New measures of the color-matching functions in foveal vision

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ABSTRACT

Over time, much work has been carried out to ascertain the validity of the laws of Grassman, of the law of Abney and of the CIE standard color-matching functions and, up to now, no definitive answer has been given. In 1992 W. Thornton published a set of works on these topics attracting the attention of the scientific community. We decided to reconsider all the phenomena object of the debate and this analysis is in progress. The results for foveal vision here presented are preliminary.

1. INTRODUCTION

A long discussion regards the color-matching functions (CMF), their definition, their measurement techniques and their meaning[1]. Recently, this discussion has increased, after the long set of papers written by W. Thornton[2-5] in 1992. In 2000 the CIE TC1-56 technical committee started, whose main term of reference is the comparison of results based on the current CIE color matching functions, on color matching functions proposed by Dr. W. Thornton's laboratory, and on those of CIE TC1-36. One of the authors is a member of this committee and we decided to make an apparatus for the CMF measurement in order to observe the phenomena object of the debate, and then to analyze and understand, if possible.

2. THE COLOR-MATCHING APPARATUS

The apparatus presents the observer with a bipartite field, where lights are mixed through two integration bars according to the maximum saturation technique and the minimum saturation technique (known also as the Maxwell method).

The lights are distinguished into a spectral light and three band lights. The spectral light is produced by a Xenon lamp with a monochromator Jobin-Yvon H-10 using 2mm-width slits, it therefore has an FWHM of ~15nm. The band lights are produced by halogen lamps with different kinds of filters. The lights are guided to the integration bars by flexible fibers of 3/8 inch in size.

Any one integration bar is constituted by a chamber, whose internal surfaces reflect diffusely. At the entrance and at the exit of the chamber, the light crosses a pair of holographic diffusers with transmission efficiency greater than 85%. The uniformity of the two parts of the bipartite field has been verified by analyzing their digital images.

A metameric match is obtained by modulating the light fluxes using an iris combined with a continuously variable slit, in order to have the spectral shape of the lights entering the mixture unmodified.

The spectral power distributions of all the lights entering the mixtures and the mixed lights of any metameric match are measured with a calibrated spectroradiometer Hamamatsu PMA 11, whose calibration has been checked by a NIST retraceable light source.

The apparatus is set for foveal vision with a viewing field with a section of 1.8°.

3. PRELIMINARY RESULTS

First, as known, it appears that the metameric match realized by mixing spectral lights is dependent on the observer and on the age of the observer. The differences between observers are generally more evident below 500 nm and this is probably due to differences of absorption in the macular pigmentation and in the crystalline lens[6-7]. The measurements of the CMFs are still in progress. The results here considered are the most accurate in our laboratory and have been produced

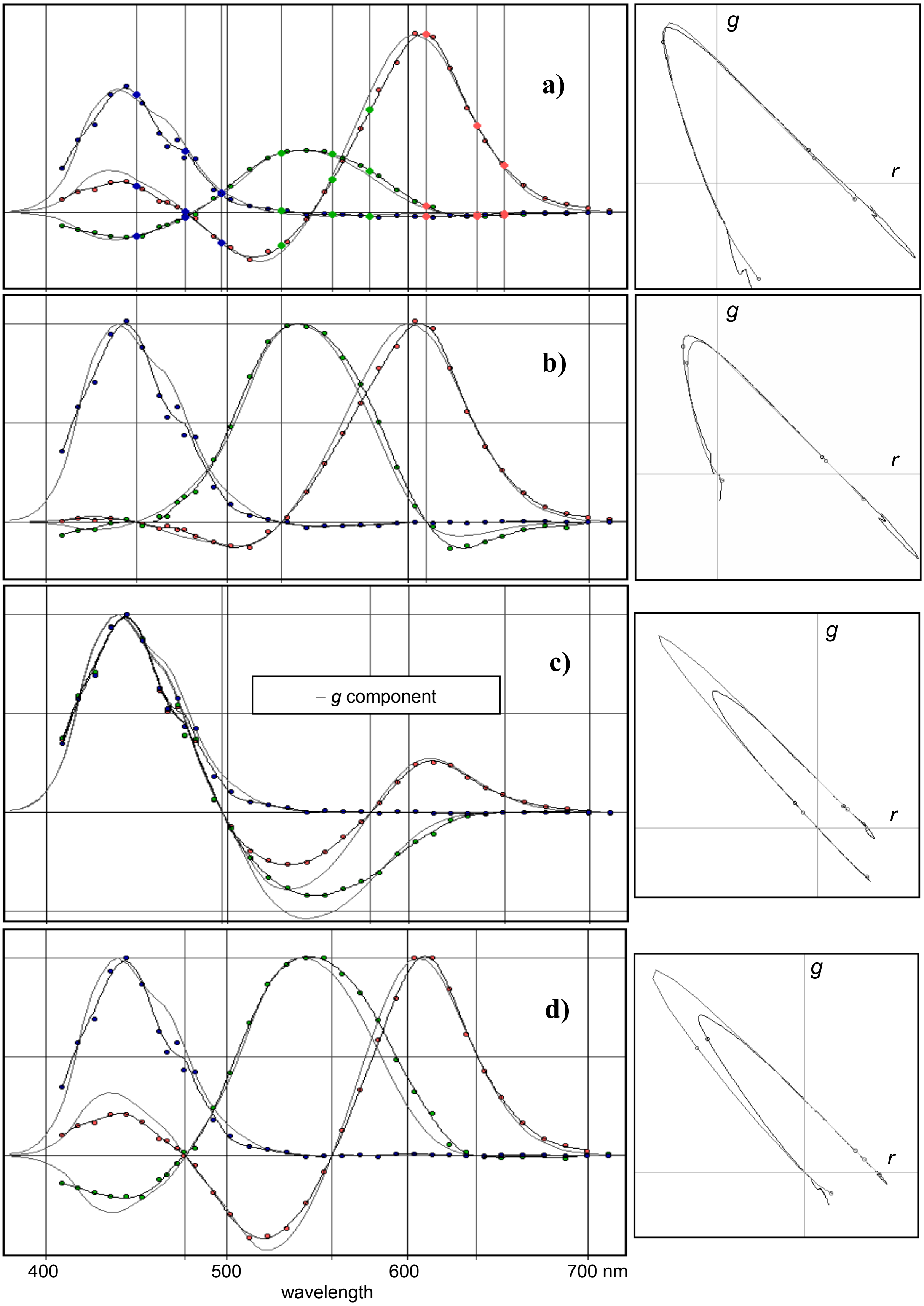

Figure 1: CMFs measured by maximum saturation technique and related chromaticity diagrams (black line and colored dots) compared to the Vos observer[8] (gray line) in four different reference frames: a) *RGB* of the laboratory; b) Thornton's "prime-color" primaries; c) Thornton's "antiprime" primaries; d) Thornton's "nonprime" primaries.

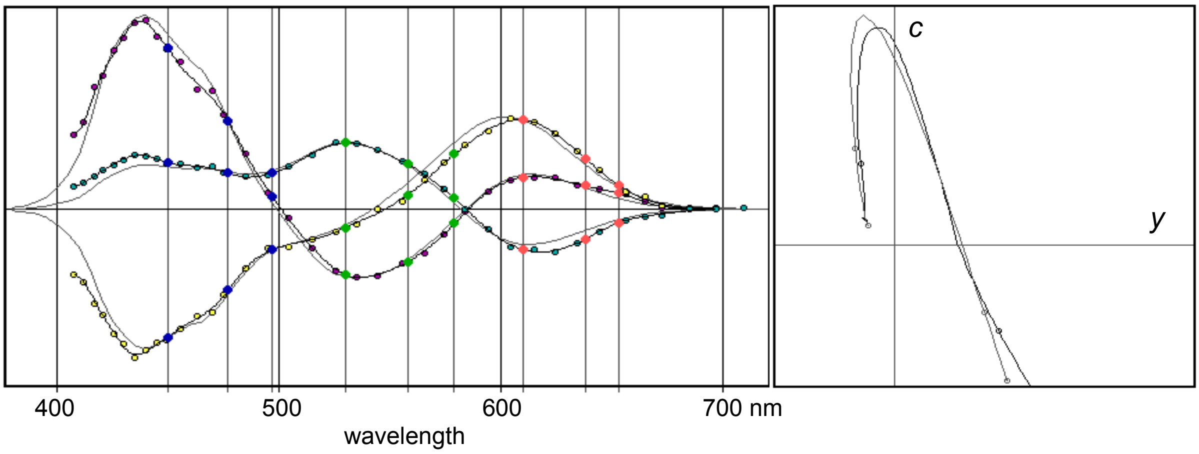

Figure 2: CMFs measured by maximum saturation technique and related chromaticity diagram (black line and dots) compared to the Vos observer[8] (gray line) in *CMY* reference frame of the laboratory.

by only one observer, a 33 year old woman with normal color vision. Up to now, two very different sets of band-light primaries *RGB* and *CMY* are considered (the chromaticities are related to the Vos observer[8])

$$\boldsymbol{R} = (x' = 0.687, y' = 0.307), \boldsymbol{G} = (x' = 0.277, y' = 0.688), \boldsymbol{B} = (x' = 0.121, y' = 0.161)$$
$$\boldsymbol{C} = (x' = 0.336, y' = 0.480), \boldsymbol{M} = (x' = 0.426, y' = 0.219), \boldsymbol{Y} = (x' = 0.520, y' = 0.462).$$

The spectral lights used have a band with an FWHM of ~15nm, therefore the measured CMFs need deconvolution. Because the deconvolution techniques amplify the noise, the measured CMFs need a refinement with additional measures in order to reduce the noise to a minimum. The CMFs here considered are undeconvoluted. The results of our measurements are here summarized and are a confirmation of a set of known phenomena, some understood and some others not yet understood:

1) The CMFs measured with the maximum saturation method are in general in good agreement with the Vos[8] ones (figure 1 and 2): there is remarkable a shoulder around 465 nm in the CMFs of both sets of our primaries and of Vos, although at a different height.
2) Comparison with the CMFs optimized by Shaw & Fairchild[9] shows that the shoulder in the region below 500 nm is confirmed by our measures.
3) The CMFs measured by Thornton have a systematic shift in wavelength that our measurements do not confirm, although the maxima of our CMFs are not exactly coincident with those of Vos and CIE '31.
4) The measured CMFs, although not yet deconvoluted, are represented in the reference frame of the laboratory primaries and of the Thornton's "prime color", "antiprime" and "non-prime". The transformations between reference frames need the knowledge of the chromaticities of the primaries of the final frame in the starting frame, and any uncertainty of these

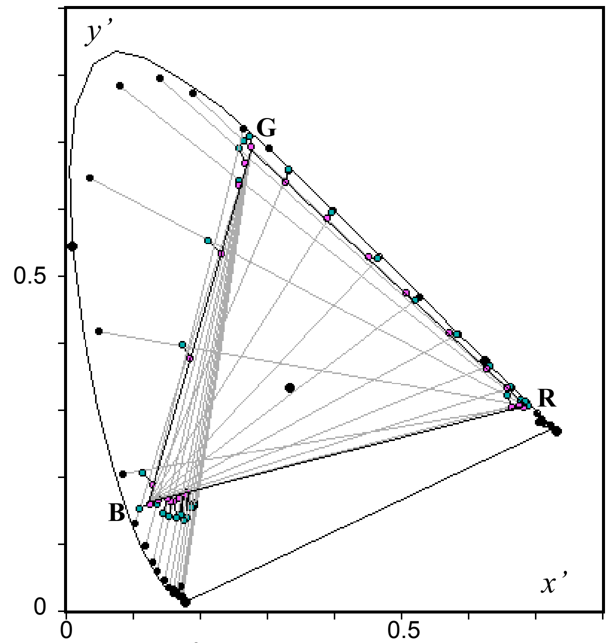

Figure 3: Vos[8] diagram with the chromaticities of the pairs of metameric colors in the CMF measurement with the *RGB* primaries of the laboratory and with the maximum saturation technique. Systematically the part containing the spectral light is external to the RGB triangle.

chromaticities has important consequences. Moreover the transformations from the laboratory primaries to the “antiprime” amplify some differences. The differences are smaller in the reference *RGB* and *CMY* of the laboratory and this suggests we define the final CMFs by taking into account empirical data produced by different laboratory-reference frames.

5) For a correct evaluation of Grassman’s laws, the tristimulus space of the individual observer must be considered. Anyway, the distances between the chromaticities of the two metameric colors of the bipartite field on the chromaticity diagram of Vos are representative of the goodness of Grassman’s laws and of the difference between the individual observer and the Vos observer. Figure 3 represents these chromaticities corresponding to the CMFs of figure 1 a). The regularity of the mutual distances between the two metameric colors recalls the Thornton’s result, but with smaller differences. Such regularity induces us to consider the differences as individual and supports Grassman’s laws. Analogous differences exist between the (computed and measured) luminances of the metameric color pairs.
6) The CMFs measured with the Maxwell method are in good agreement with both observers, CIE31 and Vos, in the wavelength ranges close to the maxima, but do not have the shoulder around 465 nm and have high uncertainty in the low wavelength values.

4. CONCLUSION

The preliminary data here presented suggest that in order to arrive at the final individual CMFs we should consider data obtained from different sets of laboratory primaries. The considered metameric color pairs induce us to consider Grassman’s laws as good laws, although the last response can arrive once the final CMFs are defined. The difference between maximum saturation and Maxwell’s technique suggests we improve the color-matching apparatus in order to go continuously from the maximum saturation match to the minimum saturation one by adding equal desaturating lights to both sides of the bipartite field. The aim is to know and understand what induces the differences between the two matching methods. Moreover the effect of the surround adaptation will be considered on the CMF measurements.

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