A Spectral Neutrality Index for Evaluating Neutral References

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11 March 2024

Abstract

Many imaging workflows utilize neutral reference materials for some of their operations. The neutrality of these materials is often evaluated visually or using visual based numeric methods such as CIE L*a*b* or CIECAM02. Being visually oriented, such methods are dependent on the illumination emission spectrum and the sensor's sensitivity and adaptation methods. Metameric issues can result with changes in illumination or the sensing system.

A Spectral Neutrality Index is proposed that eliminates these visual and metameric issues by evaluating neutral materials solely on the reference material's spectrum. The index is calculated for many commonly used neutral materials.

Introduction

Many imaging tasks require the use of reference materials. For example, some tasks include compensating images for lens and lighting intensity variations (i.e. flat-fielding), setting a camera's white balance, providing an image independent viewing environment, and determining a device's tonal reproduction curve, amongst others.

These reference materials are often referred to by their visual appearance; white card, gray card, gray surround, gray scale, black backing, etcetera. The common attribute of these materials is that each is also known as an achromatic, or neutral, color, defined by Wyszecki and Stiles as a "perceived color devoid of hue".[1] Hunter and Harold added more to the description as "a neutral color, such as white, gray or black, that has no hue (also termed nonchromatic)"[2]. ANSI defines that a "perceived color depends greatly on the spectral power distribution of the color stimulus, but also on the size, shape, structure, and surround of the stimulus area, the state of adaptation of the observer's visual system, and the observer's experience with similar observations."[3] By inference, if any of these attributes change, the perceived color may also change.

One popular method for assessing neutral colored materials is to use CIE L*a*b* values. In this coordinate system, Lightness is represented as L* and redness/greenness as a* and yellowness/blueness as b*. If either the a* or b* values are non-zero, the material is non-neutral. Expressing a* and b* in their cylindrical coordinate equivalents C* (chroma) and h (hue angle) make evaluating the amount of hue easier since any hue would be represented as a non-zero value for C*. The formulas that produce the C*h values are dependent on the observer and the illumination. To interpret these values requires that these conditions accompany the values, something which is often not provided, which adds uncertainty to the evaluations.

To evaluate the differences between achromatic materials and their suitability for a given task, an attribute independent of human perception and illumination is needed to calculate a metric for each material. One such attribute is the material's spectral reflectance or transmittance factors. These are measured and calculated from the material using a variety of readily available spectral measurement devices.

Method

A formula is proposed here with several goals.

1. To result in a single value, called the *Spectral Neutrality Index,* abbreviated as *SNI*, to represent the uniformity of the specimen's spectrum in the range of 0 to 100, where 100 represents a spectrum with the same value at each sampling interval and 0 is a maximally varying spectrum.

2. The formula must be independent of the illumination.

3. The formula must also be independent of the spectral response of any observer; human or machine.

4. Since the final spectral range for applying the neutral reference is unknown, the formula must use the entire available visible spectrum from 380 to 780 nm, if possible. If the entire range is not available, it should be evaluated from the full measured range.

To satisfy design goals 2 and 3, it was decided to make a formula utilizing only the spectral reflectance or transmittance factors of the material being evaluated.

The first step is to define a reference value which can be compared to the test spectrum values at each sampling interval. For a mathematically monotonic spectrum, each spectral sample value must equal all the other spectral sample values and the mean spectral response would also be equal to each spectral sample value. The first step is to calculate the mean spectral response.

$$\mu = \frac{1}{n}\sum_{i=1}^{n} R_i$$

where R_i is the spectral reflectance factor at each sampling interval *i,* and *n* is the number of spectral samples.

At this point the first attempt at a Spectral Neutrality Index formula is to sum the total deviation from the mean across the spectrum.

$$SNI = \sum_{i=1}^{n}\left(R_i - \mu\right)$$

where μ is the mean of the test specimen's spectral response.

This resulted in spectra with lower mean values getting unnecessarily higher SNI values. By dividing by the mean the results for spectra with high and low mean values can be treated more equitably.

$$SNI = \sum_{i=1}^{n}\left(\frac{(R_i - \mu)}{\mu}\right)$$

The values produced with this equation are below 1, so a scale factor is introduced to bring the values into the desired 0 to 100 range.

$$SNI = \sum_{i=1}^{n}\left(\frac{100(R_i - \mu)}{\mu}\right)$$

This improves the result toward meeting goal 1, but when responses are above and below the mean value by the same distance, they cancel each other out, producing too high an SNI value for an obviously non-uniform spectrum. By squaring the result only positive values are used and the sensitivity to minor spectral fluctuations is improved.

$$SNI = \sum_{i=1}^{n} \left(\frac{100(R_i - \mu)}{\mu} \right)^2$$

At this point the result is a total sum the average deviation is a more useful value.

$$SNI = \frac{\sum_{i=1}^{n} \left(\frac{100(R_i - \mu)}{\mu} \right)^2}{n}$$

Having squared the difference to improve minor spectral difference sensitivity, the square root is needed to bring the values within our desired 0 to 100 range.

$$SNI = \left(\frac{\sum_{i=1}^{n} \left(\frac{100(R_i - \mu)}{\mu} \right)^2}{n} \right)^{\frac{1}{2}}$$

This equation almost meets goal 1, but the values are inverted. Subtracting from 100 converts the value into the desired range.

$$SNI = 100 - \left(\frac{\sum_{i=1}^{n} \left(\frac{100(R_i - \mu)}{\mu} \right)^2}{n} \right)^{\frac{1}{2}}$$

This is the final form of the SNI equation with one adjustment to its usage. During testing it was found that this formula can be effectively used for any spectra with a spectral mean greater than 10^{-4}. Spectra below this threshold should be assigned an SNI of 100.

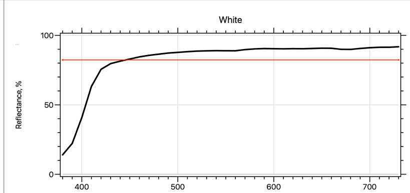
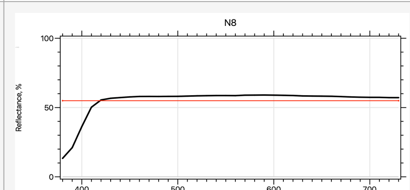
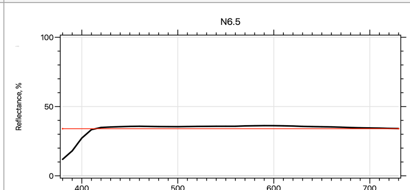
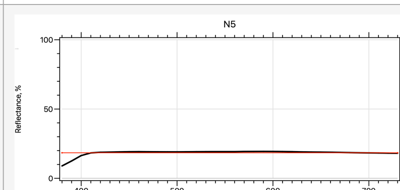
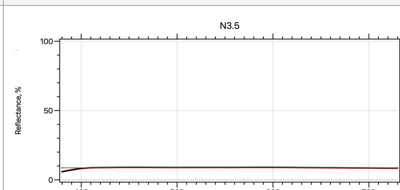
Testing

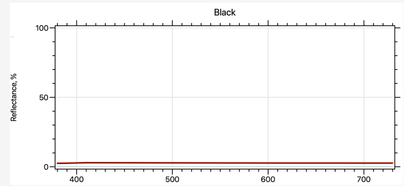
For testing the SNI formula, a set of materials was assembled consisting of real world specimens commonly used for references.

ColorChecker® Classic neutral patches

In the following spectral graphs the mean has been marked with a red line, the specimen reflectance factors in black.

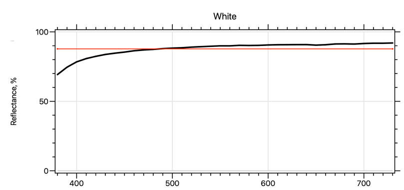
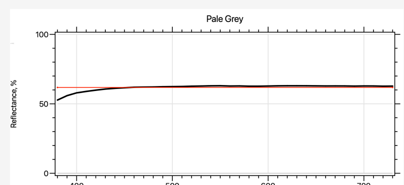
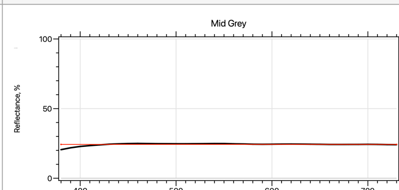
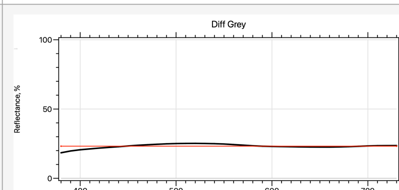
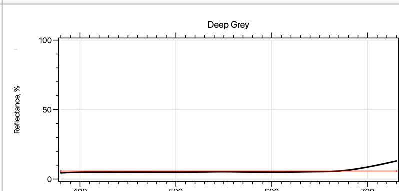
The ColorChecker® Classic (Calibrite)[4] neutral patches are painted using mixtures of a white pigment consisting of titanium dioxide and a black pigment. Titanium dioxide is the most used white pigment because it absorbs violet and ultraviolet wavelengths thus protecting the materials upon which it is applied. This absorbance causes a lower SNI the more titanium dioxide in the mixture.

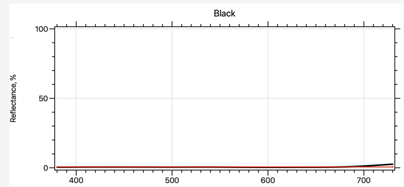
Specimen	SNI	Spectrum
White	80.04	
N8	84.11	
N6.5	87.78	
N5	91.16	
N3.5	94.74	

Specimen	SNI	Spectrum
Black	97.28	

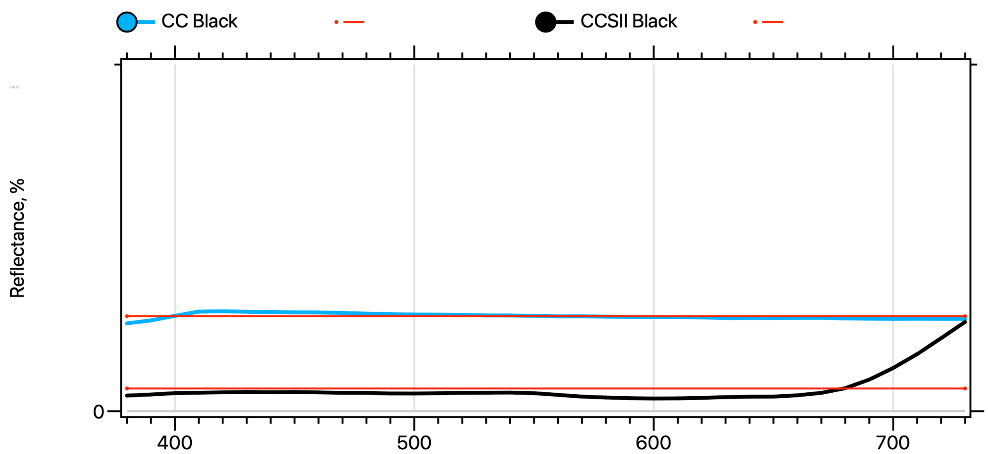
Lucideon CCSII Tiles

The CCSII ceramic tiles (Lucideon)[5] have been used for decades to calibrate spectrometers. Their appearances are due to glaze mixtures, which do not use the same as the pigments as paint so the effect on the SNI may be different.

Specimen	SNI	Spectrum
White	94.82	
Pale Grey	96.93	
Mid Grey	96.92	
Diff Grey	94.03	
Deep Grey	69.88	

Specimen	SNI	Spectrum
Black	33.22	

The SNI of 33.22 for the CCSII Black tile appears to be extraordinarily low in comparison to the ColorChecker black. Here is a graph of both spectra at 10x magnification.

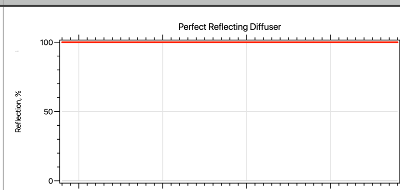


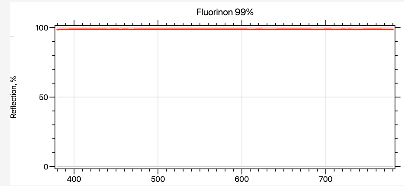
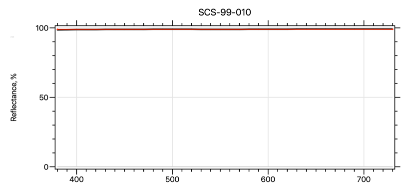
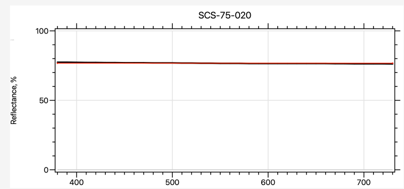
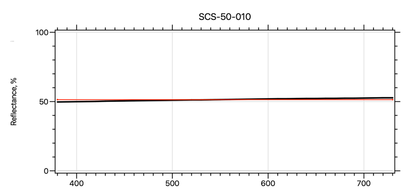
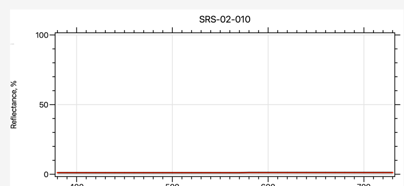
As shown in the graph, the ColorChecker Black (marked as CC Black) is much more spectrally uniform than the CCSII Black, which accounts for the CCSII Black receiving a lower SNI.

Reflectance Standards

Ideally, a perfectly neutral material would reflect all light wavelengths equally and it would have an SNI value of 100. This theoretical material is called the Perfect Reflecting Diffuser (PRD). Although there is not a real, physical material that is a PRD, a mathematical version is used in the spectrometer calibration process.

The closest material currently available that approximates the perfect reflecting diffuser, a surface that reflects all incident light uniformly in all directions, is PTFE, polytetrafluoroethylene, also known as Teflon®, which reflects 99% of the incident light. Available in a tile format with trade names such as Fluorilon® (Avian Technologies)[6] and Spectralon® (Labsphere)[7], it is used for calibrating spectrometers and cameras. It is also available mixed with a black pigment to produce visibly gray materials.

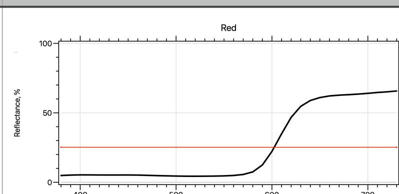
Specimen	SNI	Spectrum
Perfect Reflecting Diffuser	100.00	

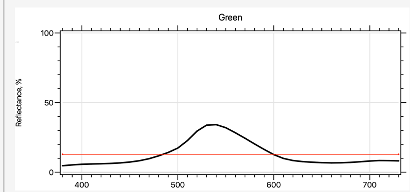
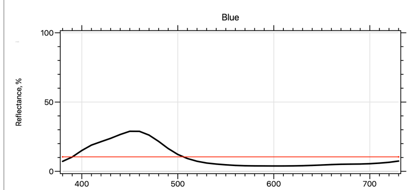
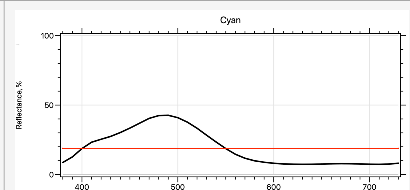
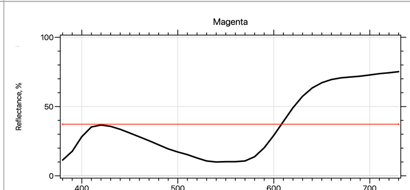
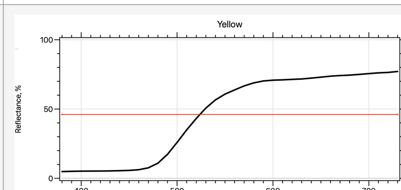
Specimen	SNI	Spectrum
Fluorilon FWS-99	99.95	
Spectralon SCS-99	99.88	
Spectralon SCS-75	99.58	
Spectralon SCS-50	98.29	
Spectralon SCS-02	95.67	

The SNI appears to be working as expected for these neutral materials. Applying the SNI to colored materials will test its utility for any material.

Colored Materials

Patches from the ColorChecker Classic can be used to evaluate the SNI applied to chromatic colors.

Specimen	SNI	Spectrum
ColorChecker Red	3.89	

Specimen	SNI	Spectrum
ColorChecker Green	31.49	
ColorChecker Blue	21.15	
ColorChecker Cyan	33.72	
ColorChecker Magenta	37.26	
ColorChecker Yellow	35.90	

The SNI has no problems working with colored material spectra. Although not shown here, the SNI formula also works with transmissive spectra.

Summary

The Spectral Neutrality Index (SNI) formula, as demonstrated here, shows that while it is insensitive to the lightness of the specimen, it is, however, sensitive to small deviations in spectral response. This makes it useful for evaluating the neutrality of various materials.

The SNI is useful for evaluating calibration materials such as PTFE, paints for viewing environments, plastics for camera calibration, filters used for light attenuation and much more.

References

1. *Color Science: Concepts and Methods, Quantitative Data and Formulae, Second Edition*, Wyszecki, R. G. and Stiles, W. S., 1982, ISBN 0-471-02106-7, page 487.

2. *The Measurement of Appearance, Second Edition*, Hunter, R. S. and Harold, R. W., 1987, ISBN 0-471-83006-2, page 391.

3. ANSI E284-22, *Standard Terminology of Appearance*, www.ansi.org, downloaded on 2024-01-05.

4. ColorChecker Classic, calibrite.com (formerly part of X-Rite).

5. CCSII tiles, www.lucideon.com/colour-standards (formerly known as BCRA).

6. Fluorilon, www.aviantechnologies.com.

7. Spectralon, www.labsphere.com.