Investigation of Color Rendering Performance Indicators for Lighting Systems

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Problem

Determine what level of knowledge is available regarding the correlation of spectral power distributions and color rendering indices, knowing the existing problems with the CIE's recognized Color Rendering Index (CRI) metric.

Why: NASA has historically used CRI as a metric to define the acceptable color rendering environment a lighting system provides. Industry has determined this metric is not accurate for solid state lighting systems, but has not provided a better "recognized" metric. The usage of this metric could give the false impression of a lighting system that "passes" the CRI requirement but fails to render colors in the environment properly, possibly leading to task performance failures on critical color matching tasks.

Examples of Color Critical Tasks

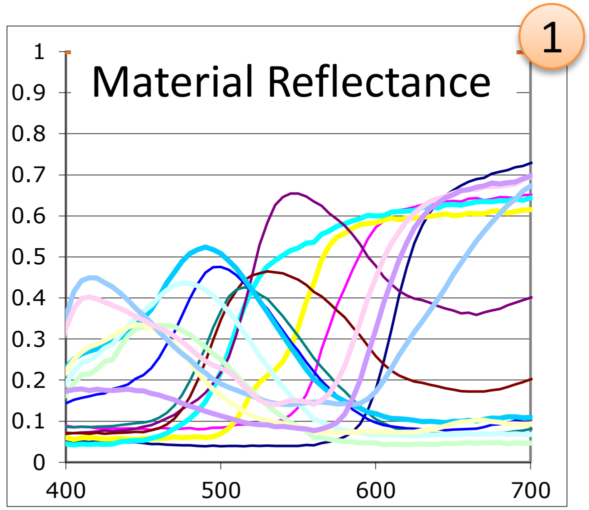
- Examination of purity of water: NASA-STD-3001, Volume 2, 6.3.1.3. Reagent in test absorbs light at the following wavelengths: 430nm, 455nm, 480nm, 510nm. If a light source does not produce light at these wavelengths, the color of the reagent will look different.
- Colored Indicators:
  - Hatch Cover Pressure Indication: NASA-STD-3001, Volume 2, 8.4.3.3
  - Mobility Aids: NASA-STD-3001, Volume 2, 8.5.6
  - Hardware Mounting: NASA-STD-3001, Volume 2, 9.5.1
  - Incorrect Mating, Demating Prevention: NASA-STD-3001, Volume 2, 9.5.2.3
  - Cable Identification: NASA-STD-3001, Volume 2, 9.6.2
  - Display Standards & Icon Library: NASA-STD-3001, Volume 2, 10.1.3.3
  - Display-Control Relationships: NASA-STD-3001, Volume 2, 10.2.3.1
  - Caution & Warning Colors (Red/Yellow): NASA-STD-3001, Volume 2, 10.7.2.5-6
  - EVA Mobility Aid Standardization: NASA-STD-3001, Volume 2, 11.1.2.3
- Lighting Color shall be compatible with tasks: NASA-STD-3001, Volume 2, 8.7.4

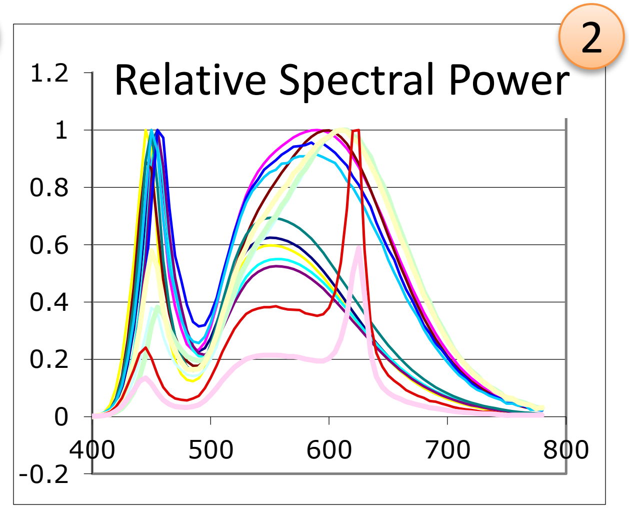
The Fingerprint of Color

- Humans and camera systems see color because of how their respective optical systems are designed.
- Both the human eye and color cameras have a visual response that is enhanced at certain wavelengths and intensities of light.
- The varying intensity of wavelength, across the visual spectrum, emitted or reflected off a surface is called the Spectral Power Distribution (SPD).
- The SPD is the unique fingerprint of a color. Any other method to define color could result in many surfaces or light sources that qualify for the same color definition.

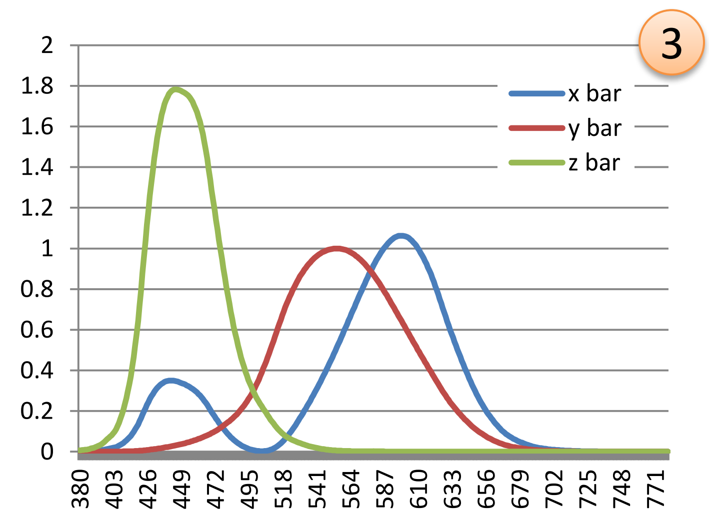
Spectrum

- For a person or camera to see color, there must be a light source and there must be a material that either absorbs or reflects light.
- Both the light source and the material have a characteristic spectral response. The product of these two spectrums, and the vision system's spectral response determine the final color a vision system sees for a specified color space.





1. Variety of spectral reflectance curves for a sampling of colored materials.
2. Variety of relative spectral power curves for a sampling of light sources.
3. Human visual response forcing functions.



Color Space & Color Rendering Metrics

- A color space is a 2 dimensional or 3 dimensional representation of a color gamut.
- The design of the color space is application specific (seeing, lighting, printing, displaying color).
- Major color spaces are the CIE 1931, CIE 1976, CIELAB.
- Color system for printed materials: Munsell
- Color Vision Tests: Farnsworth-Munsell 100 Test
- Metrics: Color Rendering Index, Color Quality Scale, Full Spectrum Color Index, and more…

Color Rendering Index (CRI)

- CRI is the symbol for the CIE's Test Color Method. It is the industry standard for describing the quality of the color rendering environment a light source produces.
- It was developed in 1965 and has had several revisions.
- It has multiple limitations, not only because of the level of lighting technology it is based on, but the level of understanding of color theory when it was originated.
- The standard is based on unsaturated test colors. It is been shown that good scores on unsaturated colors does not necessarily produce good color rendering of saturated colors, especially for solid state light sources.
- It is a difficult metric to eliminate because it is part of the lighting manufacturer's design, fabrication, and verification process.
- Departing from CRI would be a major cost impact to manufacturers and could cause previously "good" lamps to be reclassified as "not-so-good".
- There is a strong financial incentive not to change.

TCS01
TCS02
TCS03
TCS04
TCS05
TCS06
TCS07
TCS08

The reflected spectrum of each of these samples is applied against the test light. The final color is compared against a "perfect" light source closest to color temperature. The color difference generates a "R number". The value of each R number is averaged to produce Ra = CRI.
A perfect CRI = 100.

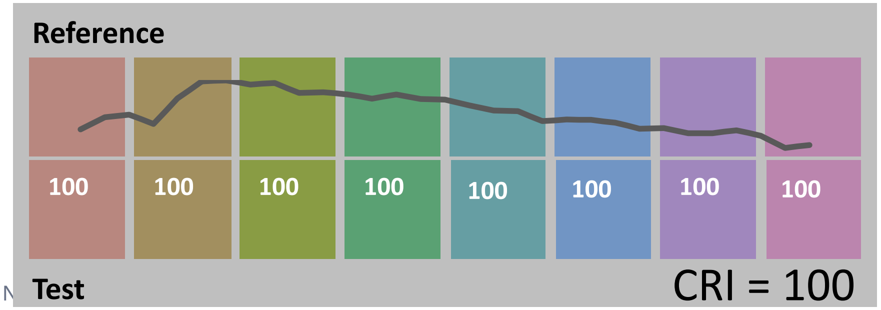
TSS09 thru 14 are supplementary. Their R numbers are not part of the CRI average. However a negative R value for TSC09 renders skin color as "unnatural".

TCS09
TCS10
TCS11
TCS12
TCS13
TCS14

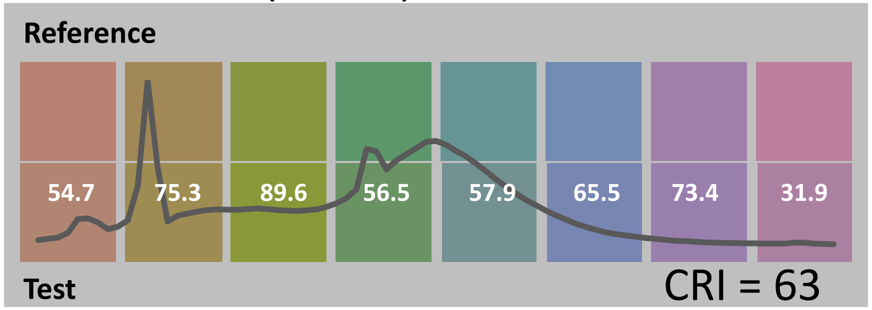
Understanding CRI

- CRI consolidates information to an average value. While this is useful for a fast track manufacturing and test program, useful information is lost to most users.
- Because, light sources have different intensities across the visual spectrum, certain colors may look better than others.
- It is possible for a light source with a "good" CRI, to render a critical color poorly.
- Don't let individual colors fool you, the light impacts the color of the entire environment!

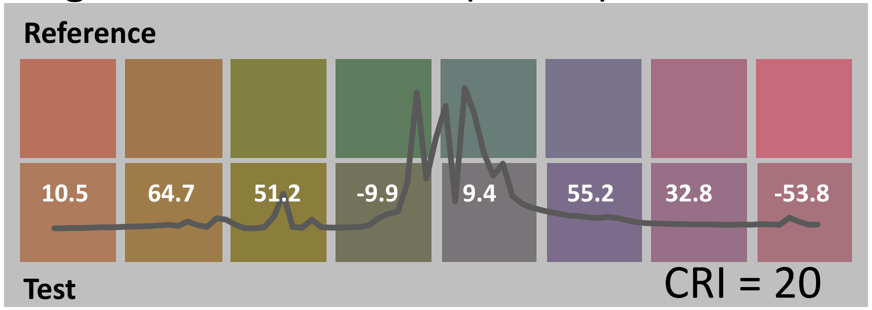
CIE D65 (6500K sunlight-daylight equivalent)



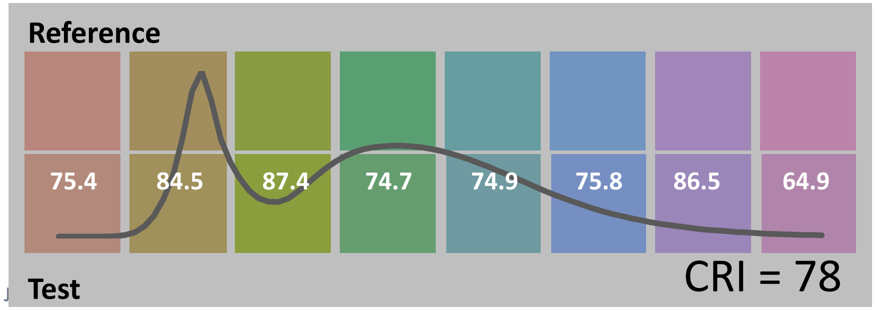
Fluorescent (4290K)



High Pressure Sodium (2000K)

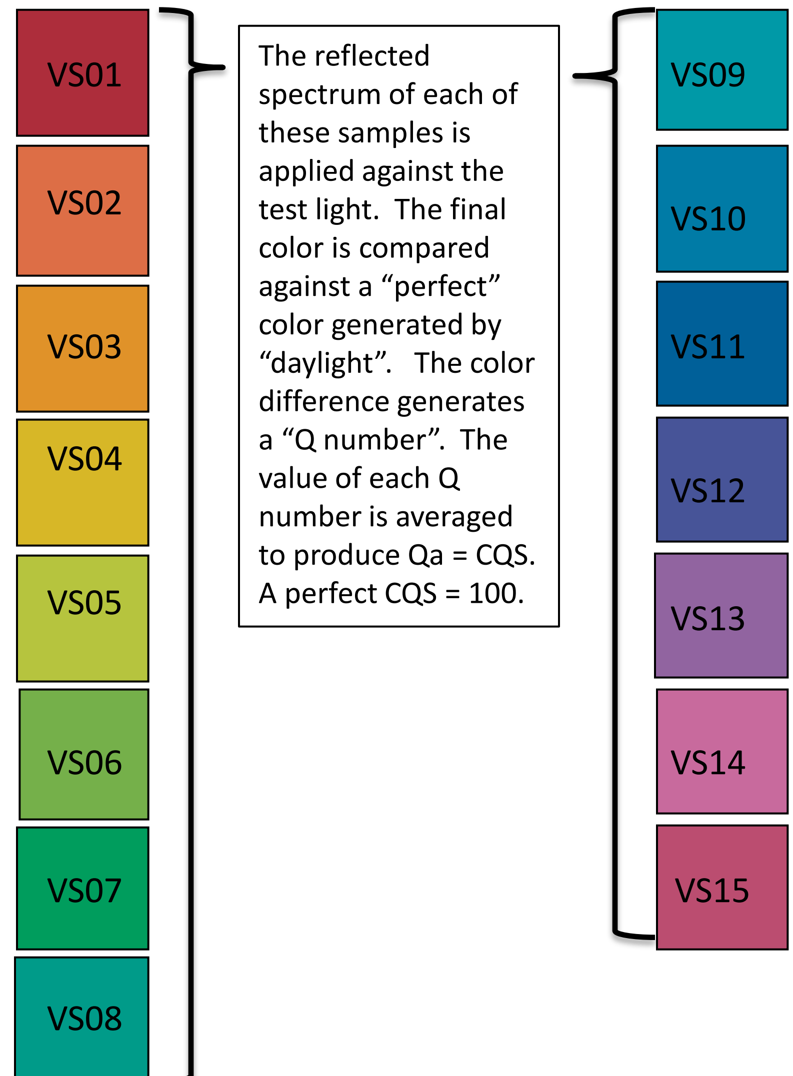


White Phosphor LED (6000K)



Color Quality Scale

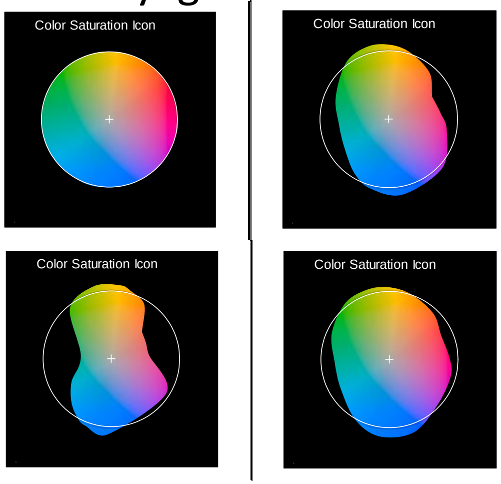
- The Color Quality Scale (CQS) was developed by Dr. Yoshi Ohno, of the National Institutes of Standards and Technologies (NIST), in 2010 to address problems with CRI and disconnects between how people viewed an LED lit environment and CRI scores for LED based lighting systems.
- The system, like CRI, uses reference colors, but an increased number to represent the visual spectrum.
- The colors are saturated on purpose because it was determined that the deviation in the appearance of saturated colors was more realistic for human perception of color and it also worked better with narrowband LED light sources.
- The CQS also has the advantage that the sample colors have a consistent chroma and thus patterns in the reshaping of the CQS color gamut due to the test light can be observed.
- The CQS uses root-mean-square averaging to penalize a light source that excessively changes the color of one or more of the test samples.



Understanding CQS

The CQS has some major advantages over CRI. The system gives a better understanding of the color shifts for the environment. The colors, when plotted to a color space, where "perfect" defines a circle, shows patterns in color rendering deficiencies due to the light source.

D65 Daylight | Fluorescent



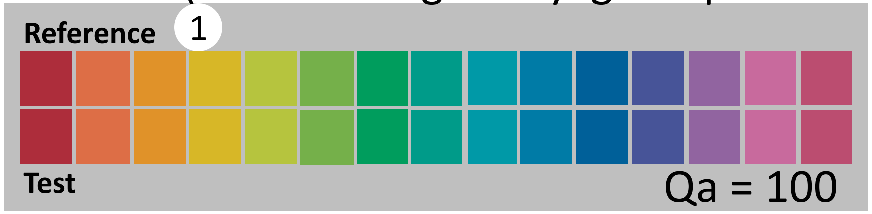
HPS | LED

Color Saturation Icon from Yoshi Ohno's CQS Excel Worksheet, rev 9

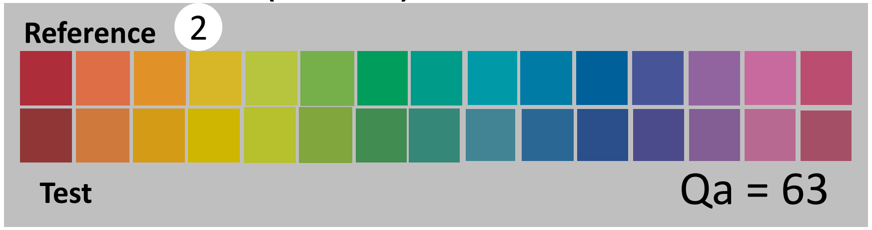
Scores

Q	1	2	3	4
1	100	38	8	65
2	100	58	32	76
3	100	60	49	73
4	100	77	80	83
5	100	94	76	93
6	100	76	54	86
7	100	62	25	78
8	100	60	30	70
9	100	60	36	67
10	100	57	40	59
11	100	60	52	65
12	100	84	90	89
13	100	71	41	85
14	100	68	42	84
15	100	54	26	75

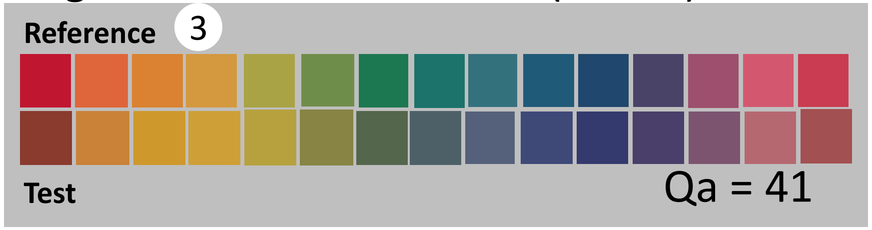
CIE D65 (6500K sunlight-daylight equivalent)



Fluorescent (4290K)



High Pressure Sodium HPS (2000K)



White Phosphor LED (6000K)

Full Spectrum Color Index

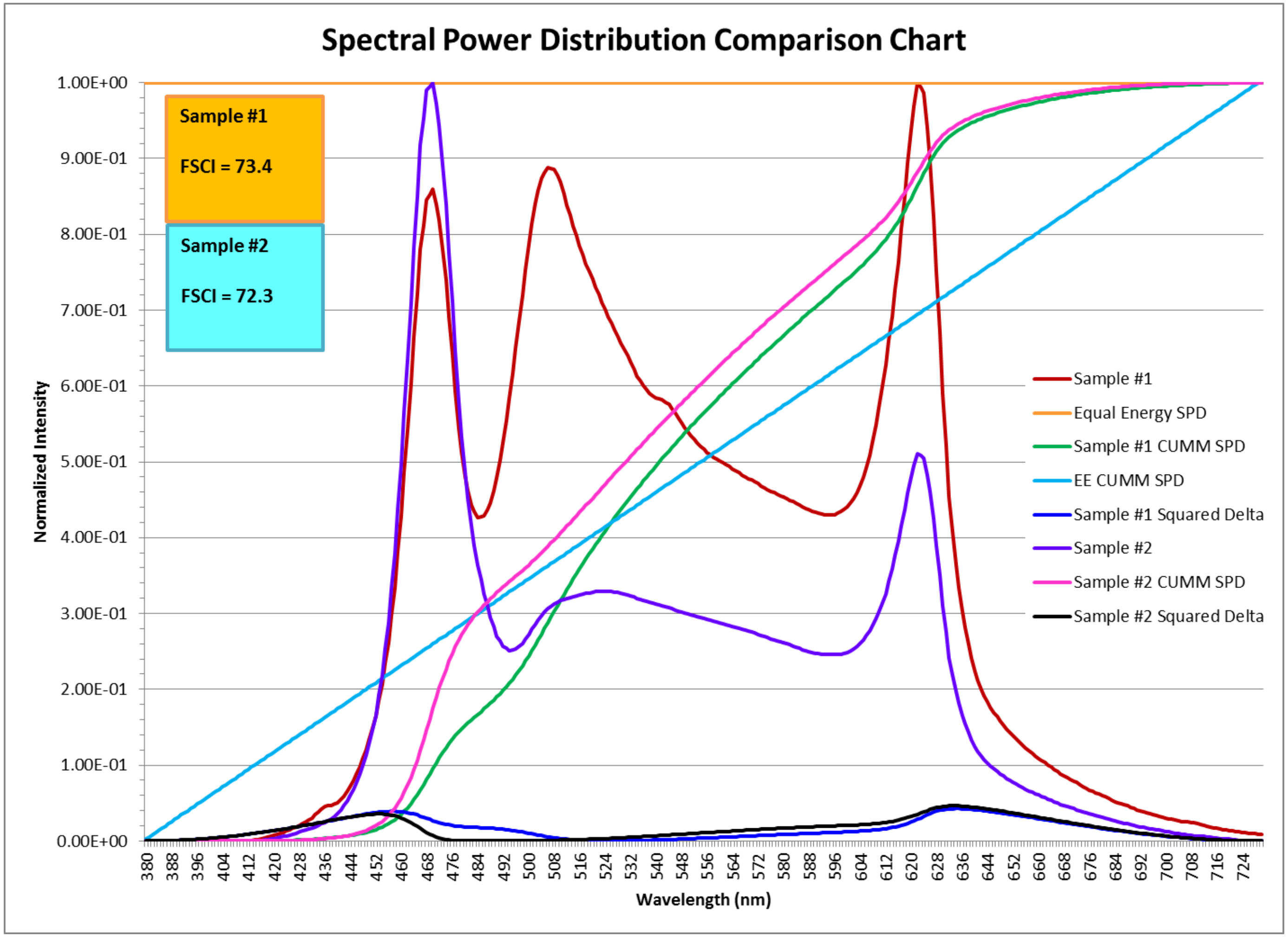
FSCI uses a method where the spectrum (SPD) is manipulated to generate a cumulative sum SPD of both the reference and the sample.

The square of the delta at each wavelength for both waveforms is computed.

The resulting waveform is then arranged to form a periodic waveform.

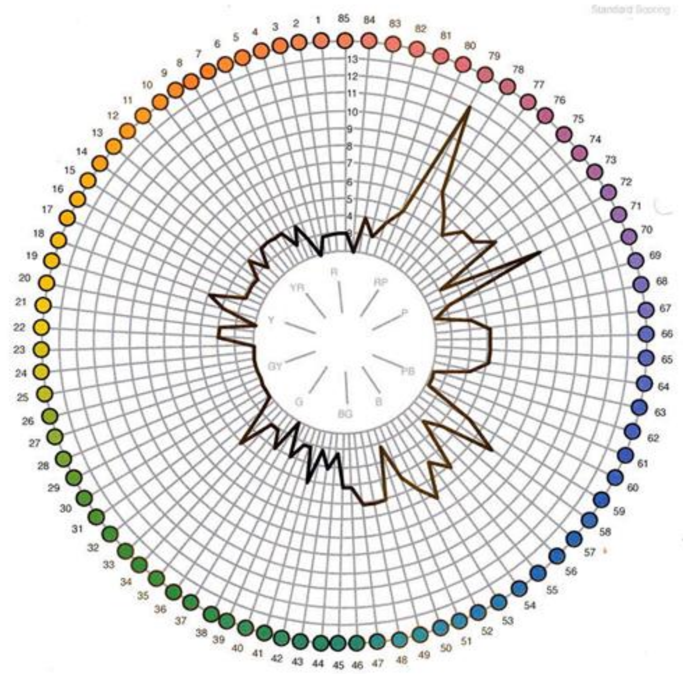
A moving sum the periodic squared SPD, where the number of elements is the number of wavelength increments.

The moving sum is then averaged to ultimately generate the FSCI.



The Farnsworth-Munsell 100 Test

- The Farnsworth-Munsell 100 (FM100) test was developed 1943 by Dean Farnsworth.
- The test utilizes 100 color chips that represent a constant unsaturated chroma from the Munsell color system.
- The colors are unsaturated by design to minimize outsmarting the test.
- The test requires a human in the loop.
- The test subject must take a set of unorganized color chips and arrange them in linear fashion in increasing hue (like a rainbow).
- The test looks for matching errors where the test subject did not correctly locate the color chip(s) in the correct order.
- Pending on the errors, the test results will indicate good color vision, or define the extent of the test subject's color blindness for a gamut of colors.



Graphical results from a FM-100 test. The image shows how variations in color vision affects how accurately the test subject recognizes colors. The farther away from center, the more errors were made in arranging the colored chips. *Image courtesy: Dr. George Brainard, Thomas Jefferson University.*

What Color Is It?

- For all of these metrics, it all boils down to one question. "What color is it?"
- Any proposed method we use, needs to be able to predict the accuracy of color rendering of the vision system in question.
- There may be more factors at play that influence the design of the colored materials and the lighting system.
- Factors that may not play well together are:
  - System lighting power constraints (the more full spectrum the more power usage)
  - Circadian Entrainment Countermeasures (heavily blue or red enriched light will skew the appearance of a color)
  - Architectural materials selection (driven by project or behavioral health requirements, impact the total reflected spectrum within a space)
  - Camera lighting constraints (camera color vision requirements only drive the requirement to take good pictures or recognize images for automation, while human color vision impacts performance, and perception of the environment).
  - Crew age and gender (age and gender create variations in color perception that can't be captured in standard instrumented tests)

Requirements & Verification

- The requirements and verification of task performance with regards to color should impact both the specification of colors for an environment and the specification of the lighting system for an environment.
- If certain critical colors are already defined and are not easily changed (such as colors that are result of a chemical process like urine analysis), then the lighting system should have requirements to ensure the required colors are discernible. This may be accomplished by writing requirements that define allowable deltas in a color space, such as CIELAB, for critical colors.
- If colors for a specific task are being introduced to a lighting environment where the lighting system is already designed or too expensive to change, colors should be chosen that have the least deviation under the operational lighting environment for that task.
- The color vision requirements for both humans and critical camera systems should be considered as driving factors for the selection of lighting for an environment.

Proposed Method: Lighting & Materials Database

- The CIELAB color space, combined with the standard reflectance and metrics of the CRI and CQS system offer a comprehensive method of evaluating the full spectrum impact of a lighting system.
- Additionally, any reflectance spectrum can be evaluated against a proposed lighting system spectrum to predict color shift for a characterized vision system (like the human observer).
- Pass/Fail criteria pending on performance requirements that can be related to color shifts or Just Noticeable Difference (JND) criteria can be established.
- Propose a comprehensive lighting and materials database could be established to provide a tool for the development and verification of lighting and color systems for operational environments.

Final Recommendations

- Development of a Lighting & Materials database will improve the reliability of requirements for lighting and color systems to work properly for their applied environments.
- Additional study on NASA human based color critical tasks to determine margin of failure will help define allowable color shift.
- Additional study on the usability and behavioral health impacts on the appearance of colors within an environment is necessary to determine programmatic pass/fail criteria for the color spectrum of a light source and allowable colors for the selection materials for a proposed architecture. This study needs to determine at what point crew behavior and mental health is impacted by the colors in their overall environment.
- Studies need to separate the influence of circadian entrainment from the appearance of a environment to establish clear boundaries on the impact of color or spectrum based requirements.

References

Many references were reviewed to investigate current knowledge on the issue of understanding how a light source's spectrum impacts color perception and metrics that can be used to classify the usability of a light source with respect to the accuracy of color perception. Following is a list of those references.

#	Reference Source
1	"A Two-metric Proposal to Specify the Color-rendering Properties of Light Sources for Retail Lighting", Jean Paul Freyssiner, Mark Rea, Poc. SPIE Vol. 7794-77840V, Copyright SPIE 2010
2	"Applications Note, Insight on Color, CIE L*a*b* Color Scale", http://www.hunterlab.com
3	"CMC 2000 Chromatic Adaptation Transform: CMCCAT2000", Changjun Li, M. Ronnier Luo, Bryan Rigg, Robert W.G. Hunt, Color Research and Application, Vol. 27, Number 1, February 2002
4	"Color Quality Scale"; Wendy Davis, Yoshi Ohno; Optical Engineering 49(3) March 2010
5	"Color Rendering : Beyond Pride and Prejudice" M.S. Rea, J.P. Freyssiner, Color Research and Application, Vol 35, No. 6, Dec 2010
6	"Color Rendering Properties of LED Light Sources", Nadarajah Narendran, Lei Deng; Solid State Lighting II: Proceedings of SPIE, Copyright 2002 Society of Photo-Optical Instrumentation Engineers.

References Continued

#	Reference Source
7	"Color Rendering: A Tale of Two Metrics", M. S. Rea and J. P. Freyssiner-Nova, Color Research and Application, Vol 33, Number 3, June 2008
8	"Hue Sensibility to Dominant Wave-Length Change and the Relation Between Saturation and Colorimetric Purity", Dorothy Nickerson, Walter C. Granville, Journal of the Optical Society of America, Volume 30, April 1940, pp 159-162.
9	"Visual Sensitivities to Color Differences in Daylight", David MacAdam, Journal of the Optical Society of America, Vol. 32, No. 5, May 1942.
10	A Practical and predictive two-metric system for characterizing the color rendering properties of light sources used for architectural applications", Mark S. Rea, Proc. SPIE 7652: 765206, Copyright SPIE 2010.
11	ANSI_ANSLG C78.377-2011, American National Standard for electric lamps, "Specifications for the Chromaticity of Solid State Lighting Products".
12	ASTM D1209-05, Standard Test Method for Color of Clear Liquids (Platinum-Cobalt Scale)
13	ASTM D1535-12a, "Standard Practice for Specifying Color by the Munsell System."
14	ASTM E1499-97, "Standard Guide for Selection, Evaluation, and Training of Observers".
15	Illuminating Engieneering Society, The Lighting Handbook, 10th ed., 2011, Illuminating Engineering Society of America
16	NASA/SP-2010-3407, Human Integration Design Handbook
17	NASA-STD-3001, Vol. 2, NASA Space Flight Human System Standard, Sections 5.1, 6.3.1.3, 8.4.3.3, 8.5.6, 8.7.4, 9.5.1, 9.5.2.3, 9.6.2, 10.1.3.3, 10.2.3.1, 10.7.2.5, 10.7.2.6, 11.1.2.3,
18	"The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision", Dean Farnsworth, Journal of the Optical Society of America, Vol. 33, No. 10, Oct. 1943

Appreciation

Appreciation and thanks for go to the individuals who supported and funded this exploratory investigation on light source color spectrum. Information discovered from this research has developed a potential collaboration with NIST and has also assisted with a current NASA project to replace the ambient lighting system on the ISS.

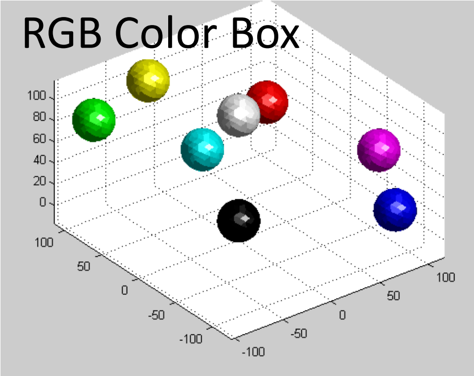
Backup Slides

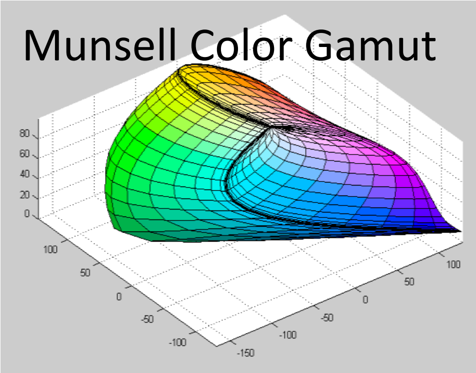
Usefulness of the FM100 Test

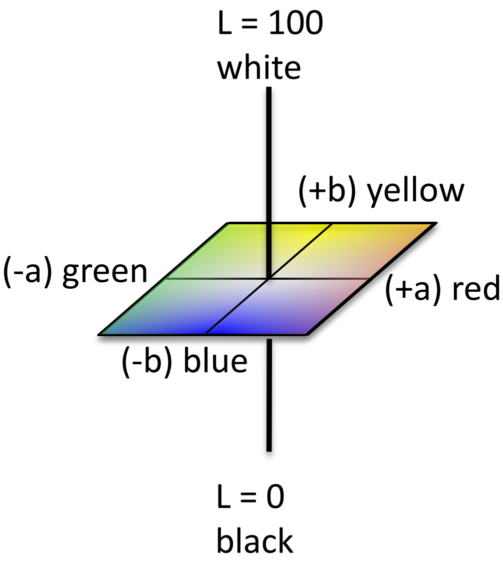
- The FM100 test is the ultimate test for determining if a light source will generate a deficiency with color vision, because it uses an actual human observer.
- The test can be run under any light source, with the scores compared to a control, made by the same test subject.
- The test subject should be an individual that is typical of the user who would be operating under the light source under test.
- If the test subject makes more mistakes than what is allowable for that specific range of colors, the light under test should not be considered for that specific application.
- Additionally, the same methods used to analyze the shift in colors for the CRI and CQS tests could also be applied to mechanically determine an unbiased evaluation of color shift to FM100 colors due to the light source under test.
- The FM100 test should be considered a required test for all crewed vehicle lighting evaluations, for light sources that may be used for critical tasks.

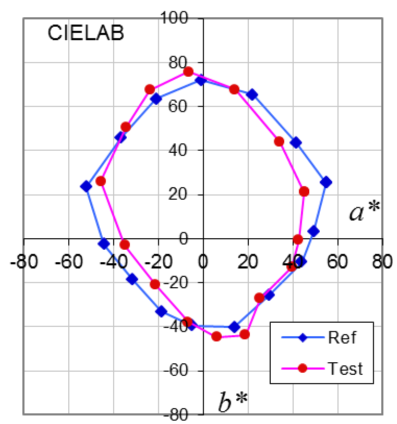
The Usefulness of the CIELAB Color Space

- The CIELAB color space is a 3 dimensional color system.
- The units are L*, a*, and b*.
- The center axis (L*) represents lightness.
- Angular displacement around the axis represents a change in hue.
- Radial increase in value from the axis indicates a change in chroma.
- For a gamut of colors, this is a useful space to observe deviations in the color of materials due to a change in light sources.
- The deviation from a “perfect” shape can be documented.
- Patterns of unacceptable deviations can be identified for critical colors.
- Deltas in chroma, hue, and lightness for a particular color can be documented and reviewed as part of a verification process.









CQS Color Gamut
(under reference and
LED test light source)

National Aeronautics and Space Administration

Full Spectrum Color Index

- CRI and CQS are examples of reference based indices for color perception. In this case, the color of the reference is designated as "perfect".
- Reference based indices, by design, allow for more than one light source spectrum to produce exactly the same "color". While this may be convenient, it does not provide insight into how the pattern of a spectral power distribution compares to the definition of a "perfect" light source.
- Spectrum based color perception indices define a "perfect" spectrum to compare sample spectrums (spectral power distribution (SPD)) to it.
- The Full Spectrum Color Index (FSCI) was developed in 2004 by M. Rea of the Lighting Research Center to address failings of CRI.
- The Full Spectrum Color Index defines an equal energy spectrum as "perfect". An equal energy spectrum is one that produces the same radiant power at all wavelengths of the visual spectrum. This approximates the radiant power of sunlight across the visual spectrum.
- The process for calculating a FSCI utilizes an average of periodic squared deltas between the equal power spectral power distribution and the light source spectral power distribution.
- This method is useful if the definition of "perfect" is broadband spectrum, and thus gives high scores to light sources that have a broad spectrum.

Considerations for More Study

- The allowable delta in color space for ISS color critical tasks are unknown.
- Currently, allowable deltas are validated by a human-in-the loop test of a specific light source instead of determining at what point the human will fail in a proper assessment.
- If it can be determined what extent of changes to a color gamut (say for a water quality test) would cause discernible increments of color to be less than a Just Noticeable Difference (JND), then human-in-the loop testing is not required, only defined deltas.
- It is not known, at this time, what acceptable overall environmental shift in color would be displeasing or distracting to the crew. This limits our ability to predict or write valid requirements regarding an ambient lighting system. At what point does the perception of the environment impact the human's ability to be satisfied in operating in that environment?