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REFERENCE DATA SET AND VARIABILITY STUDY FOR HUMAN SKIN REFLECTANCE

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Abstract

The optical properties of human skin have been of interest to researchers for some time. Their interest is based on a need to know for a variety of different applications, which range from spectral imaging for automated or stand-off detection, non-invasive clinical diagnostic tools, improved models for understanding light propagation, to colour-based applications, such as reproduction of skin colour in photography and printing and colour-matching in cosmetics industries. Here we present a summary of a study that aimed to create a large data set of high-quality, human-skin reflectance spectra and quantify the variability of the resulting data set.

Keywords: Reflectance, skin colour, skin colour variation, spectral

1 Motivation

In 2012, NIST began collecting the reflectance spectra of human skin over a broad spectral range. The rapidly expanding application of spectral imaging to numerous measurement challenges involving human skin highlighted the importance of establishing a traceable, reference data set of human skin. Published literature of the optical properties of human skin for the visible region is prevalent, but data is sparse in the ultraviolet and shortwave infrared. Furthermore, spectra published up to that time typically involved only a small number of participants. This proceedings paper describes a large reference data set of human skin reflectance spectra covering the ultraviolet, visible, near-infrared, and shortwave infrared spectral regions. Several measures of variability are applied to the data, including a colour analysis.

2 Reference Data Set

NIST published a reference data set of 100 reflectance spectra of human skin, spanning the wavelength range from 250 nm to 2500 nm (Cooksey et al., 2017). The spectra are directly traceable to the national scale for directional-hemispherical reflectance factor. The methods of data collection, processing, and estimating uncertainties is described extensively in Cooksey et al., 2017. It is briefly summarized below.

2.1 Human Subjects

Volunteers participated in the human subject study, Reflectance Measurements of Human Skin, which was approved by the NIST Institutional Review Board reviewed and approved. All subjects provided written informed consent. Subjects were not selected based on age, gender, or ethnicity, nor was this information collected as metadata. Subjects were not excluded for the use of sunscreen, body lotion, or medication, or for the presence of freckles, moles, tattoos, or skin conditions or disorders.

Each subject participated in one measurement session, which consisted of acquiring reflectance measurements of the test area. The test area was a 25 mm diameter circle located on the inside of the subject's right forearm.

2.2 Reflectance Measurement

The reflectance measurements were acquired using a commercially available spectrophotometer equipped with a 150 mm integrating sphere. The subject positioned his/her bare, right forearm next to the sample port of the integrating sphere during measurement acquisition. For each subject, 3 scans were collected. The subject was permitted to rest his/her arm, removing it from the testing position, in between each scan. The parameters for the measurements are provided in Table 1.

Table 1 – Measurement parameters

Wavelength Range (nm)	Wavelength Interval (nm)	Spectral bandwidth (nm)	Source	Detector
250 to 319	3	3	Deuterium lamp	Photomultiplier tube
319 to 860	3	3	Tungsten-halogen lamp	Photomultiplier tube
860 to 2500	3	≤ 20 (variable)	Tungsten-halogen lamp	Indium-gallium-arsenide

2.3 Calculation of Reflectance Factors and Uncertainties

The resulting data was processed to produce spectra of reflectance factor values for a measurement geometry with an 8° angle of incidence and hemispherical detection, abbreviated as 8°/di. The reflectance factor values from the 3 scans were averaged to obtain the final 8°/di spectral reflectance factors for each participant.

The reference standard used for these measurements was sintered polytetrafluoroethylene (PTFE). The spectral reflectance factors for this standard are traceable to the scale for spectral reflectance factor of pressed PTFE, which was established using the absolute method of Van den Akker (Venable, 1977) in the NIST Spectral Tri-function Automated Reference Reflectometer (STARR) facility (NIST, 1998).

The estimated measurement uncertainties for the reflectance measurements are calculated according to the procedures outlined in NIST, 1994. Sources of uncertainty are the 8°/di spectral reflectance factor of the sintered PTFE standard, the sphere geometry, the wavelength, and random effects or repeatability. The evaluated contributions of each source and the expanded uncertainty (k = 2) are given in Table 2. These uncertainties are representative of the manner in which the instrument was used in this study.

Table 2 – Instrument uncertainty and its components

Source of Uncertainty	Standard Uncertainty	Uncertainty Contribution
Reflectance Standard	0.002	0.002
Geometry	0.001	0.001
Wavelength	0.3 nm	0.0008
Repeatability	0.0003	0.0003
		Expanded Uncertainty (k=2)
		0.0048

3 Data Analysis

The variability of the reflectance spectra for the 100 human subjects that participated in the study can be described in several ways (Cooksey, 2013; Cooksey, 2014; Cooksey, 2015). Figure 1 shows selected spectra from the set. The spectrum depicted by the black dashed curve is the representative of the mean spectral reflectance values of all subjects participating in the study. The representative spectrum was selected from among the set of reflectance spectra based on its similarity to the mean spectrum using the following equation:

$$\theta_i = \cos^{-1}\left(\frac{s_m{}^T s_i}{\|s_m\|\|s_i\|}\right) \tag{1}$$

where

θ_i is the difference between spectra (reported in radians);

s_m is the mean spectrum of reflectance factors for the full set of scans acquired (300 scans);

s_i is an individual spectrum from the full set of scans.

The selected spectrum has the smallest resulting angle and is considered the closed match to the mean spectrum. Selecting a representative spectrum form the overall set prevented the loss of spectral features that would have resulted from averaging the small shifts inherent in the spectral variability.

The variability observed for the full set of scans was calculated using the standard deviation and is referred to as the population variability. It is depicted in Figure 1 by the grey shaded area about the representative of the mean. The spectra (grey solid) representing the total range of observed reflectance factors are also shown in Figure 1.

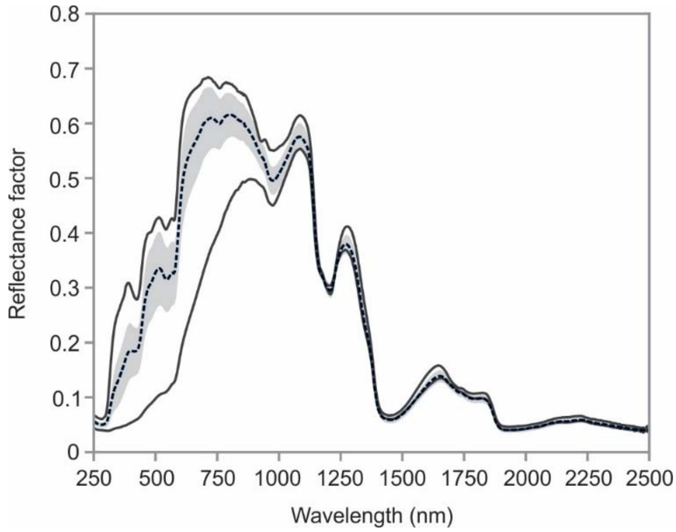

Figure 1 – The reflectance spectrum of the representative of the mean (black dashed) with grey shaded area representing the population variability for all subjects. Representative spectra (grey solid) show the range of variation in reflectance factors observed in the data set.

The greatest variation in spectral features is observed in the ultraviolet and visible spectral regions. In this spectral region, the incident light probes the epidermis, where the spectral response due to various blood-borne pigments is tempered by the absorption of light due to the presence of melanin. In contrast, there is significantly less variability observed in the near- and shortwave infrared where the incident light probes the hydrated dermal layer. The "valleys" observed in this region correspond to water absorption peaks.

Figure 2 plots the population variability with the instrument uncertainty (see Table 2) and the subject variability for selected subjects. The subject variability is the standard deviation of three scans of each subject, and it represents the dynamic nature of human skin observed for each subject. Overall, the population variability is the most significant source of uncertainty for skin's spectral response from the ultraviolet to the near-infrared regions. In the shortwave infrared, the instrument uncertainty is a dominant source of uncertainty.

With regards to human vision, the spectral features of each subject in the visible region can be described using the CIE colour space coordinates, commonly referred to as CIELAB or CIE $L^*a^*b^*$. The coordinate L^* represents lightness of colour where $L^*=0$ indicates black and $L^*=100$ indicates diffuse white. The coordinates a^* and b^* represent colour along the magenta-green and yellow-blue continuums, respectively. The resulting CIE $L^*a^*b^*$ values for all subjects are plotted on the left side in Figure 3.

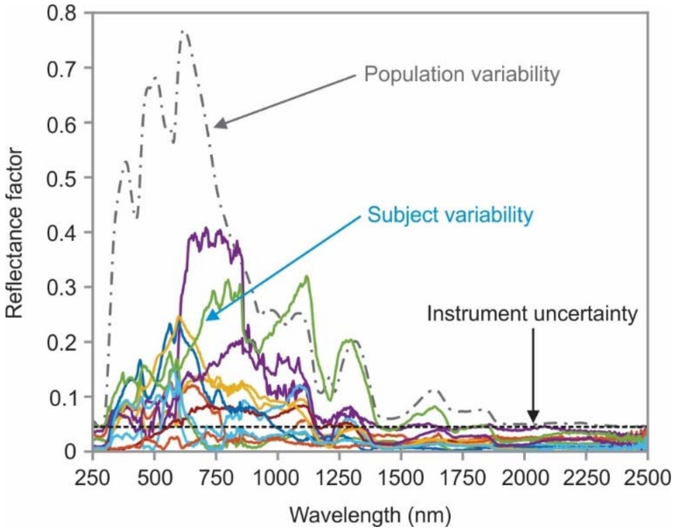

Figure 2 – The instrument uncertainty (black dashed), subject variability for several subjects (solid coloured), and population variability for all subjects (grey dot-dashed).

Additionally, the Euclidean distance between the CIE $L^*a^*b^*$ coordinates for each subject with respect to the coordinates for the representative of the mean was calculated according to:

$$\Delta E^*_{ab} = \sqrt{(L^*_i - L^*_m)^2 + (a^*_i - a^*_m)^2 + (b^*_i - b^*_m)^2} \quad (2)$$

where

L^*_i, a^*_i, b^*_i are the CIE $L^*a^*b^*$ coordinates for subject i;

L^*_m, a^*_m, b^*_m are the CIE $L^*a^*b^*$ coordinates for the representative of the mean.

The ΔE^*_{ab} for each subject are plotted as a histogram on the right side of Figure 3.

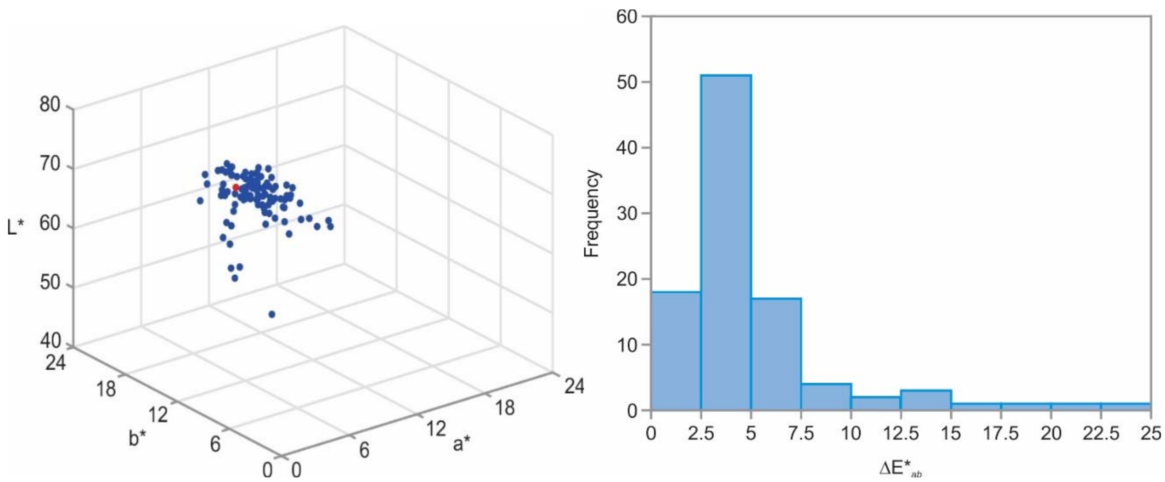

Figure 3 – Left: A three-dimensional plot of the CIE $L^*a^*b^*$ values for all subjects. The CIE $L^*a^*b^*$ coordinates denoted in red are those of the representative of the mean. Right: A histogram of ΔE^*_{ab} for each subject with respect to the representative of the mean.

4 Conclusions

The reference data set presented here provides reliable, traceable spectra of human skin reflectance with stated measurement uncertainties. The data set reveals a range and distribution of "typical" human skin reflectance values. While a larger sample size would better reflect the population at large, it can be expected that the variability of human skin reflectance is no smaller than the distribution represented by this set. Indeed, the range of colour coordinates calculated for this data set is similar to that of the database, which includes nearly 1000 skin colour measurements (Xiao, 2016).

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