STUDY OF OBSERVER VARIABILITY IN MODERN DISPLAY COLORIMETRY: AN ANALYSIS OF CIE 2006 MODEL

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ABSTRACT

CIE 2006 model presents a convenient framework for calculating the cone fundamentals, and thus the color matching functions, for various ages of an average observer. CIE 2006 model incorporates three major physiological factors affecting observer variability, namely optical densities for the ocular media absorption, macular pigment absorption, and visual pigments in the outer segments of the photoreceptors. However, it does not have a provision for a peak-wavelength shift in the photopigment absorption spectra, a significant but difficult-to-model contributor to observer variability. In the context of color reproduction with modern emissive displays based on different technologies, we performed a theoretical analysis of various aspects of CIE 2006. Out of the above four factors, L-cone peak-wavelength shift was found to be the second most significant contributor to observer variability, after ocular media absorption. Excluding this factor from the CIE 2006 model, while understandable, can undermine the usefulness of age-dependent observer color matching functions.

Keywords: Color Vision, Cone Fundamentals, Color Matching, Observer variability, Display colorimetry

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1. INTRODUCTION

In 2006, CIE's (Commission Internationale de l'Eclairage) technical committee TC 1-36 published a report[1] (described hereafter as CIE06) on the choice of a set of Color Matching Functions (CMF) and estimates of cone fundamentals for the color-normal observer. The CIE06 model, largely based on the 1959 Stiles-Burch 10° CMFs[2,3], defines 2° and 10° reference observers, and provides a convenient framework for calculating average cone fundamentals for any field size between 1° and 10° and for an age between 20 and 80. Each set of CIE06 cone fundamentals can be converted to CMFs through a linear transformation. In order to assess the merits of this new set of age-dependent CMFs, it is pertinent to investigate whether the CIE06 framework incorporates all major sources of observer variability, particularly the ones that are age-independent. In fact, if this is not the case, observer variability within a given age-group can significantly undermine the usefulness of considering an age-dependent observer in color imaging applications. The relevance of this issue is obviously quite dependent on the application context. While in case of cross-media color reproduction the significance of observer variability is questionable[4], for application contexts relevant to the display and media and entertainment industries (content creation and distribution in particular), this can be rather a critical issue, so a better modeling of observer variability is highly desirable.

In this work, we performed a theoretical analysis of various aspects of CIE06 cone fundamentals from the perspective of display colorimetry. In the first part of our analysis, we altered the CIE06 model in four different ways to explore the contributions of various physiological factors to the overall variations in the cone fundamentals, and ultimately on the predicted observer variability while viewing colors on various displays. Since CIE06 is mainly based on Stiles-Burch 10° CMFs, and since we also use them as the "ground-truth" for evaluation of the CIE06 model, 10° field size has been used throughout the analysis, unless otherwise stated.

2. CIE06 PHYSIOLOGICAL FACTORS

Three physiological factors have been incorporated in the CIE06 framework, in the form of optical density functions for: a) lens and other ocular media absorption, b) macular pigment absorption, and c) visual pigments in the outer segments of photoreceptors. While these physiological factors are important contributors to observer variability, there is another important but more complex source of variability that has not been included in the CIE06 model. A number of studies have suggested that individual differences in the color vision are partly due to the variations in the peak wavelength (λ_{max}) of the cone photopigment[5]. These differences can be due to individual variability, but can also be due to a variation in genetic composition or polymorphism, for example, a single amino-acid substitution (Alanine for Serine) at position 180 of the L-cone photopigment opsin genes[6].

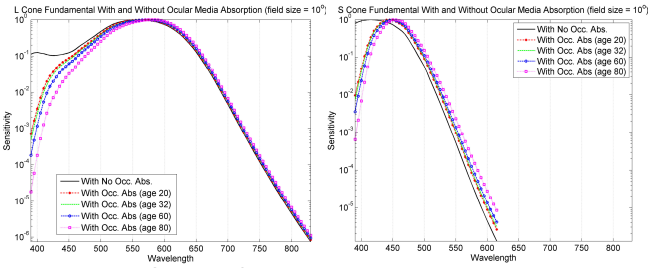

Fig 1: L- and S- cone fundamentals with and without ocular media absorption, as described in case (i)

In order to explore the effects of various physiological factors on the cone fundamentals, we considered four hypothetical cases, where there is: i) no ocular media absorption (relevant optical density set to 0), ii) no macular pigment absorption (relevant optical density set to 0), iii) very high absorption in the outer segments of visual pigments, (peak optical density of low-density absorption spectra arbitrarily set to 1), and iv) a wavelength shift of the L-pigment peak absorption toward shorter wavelength, without changing the shape of the curves in wavenumber scale (peak of low-density absorption spectra increased by 250 cm^{-1}). Case (iii) signifies very high photoreceptor self-screening, resulting in the broadening of low-density absorption spectra[1], while case (iv) signifies L-cone peak-wavelength shift described earlier. Here, we used the same amount of peak-wavelength shift used by Webster and MacLeod[7] in their analysis of Stiles-Burch data, which translates to about 7.7 nm shift at 560 nm.

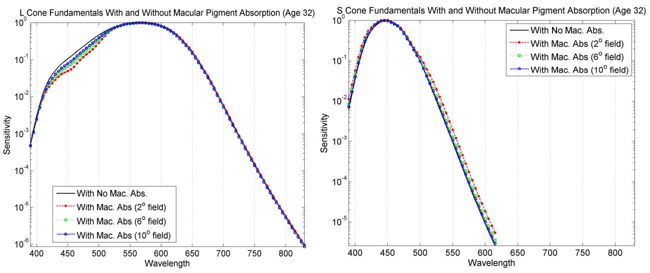

Fig 2: L- and S- cone fundamentals with and without macular pigment absorption, as described in case (ii)

In each of these four cases, modified CIE06 cone fundamentals for various field sizes and ages were computed, and were compared to corresponding CIE06 cone fundamentals under normal conditions. The difference between the two sets of functions indicates the contribution of a given physiological factor. Because of space constraint in this paper, we show only a few representative plots.

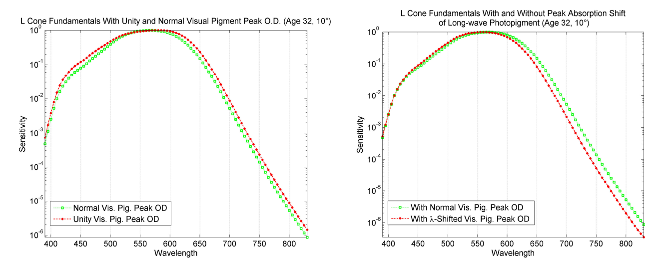

Fig 3: L- cone fundamentals with normal and modified visual pigment absorption function, as described in case (iii) [left] and case (iv) [right]

Fig 1 shows log plots of L- and S- cone sensitivities with and without ocular media absorption for various ages. For L- (similar in case of M-), the effect of ocular absorption is more significant at lower wavelengths. In case of the S-function, the effect is to shift the peak wavelength toward longer wavelengths. In both cases, the effect increases with age. Fig 2 shows the log plots of L- and S- cone fundamentals with and without macular pigment absorption for various field sizes. Because of macular pigment absorption, the sensitivity slightly reduces for the L- function (similar trend for M-) between 420 and 520 nm, and increases at higher wavelengths for the S-function. Clearly, the effect is less significant for 10°, but increases as the field size is reduced. Fig 3 illustrates the effect of visual pigment absorption under conditions described in cases (iii) and (iv) above. The effect of unity peak optical density is to increase the sensitivity both below and above the peak wavelength, while for the peak wavelength-shift the sensitivity reduces above the peak wavelength (since the shift is in the wavenumber scale).

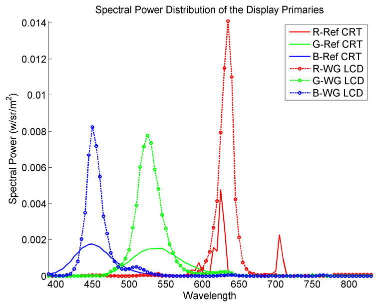

Fig 4: Spectral Power Distribution of the two displays used in the analysis

3. DISPLAYS

In our analysis, we used four displays, two of which are included in this paper. The first is a Sony BVM32 Cathode Ray Tube (CRT) display widely used as a reference studio display (hereafter referred to as Ref-CRT). The display has a peak white luminance of 107.4 cd/m^2. The second is a Hewlett-Packard DreamColor LP2480zx professional 30-bit Wide-Gamut Liquid Crystal Display with LED backlight (hereafter referred to as WG-LCD), and a peak white luminance varying between 40-250 cd/m^2.

The spectral power distributions of the two displays are shown in fig 4. There is a significant difference in the spectral power and characteristics between the two displays, so we can hope to see very different effects of observer variability on them. WG-LCD is representative of modern wide-gamut displays with peaky primaries.

4. EFFECT OF PHYSIOLOGICAL FACTORS ON DISPLAY COLOR PERCEPTION

In order to simulate the effect of various physiological factors when viewing color stimuli on various displays, chromaticities of these stimuli for a given display and a given set of cone fundamentals must be computed. In this analysis, 24-Colorchecker (CC) color patches were used as the stimuli. XYZ tristimulus values of the CC patches were computed using 10° standard observer and D65. 3x3 primary tristimulus matrices of the two displays, computed from the measured XYZ values of the display primaries, were used to convert the XYZ of the CC patches to the linearized RGB values corresponding to two displays. The product of the linearized RGB values and the spectral data of the display primaries gave the spectral power distributions of the CC patches for a given display. Finally, these spectral data were vectorially multiplied by a given set of 10° CMFs, resulting in the XYZ tristimulus values for the CC patches, the given display and a given set of CMFs. The 10° CMFs were computed from various normal and modified CIE06 10° cone fundamentals. Corresponding CIELAB values were computed using these XYZ values and the XYZ of the white, computed using spectral power distribution of the display white and the CMFs under consideration.

Since the 3x3 matrix for converting the CIE06 cone fundamentals to CMFs has not yet been made available by the CIE committee TC 1-36[8], an approximate 3x3 matrix was computed using the available 1964 10° x-bar, y-bar, z-bar functions and the cone fundamentals for the average 10° Stiles-Burch observer, which was used throughout the analysis. Since all the CIE06 cone fundamentals (and thus the CMFs) are essentially based on 10° Stiles-Burch data (except for the S- function at higher wavelengths), this approximation is not likely to significantly affect the results and the inferences.

Fig 5 shows the color difference (ΔE^*_{00}) values for CC patches between the chromaticities obtained from normal cone fundamentals and those obtained from modified cone fundamentals corresponding to the four cases described in Section 1. All values correspond to 10° field size and age 32. For the wide-gamut LCD, while ocular media absorption affects the perception of blue the most, peak wavelength-shift in the low-density absorption spectra [case (iv)] greatly affects the perception of cyan. Comparatively, difference in color perception is not as drastic in case of Ref CRT, supporting suggestion of other researchers[9] that modern displays with narrow-band primaries are more susceptible to observer variability than broadband CRTs. In terms of the maximum and average ΔE^*_{00} values for the two displays, ocular media absorption has the most significant effect on variations in color perception, followed by the peak-wavelength shift in the L-cone photo-pigment absorption.

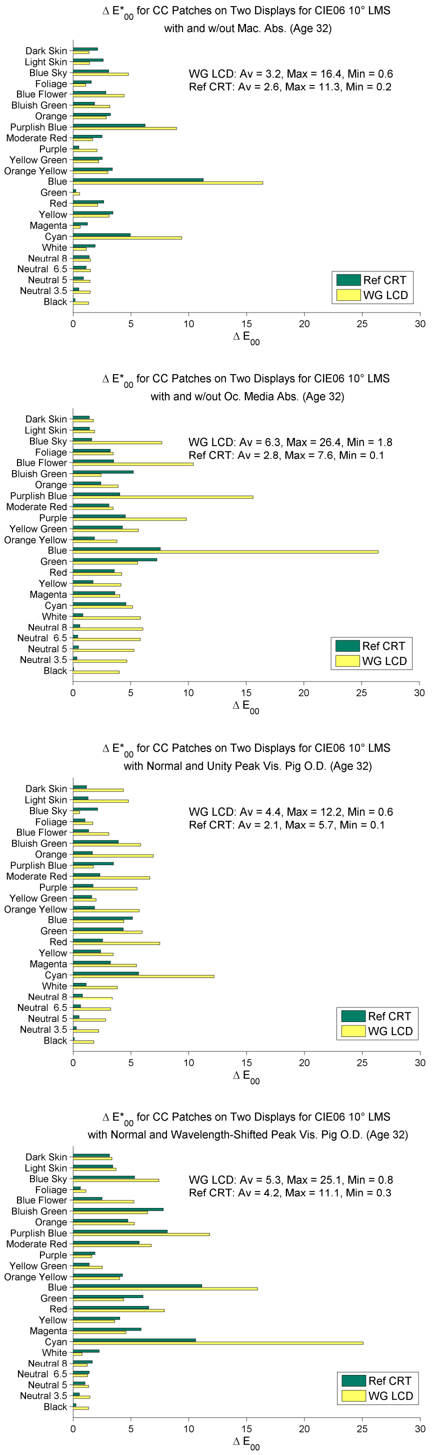

Fig 5: Simulated ΔE^*_{00} plots for Colorchecker patches shown on two displays and computed for CMFs derived from normal and modified cone fundamentals, as described in cases (i) through (iv) [top to bottom respectively]

5. CONCLUSION

If two observers of similar ages but having different peak wavelengths of L-cone photo-pigment absorption spectra are asked to evaluate colors on a modern wide-gamut display with narrow-band primaries (and to a lesser extent, in case of a broad-band display), they are likely to disagree on several color perceptions, particularly in the cyan and blue region of the color space. However, CIE06 model will be unable to predict any variation. This discrepancy is likely to propagate to color matches across displays.

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