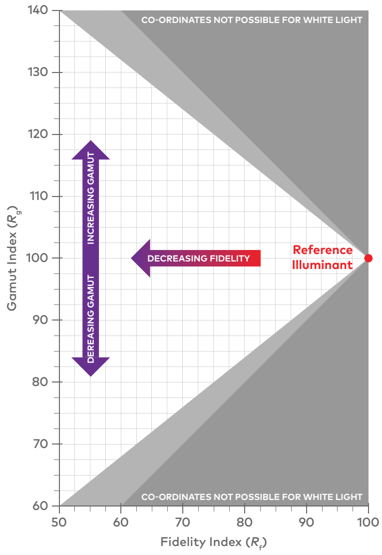


Figure 5.5: TM-30 Two-axis diagram representing the relationship of R_g vs. R_f

For easy comparison, the polygons shown in figure 5.4 of the reference illuminant (black) and tested light source (red line) is normalised such that the reference illuminant (black line) creates a circle with a radius of 1 as shown in figure 5.6. As each hue bin is compared, any edge of the test source that lies within the reference illuminant circle results in a decrease in chroma respectively, while anything that exceeds the boundary refers to an increase in chroma. The normalised colour vector graphic can also explain whether any colours have undergone a hue-shift (a change in colour, not a change in saturation). This becomes important when comparing two different light sources that have the same R_f and R_g value, and thus the comparison chart in figure 5.5 cannot be used and the colour vector graphic must be referred to for any differences – keeping in mind these are only averages and not each individual CES.

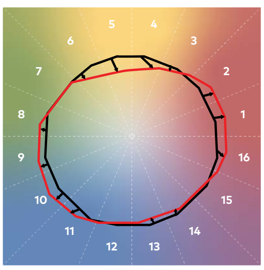


Figure 5.6: Normalised Colour Vector Graphic of the reference illuminant and test source[15]

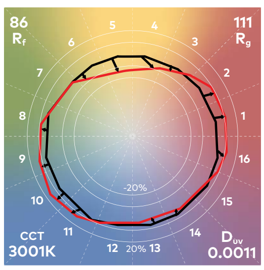


Figure 5.7: Advanced vector graphic[15]

The colour vector graphic can be taken a step further to provide more information for the interpreter, and is recommended to be displayed as figure 5.7.

Local Chroma Shift ($R_{cs,hj}$)

Local chroma shift analyses the comparison of each radial shift for each of the 16 hues. This can be determined using the equation below where j is the hue bin number:

$$R_{cs,hj} = \frac{(a'_{test,j} - a'_{ref,j})}{\sqrt{(a'^{\,2}_{ref,j} + b'^{\,2}_{ref,j})}}cos\theta_j + \frac{(b'_{test,j} - b'_{ref,j})}{\sqrt{(a'^{\,2}_{ref,j} + b'^{\,2}_{ref,j})}}sin\theta_j$$

This allows the user to quickly identify the average chroma shift for each hue bin. A negative value results in a decrease in chroma while a positive value results in an increase in chroma. Local chroma-shift is commonly represented as a bar graph for easier interpretation as shown in figure 5.8.

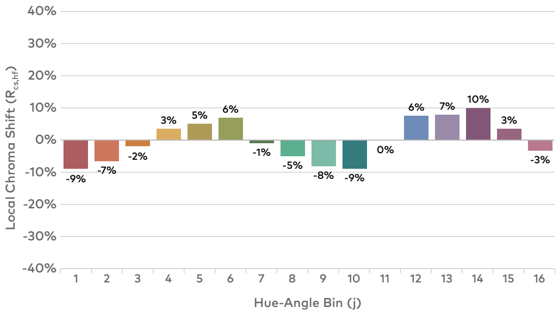


Figure 5.8: Bar graph graphical representation of local chroma shift[15]

Local Hue Shift ($R_{hs,hj}$)

Local hue shift analyses the vectors shown in figure 5.7, and the tangential shift of the reference illuminant in comparison to the test source. Similarly to local chroma shift, this is repeated for each of the 16 hue bins and can be calculated using the formula below where j remains the hue bin number:

$$R_{hs,hj} = -\frac{(a'_{test,j} - a'_{ref,j})}{\sqrt{(a'^{\,2}_{ref,j} + b'^{\,2}_{ref,j})}}sin\theta_j + \frac{(b'_{test,j} - b'_{ref,j})}{\sqrt{(a'^{\,2}_{ref,j} + b'^{\,2}_{ref,j})}}cos\theta_j$$

For each of the local hue shifts, a negative value indicates a clockwise shift (for example, orange towards red, blue toward green), while a positive value indicates an anti-clockwise shift. Local hue shift is commonly represented as a bar graph for easier interpretation as shown in figure 5.9.

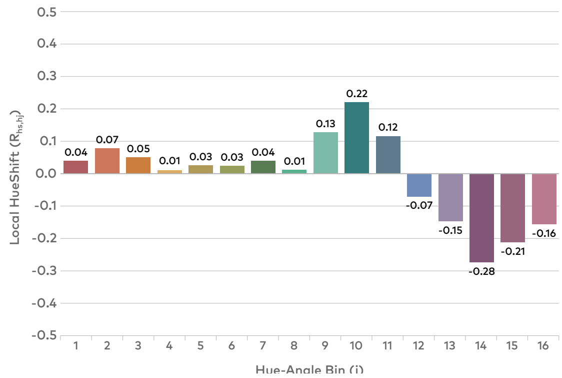


Figure 5.9: Bar graph graphical representation of local hue shift[15]

Local Colour Fidelity ($R_{f,hj}$)

Each hue bin can determine specific colour fidelity for the average number of samples in each respective hue bin. Each local colour fidelity value also has a value range between 0 to 100 similar to the fidelity index and can be calculated using the formula below where j remains the hue bin number:

$$R'_{f,hj} = 100 - 6.73\left[\frac{1}{m}\Sigma^{m}_{i=1}(\Delta E_{Jab,i})\right]$$

$$R_{f,hj} = 10ln\left[\exp\left(\frac{R'_{fh,j}}{10}\right) + 1\right]$$

As the result is an average of colour samples in each hue bin, it cannot be extrapolated for each CES within each hue bin thus will not equal the same value as the fidelity index R_f. Local colour fidelity is less often used as a comparison, as it does not take into the consideration the direction of hue shift, thus makes it difficult in predicting how coloured objects will appear in comparison to the reference illuminant. Similarly to the other local measurements, local colour fidelity is best interpreted via a bar graph diagram as shown in figure 5.10:

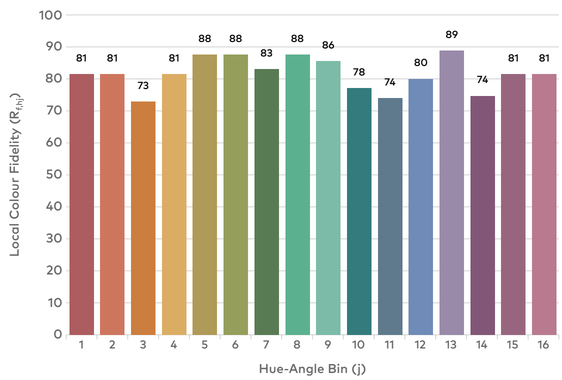


Figure 5.10: Bar graph graphical representation of local fidelity shift[15]

6. Conclusion

It is astonishing to see the speed at which lamp sources (namely LEDs) and their efficacy has continually developed over the last decade. As the population continues to climb, and more buildings are built, it is of upmost importance to continually reduce our carbon footprint in all energy consuming aspects that coincide with it.

This paper has covered the perspective to also appreciate the beauty and importance that colour quality can also have within our daily lives. It's purpose was to first bring to light what key colour criteria should be addressed and what those entail. Not only is colour rendering quality the most important to recreate accurate representations of real-world objects, but to not forget about selecting the right colour temperature to best suit an environment, and to maintain colour consistency throughout.

A new method, TM-30 details a more thorough approach to measuring colour rendering via two main criteria – the fidelity index and gamut index, along with individual measures of each hue angle bin to allow a designer to select purposeful luminaires to achieve their design intentions. It will be interesting to see how or if the TM-30 measure will be adopted throughout the lighting industry and the question to be asked, is there any other measure to rival or consider instead?

In the interim, if a higher quality colour rendition is required, it is suggested to use traditional data of CRI from R1-R15 (or at least Ra + R9 if available) and/or paired with TM-30 data for a clear understanding of a luminaire's colour reproduction qualities.

7. References

1. U.S. Energy Information Administration, "Commercial Buildings Energy Consumption Survey (CBECS)," 17 May 2017. [Online]. Available: https://www.eia.gov/consumption/commercial/reports/2012/lighting/. [Accessed 06 February 2020].

2. Illuminating Engineering Society, "Color," 15 June 2018. [Online]. Available: https://www.ies.org/definitions/color/. [Accessed February 2020].

3. Lighting Research Center, "How are the color rendering properties of light sources defined?," Rensselaer Polytechnic Institute, October 2004. [Online]. Available: https://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightsources/colorRendering.asp#. [Accessed February 2020].

4. NASA, "Tour of the Electromagnetic Spectrum," 10 August 2016. [Online]. Available: https://science.nasa.gov/ems/09_visiblelight. [Accessed February 2020].

5. Illuminating Integration, "The Importance of Color in Lighting," 24 February 2019. [Online]. Available: https://illuminated-integration.com/blog/importance-of-color-in-lighting/. [Accessed February 2020].

6. Kenan-Flagler Business School, "How lighting affects the productivity of your workers," 11 September 2017. [Online]. Available: https://onlinemba.unc.edu/news/how-lighting-affects-productivity/. [Accessed February 2020].

7. L. Knoezer, "What is color temperature?," The Lighting Practice, [Online]. Available: https://www.thelightingpractice.com/what-is-color-temperature/. [Accessed February 2020].

8. T. Erdem and H. V. Demir , "Color science of nanocrystal quantum dots for lighting and displays ," Nanophotonics, vol. 2, pp. 57-81, 2013.

9. Illuminating Engineering Society, "ANSI/IES TM-35-19," Technical Memorandum: Projecting Long-term Chromaticity Coordinate Shift of LED Packages, Arrays, and Modules, p. 59, 2019.

10. M. Royer, C. Stalker, and R. Tuttle, U.S. Department of Energy, 15 April 2014. [Online]. Available: https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/color-stability-webinar_4-15-2014.pdf. [Accessed February 2020].

11. Next Generation Lighting Industry Alliance, "LED Luminaire Reliability: Impact of Color Shift," 2017. Available: https://www.energy.gov/sites/prod/files/2019/10/f67/lsrc_colorshift_apr2017.pdf. [Accessed February 2020]

12. M Royer et al, "Color Maintenance of LEDs in Laboratory and Field Applications," U.S. Department of Energy, 2013. Available: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22759.pdf. [Accessed February 2020]

13. C. LED, "COB Series Version6," Citizen Electronics Co., LTD, [Online]. Available: http://ce.citizen.co.jp/productse/info.php?no=116. [Accessed February 2020].

14. C. Teunissen et al, "Application of CIE 13.3-1995 with Associated CRI-Based Colour Rendition Properties." (June 2019). Available: http://files.cie.co.at/x046_2019/x046-PO044.pdf. [Accessed February 2020].

15. Illuminating Engineering Society, "ANSI/IES TM 30-18 IES Method for Evaluating Light Source Color Rendition," 2018. [Online]. Available: https://www.ies.org/product/ies-method-for-evaluating-light-source-color-rendition/. [Accessed February 2020].

16. NCS Colour, "NCS – Natural Colour System®," [Online]. Available: https://ncscolour.com/ncs/. [Accessed February 2020].