

CRI

GAI



A PRACTICAL GUIDE FOR BUILDINGS

COLOUR BEYOND CRI

Understanding spectral sensitivity, colour fidelity, gamut and the light that shapes a space.

GIRISH BHARDWAJ

For the people who shape spaces

For a developer, owner or end user, colour is experienced before a lighting specification is read. It determines whether food looks inviting, merchandise looks true to its materials, art retains its character, and a room feels coherent from one area to the next.

For architects, interior designers, lighting designers, engineers and procurement teams, those experiences must become decisions that can be specified, tested and repeated. A familiar number such as CRI helps, but it cannot describe every change a light source makes to the colours in a space.

This book begins with the eye and the spectrum, then explains colour fidelity, gamut and the TM-30 graphics. It uses images from my presentation to connect the measurements with design decisions. The aim is to help the project team ask better questions of a luminaire sample and its data sheet.

When a finish, fabric or product matters, view the actual material under the proposed light. Ask for the spectral power distribution and the full colour rendition report. Compare samples at the intended light level, with the intended dimmer and optics. The right source is the one that serves the space and its occupants.

Girish Bhardwaj

The spectrum in a space

Light reaches an object with a particular distribution of wavelengths. The object reflects some wavelengths and absorbs others. The eye and brain interpret the reflected light as colour.

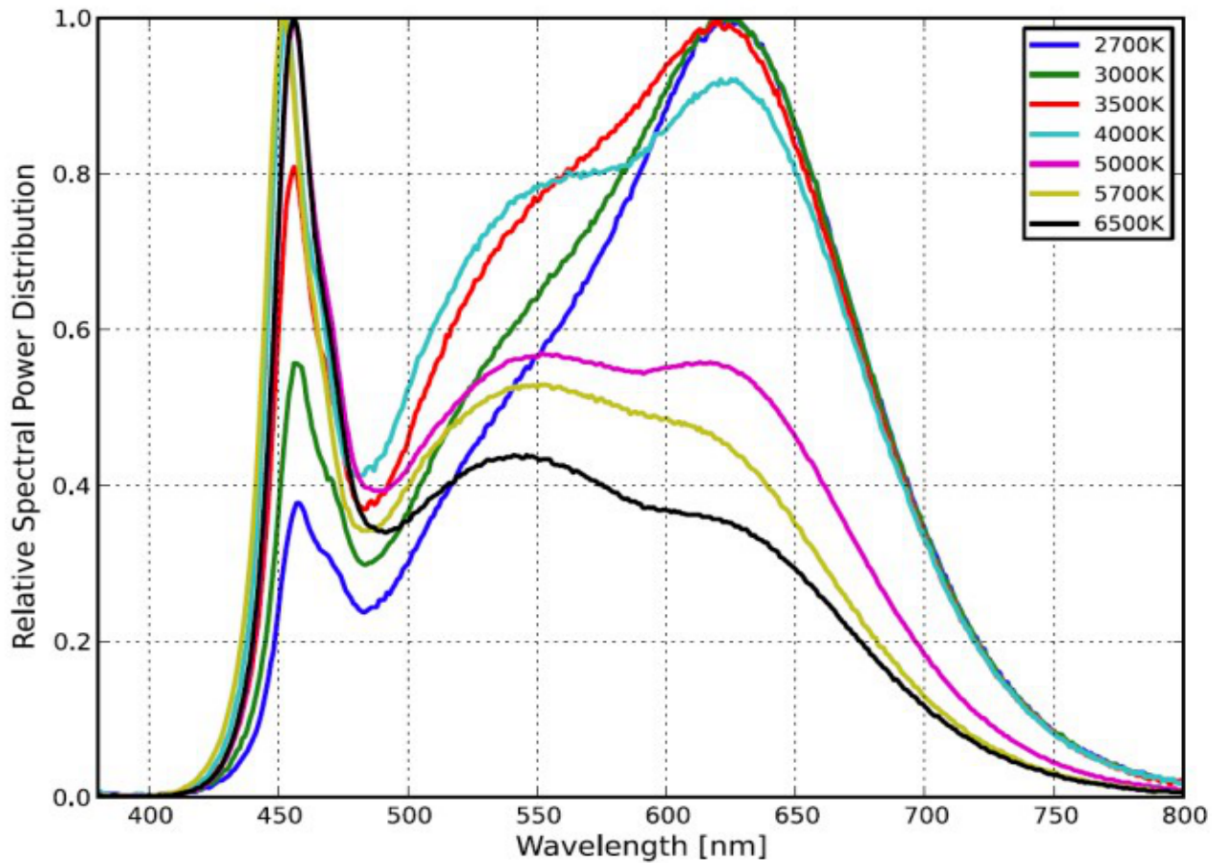


Figure 1c. Typical normalized power vs. wavelength for L130-xx90001400001 at 60mA, $T_j=25^\circ\text{C}$.

Presentation slide 3: spectral power distribution at several nominal white appearances.

- A colour label such as “warm white” cannot reveal the whole spectrum.
- Specify the actual source and examine important finishes under it.

Why test colours matter

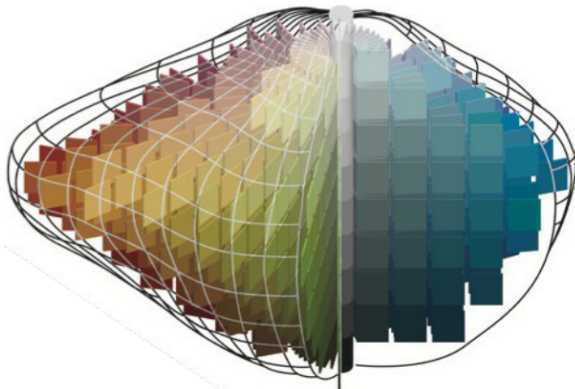
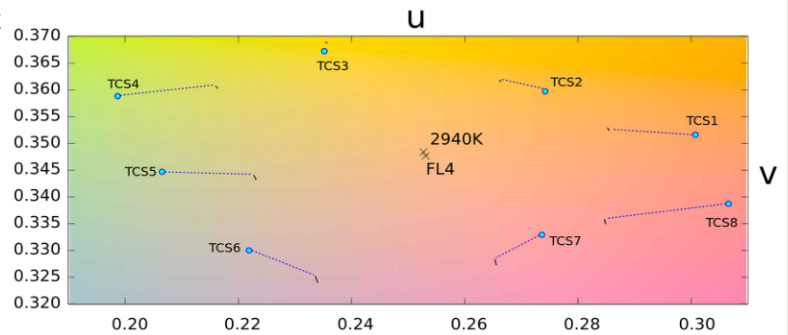
A rendition metric needs a set of surfaces against which to compare a test source and a reference. Traditional CRI uses eight moderately saturated test colour samples originally based on Munsell colours.

As specified in CIE (1995), the original test color samples (TCS) are taken from an early edition of the Munsell Atlas.

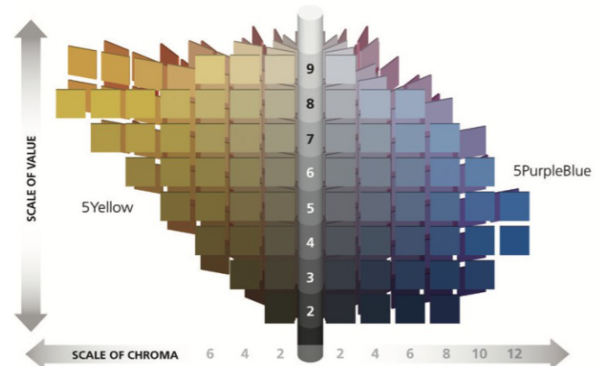
(100 Hue Color Vision test is a test of the human visual system often used to test for color blindness. The system was developed by Dean Farnsworth in the 1940s.)

These eight samples are relatively low saturated colors and are evenly distributed over the complete range of hues.

These eight samples are employed to calculate the general color rendering index Ra.



view of the Munsell color solid showing notation scales of hue, value, and chroma



A three-dimensional representation of the Munsell color tree

Presentation slide 2: Munsell colour solid and the eight traditional test samples.

- The test set helps make measurements repeatable, but eight samples cannot represent every product or finish.
- The Farnsworth-Munsell 100 Hue test assesses a person's hue ordering ability. It is distinct from the eight CRI test samples.

Spectral sensitivity

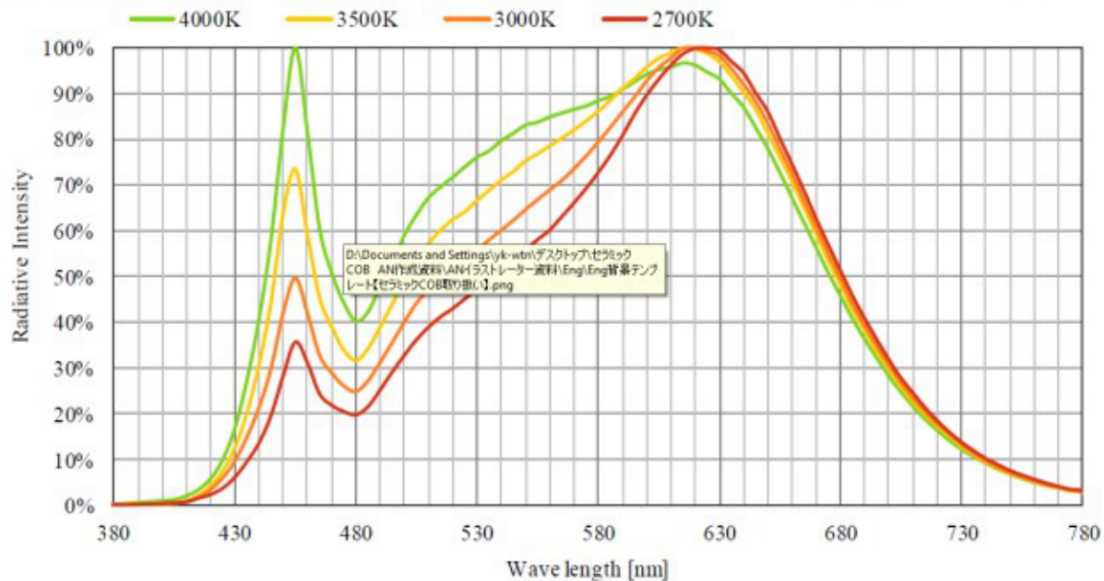
Our visual response varies across wavelengths and with viewing conditions. An SPD plot displays source output by wavelength; perceived brightness and object colour also depend on human sensitivity and surface reflectance.

CITILED.
The Light Engine

4-2. Optical Characteristics

Spectrum : CRI(Ra) 90 Min.

$T_j=85^{\circ}\text{C}$ $I_f=360\text{mA}$

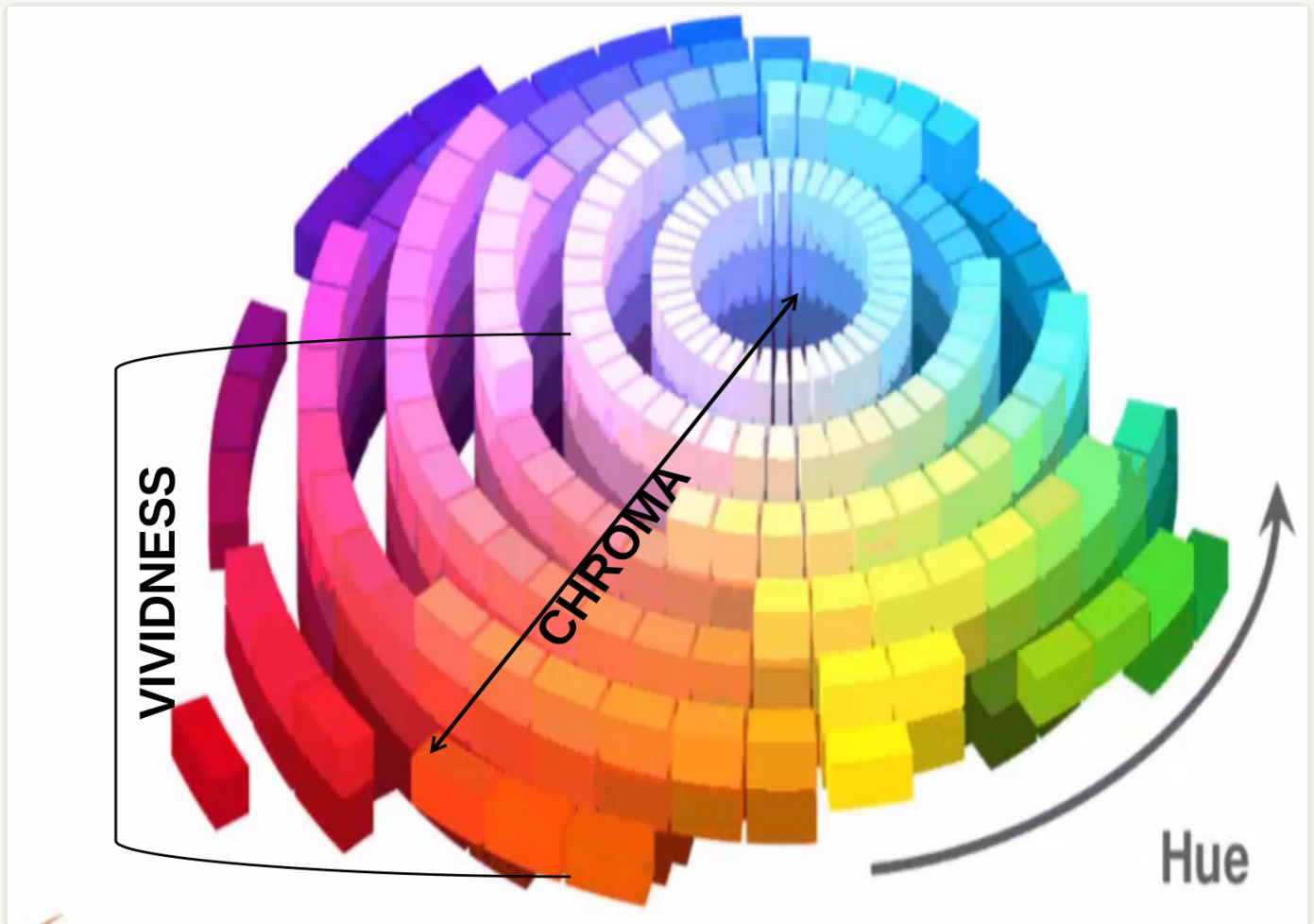


Presentation slide 6: example LED spectral output.

- A spectral peak does not alone establish whether a source will render objects faithfully.
- Do not confuse the eye's spectral sensitivity, a light source's SPD and a material's reflectance curve.

Hue, chroma and value

Hue identifies a colour family. Chroma expresses its colourfulness. Value or lightness describes how light or dark it looks. These are separate aspects of appearance.

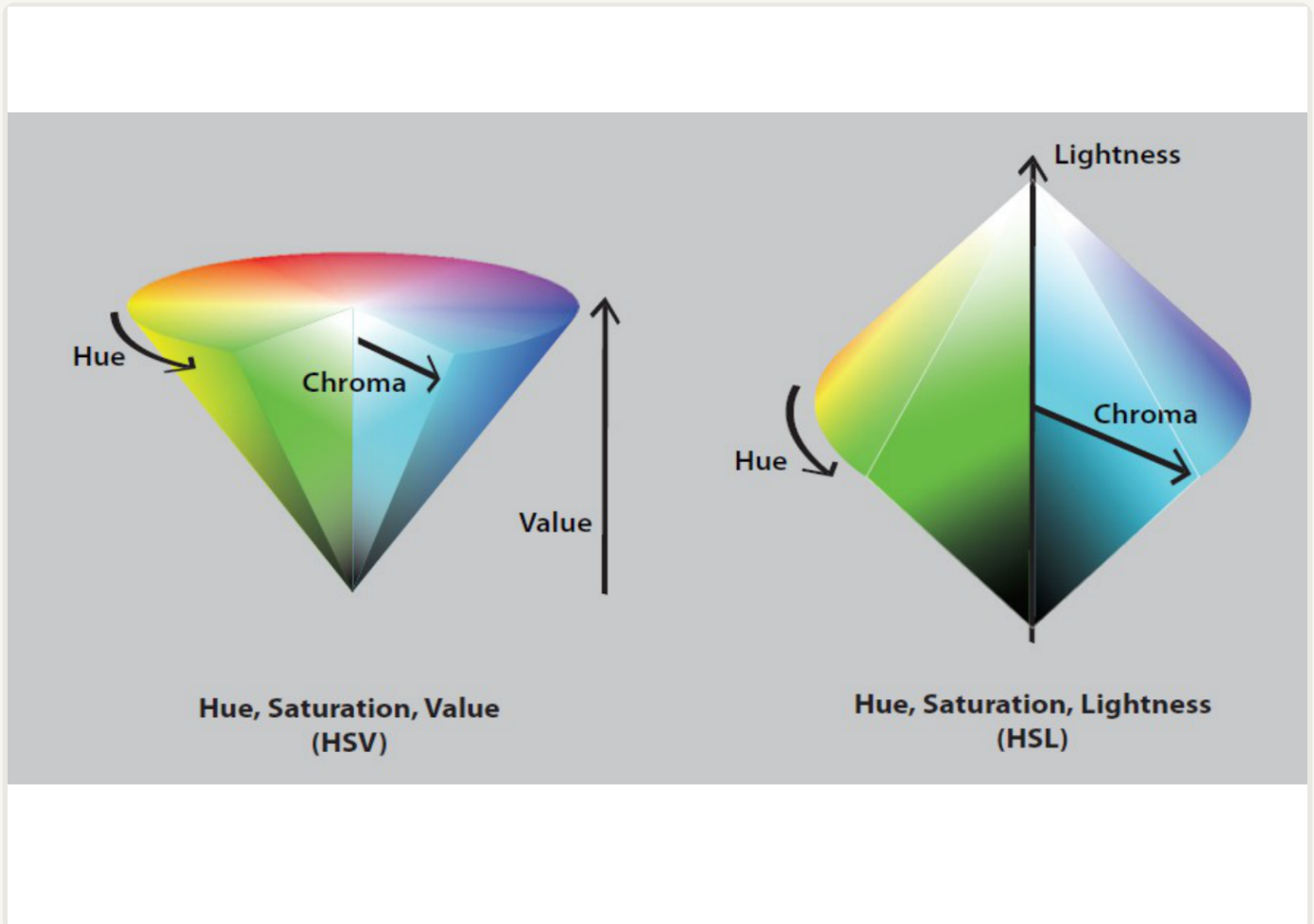


Presentation slide 11: three-dimensional illustration of hue, chroma and vividness.

- A high fidelity score can coexist with an appearance that feels flat or vivid in particular hue regions.
- Observe materials at their intended light level and in their final surroundings.

Two ways to map colour

HSV and HSL are useful conceptual diagrams for hue and saturation. Perceptual colour spaces used for scientific comparison have different coordinates and calculation rules.

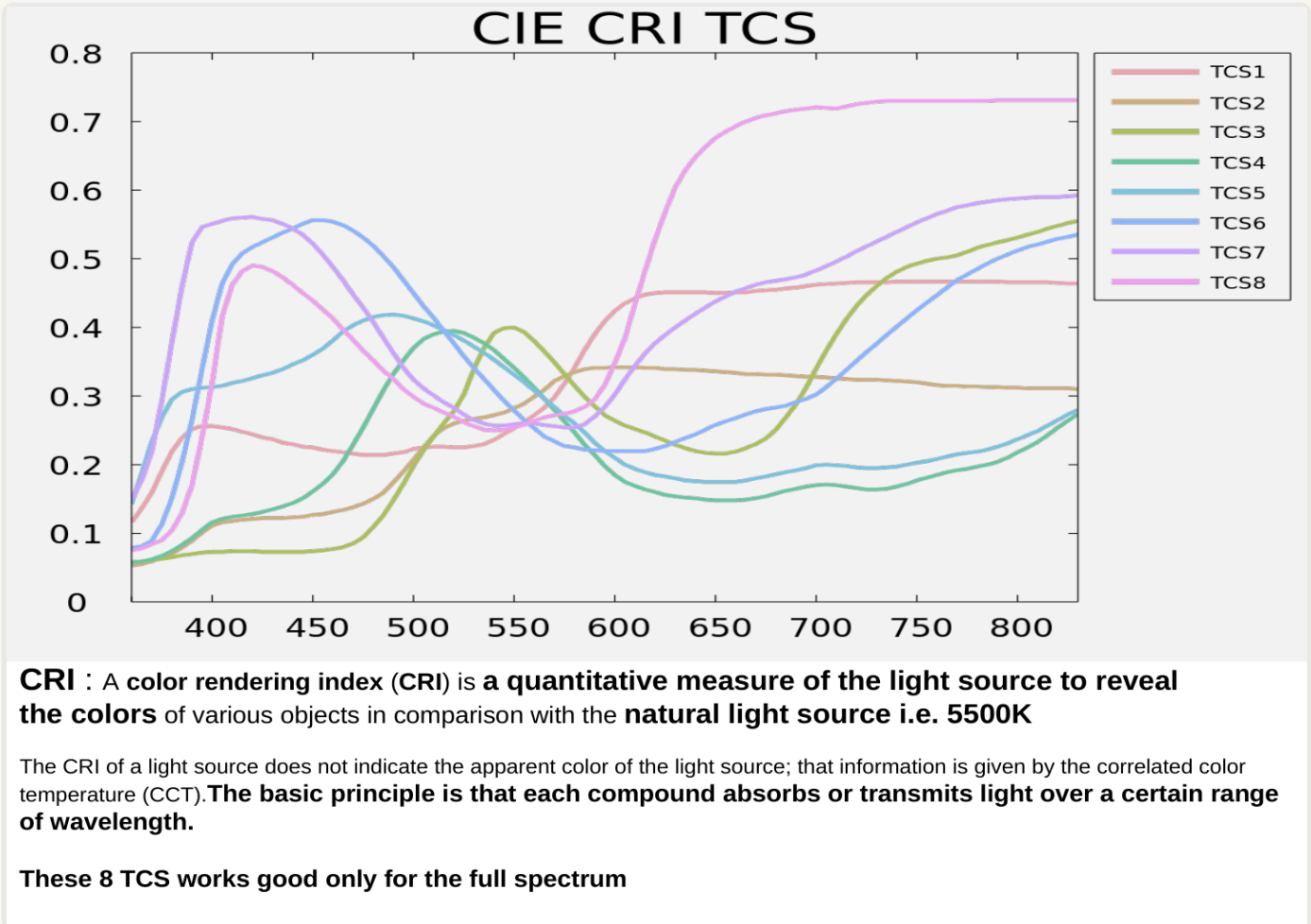


Presentation slide 12: HSV and HSL colour models.

- The diagrams explain terminology; they are not themselves a lighting specification method.
- A change in chroma and a change in lightness can both alter how a finish feels.

What Ra measures

The general Colour Rendering Index, Ra, averages colour differences for eight samples between a test light and a reference with approximately the same correlated colour temperature.



Presentation slide 4: reflectance curves for the traditional test samples.

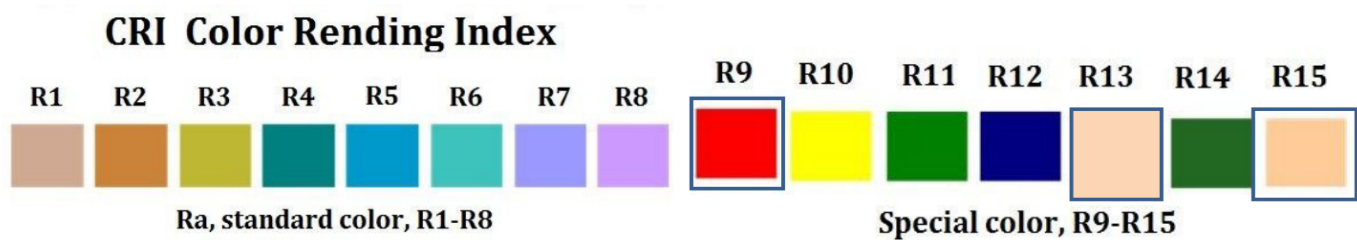
- A larger Ra indicates closer average agreement for those samples, within the method's limits.
- Ra does not directly describe how pleasant, vivid or appropriate a light will appear.

The limits of eight samples

Averages can hide the direction and size of a shift in a specific hue. The traditional CRI framework also uses older colour difference and adaptation methods.

Limitations

1. The color space in which the color distance is calculated (CIEUVW) is obsolete and non uniform.
2. The chromatic adaptation transform used is inadequate.
3. The CRI cannot be calculated for light sources that do not have a CCT (non-white light).
4. LEDs does not have full spectrum thus these 8 TCS has limitation on furnishing the exact color of the objects or the surroundings.



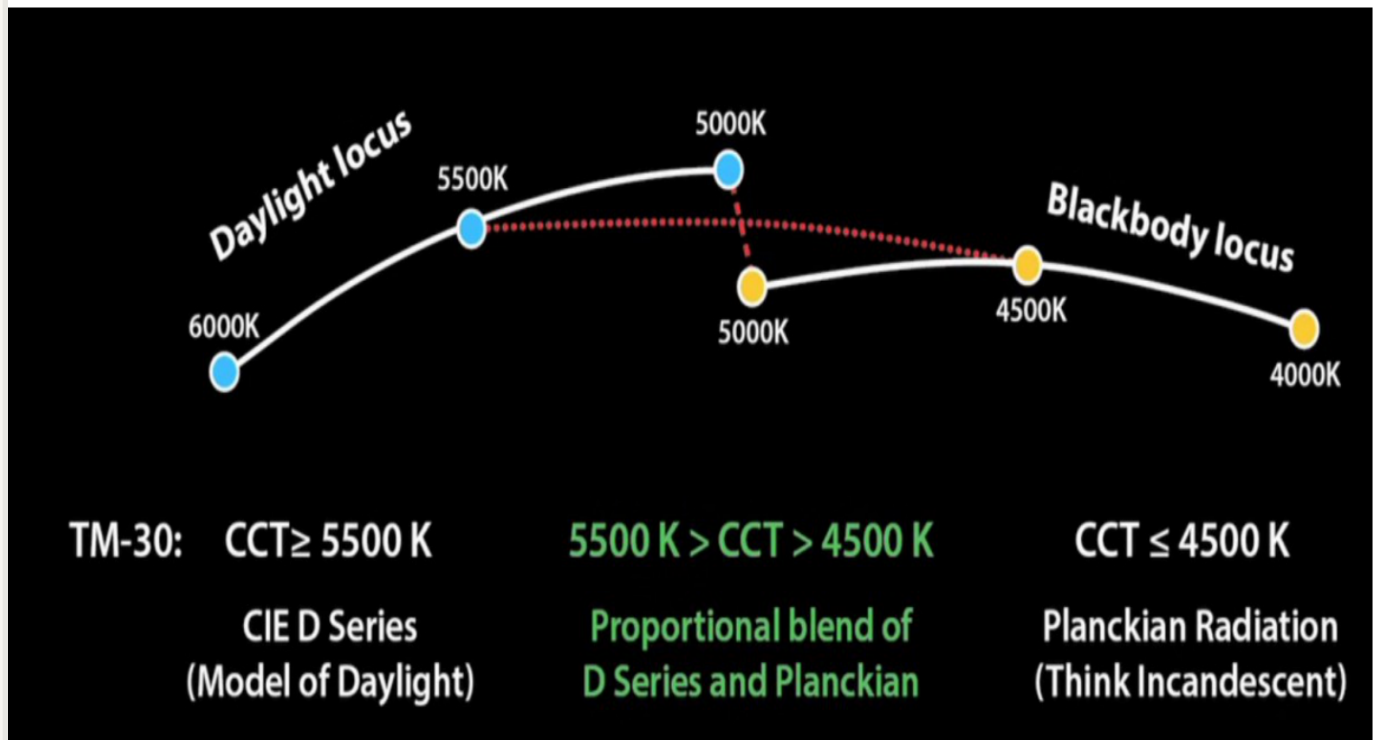
Presentation slide 5: original list of CRI limitations and special indices.

- The source slide's "5500 K natural light" description is too narrow; the reference varies with CCT.
- LED spectra vary greatly. Neither an LED label nor an assumption of "full spectrum" determines colour quality on its own.

Planckian and daylight

The Planckian locus describes the chromaticities of ideal thermal radiators. CIE daylight models describe daylight chromaticities and spectra. Both help define references for white light comparisons.

Planckian locus & CIE D series



Presentation slide 7: Planckian locus and CIE daylight series.

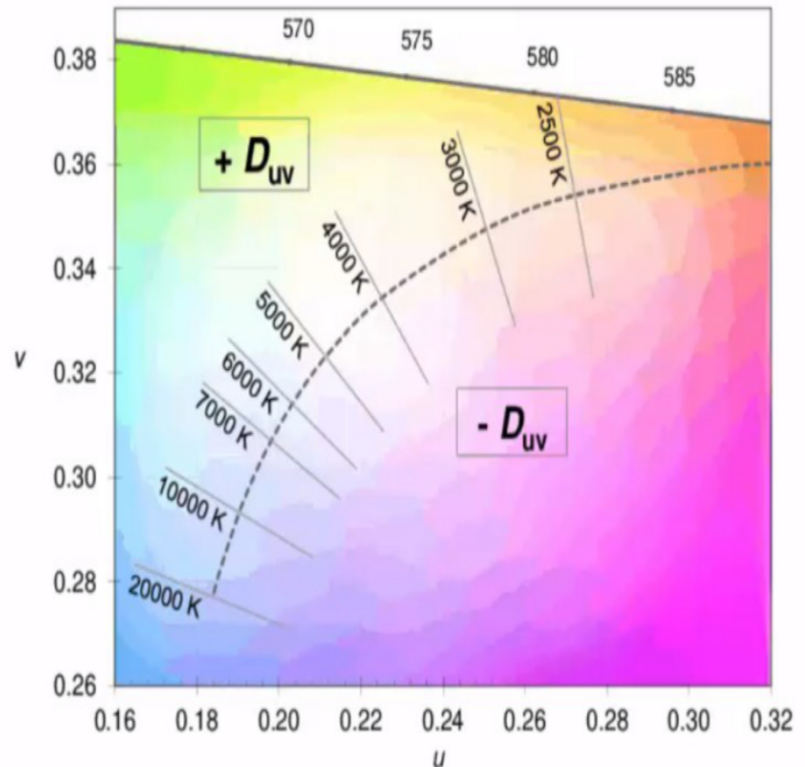
- CCT gives an approximate warm to cool descriptor for near-white sources.
- Two sources at the same CCT can have different SPDs and produce different object colours.

Distance from the locus

Duv describes whether a near-white source falls to one side or the other of the Planckian locus, and by how much. This helps explain why two sources sharing a CCT may appear differently tinted.

Distance from Planckian Locus (D_{uv})

- Approximately purple-green
- Equal CCT and D_{uv} specifies matching appearance for standard observer (real observers may vary)
- Neutral white can cover a wide area



Presentation slide 8: diagram of distance from the Planckian locus.

- Ask for both CCT and Duv where white appearance is sensitive.
- Compare proposed sources at realistic illuminance and against adjacent daylight or finishes.

MacAdam ellipses

MacAdam ellipses map regions of small chromaticity differences observed in colour matching experiments. In LED specifications, step tolerances are often used to discuss how closely units match in chromaticity.

In the study of color vision a **MacAdam ellipse** is a region on a chromaticity diagram which contains all colors which are indistinguishable, to the average human eye, from the color at the center of the ellipse.

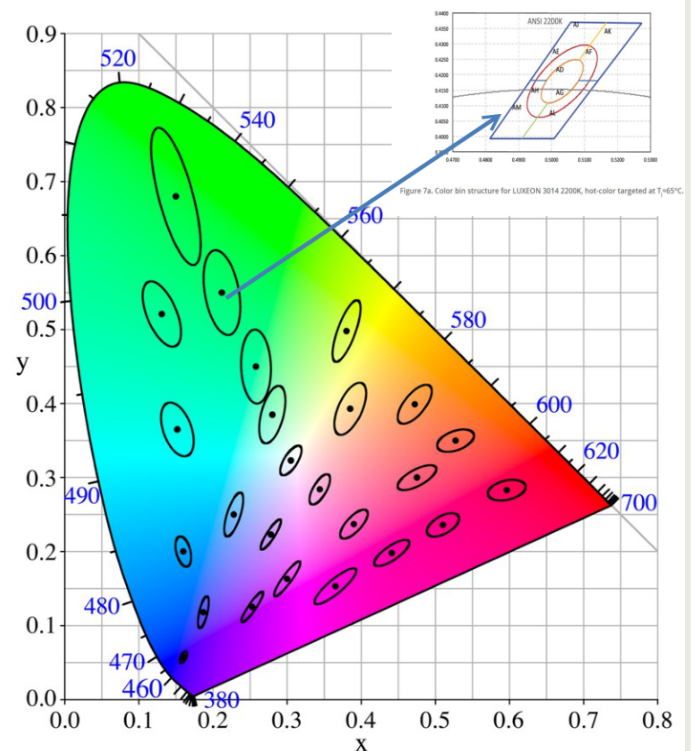
The contour of the ellipse therefore represents the just noticeable differences of chromaticity **Standard Deviation Color Matching** in LED lighting uses deviations relative to MacAdam ellipses to describe color precision of a light source.

It was found by MacAdam, however, that all of the matches made by the observer fell into an ellipse on the CIE 1931 chromaticity diagram.

The measurements were made at 25 points on the chromaticity diagram, and it was found that the size and orientation of the ellipses on the diagram varied widely depending on the test color. These 25 ellipses measured by MacAdam, for a particular observer, are shown on the chromaticity.

MacAdam generalized these ellipses to human populations, and asserted standard statistical variance of perception can be mapped onto the color space as well.

In practical terms, a MacAdam ellipse for a particular color point is defined to encompass one standard deviation of a "standard observer." Roughly 65% of the population would situate or place their perception of the same color as a point within a MacAdam ellipse. Larger ellipses can be defined to enclose two, three or more standard deviations allowing a higher percentage of observers, 95% to 99%, to perceive the same color as a point somewhere within these ellipses.



Presentation slide 9: MacAdam ellipses on a chromaticity diagram.

- A smaller binning tolerance can help rows of luminaires look more uniform.
- Ellipses address white point consistency, not the full question of colour rendering. The presentation's population percentages are an oversimplification.

Brightness and colour

Chromaticity diagrams show colour coordinates, but cannot by themselves convey how light or dark an object appears. A more complete account of appearance includes a lightness dimension.

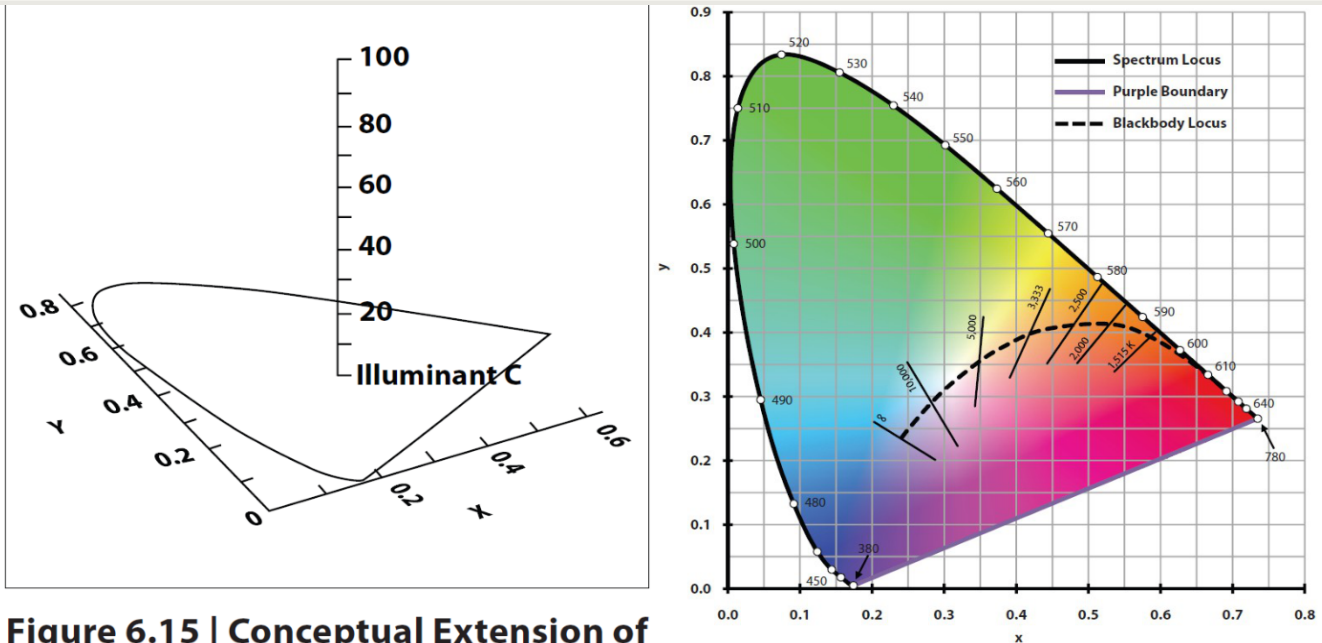


Figure 6.15 | Conceptual Extension of Chromaticity Diagram for Lightness

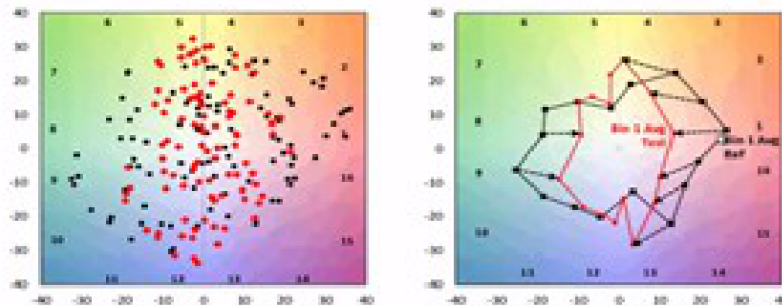
Presentation slide 10: conceptual extension of chromaticity to include lightness.

- Assess wall finishes, shadows and contrast in a real scene.
- The same source can give a different visual impression when the light level or surround changes.

The idea of vividness

Colour gamut describes the spread of a selected set of rendered colours. If the spread grows relative to a reference, some colours may appear more saturated on average.

Gamut Area: TM-30



Presentation slide 14: two gamut plots for comparing a test source with a reference.

- Greater gamut is a design choice, not a universal quality ranking.
- Look for changes in the particular hues that define the project.

The earlier gamut index

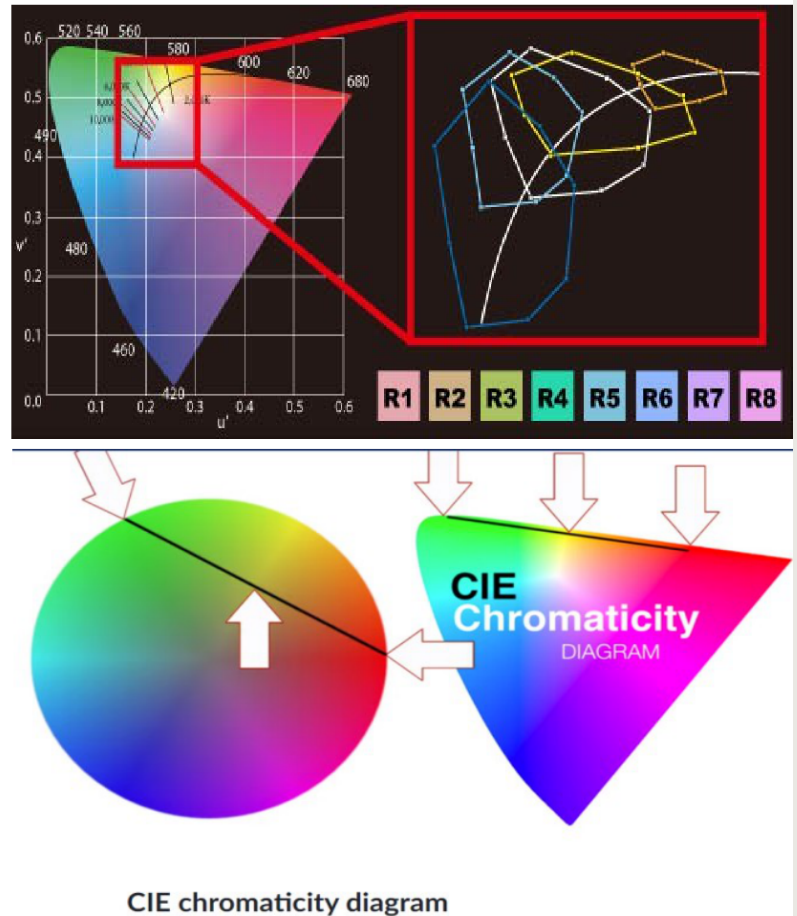
GAI uses the traditional eight CRI test colours to compare the polygon area of their rendered chromaticities with a reference. It complements fidelity with a summary of colour spread.

Gamut Area Index (GAI),

which measures color saturation or vividness, is derived from a light source's SPD and the same eight test colors that determine CRI.

Calculations are done on a uniform CIE color space to produce chromaticity coordinates that form a polygon.

Unlike CRI, GAI is not a fidelity metric, and an index greater than 100 is possible.

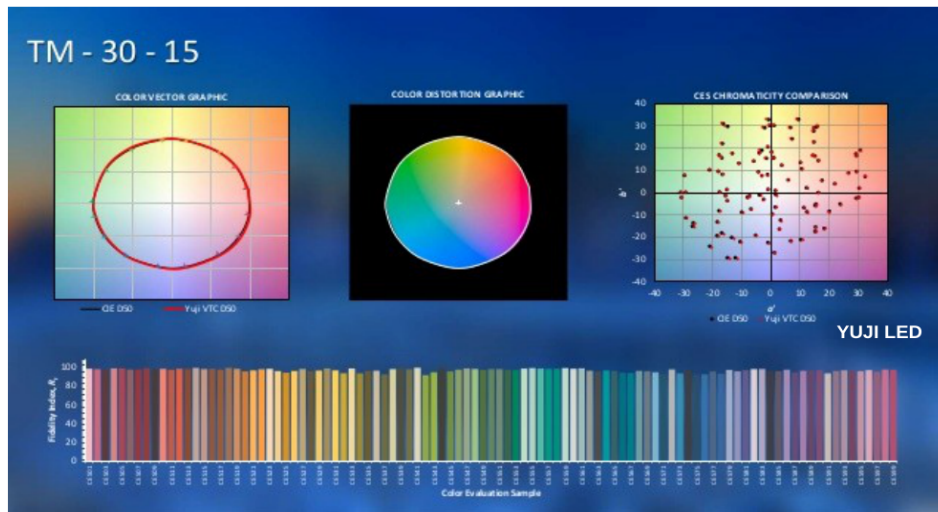


Presentation slide 13: GAI and polygon area.

- GAI may exceed 100 because its scale represents relative area.
- GAI and TM-30 Rg use different sample sets and calculation methods. Do not treat the numbers as interchangeable.

A broader method

TM-30 assesses 99 colour evaluation samples and reports several related measures and graphics. The familiar starting points are Rf for average fidelity and Rg for relative gamut.



To obtain maximum benefit from TM-30, one must move beyond a higher-number-is-better mentality; the best source depends on the needs of the application,.

IES TM-30-15 documents a calculation procedure; it does not specify criteria (i.e., minimum values) for any measure or stipulate how the measures should be applied.

Presentation slide 15: an example TM-30 report.

- The original presentation discusses TM-30-15. Current project reports should state the edition; TM-30-24 is available.
- A report is more informative when its graphic and hue detail accompany Rf and Rg.

R_f, R_g and the graphic

R_f summarizes average colour fidelity. R_g summarizes average relative gamut. The colour vector graphic shows how changes vary around the hue circle.

IES **TM-30-15** is a new system of several related measures and graphics that can be used together to effectively evaluate and communicate a light source's color rendering properties.

The development of the method involved

- A. Synthesizing multiple related research efforts.
- B. Combining ideas into a single, **cohesive system of objective information to select the preferred light source for a given application**
- C. Evaluating the tradeoffs between efficacy and color rendering.

TM-30-15 is a method of evaluating color rendition. It comprises three primary components:

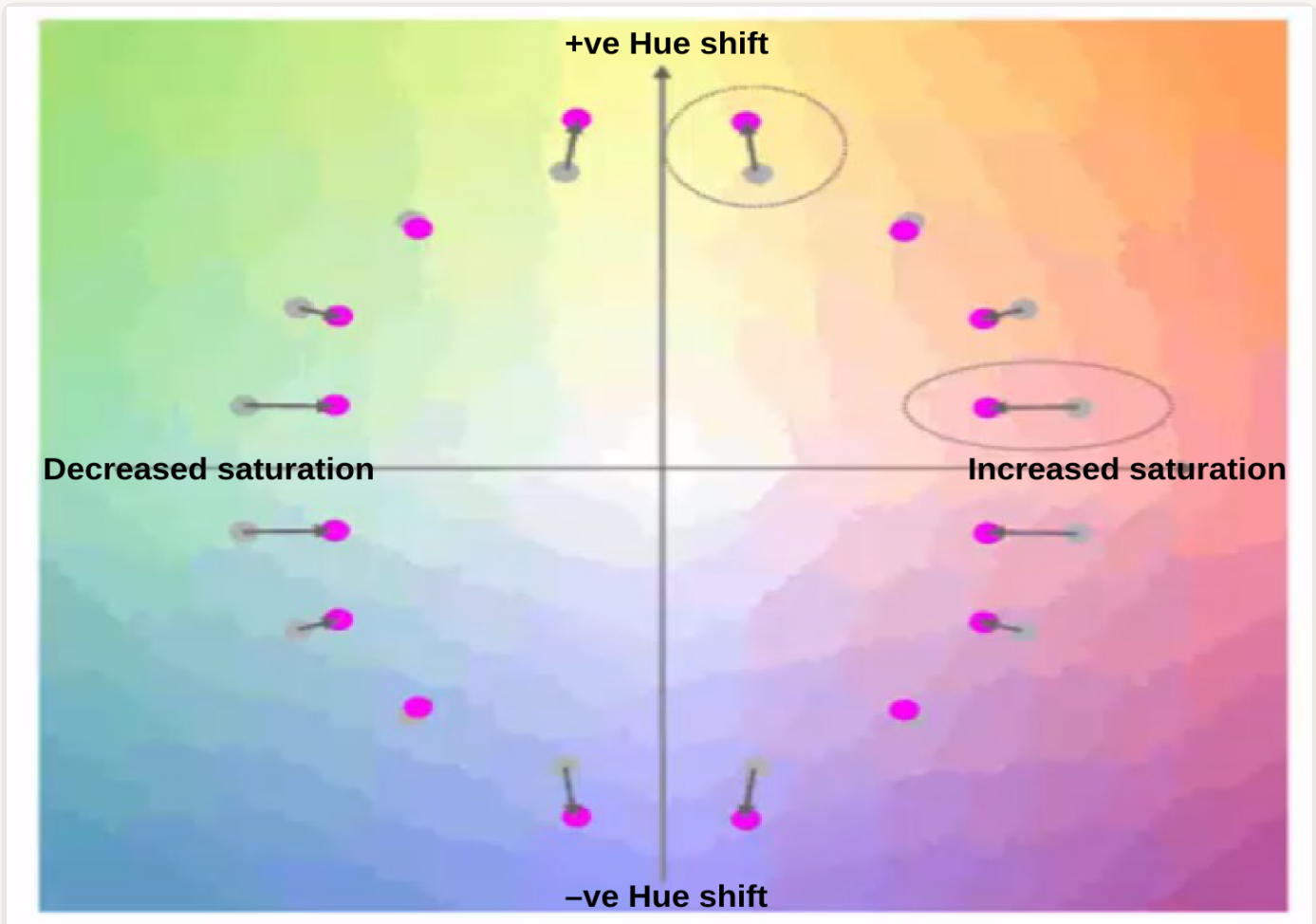
1. R_f- a fidelity index that is similar to the commonly used CRI
2. R_g- a gamut index that provides information about saturation
3. Color vector graphic- a graphical representation of hue and saturation relative to a reference source.

Presentation slide 16: overview of the TM-30 method.

- High R_f does not ensure every hue remains unchanged.
- Two sources can have similar R_g and change different colours in different ways.

Direction of the change

A change in hue moves a colour around the hue circle. A change in chroma moves it inward or outward. These effects should be considered separately even when a diagram displays them together.

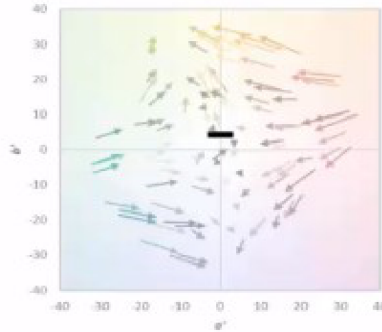
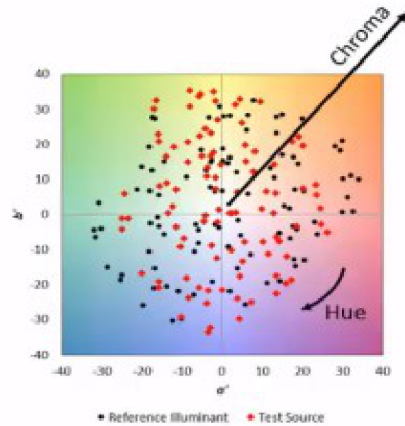


Presentation slide 17: schematic directions for hue and saturation shifts.

- The direction and location of a shift matter more than a generic claim of vividness.
- Inspect physical samples of the most important reds, skin tones, greens or brand colours.

Average versus local errors

A fidelity average can hide a conspicuous error for a narrow range of colours. TM-30 provides more detailed views of sample and hue region performance.



Average Color Fidelity

On average, how similar are colors rendered by the test source to the same colors rendered by the reference illuminant?

- Average length of arrows
- Does not capture direction of shift

TM-30 Fidelity Index (R_f)

Range is 0 to 100, where 100 is an exact match.

$$\text{TM-30-18 } R_f = \text{CIE 224 } R_f$$

This is really a sphere, but it's compressed to 2D for ease of visualization!

6/12/2018 | 19

Presentation slide 18: comparison of average colour fidelity calculations.

- Find out whether the average masks a weak result for critical materials.
- Use the detailed hue information to choose test samples for a mockup.

Reading the vectors

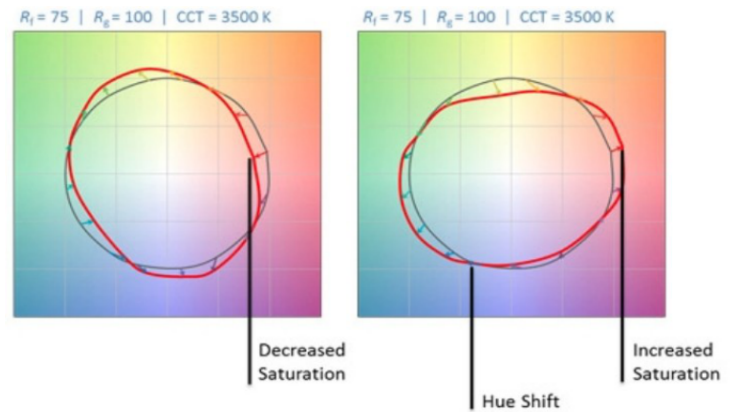
The TM-30 colour vector graphic compares the test source with the reference across 16 hue regions. Outward shifts generally show increased chroma, inward shifts decreased chroma, and tangential shifts reveal hue change.

The Color Vector Graphic is a visual representation of **hue and chroma shifts for all colors**.

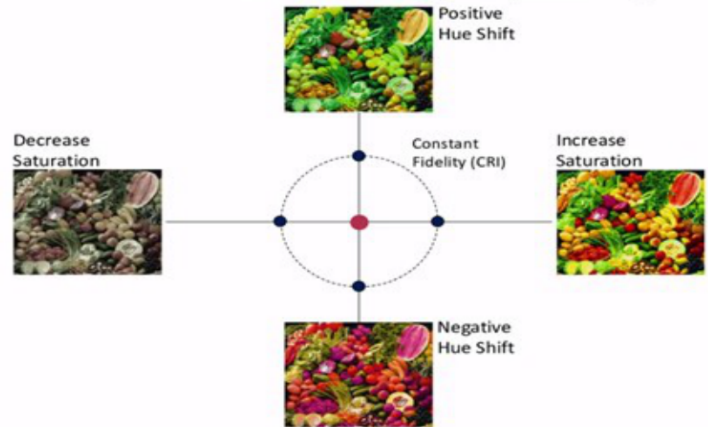
It is based on the average chromaticity coordinates calculated for the color evaluation samples in each of the 16 hue angle bins

The Color Vector Graphic **conveys what types of colors are more or less saturated** under the test light source relative to the reference illuminant and where hue shifts occur.

These specific changes are important to understanding what source will be preferred in a given application.



Limitations of considering only fidelity

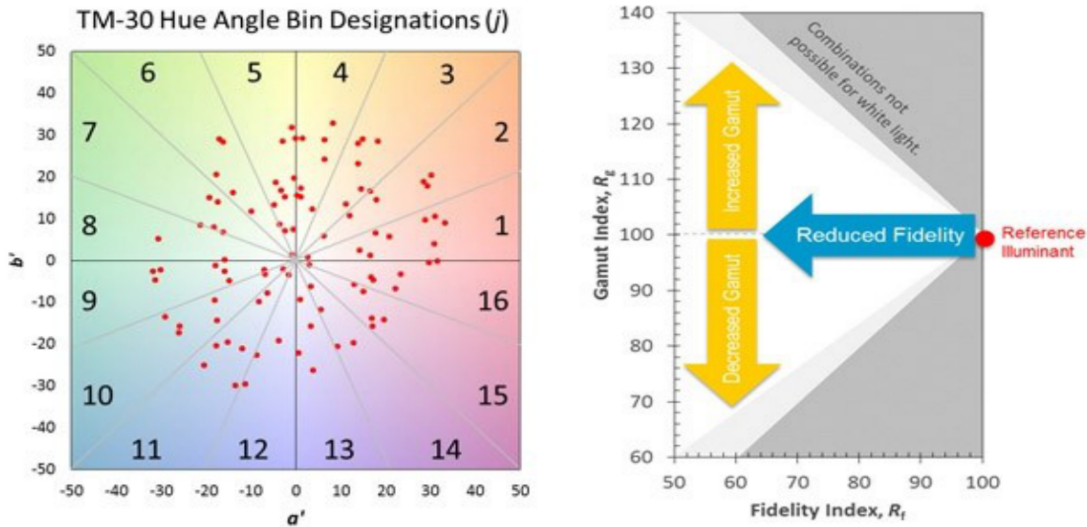


Presentation slide 19: colour vector graphic and application examples.

- Read the shape before judging the headline scores.
- The graphic describes a reference comparison; preference still depends on purpose and viewing context.

How gamut is summarized

TM-30 groups the 99 samples into 16 hue bins. Their average coordinates form reference and test polygons whose relative areas yield R_g .



R_g is the TM-30 measure for average relative gamut.

Calculating TM-30 R_g first requires the 99 TM-30 color evaluation samples to be divided into 16 bins, based on the hue angle of the object chromaticity coordinates.

The chromaticity coordinates of each sample in each bin are averaged, forming the vertices of one 16-sided polygon each for the test and reference conditions.

Although both hue and chroma shifts contribute to changes in gamut.

Values greater than 100 indicate an average increase in gamut, whereas values less than 100 indicate an average decrease in gamut.

Presentation slide 20: hue bins and fidelity-gamut relationship.

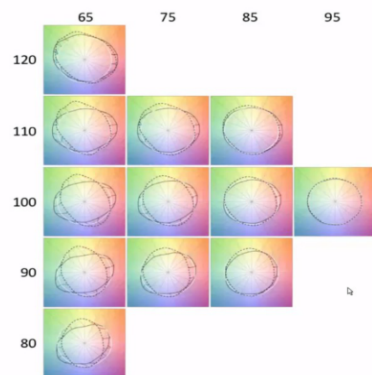
- R_g above 100 indicates a larger average relative gamut; below 100 indicates a smaller one.
- An average cannot show whether changes are concentrated in only a few hue regions.

The full report matters

TM-30 reports can include the colour vector graphic, sample fidelity, hue bin fidelity and chroma shift. A graphic selected for a slide is only one view of the underlying calculation.

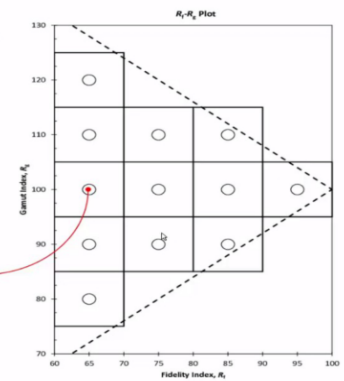
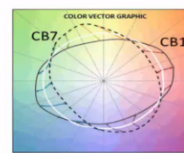
Method: CVGs

- CCT = 3500 K
- $D_{uv} = 0.000$
- E = 600 lx
- 24 spectra
- 4 R_f values
- 5 R_g values
- 2 CVG orientations (CB)



Method: SPDs

- CCT = 3500 K
- $D_{uv} = 0.000$
- E = 600 lx

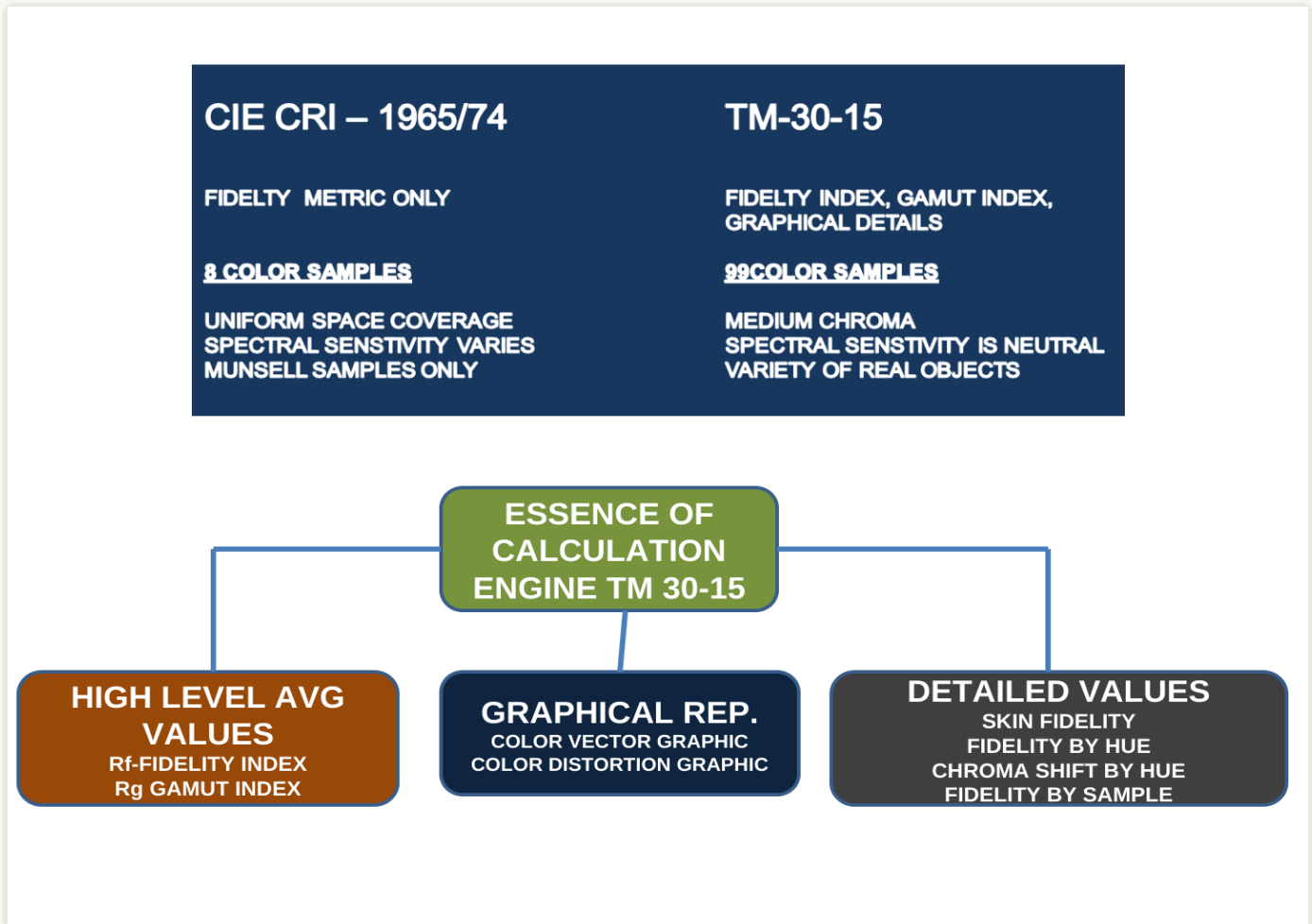


Presentation slide 21: alternative colour renderings and graphics.

- Ask the supplier for a full calculation report and measured SPD for the actual product configuration.
- Keep the model, CCT, drive condition and test method tied to the report.

A hierarchy of evidence

A fast screen begins with Rf and Rg. Deeper comparison looks at the vector graphic and detailed sample or hue data. A final decision returns to actual materials in the space.

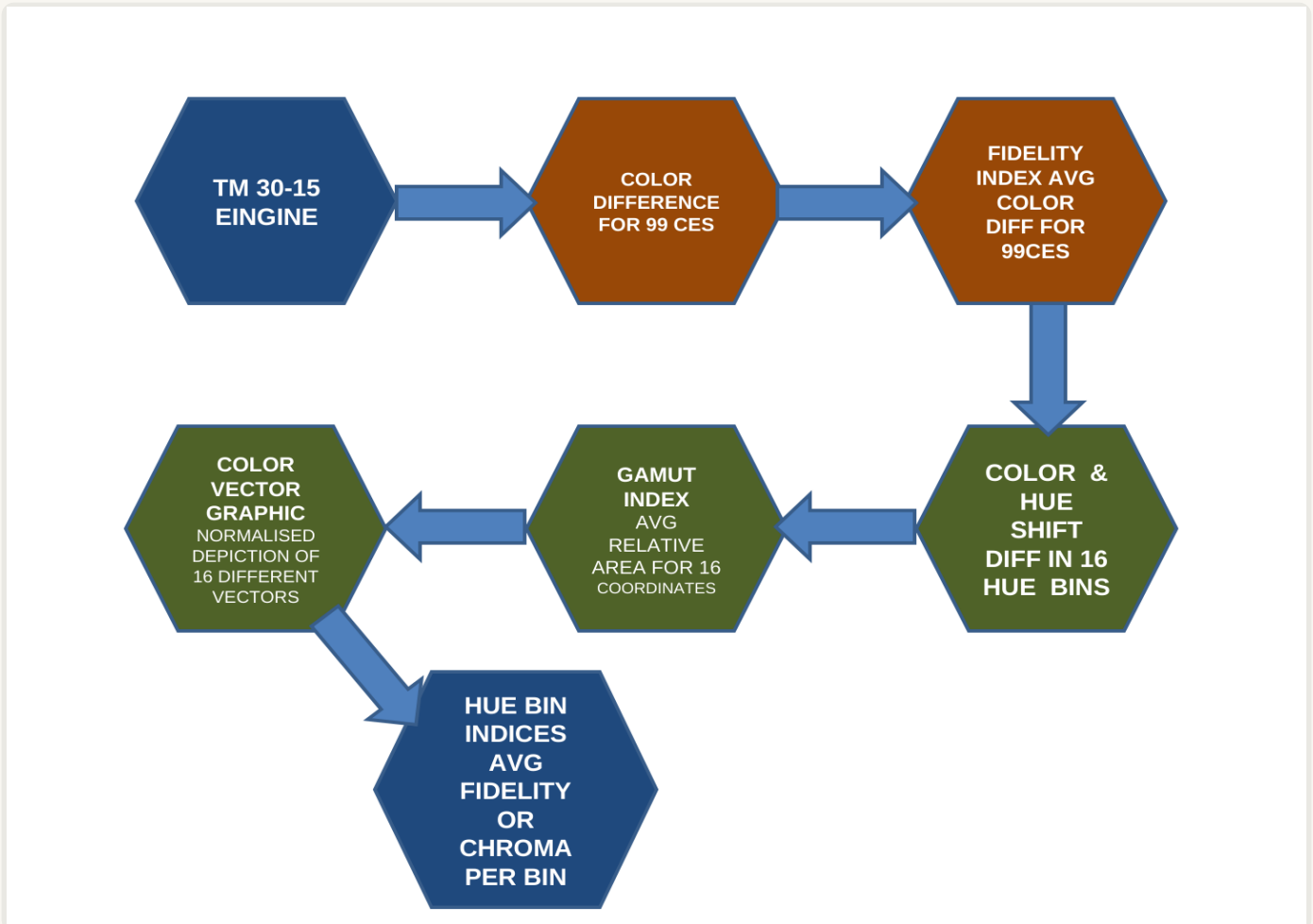


Presentation slide 22: hierarchy of TM-30 information.

- A single “best” number cannot substitute for a stated design intent.
- Document the observations and the product configuration approved in the mockup.

From samples to outputs

TM-30 compares the calculated appearance of each evaluation sample under test and reference sources, then summarizes differences as indices and graphics.



Presentation slide 23: flow from colour differences to fidelity, gamut and vector graphics.

- The calculation translates measurements into comparable information.
- It does not choose a fixture, beam distribution or illuminance for the building.

Preference, vividness, fidelity

The presentation introduces TM-30 Annex E. Its recommendation framework groups common aims into preference, vividness and fidelity, with different priorities.

**Introducing TM-30 Annex E:
Recommendations for Specifying Light Source Color Rendition**
[Published Summer 2019]

Decision Framework:
Design intent/goal
Priority level
Objects being illuminated
Illuminance level
Hue stability requirements
Uncertainty tolerances
Viewing population age/culture
Viewing conditions
Practitioners' discretion

Design Intent
The desired effect of color rendition on the illuminated environment.

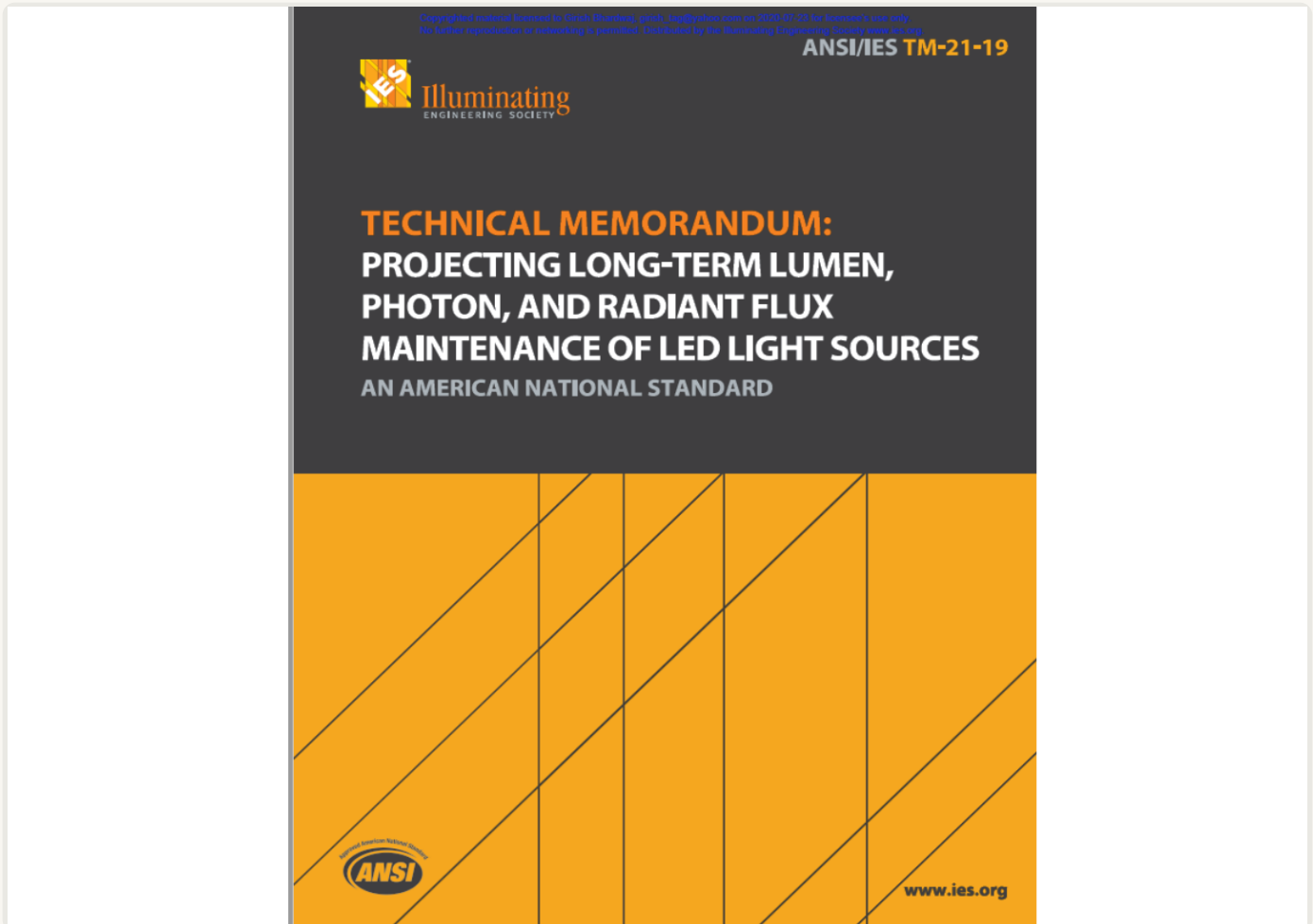
		Design Intent				
		Preference (P)	Vividness (V)	Fidelity (F)		
Priority Level The balance between allowing for tradeoffs and increasing the likelihood of meeting the design intent.	1	P1	$R_f \geq 78$ $R_g \geq 95$ $-1\% \leq R_{cs,h1} \leq 15\%$	V1 $R_g \geq 118$ $R_{cs,h1} \geq 15\%$	F1 $R_f \geq 95$	
		2	P2	$R_f \geq 75$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$	V2 $R_g \geq 110$ $R_{cs,h1} \geq 6\%$	F2 $R_f \geq 90$ $R_{t,h1} \geq 90$
			3	P3	$R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$	V3 $R_g \geq 100$ $R_{cs,h1} \geq 0\%$

Presentation slide 24: Annex E recommendation framework as shown in the source.

- Start with the visual purpose and use the relevant edition of IES guidance for criteria.
- For conservation or colour matching, preserving fidelity may matter more than making colours appear more vivid.

Performance over time

LED output may change during operation. A projection of long-term luminous, photon or radiant flux concerns maintained output; it does not by itself establish maintained colour appearance or retained TM-30 results.



Presentation slide 25: cover of a technical memorandum on long-term LED output maintenance.

- If a project depends on stable appearance, request available colour maintenance and chromaticity shift data alongside output maintenance.
- Ask how operating temperature, drive current and dimming affect the installed system over its service life.

A short brief for the project team

Use this checklist when colour appearance affects a purchase decision.

01 Identify critical colours

Name the finishes, products or objects whose appearance has to be protected.

02 Request complete source data

Collect SPD, CCT, Duv, CRI and TM-30 Rf, Rg and colour vector graphic. Record the report edition.

03 Set a project intent

Decide whether close reference fidelity or a particular controlled increase in saturation best serves the space.

04 Mock up at real conditions

Use the intended luminaire, beam, mounting position, dimming level and surrounding materials.

05 Approve by observation

Bring the end user and specifier together to compare the actual samples. Document the agreed result.

Terms and source notes

CRI / Ra	Traditional general colour rendering index. Ra averages eight test sample indices.
CCT	Correlated colour temperature, a descriptor of a white source's chromaticity.
SPD	Spectral power distribution, the light source output across wavelengths.
Duv	A measure of chromaticity displacement from the Planckian locus.
GAI	Gamut Area Index, a relative gamut measure derived from eight traditional test colours.
TM-30 Rf / Rg	Fidelity and relative gamut measures calculated from 99 colour evaluation samples.

Figures are reproduced from the presentation “GRB SS CRI GAI.ppt” supplied by Girish Bhardwaj. The educational prose has been reorganized and corrected where needed. Figures may include labels from the original presentation and are best read alongside the updated explanation in this edition.

Further reading: CIE 13.3-1995, Method of Measuring and Specifying Colour Rendering Properties of Light Sources; ANSI/IES TM-30-24, Method for Evaluating Light Source Color Rendition; IES, Using TM-30 to Improve Your Lighting Design ([ies.org/fires/using-tm-30-to-improve-your-lighting-design/](https://www.ies.org/fires/using-tm-30-to-improve-your-lighting-design/)).



THE COLOUR QUESTION

What will this light do to the colours that matter in your space?

A guide to reading CRI, gamut and TM-30 with the materials, people and purpose of a building in view.

GIRISH BHARDWAJ