Comparison of the Primary Spectra and Color Triangles Associated to Several Digital Cameras

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Abstract

In this work we present a method to calculate the spectrum of the fundamental primaries of a digital camera from the experimental knowledge of its spectral sensitivities. The color triangle of the camera, linked to the chromaticities of its primaries, is compared below with the theoretical options of Ives-Abney-Yule and MacAdam. Therefore, this is a simple method to determine at first approximation the color gamut of an input device. This methodology may apply to any kind of camera and scanner. Results obtained with a particular digital camera (Sony DXC-930P) show that the red and purple zone, like the blue-green zone but in minor extend, is not well filled by this input device.

Introduction

Like displays and projectors, input device (scanners and digital cameras) are additive color devices.[1,2] The basic spectral property of displays and projectors is the set of spectra of their primaries. Their color-matching functions can be inferred from these data so that the spectral sensitivities of the input devices can be designed accordingly.[3] However, the basic spectral property known a priori of the input device is the set of the spectral sensitivities, but not directly the associated primary spectra.

It is well stablished[4] that the basic color profile of an input device is a 3x3 matrix M relating the color-matching functions T_{RGB} and T_{XYZ} of the color device and colorimetric standard observer. This means that the matrix components arranged in each column are the XYZ tristimulus values of the RGB primaries of the input device (Eq. 1). This matrix can be obtained by several regression methods.[5] For this work, we have selected the maximum ignorance using least squares regression because it is the best simple. Therefore, from these matrix components the color triangle of the input device can be plotted, as for displays and projectors, as first approximation of the color gamut of this type of color device. That is,

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \Leftrightarrow T_{XYZ}{}^{t} = M \cdot T_{RGB}{}^{t}, \quad \text{with} \quad M = \begin{bmatrix} X(P_R) & X(P_G) & X(P_B) \\ Y(P_R) & Y(P_G) & Y(P_B) \\ Z(P_R) & Z(P_G) & Z(P_B) \end{bmatrix} \tag{1}$$

where P_R , P_G and P_B are the primary spectra in column format, which are not known a priori. (A^t is the transpose matrix of the matrix A.)

We propose in this work a simple methodology to determine the fundamental[6] primary spectra P_{RGB} from the color-matching functions T_{RGB} without knowing directly the basic color profile M.

It is also well proved that input devices are not colorimeters because their color-matching functions do not fulfill the Luther condition,[7,8] that is, they are not exact linear combinations of the color-matching functions of the colorimetric standard observer. This means that input devices generate systematic color errors. The sets of color-matching functions of Ives-Abney-Yule[9] and MacAdam[10] (Fig. 1) are theoretical options of sensors verifying just the Luther condition. In the first case, the color triangle of the sensor set is the minimal area which includes the spectral locus. In the second case, it is the exact linear combination of T_{XYZ} with minimal spectral overlap. Therefore, it is always interesting to compare the color triangle of a real camera relative to these theoretical color triangles in order to assess the color reproduction quality. This is just what we will do with a particular digital camera, but this methodology may apply to any kind of camera and scanner. Therefore, it should be interesting in the future to extend this work to more scanners and digital cameras in order to determine how the current optical technologies for spectral sensitivities design come near the theoretical options.

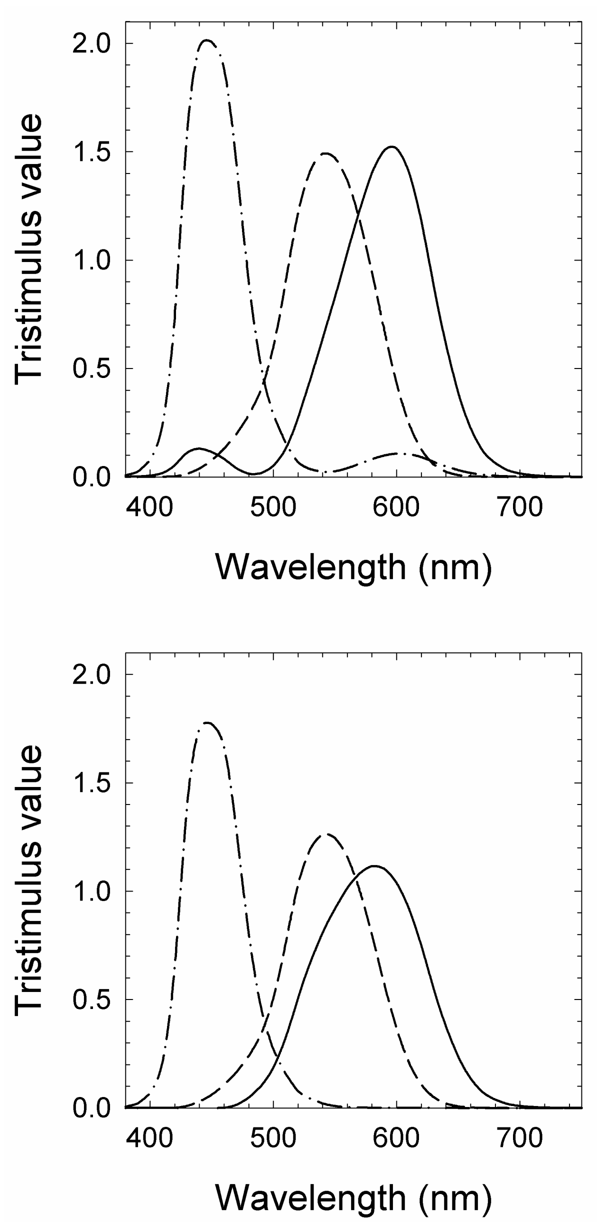

Figure 1. Color-matching functions according to Ives-Abney-Yule (top) and MacAdam (right). (Solid line: X channel; dashed line: Y channel; dash-dot line: Z channel)

Experimental Set-Up

Our input device consists of a Sony DXC-930P camera and a Matrox MVP-AT 850 frame grabber. The ISO 17321[11] guidelines are followed to work with the raw response camera. On this way, the white balance and gain control are configured to offset values. Likewise, the gain and offset of the analogue-to-digital converter are configured to ensure that the raw camera response is not changed.

The monochromator[12] set-up has been used to determine the spectral sensitivities of our digital image capture device. Then, two scaling factors, joint type and equal-energy white balance, are applied to the spectral sensitivities to convert them into the colour-matching functions T_{RGB} (Fig. 2).

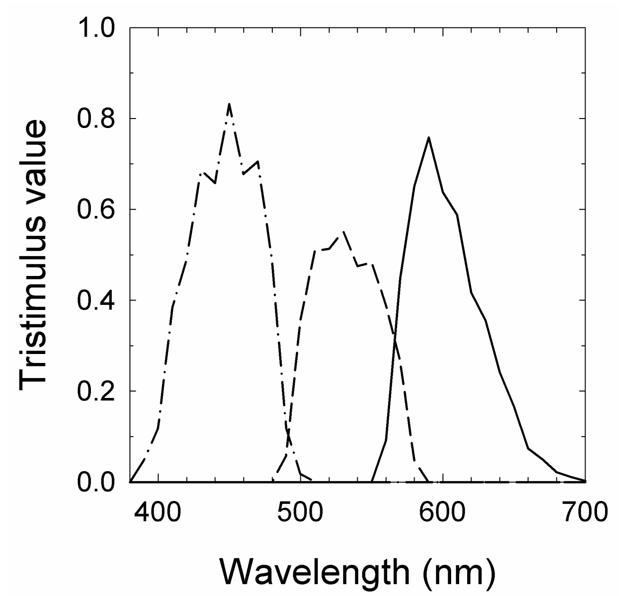

Figure 2. Color-matching functions of our input device. (Solid line: R channel; dashed line: G channel; dash-dot line: B channel)

Methodology and Results

The mathematical background of colorimetry is linear algebra.[4-6] According to this formalism, color-matching functions T (41 rows by 3 columns, from 380 nm to 780 nm at 10 nm steps) and primary spectra P (41 rows by 3 columns) of any color space associated to additive color reproduction systems (device or human eye) are linked into a dual relationship as follows:

$$T^t \cdot P = I, \qquad (2)$$

where I is the 3x3 identity matrix.

Therefore, if primary spectra P_{RGB} of a display or projector are known we can calculate their color-matching functions. On the same way, if color-matching functions T_{RGB} of an input device are known we can determine the primary spectra P_{RGB} as follows:

$$P_{RGB} = T_{RGB} \cdot \left(T_{RGB}{}^t \cdot T_{RGB}\right)^{-1} \qquad (3)$$

In figure 3 we can compare the fundamental primary spectra of our input device with the corresponding ones of the options of Ives-Abney-Yule and MacAdam. It can be seen that some of these spectra have got negative components, which means that it is possible that some XYZ tristimulus value was negative. If the XYZ tristimulus values of these spectra are conventionally calculated, it is proved that these values agree with the columns of the matrix M obtained by maximum ignorance least squares regression method[5]:

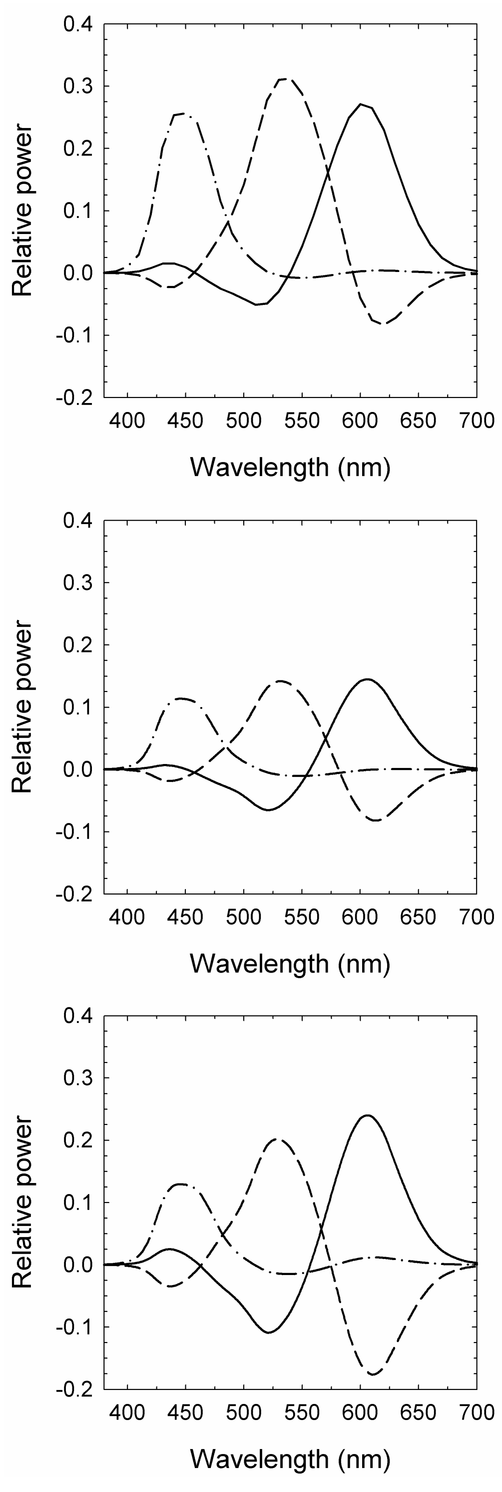

Figure 3. Fundamental primary spectra of our digital camera (top) and the theoretical cameras of Ives-Abney-Yule (center) and MacAdam (bottom).

$$M = T_{XYZ}{}^{t} \cdot T_{RGB} \cdot \left(T_{RGB}{}^{t} \cdot T_{RGB}\right)^{-1} = \\ = \begin{bmatrix} 1.5798 & 0.4016 & 0.3643 \\ 1.0086 & 1.6157 & 0.0742 \\ -0.0107 & 0.1573 & 2.0189 \end{bmatrix} \quad (4)$$

Finally, transforming the tristimulus values into chromaticity coordinates we can plot the color triangle of our color device in any chromaticity diagram. This is shown at Figure 4 alongside the theoretical color triangles of Ives-Abney-Yule and MacAdam in the UCS-(u',v') chromaticity diagram. As it can be seen, the red and purple zone, like the blue-green zone but in minor extent, is not well filled by our input device. We think that both the scaling of T_{RGB} relative to T_{XYZ} and the spectral overlapping in T_{RGB} are the cause of these differences. We hope for the poster presentation to extend this study with new commercial digital cameras (Nikon Coolpix 5700, Pixelink PL-662, QImaging RetigaEX color, etc) in order to compare among them from this point of view.

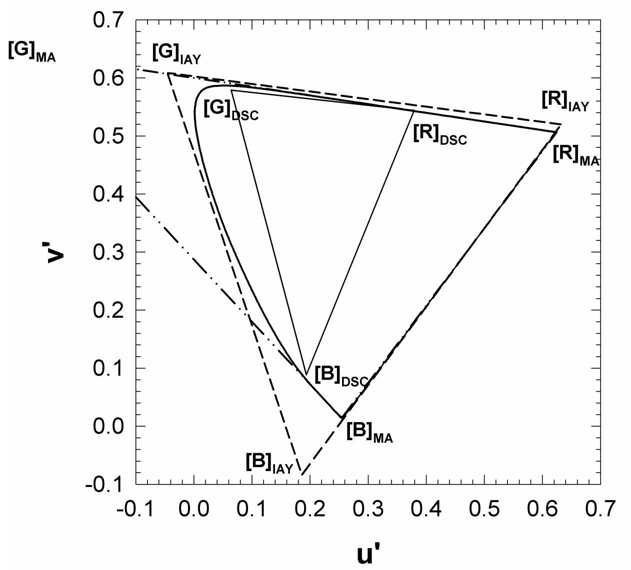

Figure 4. Color triangles of our input device (DSC, solid line) and the theoretical sensors of Ives-Abney-Yule (IAY, dashed line) and MacAdam (MA, dash-dot line).

Conclusions

The knowledge of the color gamut of an input device is important in Color Imaging but its determination is complex, because these color devices verify the univariance principle but do not fulfill the Luther condition. Moreover, opto-electronic performance is not completely ideal for the basic assumptions of colorimetry to hold. We have presented in this work a method to reach an acceptable solution of this problem, which can be applied to any digital camera or scanner.

The procedure we have developed is based on the determination of the color triangle of these color devices from the fundamental primary spectra. Although this algorithm is simple, it is very useful because we use as reference theoretical sensors (Ives-Abney-Yule and MacAdam). In this way we can determine the effect of the scaling of the spectral sensitivities and its spectral overlap on the shape of the color triangle.

Acknowledgements

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Biography

Francisco Martínez-Verdú received his BS in Physics from the University of Valencia in 1993 and a Ph.D. in Physics from Technical University of Catalonia at Terrassa (Barcelona) in 2001. Since 1998 he teaches Vision Sciences at the School of Optics & Optometry in the University of Alicante (Spain). His work is primarily focused on Color Imaging (device calibration and characterization, color management) and Industrial Colorimetry. He is a member of the IS&T and the Spanish Optics Society. E-mail: verdu@ua.es.