Comparison of colorimetric data from spectroradiometers and spectrophotometers

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ABSTRACT

This study evaluates how similar spectral data is from a spectrophotometer and a spectroradiometer. Both devices had similar measurement geometries: diffuse/8° for the spectrophotometer and diffuse/0° for the spectroradiometer with the VeriVide DigiEye lighting box. A total of 60 opaque pantone samples (i.e. 30 glossy and 30 matte) were measured. CIEDE2000 was calculated to determine the difference between the data from the two devices. Results showed that both devices produce similar CIELAB values with a mean colour difference of about 2. Both devices produced mean colour difference of about 8 between glossy and opaque samples. It is unclear how perceptible this colour difference value is.

Keywords: *colour measurement, spectral data, colour difference*

INTRODUCTION

Colour is one of the most important attributes of appearance for many industries such as the fashion industry, dentistry, paints, food products, etc. Producing the 'correct' colour is critical. Established methods exist for measuring the colour of opaque, flat, and spatially uniform objects (Wyszecki and Stiles 2000). Devices such as spectrophotometers, spectroradiometers, and colorimeters are employed to take physical colour measurements. While spectrophotometers are generally considered the most 'accurate' method to measure the colour of opaque objects (Pan and Westland 2018), they are not always suitable for samples such as objects of a small size, non-planar objects, objects that are inaccessible (i.e. teeth *in vivo*), or small translucent materials. Although imaging spectrophotometers are now appearing on the market which can measure spectral data at every pixel and may help to provide a solution for some of these problems, their accuracy is untested in many circumstances.

Measuring the colour of teeth is particularly difficult due to their small size, non-planar shape, translucency, as well as being *in vivo*. One of the major issues for teeth is edge-loss, which is when light is lost via the back or the sides and is not reflected back to the sensor, producing measurement errors. In dentistry, there is a debate about which is the best way to measure the colour of teeth to combat this edge-loss issue: spectrophotometers or spectroradiometers (Bolt et al. 1994, Joiner and Luo 2017). It is pertinent to understand how accurate the spectrophotometer and spectroradiometer diffuse/8° or 0° instruments are in their ability to measure colour with planar, opaque samples in order to gain understanding what is contributing to errors for unconventional materials. The point of this study is to investigate how similar spectral data is from spectrophotometers compared to spectroradiometers on both glossy and matte opaque samples.

PROCEDURES

For comparison of spectral data, opaque samples were measured with a Konica Minolta CM-2600 handheld spectrophotometer as well as a Konica Minolta CS-2000 tele-spectroradiometer. The spectrophotometer has a diffuse/8° geometry with built in D65 lighting (Konica Minolta 2016). Spectroradiometers do not have a built-in light source so the use of ambient illumination is required. The spectroradiometer was used with a VeriVide DigiEye lighting box in order to achieve an approximated diffuse/0° geometry (Figure 1).

Figure 1: Spectroradiometer setup. On the left side is the outside of the spectrophotometer with the VeriVide DigiEye lighting box, and on the right is the inside of the setup to show the general diffuse/0° geometry of the device.

Spectrophotometers are capable of measuring both specular component included and excluded. The geometry used for the spectroradiometer with DigiEye lighting box explicitly excludes the specular component. Therefore, specular excluded data from the spectrophotometer was used for comparison. Both devices were calibrated for a 10° observer.

A set of 60 opaque samples (taken from the Pantone: The Plus series CMYK guide) were measured to compare the instruments. Pantone samples were chosen as they have become a standard for communicating colour (Burgett 2015). There are two different series: coated and uncoated. The Pantone uncoated set of samples were measured using a Konica Minolta CM-2600d spectrophotometer (2,868 total). An algorithm, developed in MATLAB, was used to randomly generate a selection of 30 pantone 'colours' from the 2,868 uncoated pantone samples. The algorithm selected 30 CIELAB values that were as different as possible from each other in colour space as shown in Figure 2 (Cheung and Westland 2006).

Figure 2: Thirty pantone randomly selected samples. These are the samples that were used in the study, it should be noted that they will not visually appear the same as in the study due to the medium in which they are presented.

A total selection of 60 samples were measured: 30 CMYK uncoated samples and 30 CMYK coated samples. process yellow, process magenta, and process cyan were 2.3 cm × 4.3 cm. The rest of the samples were 1.75 cm × 2.08 cm. To ensure the small apertures of the devices did not measure any white edges, the center of the sample was measured. Each sample was measured 3 times with a handheld spectrophotometer and with tele-spectroradiometer and the repeat measurements were averaged.

DATA ANALYSIS

The spectrophotometer collected reflectance data for 360-740 nm at 10 nm intervals. The spectroradiometer collected radiance data from 380-780 nm at 1 nm intervals. Each sample was measured three times and these spectral data were averaged. The averaged data were truncated to 380-740 nm to ensure the measurements from the two instruments were comparable. Irradiance data from the spectroradiometer must be converted into reflectance data. The averaged irradiance spectral data was divided by an average spectral irradiance data of a standardized white and then multiplied by reflectance spectral data from a standardized white measured by a spectrophotometer (Zwinkels 1996). The spectrophotometer white data was interpolated in order to produce data at 1 nm intervals in order to convert the spectroradiometer data into reflectance data. Interpolation method was used in comparison to extrapolation as it is more accurate (Cheung and Westland 2006). In order to make colorimetric comparisons, averaged spectral data from each device for each sample was converted into CIELAB values.

The CIEDE2000 colour difference formula was used to quantify difference between the colorimetric data from the spectrophotometer and the spectroradiometer for the same samples. CIEDE2000 is considered the best formula for the assessment of small colour differences (i.e. under 5 units) (Wang et al. 2012, Luo et al. 2001).

RESULTS & DISCUSSION

The average colour difference between the two instruments is relatively small (Table 1). This indicates that there is little difference between the two instruments when comparing the same samples and where, as in this case, the optical geometry between the two instruments has been matched. Note that whether the samples are glossy or matte has no effect on this finding.

Colour differences between glossy and matte samples are larger (Table 2). It is interesting to note that the mean colour difference values are similar for both devices indicating that they eliminate specular component to a similar extent.

ΔE_{00}	Uncoated	Coated
Min	1.27	1.30
Max	4.15	3.73
Mean	2.11	2.09

Table 1: The max, min, and averaged CIEDE2000 colour difference values between spectrophotometer and spectroradiometer of uncoated and coated pantone samples.

ΔE_{00}	Spectrophotometer	Spectroradiometer
Min	1.61	1.94
Max	15.56	14.59
Mean	8.24	8.15

Table 2: The min, max, and averaged CIEDE2000 colour difference values between the uncoated and coated samples when using the spectrophotometer and spectroradiometer.

Figures 3 and 4 show two examples out of 30, comparing the spectral data between spectrophotometers and spectroradiometers over 380-740 nm at 10 nm intervals. On the spectral level, there are differences between the two devices even after converting irradiance into reflectance. It is interesting to see how the spectral data changes with the glossy materials versus the uncoated. The matte samples in Figures 3 and 4 show little difference between the spectrophotometer and spectroradiometer. Greater difference can be seen for the glossy/coated samples, which could be due to how the light interacts with the glossy finish. When all 30 samples are considered, there is more difference in spectral data for certain colours than for other.

Li (2019) has reported errors of up to 18 ΔE can be found by changing the method of how the tristimulus values (i.e. CIEXYZ) are calculated (although this was for an F11 illuminant). There are also different methods for which ΔE can be calculated provided a wide range of values (i.e. CIELAB, CIEDE2000, CIE94, CMC, CIELUV) (Wang et al. 2012). In industry there are two different colour difference thresholds: values that are perceptibly different as well as colour difference values that are considered acceptable. It is difficult, if not impossible, to put a single universal colour difference value for what will be perceptually different. The size of perceptibility and acceptability for colour difference could be completely different and will change based on the industry. Thresholds must be put into place to produce meaningful colour difference results.

This study only compared spectrophotometers and spectroradiometers with near-identical geometries, diffuse/8° and diffuse/0°. The mean colour difference results indicate that, for diffuse illumination geometries, either instrument can be used for the measurement of opaque samples. It should be noted the use of a VeriVide DigiEye illumination cabinet has shown to be a good way to produce diffuse/0° geometry for a spectroradiometer. The spectrophotometer had a geometry of diffuse/8°, while the spectroradiometer had a geometry of diffuse/0°. It could be that the colour differences shown in Table 1 could be smaller if the two geometries were identical instead of an 8° difference. While this instrumental geometry has produced small colour difference results, there are different measurement geometries such as a 45/0° which could produce more 'accurate' colour measurements. Comparison between diffuse/0-10° geometries and 45/0° should be investigated especially if changing the geometries could improve measurements for unconventional materials.

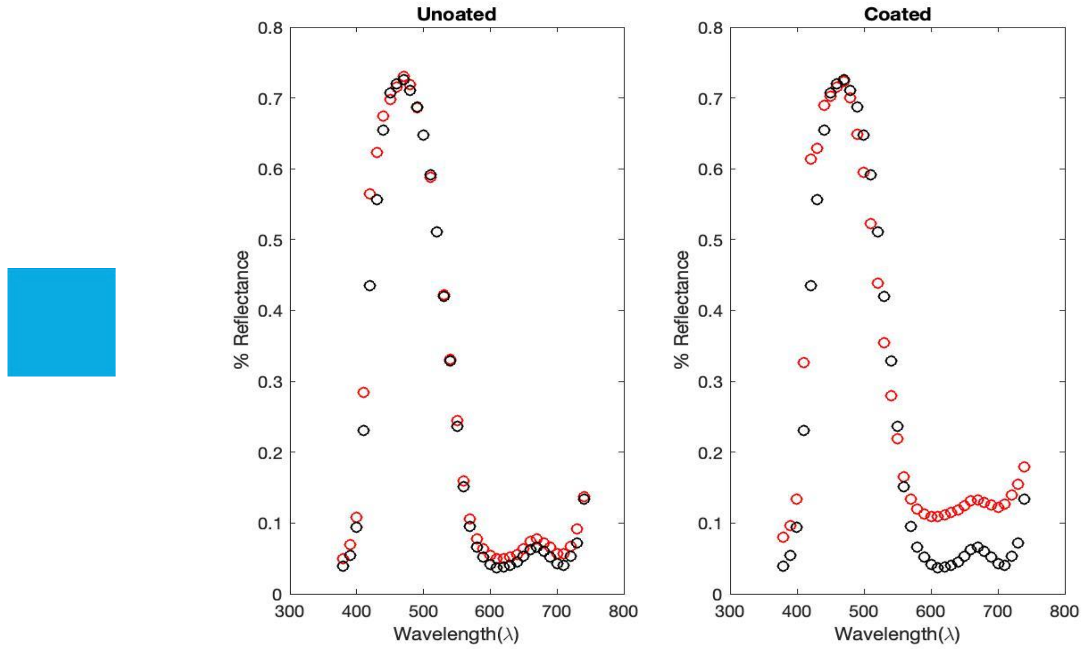

Figure 3: Spectroradiometer spectral data after conversion (red) compared to spectrophotometer spectral data (black) for process cyan pantone sample for wavelengths 380-740 at 10 nm intervals. The uncoated process cyan spectral data is on the left and coated process cyan spectral data on the right.

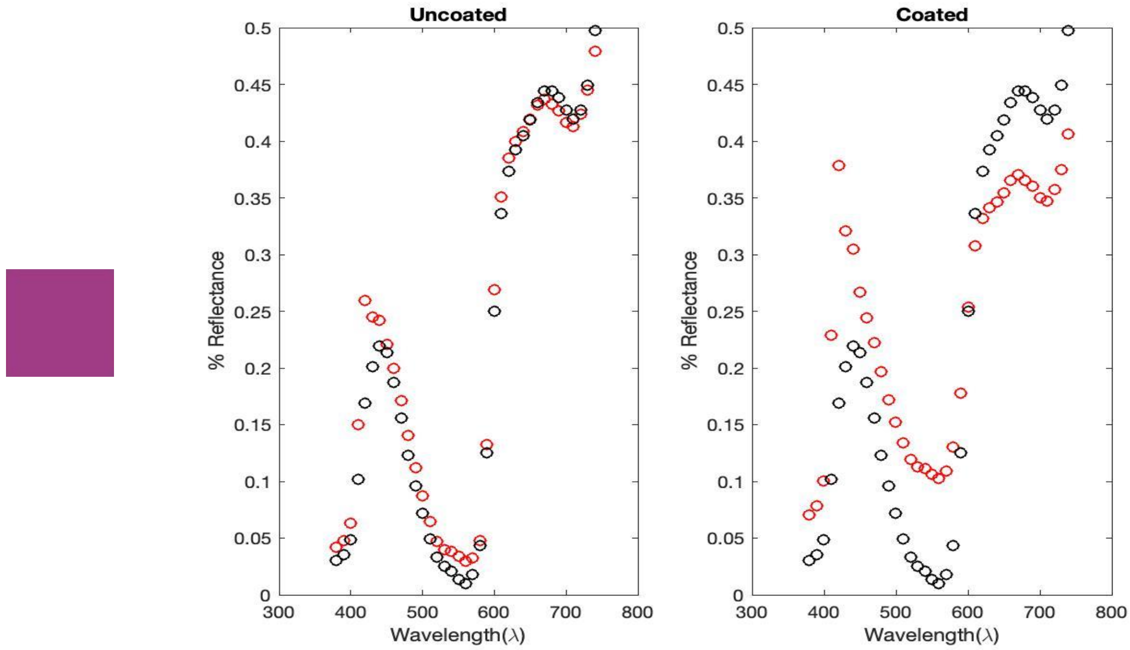

Figure 4: Spectroradiometer spectral data after conversion (red) compared to spectrophotometer spectral data (black) for 83.16 Pantone sample at wavelengths 380-740 at 10 nm intervals. The uncoated 83.16 pantone spectral data is on the left and the coated 83.16 samples spectral data the right.

The instrument devices used in this study were designed for the measurement of opaque samples. Opaque samples were used in this experiment, which could be the reason for such a small colour difference between spectrophotometers and spectroradiometers. However, unconventional materials (i.e. teeth, skin, food) could introduce further problems. Teeth specifically introduce many problems due to their attributes of being non-planar, small, and translucent.

Translucency introduces edge-loss, which is when light scatters through the material and is released out the back or the sides of the material and is not reflected back to the sensor of an instrument causing inaccurate colour measurement (Joiner et al. 2008, Bolt et al. 1994). For teeth, one study suggests there is less edge-loss when using spectroradiometers than with spectrophotometers due to difference in ratio between illumination and aperture/viewing size (Bolt et al. 1994). While in agreement with Bolt et al., others suggest that the cause of edge-loss is due to being contact based measurements (spectrophotometers) versus being a non-contact colour measurement system (spectrophotometers) (Joiner and Luo 2017).

Edge-loss is a major issue for physical measurements using instrumentation. By conducting this study, it has determined that spectrophotometer and spectroradiometers produce nearly similar results for each sample. This information can help with producing a solution for determining the best way to measure unconventional materials such as teeth.

CONCLUSION

Gaining insight on the ability of spectrophotometers and spectroradiometers to 'accurately' measure opaque samples can help determine what is happening when measuring unconventional materials such as teeth. Based on the results from this study, there is a very small colour difference between the two devices. Either device can be used to measure the colour of opaque materials and produce colour results for both glossy or matte finishes. Larger colour difference values are produced when comparing matte samples to glossy samples, indicating that instruments can pick up the different finishes on the samples.

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