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OBTAINING SPECTRAL DATA FOR COLORIMETRY

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ABSTRACT

Simulation analyses have been conducted on the colorimetric errors associated with the data interval, bandpass, and wavelength errors of a spectrometer, using spectral data of 43 object color samples including those from CIE 13.3, BCRA tiles, and the Macbeth ColorChecker. The results showed that errors due to abridgement to 5 nm intervals compared with the standard 1 nm intervals are negligible (<0.03 ΔE^*_{ab}) for all samples. The results also showed that a bandwidth of 5 nm or less is acceptable for practical colorimetry of object colors as well as common light sources.

Keywords: bandwidth, chromaticity, colorimetry, data interval, interpolation, measurement uncertainty, object color, spectroradiometer, spectrophotometer

1. INTRODUCTION

Colorimetry for objects and light sources is commonly performed using spectrometers (spectrophotometers and spectroradiometers). Many different types of commercial instruments are used, having different specifications of bandwidth, scanning interval, wavelength range, wavelength accuracy, and other parameters. The accuracy of colorimetry depends on how accurately tristimulus values can be obtained by spectral measurements and is affected by all these parameters. Among these parameters, the spectral data interval (and thus the interval for spectral summation) has been discussed at CIE TC1-48 and is an issue in TC1-38 and in some ISO committees. However, the calculation errors associated with data intervals are much smaller and insignificant compared with the measurement errors caused by factors such as bandwidth and wavelength errors of spectrometers. In addition, many commercial instruments are designed to have the bandwidth matched with scanning interval for gap-less scan of spectra. Thus, the data interval is often tied to the bandwidth and cannot be treated separately. CIE 15.2 [1] does not provide clear recommendations on selection of bandwidth though it is critical for colorimetric accuracy. Therefore, for practical colorimetry, evaluation needs to be made not for data interval alone but for overall effects of bandwidth and other parameters as well as the data interval. While the CIE's current position is not to recommend intervals greater than 5 nm for colorimetry [1], there have been proposals in some CIE TCs and ISO committees to standardize all color calculation to 1 nm intervals, or to endorse ASTM E308 [2] that accepts use of 10 nm and 20 nm intervals. To provide data for discussion on such questions, a series of simulation analyses has been conducted evaluating colorimetric errors associated not only with data intervals but also bandwidth and wavelength errors of a spectrometer, simulating spectral measurements of 43 object color samples and several light source spectra. The results of these simulations and analyses are presented and discussed.

2. DATA INTERVAL FOR OBJECT COLOR MEASUREMENT

To examine the effect of different data intervals on calculated color, calculation analyses were made using spectral data of 43 object color samples including the 14 samples used in CIE 13.3 [3], 11 samples of BCRA (British Ceramic Research Association) tiles, and the 18 samples of Macbeth[1] ColorChecker (excluding 6 achromatic samples). Among these samples, several strongly saturated colors (blue, green, red, etc.) are included. The spectral radiance factor data (5 nm intervals) were first converted to 1 nm intervals by cubic spline interpolation in the range 360 nm to 830 nm to serve as the noiseless standard data. Then, the data were sampled at every 5 nm, 10 nm, and 20 nm intervals. The tristimulus values of these data sets were calculated with CIE standard Illuminant D65 and Illuminant A, using the 5 nm, 10 nm, and 20 nm abridged tables of the standard illuminants and the color matching functions. The errors of the abridged data in CIE 1976 (u', v') chromaticity coordinates were

[1] Specific firms and trade names are identified in this paper to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

calculated as the difference from the results for the standard 1 nm interval data, as shown in Eq. 1.

$$\Delta u'v' = \{(u'_{abridged} - u'_{1nm})^2 + (v'_{abridged} - v'_{1nm})^2\}^{1/2} \quad (1)$$

The chromaticity coordinates are also converted to CIE 1976 *L*a*b** color space, and the color differences ΔE^*_{ab} (from the 1 nm interval data) are calculated using a perfect diffuser as the white reference.

The results of calculations for the 14 samples in CIE 13.3 are shown in Fig. 1. The results for the BCRA tiles and the Macbeth ColorChecker samples are similar. As shown in Fig. 1 (a) and (b), the errors at 5 nm intervals are less than 0.00006 in (*u', v'*) or 0.03 ΔE^*_{ab}. If two strong blue samples are removed, the errors for the 41 samples are within 0.00002 in (*u', v'*) or 0.01 ΔE^*_{ab}. The results confirm that the errors caused by abridgement at 5 nm intervals are insignificant and negligible for all the samples, especially compared with other measurement errors (See sections 3 and 5). It is also noted that the errors with Illuminant A at 5 nm intervals are nearly zero. The errors with D65 are much larger because the currently defined D65 values were linear-interpolated from the original 10 nm interval values. A new procedure to redefine D65 values as proposed [4] will nearly eliminate these errors for D65 though they are already practically negligible.

Fig.1 (c) and (d) show the results for 10 nm interval abridgement. The results for the BCRA tiles and ColorChecker samples are similar and less than the maxima shown in these figures. Also, there are no differences in the magnitude of errors between D65 and Illuminant A for this condition. The level of errors at 10 nm interval ($\sqcup$ 0.1 ΔE^*_{ab}) may be acceptable in many practical applications. Fig.1 (e) and (f) show the results for 20 nm interval abridgement. The results for the BCRA tiles and ColorChecker samples are similar. This level of error at 20 nm interval ($\sqcup$ 1 ΔE^*_{ab}) is not acceptable in many applications. It is also noted that the errors for D65 at 20 nm intervals are an order of magnitude larger than at 10 nm intervals; the increase is much larger than that for Illuminant A. This may be due to the structured spectral distribution of D65.

From these results, it can be concluded that a 5 nm interval for spectral summation will

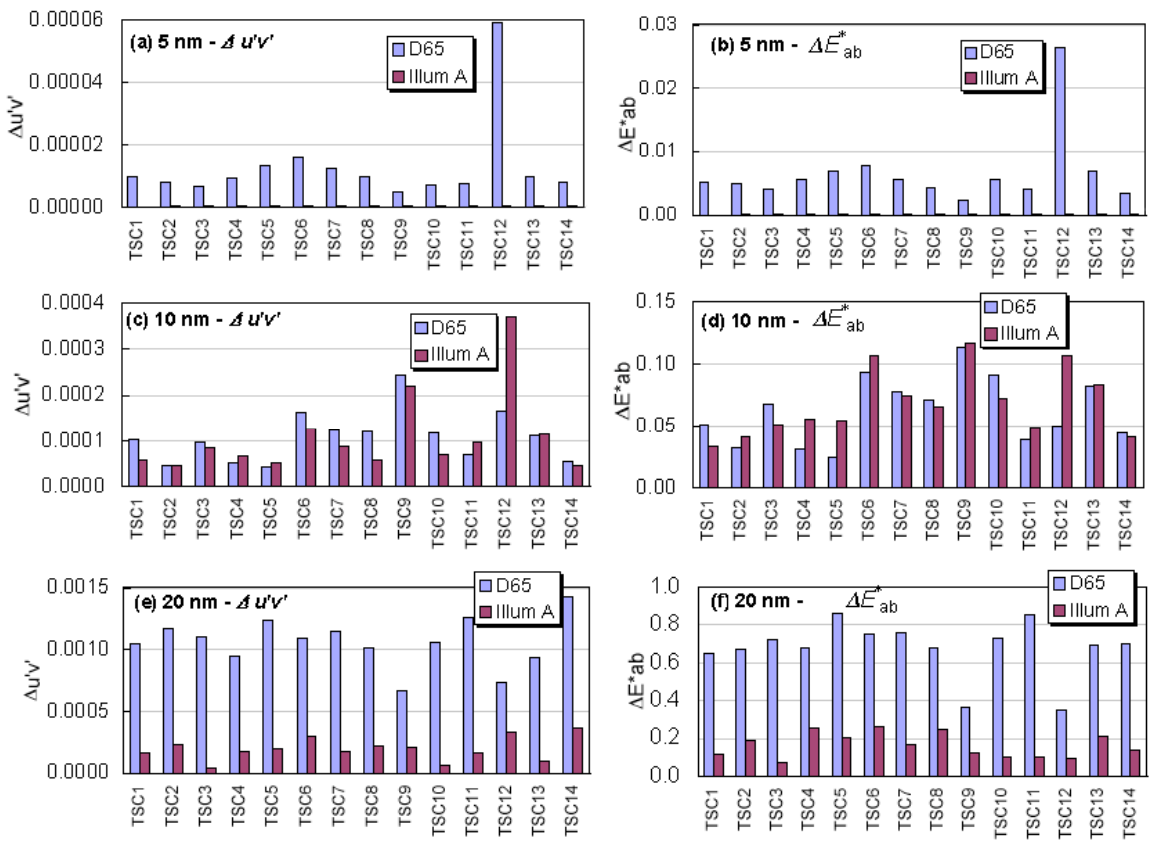

Figure 1. Errors in chromaticity coordinate (*u',v'*) and in ΔE^*_{ab} caused by abridgement of data at intervals of 5 nm, 10 nm, and 20 nm, for the 14 color samples used in CIE 13.3.

suffice for all practical measurements of object colors, and that there is no need for interpolating 5 nm-interval data into 1 nm intervals as sometimes proposed. Even a 10 nm interval may be acceptable for most common surface color samples. The errors due to abridgement at 10 nm and 20 nm intervals can be reduced by using the procedure given in Ref. [2]. However, this procedure may not be effective for some strongly saturated colors. For example, the 14 samples in CIE 13.3 abridged at 20 nm intervals were calculated using the Tables 5.2 and 5.18 of Ref. [2] for Illuminant A and D65, respectively. The results are shown in Fig. 2, which shows that errors are increased for sample TSC12 (strong blue) while the errors for other samples are reduced significantly.

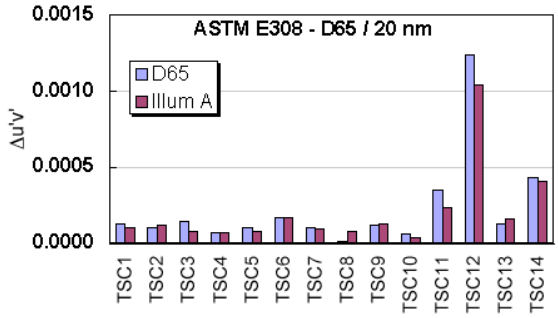

Figure 2. Errors in chromaticity coordinate (u',v') at 20 nm interval data calculated with the procedure given in ASTM E308. Compare with Fig. 1 (e).

The analysis reported above assumed zero bandwidth of each spectral radiance factor value of the samples and analyzed only the effect of data interval. In this respect, this calculation can also be interpreted as a simulation of spectral measurements using a spectrometer with a negligible bandwidth (e.g., 1 nm) at given intervals. Measurements at 5 nm intervals provide accurate results though the bandwidth and the scanning interval are not matched. This confirms that the matching of bandwidth and scanning interval is not necessary in object color measurement, though they need to be matched if the bandwidth correction [2,5] is to be applied.

3. EFFECT OF BANDPASS ON OBJECT COLOR MEASUREMENT

When a spectral measurement is made, errors will occur not only due to the data interval (scanning interval) as discussed above, but also, more importantly, due to the bandwidth of the spectrometer which is normally larger than 1 nm, often 5 nm, and sometimes even larger. To examine the errors caused by the bandwidth of instruments, a spectrometer is simulated by carrying out convolution of given spectral radiance factor data with a given bandpass function and calculating measured chromaticity coordinates. A 5 nm or 10 nm (FWHM) triangular bandpass at 5 nm scanning interval was used, and the chromaticity coordinates of the 43 color samples illuminated by D65 were calculated using the 5 nm tables. The results are shown in Fig. 3. The errors caused by the 5 nm bandwidth were found to be up to 0.00026 in (u', v') or 0.1 ΔE^*_{ab}. The average errors ($\sqcup$ 0.05 ΔE^*_{ab}) are an order of magnitude larger than the average errors due to a data interval at 5 nm ($\sqcup$ 0.006 ΔE^*_{ab}; see Fig. 1-b). The errors caused by a 10 nm bandwidth are up to 0.0013 in (u', v'), or 0.48 ΔE^*_{ab}, which is not acceptable for high-accuracy applications.

The errors due to bandwidth of instruments can be corrected by use of Table 6 in ASTM E308 [2] (applied to 10 nm and 20 nm bandwidth) or by Stearns and Stearns' formula [5]. Calculations on these samples have demonstrated that these methods are very effective in reducing bandwidth errors. Stearns and Stearns' formula can be more widely recommended though it requires a triangular bandpass function that is matched with (integer multiple of) the scanning interval.

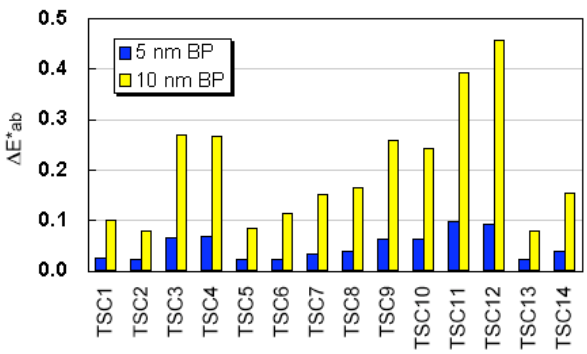

Figure 3. Errors in ΔE^*_{ab} due to a 5 nm and 10 nm bandwidth of a spectrometer measuring the 14 samples in CIE 13.3.

4. EFFECT OF BANDPASS ON LIGHT SOURCE COLOR MEASUREMENT

The treatment of the scanning interval and the bandwidth of spectrometers is more critical in measurement of light sources containing emission lines and narrowband peaks. For such applications, one should use a triangular bandpass function that is matched with (an integer multiple of) the scanning interval so that the whole spectrum is scanned by the bandpass

function evenly without gaps. A simulation was made for a spectroradiometer with a triangular bandpass of 5 nm, 10 nm, and 20 nm, measuring several light sources of different type at 5 nm intervals. Table 1 summarizes the results. The errors for a Planckian source (very smooth spectral distribution) are shown to be negligible, even with a 20 nm bandwidth. Errors are larger for sources having narrow-band emissions and are nearly proportional to the square of the bandwidth. The errors for the two types of fluorescent lamps with a 5 nm bandwidth are practically negligible. Even with LEDs and LCD spectra, the level of errors for 5 nm bandwidth is acceptable for most practical applications. Corrections using Stearns and Stearns' formula [5] should further reduce these errors. A 10 nm or 20 nm bandwidth for these sources would not be acceptable in many applications. Further analysis demonstrates that a bandwidth-mismatched condition can significantly increase the errors (e.g., $\Delta u'v'$=0.004 for Cool White fluorescent lamp with a 3 nm bandwidth at 5 nm intervals.) It has also been shown that, if such spectral data of discharge lamps (including emission lines) are interpolated to 1 nm intervals, the errors can get worse. Interpolation would also confuse the uncertainty information of original spectral data. The uncertainty in color quantities will not be reduced by interpolation due to correlation.

Table 1. Errors in (u',v') due to a 5 nm, 10 nm, and 20 nm triangular bandpass of a spectroradiometer.

Source		$\Delta u'v'$		
		5 nm BP	10 nm BP	20 nm BP
Planckian	3000 K	0.0000	0.0000	0.0001
Cool white FL	4300 K	0.0001	0.0005	0.0019
Triphosphor FL	3265 K	0.0002	0.0006	0.0025
LED (20 nm half-width)	450 nm	0.0004	0.0017	0.0070
	510 nm	0.0005	0.0019	0.0076
	630 nm	0.0007	0.0028	0.0112
LCD (computer display)	Blue	0.0005	0.0020	0.0079
	Green	0.0001	0.0005	0.0020
	Red	0.0006	0.0023	0.0090

5. EFFECT OF WAVELENGTH ERROR

Another major source of error (uncertainty) in colorimetry is the wavelength error of spectrometers. Calculations on the 43 samples show that a shift on the wavelength scale by 0.2 nm leads to average colorimetric errors of ⊔ 0.0002 $\Delta u'v'$ or ⊔ 0.2 ΔE^*_{ab} with a maximum of 0.0011 $\Delta u'v'$ or 0.48 ΔE^*_{ab} (strong blue). For light sources shown in Table 1, calculations using the numerical method [6] for a 0.2 nm uncertainty (k=2) show a maximum uncertainty of 0.0018 $\Delta u'v'$ (triphosphor lamp).

6. CONCLUSIONS

The bandwidth and the scanning interval of spectrometers are critical factors in spectral measurement for colorimetry. These parameters are tied to the design of instruments and are chosen for intended applications. Unnecessary standardization on spectral data intervals would adversely affect the design requirement and cost of the instruments. The results of the analyses on the 43 samples showed that errors due to abridgement of 5 nm intervals are negligible for common object color measurements, and thus there is no need for interpolation from 5 nm to 1 nm intervals. The errors due to the bandpass of a spectrometer are found to be an order of magnitude larger than the errors due to data interval, and deserve more attention. It is also shown that a bandwidth of 5 nm or less is acceptable for practical colorimetry of common object colors and light sources, and bandwidths larger than 5 nm are generally not recommended except when measurements are limited to specific sources or applications where the errors are acceptable with appropriate bandwidth correction.

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