Microspectrophotometry of Wood Grain and Color

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ABSTRACT---- *A reflecting microscope spectrophotometer was used for the colorimetry of wood using CIE (Commission Internationale de l'Éclairage) chromaticity coordinates. A microscope scanning stage and scanning with optical fibers were used to detect grain patterns. Ten exotic woods with a fine grain structure were tested because they are highly valued in the manufacture of musical instruments and furniture, and they had a wide range in color and grain structure. With lateral illumination (45°) of samples and a large measuring aperture, the results were comparable to those that might be obtained with a commercial colorimeter detecting diffuse Lambertian reflectance. With vertical illumination and coaxial photometry in a microscope, Fresnel reflectance was dominant. The best predictor of CIE x with lateral illumination was reflectance at 400 nm (r = - 0.916, P < 0.0005) and the relationship persisted with vertical illumination (r = -0.67, P < 0.025). Scanning across woods at 520 nm with a microscope scanning stage, there were relationships of CIE x with scanning peak height (r = 0.75 P < 0.01). In scanning across 6 cm of wood with optical fibers, there was a relationship of the number of reflectance peaks (from wood grain between dark lines) with peak width (r = - 0.89, P < 0.0005). Woods with a fine grain had numerous small peaks while woods with a coarse grain had a few wide peaks. Thus, there is a connection between the color and grain pattern of wood.*

Keywords – Microspectrophotometry, Colorimetry, Wood color, Wood grain

1. INTRODUCTION

The structural properties of wood are determined by the microstructure that creates its macroscopic grain [1]. Color is important for the identification of wood [2-6], but most commercial colorimeters have measuring apertures of several square centimeters and most woods have a grain pattern down to the millimeter level. This prompts an obvious question, how is wood microstructure related to wood grain and color?

The weighted ordinate method whereby each wavelength of a spectrum is weighted by its response in a typical human eye to calculate chromaticity coordinates may be used in microscopy, but not in exactly the same way it is used in macroscopic colorimetry [7]. The countless possibilities of microscopic optics, multiplied by the different emission spectra of microscope illuminators, do not invalidate the weighted ordinate method for the quantitative analysis of what the human eye can see down a microscope [8]. But, under the microscope, macroscopic brown wood may be resolved to the human eye as a grain pattern of very bright yellows mixed with dark, almost black lines. The bright yellows may even exceed the standards used for diffuse reflectance (such as barium sulfate or Teflon) because there may be mirror-like reflective layers in the wood microstructure.

2. MATERIALS AND METHODS

Measurements were made with a Zeiss Universal microscope combined with fiber optic accessories [9]. To enable a long working distance for lateral illumination of wood samples by fiber optics the objective lens was an LD Epiplan 8/0.2. For vertical illumination through the microscope using crossed polarizers to block surface reflectance the objective lens was an Epiplan 16/0.35 Pol. CIE chromaticity coordinates were calculated for the 1931 color space [10].

Wood samples were purchased from a variety of commercial sources, which creates problems in accurate scientific reporting because of the multiplicity of commercial wood names and unproven botanical sources. However, this was not viewed as a problem because the microspectrophotometry of wood grain and color might be tested in any type of wood. Even a single tree may yield wood samples with a wide range in grain pattern and color [11]. Listed below are some presumed sample identifications, numbered for the identification of spectra in the figures that follow.

1. Cocobolo or Rosewood (*Dalbergia retusa* Hemsl)
2. Corteza (*Handroanthus chrysanthus* Jacq)
3. Gravilia or Lacewood (*Cardwellia sublimis* F Muell)
4. Guanacaste (*Enterolobium cyclocarpum* Jacq)

5. Guapinol (*Hymenaea courbaril* L)
6. Guayacán or Ironwood (*Guaiacum sanctum* L)
7. Mora or Fustic (*Maclura tinctoria* L. Steud)
8. Nazareno or Purple Heart (*Peltogyne* spp)
9. Ronrón or Tigerwood (*Astronium graveolens* Jacq)
10. Teak (*Tectona grandis* L. f.)

3. RESULTS AND DISCUSSION

3.1 Measurements with a large aperture and lateral illumination

The objective was to measure wood samples in a way that resembled most macroscopic colorimeters – lateral illumination at 45° and vertical measurement of reflectance. Wood samples had a simple reflectance spectrum - increasing smoothly from 400 to 700 nm (Figure 1). The CIE chromaticity coordinates of the spectra shown in Figure 1 are given in Table 1. Thus, the outliers gravilia and cocobolo had the extreme values for %Y and there was a strong correlation of mean reflectance across all wavelengths with %Y ($r = 0.998$, $P < 0.0005$). Looking at the spectra in Figure 1 subjectively, reflectance at 700 nm might seem a good predictor of wood color because of its high variability. However, this was not supported by data analysis. The best predictor of CIE *x* was reflectance at 400 nm ($r = -0.916$, $P < 0.0005$) and CIE y had no strong relationships with spectral data.

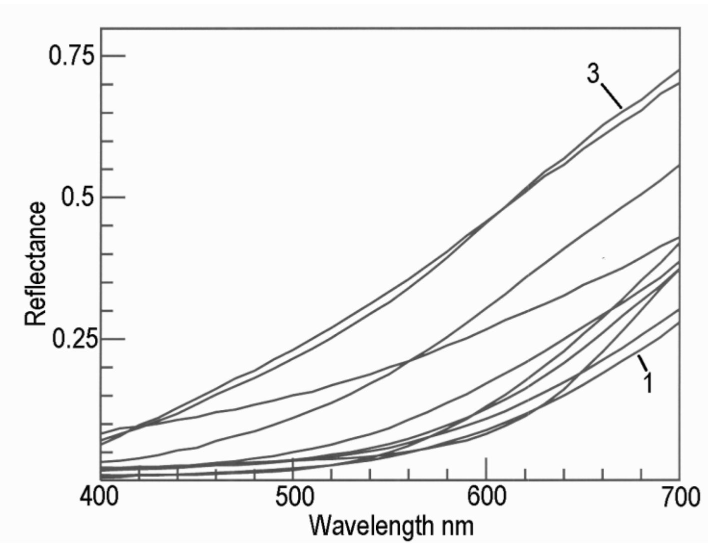

Figure 1. Microscope spectrophotometry of wood samples with 45° lateral illumination using an aperture covering 0.44 mm diameter on the specimen. The outliers were cocobolo (1) and gravilia (3).

Table 1. CIE chromaticity coordinates of spectra in Figure 1

	Wood	**CIE *x***	**CIE *y***	**%Y**
1	Cocobolo	0.52	0.39	5.87
2	Corteza	0.50	0.40	11.7
3	Gravilia	0.43	0.40	36.3
4	Guanacaste	0.42	0.38	21.7
5	Guapinol	0.50	0.38	8.6
6	Guayacán	0.44	0.40	35.2
7	Mora	0.49	0.38	7.6
8	Nazareno	0.48	0.36	6.2
9	Ronrón	0.55	0.39	7.8
10	Teak	0.47	0.40	22.1

3.2 Lateral versus coaxial illumination with a large aperture

Given that the main objective of the study was to investigate how the microstructure of wood might relate to its macroscopic appearance, a key point was to compare lateral illumination (as used in most commercial colorimeters) to vertical coaxial illumination (as used in most reflectance microscopes). Vertical coaxial illumination revealed a subsurface reflective microstructure. Surface reflectance was blocked by polarizing filters – one in the illumination pathway and the other at 90° in the viewing pathway.

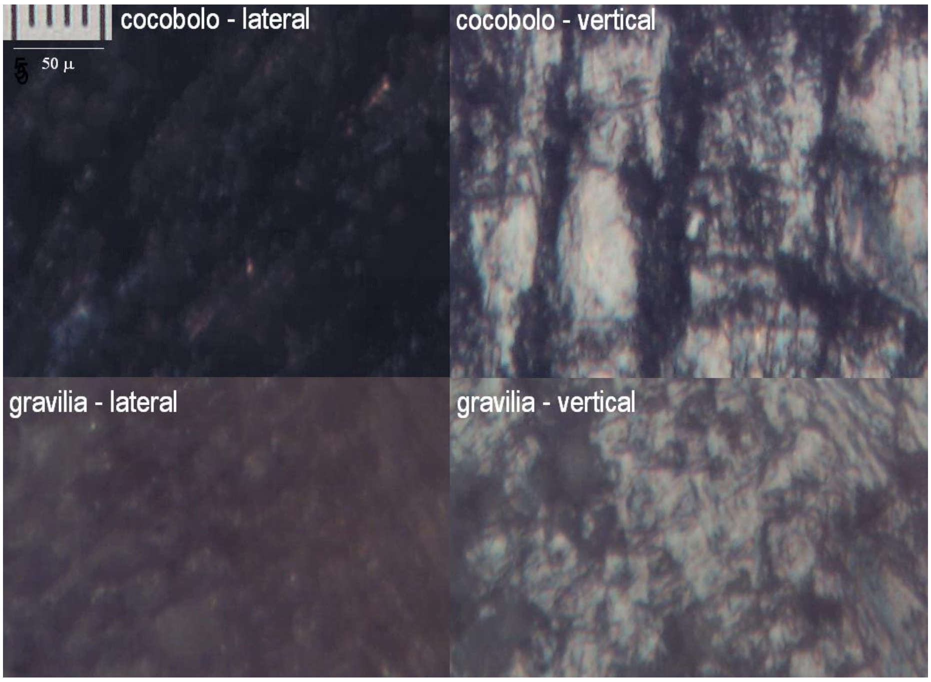

Figure 2. The darkest (cocobolo) and lightest (gravilia) woods when viewed with lateral illumination compared with the same samples viewed with vertical illumination.

If reflectance microscopy with lateral illumination gives spectra similar to those of a commercial colorimeter, a key question in going down to the level of the microstructure of wood grain was how CIE chromaticity might be affected by vertical illumination. As shown in Figure 2, vertical illumination greatly increased the Fresnel reflectance of the wood microstructure. The data in Figure 3 and Table 2 show major differences caused by vertical illumination. CIE x was decreased from 0.48 ± 0.04 to 0.39 ± 0.02 while CIE y was decreased from 0.39 ± 0.01 to 0.36 ± 0.01 (both $P < 0.0005$ using a paired t-test) while %Y was unchanged from 16.3 ± 11.8 to 16.1 ± 4.2 (not significant with a paired t-test). The correlation of reflectance at 400 nm with CIE x survived but was much weaker ($r = -0.67$, $P < 0.025$). As may be seen by comparing Figures 1 and 4, the change from lateral (Lambertian) to vertical (Fresnel) illumination caused major changes in reflectance spectra, thus the CIE chromaticity coordinates were changed and CIE x lateral was unrelated to CIE x vertical (r = - 0 .46, NS) and CIE y lateral was unrelated to CIE y vertical (r = 0.48, NS).

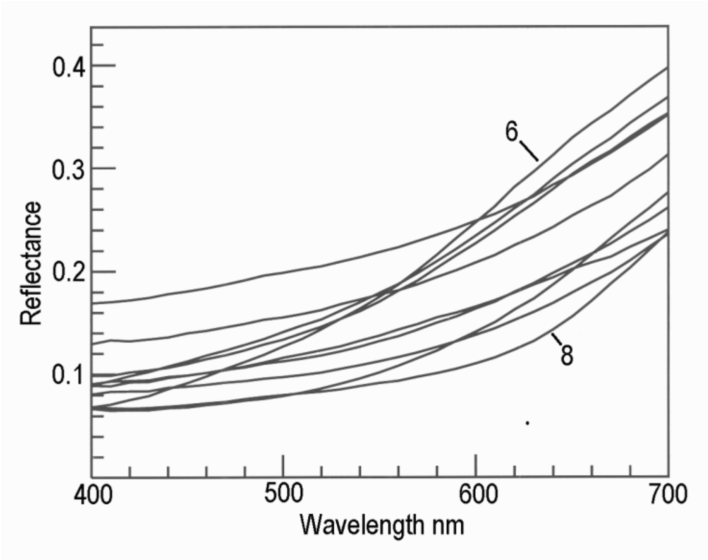

Figure 3. Microscope spectrophotometry of wood samples with vertical coaxial illumination using an aperture covering 0.44 mm diameter on the specimen and crossed polarizers to block specular reflectance from the sample surface. The outliers were nazareno (8) and Guayacán (6).

Table 2. CIE chromaticity coordinates of spectra in Figure 3

	Wood	CIE *x*	CIE *y*	%Y
1	Cocobolo	0.38	0.35	12.0
2	Corteza	0.39	0.36	14.1
3	Gravilia	0.41	0.37	19.4
4	Guanacaste	0.41	0.36	14.5
5	Guapinol	0.41	0.36	11.4
6	Guayacán	0.43	0.38	19.5
7	Mora	0.37	0.35	22.7
8	Nazareno	0.38	0.35	9.78
9	Ronrón	0.37	0.35	18.6
10	Teak	0.40	0.37	18.7

3.3 Scanning with a microscope

To prepare for monochromatic scanning of wood grain patterns it was necessary to select a suitable wavelength. Figure 4 shows the mean reflectance values from all 10 woods when measured on the pale parts between dark lines of the wood grain *versus* on the dark lines. For the pale parts between dark lines, CIE x = 0. 36 ± 0.01, CIE y = 0.34 ± 0.01, and %Y = 51.2 ± 6.9. For dark lines of the grain, CIE x = 0.37 ± 0.04, CIE y = 0.31, and %Y = 16.4 ± 7.9. For CIE x the difference was not significant (t = 1.16, n = 10) but the difference was significant for CIE y ($P < 0.01$) and %Y ($P < 0.0005$). The high point of the difference between pale and dark parts of the wood grain was at 500 nm (t = 15.2, $P < 0.0005$). Thus, a wavelength near 500 nm was chosen as the wavelength to scan across wood samples to show their grain structure.

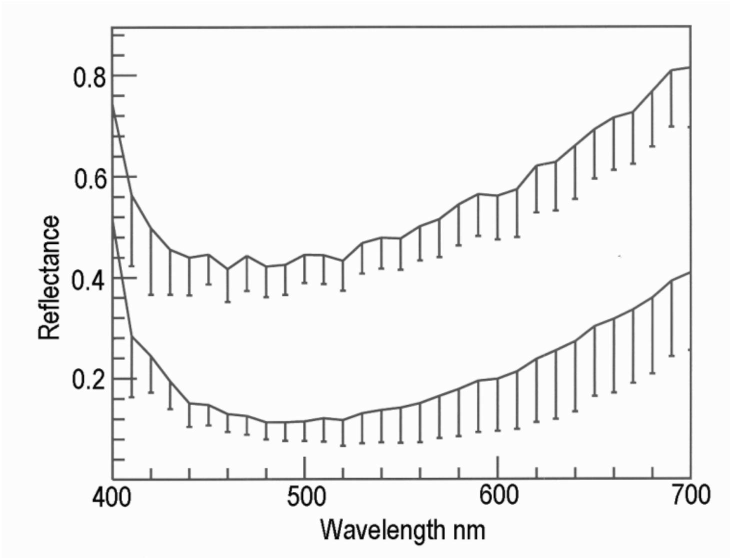

Figure 4. Means and standard deviation error bars for reflectance of dark grain (lower line) and pale grain (upper line)

Scanning across woods with a small aperture (8 µm on the specimen) and steps of 1 mm across the sample gave a statistical sample of strongly reflective parts of the sample. No relationships of mean peak heights and widths with CIE chromaticity coordinates in Table 1 were detected, but the reflectances of the three largest peaks were correlated with CIE x (peak 1, $r = 0.59$ $P < 0.05$; peak 2, $r = 0.71$ $P < 0.025$; and peak 3, $r = 0.75$ $P < 0.01$.

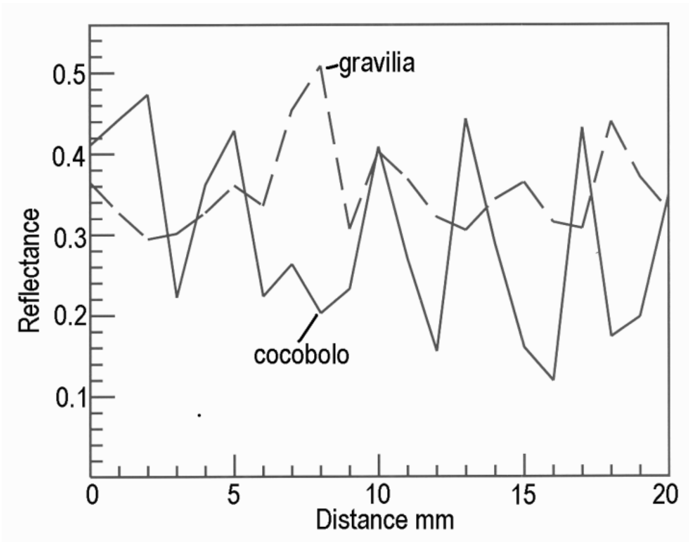

Figure 5. Scanning across woods with a small (8 µm) aperture in steps of 1 mm. The solid line is for cocobolo and the broken line is for gravilia.

3.4 Scanning with fiber optics

Reflectance measurements obtained using optical fibers are in a domain between colorimetry with lateral illumination and microscopy with coaxial illumination. The light guide contained six fibers to illuminate the specimen surrounding one fiber to measure reflected light, and there was an air gap of approximately 2 mm between the light guide and the specimen. The cone of light emitted by the illuminating fibers and the cone of light received by the recording fiber were determined by the numerical aperture of the optical fibers and the area on the specimen was approximately 1 mm in diameter. Thus, collection from a 3-dimensional cone of light by a 2-dimensional structure (the distal end of the recording fiber is sterance, given by the millivolt output of a silicon detector). The main point is that this configuration allowed diffuse Lambertian reflectance to dominate over mirror-like Fresnel reflectance so that the system was more like a typical colorimeter than a typical reflected light microscope.

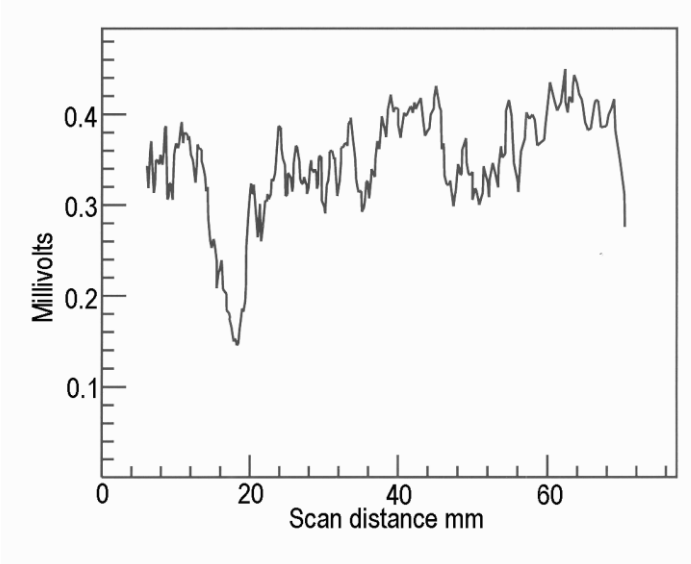

Figure 6. Fiber optic scan at 520 nm across 6 cm of nazareno wood

Table 3. Grain structure measured by fiber optic sterance (mV output from a silicon detector)

	Wood	Number of Peaks in 60 mm	Mean peak Height mV	Mean peak width mm
1	Cocobolo	20	0.36	2.36
2	Corteza	34	0.44	1.11
3	Gravilia	36	0.49	1.27
4	Guanacaste	32	0.35	1.31
5	Guapinol	54	0.43	0.87
6	Guayacán	42	0.39	1.01
7	Mora	51	0.39	0.97
8	Nazareno	68	0.35	0.60
9	Ronrón	61	0.40	0.71
10	Teak	55	0.36	0.72

Scanning across 6 cm of wood (Table 3, Figure 5) there was a relationship of the number of reflectance peaks (from wood grain between dark lines) with peak width (r = - 0.89, $P < 0.0005$). In other words, woods with a fine grain had numerous small peaks (Figure 6) while woods with a coarse grain had a few wide peaks (Table 3).

4. CONCLUSION

The implicit working hypothesis of this research was that there might be a relationship between wood color and grain structure. This was detected in ten woods with a wide range in color and grain structure – the color measurements were made with one method (spectrophotometry) and the grain structure measurements were made with a different method (monochromatic scanning). This is a new departure in wood colorimetry - how are colorimetry and structural texture interrelated?

5. REFERENCES

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