Color Diversity Index - The effect of chromatic adaptation.

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ABSTRACT

Common descriptors of light quality fail to predict the chromatic diversity produced by the same illuminant in different contexts. The aim of this paper was to study the influence of the chromatic adaptation in the context of the development of the color diversity index, a new index capable of predicting illuminant-induced variations in several types of images. The spectral reflectance obtained from hyperspectral images of natural, indoor and artistic paintings, and the spectral reflectance of 1264 Munsell surfaces were converted into the CIELAB color space for each of the 55 CIE illuminants and 5 light sources tested. The influence of the CAT02 chromatic adaptation was estimated for each illuminant and for each scene. The CIELAB volume was estimated by the convex hull method and the number of discernible colors was estimated by segmenting the CIELAB color volume into unitary cubes and by counting the number of non-empty cubes. High correlation was found between the CIELAB volume occupied by the Munsell surfaces and the number of discernible colors and the CILEAB color volume of the colors in all images analyzed. The effects of the chromatic adaptation were marginal and did not change the overall result. These results indicate that the efficiency of the new illuminant chromatic diversity index is not influenced by chromatic adaptation.

Keywords: color rendering index, color diversity index, natural scenes, color rendering

1. INTRODUCTION

The chromatic perception experienced in common everyday tasks can be dramatically influenced by the illumination selected[1-4] and therefore great care should be taken in the selection of a light source both for general and more specific tasks.

General and industrial standard descriptors of the rendering properties of light sources focus predominantly in the reproduction of the chromatic content of only 8 or 15 standard colored samples, e.g. the color rendering index (CRI)[5]. The chromatic diversity[6,7] is generally not evaluated although the effects of spectrally structure spectra on color diversity have been studied[8,9]. Several other limitations on current rendering indices are well described[10-15]. Several attempts were made to introduce other broader color rendering indices considering not only the reproduction capabilities of illuminants but also the capability to generate chromatic diversity[16-19] as a complementary way to predict the influence of the illuminant in complex scenes.

Recently proposed descriptors also addressed the use of a smaller dataset of chromatic samples such as the Munsell set to describe the influence of several types of illuminants in much more complex scenes[20]. Chromatic adaptation[21] enables to compensate for the effects of illumination changes. It is however unclear what is the effect of the chromatic adaptation on these descriptors.

The aim of this work was to study the influence of the chromatic adaptation in the context of the development of a new index, the chromatic diversity index (CDI), capable of predicting illuminant-induced variations in several types of images using a smaller color database. The colors of images of natural, indoor and artistic paintings scenes and 1269 Munsell surfaces were simulated under 55 illuminants and 5 LED light sources. The effect of the chromatic adaptation on the CIELAB color volume and on the number of discernible colors as descriptors of chromatic variations on complex scenes was evaluated.

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2. METHODOLOGY

A database with hyperspectral data from 50 images of natural scenes, 20 images of artistic paintings, 15 images of indoor scenes and spectral data of 1269 Munsell colored samples was used. Natural scenes, artistic paintings and 12 indoor scenes where imaged over the range 400-720 nm at 10 nm intervals using a fast-tunable liquid-crystal filter (Varispec, model VS-VIS2-10-HC-35-SQ, Cambridge Research & Instrumentation, Inc., Massachusetts) and a low-noise Peltier-cooled digital camera (Hamamatsu, model C4742-95-12ER, Hamamatsu Photonics K. K., Japan), with a spatial resolution of 1344×1024 pixels and 12-bit output (for more details on the hyperspectral system see Foster *et al*[22]). The remaining 3 indoor scenes are from Brainard's hyperspectral images database acquired from 400 to 700 nm in 10 nm steps using narrowband interference filters and a monochromatic CCD camera with a spatial resolution of 2000×2000 pixels and 12-bit output[23].

Figure 1. Thumbnails of some of the images of the database: (a) – Natural scenes; (b) – Brainard's indoor scenes; (c) – Indoor scenes; (d) – Artistic paintings.

In Brainard's hyperspectral images the spectral reflectance of each pixel was obtained by dividing the raw data by the illuminant spectrum of the scene obtained at a given reference location.

For the artistic paintings and indoor scenes obtained in our laboratory, illuminant and optical spatial non uniformities were minimized dividing the data obtained from the scene by the data obtained from a grey uniform reference imaged in the same place as the scene and under the same illuminant conditions[2,3]. The spectral reflectance of each pixel of the scene was estimated from a grey reference surface present in the scene at the time of digitalization.

The hyperspectral data of the natural scenes was calibrated using the spectrum of the light reflected from a grey surface present in the scene measure with a telespectroradimeter (SpectraColorimeter, PR-650, PhotoResearch Inc., Chatsworth, CA) just after image acquisition. The spectral radiance from each pixel of the image was then obtained after corrections for dark noise, spatial non-uniformities, stray light, and chromatic aberrations. The spectral reflectance of each pixel was obtained by dividing the raw data by the illuminant spectrum of the scene obtained at a given reference location.

Munsell surfaces reflectance data was used as available at the Spectral Database, University of Joensuu Color Group, *http://spectral.joensuu.fi/*.

All reflectance data were interpolated to 5 nm step using a linear interpolation algorithm to adequate the data spectral reflectance profile to the peak nature of some of the illuminants.

The radiance spectrum was estimated for each pixel of each scene by multiplying each illuminant spectrum of a set of 60 illuminants or light sources by the spectral reflectance of that pixel. Illuminants spectra were considered from 400 nm to 720 nm for our and Munsell data and from 400 nm to 700 nm for Brainard's indoor data. The used illuminants were tabulated CIE illuminants[24] and white LEDs light sources. The CIE illuminants were: CIE illuminant A, C, 21 D illuminants including D55 and D65 (CCT in the range 25,000 K to 3,600 K in steps of 1190.3 K), 27 Fluorescent illuminants (FL1, FL2, FL3, FL4, FL5, FL6, FL7, FL8, FL9, FL10, FL11*, FL12, FL3.1, FL3.2, FL3.3, FL3.4, FL3.5, FL3.6, FL3.7, FL3.8, FL3.9, FL3.10, FL3.11, FL3.12, FL3.13, FL3.14, and FL3.15) and 5 High-Pressure illuminants

(HP1, HP2, HP3, HP4 and HP5). The white LEDs, represented in Figure 2, were: LXHL-BW02, LXHL-BW03, LXML-PWC1-0100, LXML-PWN1-0100 and LXML-PWW1-0060 from Luxeon, Philips Lumileds Lighting Company, USA. These LEDs were chosen because they are widely used and are commercialized by one of the main illumination companies.

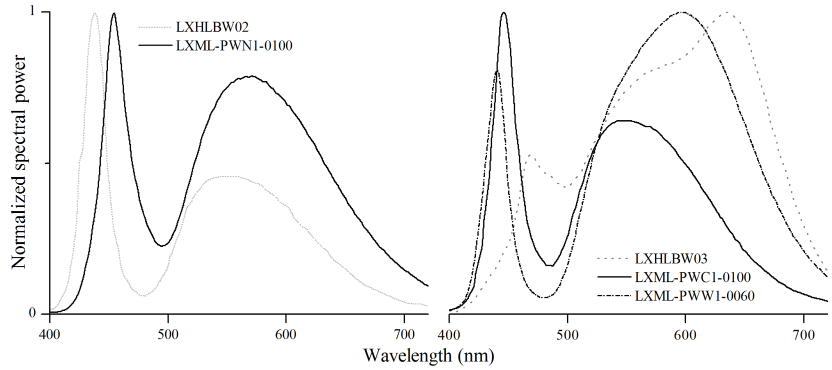

Figure 2. Normalized spectral power distribution of the 5 white LEDs used (Luxeon, Philips Lumileds Lighting Company, USA). Graphs adapted from the spectral data available from the manufacturer website (http://www.philipslumileds.com/pdfs/DS25.pdf and http://www.philipslumileds.com/pdfs/DS64.pdf).

The radiance data was then converted into tristimulus values for each illuminant assuming the CIE 1931 standard colorimetric observer[24], and the influence of the chromatic adaptation CAT02[21] estimated using the CIE D65 illuminant as the reference illuminant. The normal tristimulus values were converted into cone responses assuming the transformation matrix (Eq1), and the degree of adaptation was estimated assuming an average surround condition. The luminance of the adapting field was considered the illuminant luminance.

$$M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \qquad \text{(Eq1)}$$

The adapted tristimulus values were then converted into color coordinates in the CIELAB color space, where colors are represented in a three-dimensional way, being $L^*$the luminous intensity, a^* the amount of red or green in the color and b^* the amount of yellow or blue in the color. It was assumed that color differences represented in this color space embody perceptual differences of same magnitude.

The volume of the colors composing the CIELAB color volume for each scene and each illuminant was estimated using a convex hull algorithm by computing the smallest convex polyhedron containing all of the points and by estimating its volume.

The number of discernible colors was estimated by segmenting the CIELAB color volume into unitary cubes[25,26] and by counting the non-empty cubes. It was assumed that all the colors that were inside the same cube could not be discernible and that a filled cube represents a discernible color when compared to another filled cube.

3. RESULTS

Figure 3 represents the effect of chromatic adaptation and illuminant spectra on the CIELAB color volume of the particular scene shown in the picture: (a) represents the CIE FL3.8 illuminant with no adaptation, (b) represents the CIE HP1 illuminant with no adaptation, (c) represents the CIE FL3.8 illuminant with adaptation and (d) represents the CIE HP1 illuminant with adaptation. The CIE D65 illuminant was used as the reference illuminant.

The number of discernible colors and the CIELAB color volumes where averaged across scenes and plotted as a function of the CIELAB color volume of the Munsell set for each illuminant of the database accounted for the influence of the chromatic adaptation. Figure 4 represents such data for 21 daylight illuminants (a), 27 fluorescent illuminants (b), 5 high-pressure illuminants (c) and 5 LED spectral light sources (d), excluding CIE illuminants A and C. In each case the unweighted linear regressions (represented as straight lines) and the proportion of variance accounted for R^2 in the regression were estimated and represented in the figure and summarized in Table 1. Scales are divided by a factor of 10 000 for representation purposes.

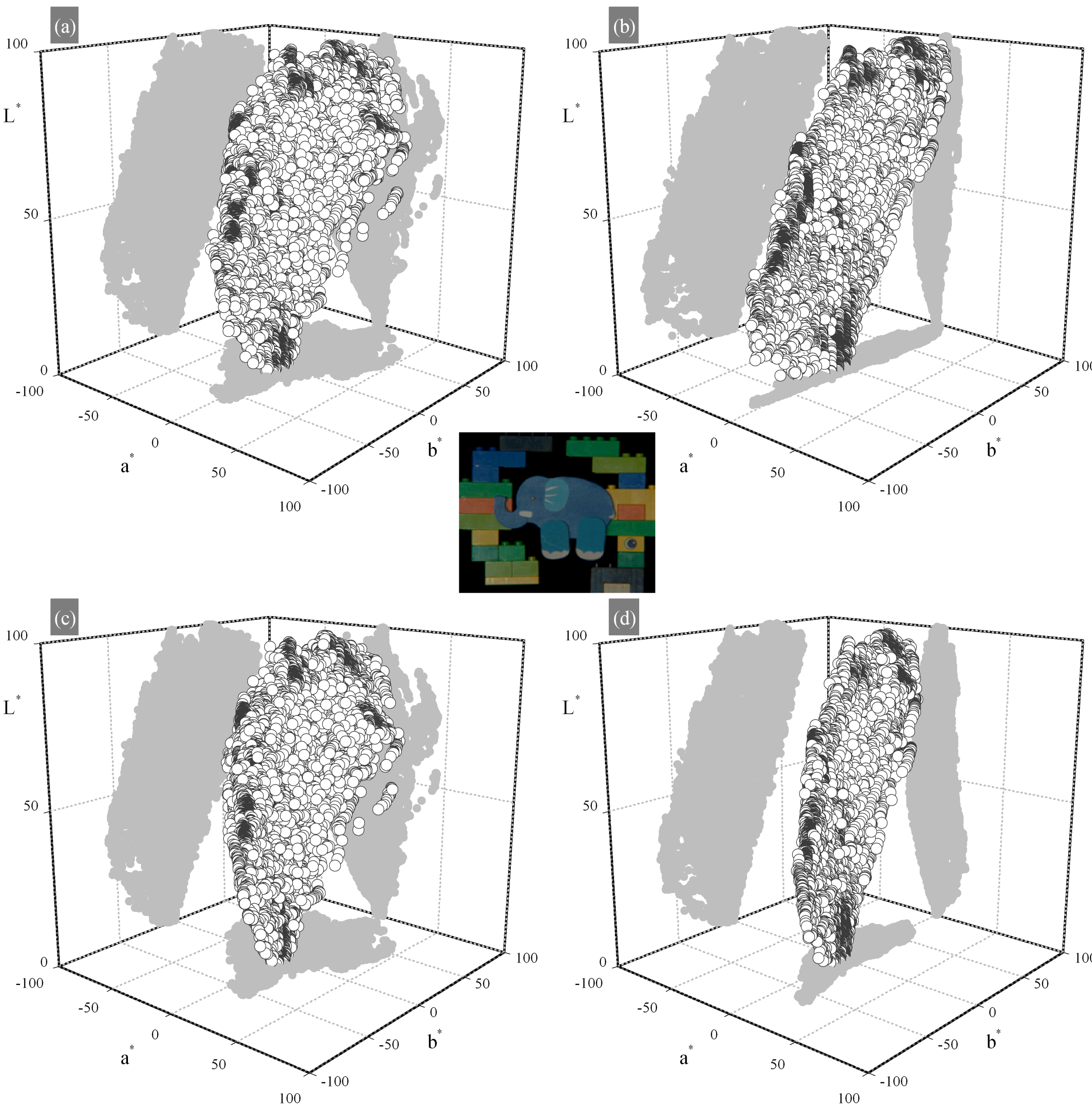

Figure 3. Illustration of the effect of the chromatic adaptation and the spectral power distribution of an illuminant on the chromatic diversity of the scene shown: (a) CIE FL3.8 illuminant with no adaptation; (b) CIE HP1 illuminant with no adaptation; (c) CIE FL3.8 illuminant with adaptation; (d) CIE HP1 illuminant with adaptation. The CIE D65 illuminant was used as the reference illuminant.

Figure 5 represents the same data as Figure 4 but considering all the illuminants and light sources in the database, including CIE illuminants A and C.

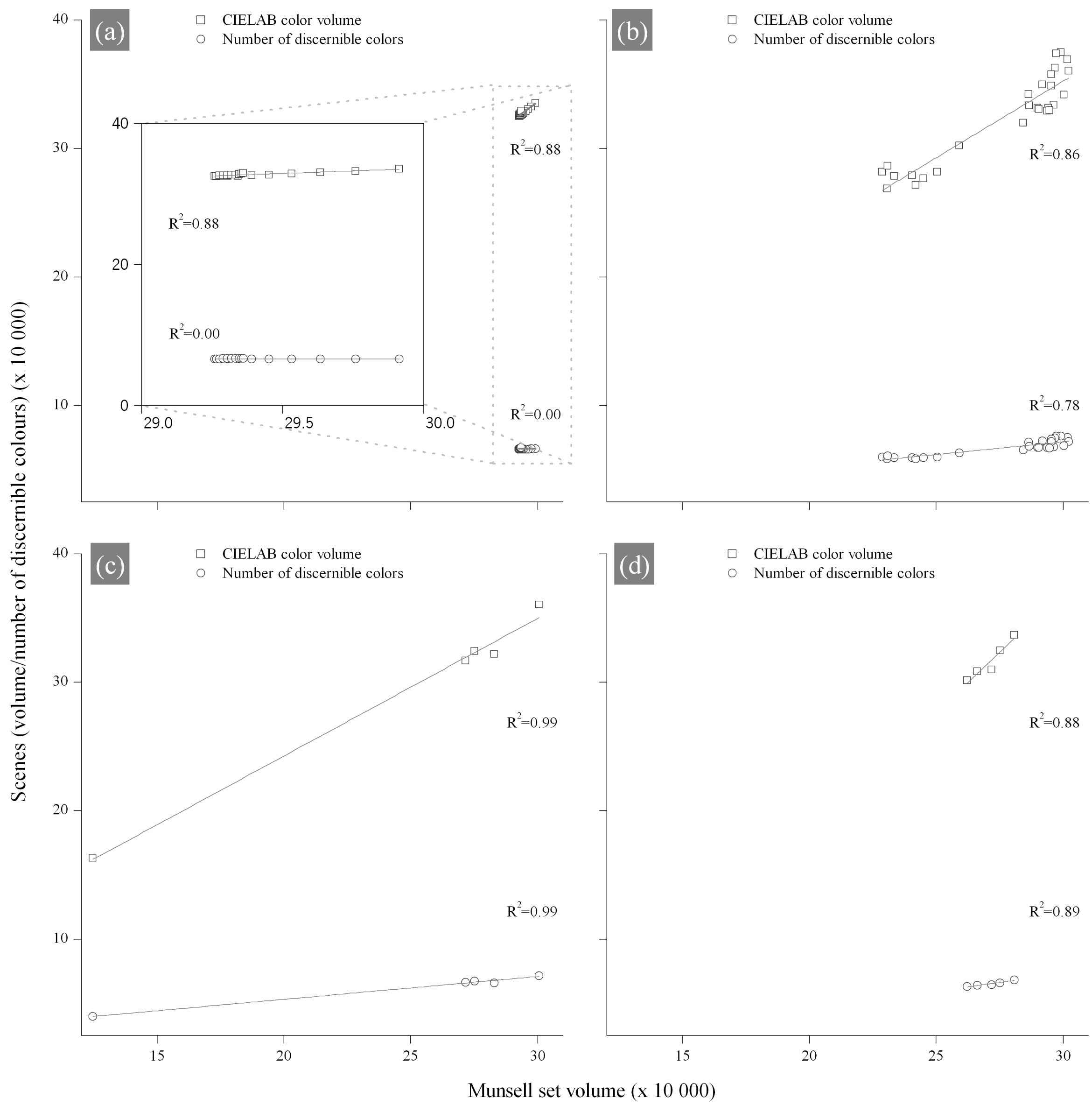

Figure 4. Average number of discernible colors (open circles) and average color volume (open squares) of analyzed scenes plotted as a function of the volume of the Munsell set, for daylight illuminants (a), fluorescent illuminants (b), high-pressure illuminants (c) and LED spectral light sources (d), excluding illuminant A and C, accounted for the influence of the chromatic adaptation in all cases. Straight lines represent unweighted linear regressions, and the proportion of variance accounted for R^2 in the regression is also represented. Inset of graph (a) represents the same data as the parent graph with smaller scale to better show data variations.

A very good degree of correlation between the CIELAB volume of the Munsell set and the CIELAB volume of all scenes was found for daylight illuminant, fluorescent illuminants, high-pressure illuminants and LED light sources. Similarly good correlation was found between the CIELAB volume of the Munsell set and the number of discernible colors of all scenes for fluorescent illuminants, high-pressure illuminants and LED light sources, but not for daylight illuminants were no correlation was found.

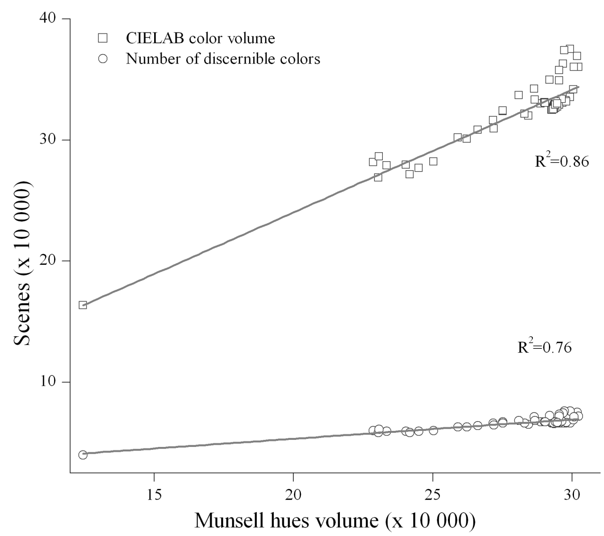

Figure 5. Average number of discernible colors (open circles) and average color volume (open squares) of analyzed scenes plotted as a function of the volume of the Munsell set, for all illuminants of the database accounted for the influence of the chromatic adaptation in all cases. Straight lines represent unweighted linear regressions, and the proportion of variance accounted for R^2 in the regression is also represented.

Figure 6 represents the same data as Figure 4 and Figure 5 but for daylight illuminants only (excluding CIE illuminants A and C) with adjusted scales for better representation and visualization, with *x* axis with the same scale in both graphs, and *y* axis with different scales but with the same difference span. The lack of linear correlation is evident in this figure.

Table 1. Summary of the proportion of variance accounted for R^2 in the unweighted linear regression of the average number of discernible colors (Nº of colors) and average color volume (Volume) of the scenes analyzed as a function of the volume of the Munsell set for each illuminant and light source category as for the average of all illuminant and light sources studied.

Type of Illuminant	R^2	
	Volume	Nº of colors
Daylight	0.88	0.00
Fluorescent	0.86	0.78
High-Pressure	0.99	0.99
LED	0.88	0.89
All	0.86	0.76

In general, as represented in Figure 5 and summarized in the last row of Table 1, there is a good degree of correlation between the CIELAB volume of the Munsell set and the CIELAB volume of the colors of all scenes and a good degree of correlation between the CIELAB volume of the Munsell set and the number of discernible colors of all scenes.

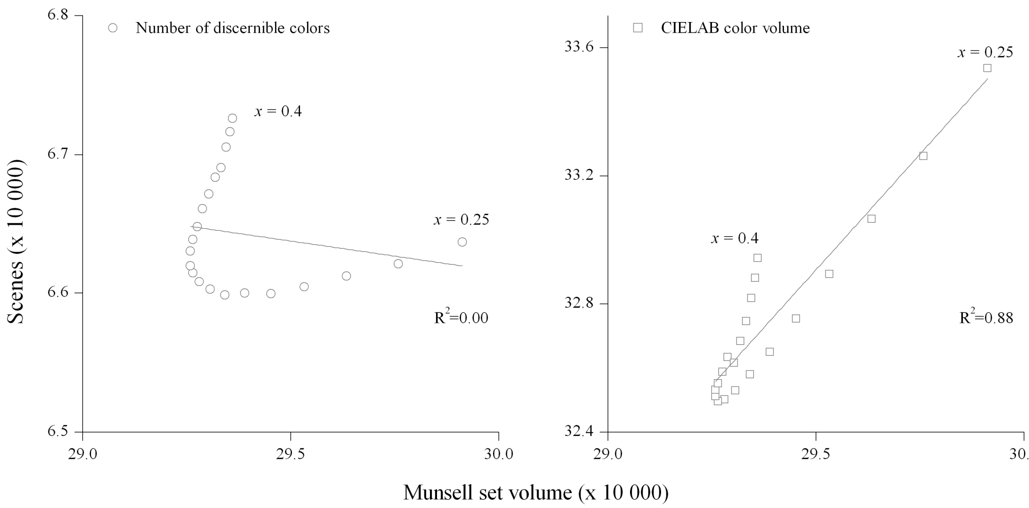

Figure 6. Average number of discernible colors (open circles - left) and average color volume (open squares - right) of analyzed scenes plotted as a function of the volume of the Munsell set, for daylight illuminants accounted for the influence of the chromatic adaptation, with adjusted scale for better representation. Straight lines represent unweighted linear regressions, and the proportion of variance accounted for R^2 in the regression is also represented. The *x* chromaticity coordinates of the extreme daylight illuminants (reddish *x*=0.40 and bluish *x*=0.25 extremes) are also represented.

4. CONCLUSIONS AND DISCUSSION

In this work hyperspectral data of natural, indoor and artistic paintings scenes and the reflectance data of 1269 Munsell surfaces were used to compare the effect of several illuminants and light sources on the chromatic diversity of very distinct sets of data, with the influence of the chromatic adaptation. A good correlation was found between the two data sets. Such result is in line with former work[20] and seems to indicate that the estimation of the volume of the Munsell set under a test illuminant and considering the chromatic adaptation of the volume to the reference illuminant CIE D65 is a good predictor of the effect of that illuminant in the chromatic variation of more complex scenes.

All the computations were done using the CIELAB color space, well known for its non-uniformities in particular in blue and gray areas[27,28]. Also, the segmentation of the color volume into unitary cubes assumes that all colors inside the same cube could not be distinguished, but in fact colors that are inside the same cube could have a color difference $\Delta E^*_{ab}>1$ which are in fact discernible. The use of unitary spheres instead of unitary cubes to estimate the number of discernible colors can partially overcome this limitation, but previous studies[26] suggests that when relative estimates of the number of discernible colors are more important than absolute estimates, as is the case in this work, it can be estimated with great robustness using the cubic method. Nevertheless the chromatic adaptation of all illuminants to illuminant D65 improves previous methods as the CIELAB color space is optimized for Illuminant D65[24].

All the estimations of the chromatic diversity regarding the Munsell set were done using the correspondent color volume. The colored samples of the Munsell sample are distributed in such a way that the number of discernible colors as no particular variation when the samples are rendered under different illuminants.

The number of discernible colors is always smaller than the estimated color volume because the first method ignores empty holes in the CIELAB color volume, while the later estimates empty holes that are inside the smallest convex polyhedron are treated as being part of the volume. Hence, the number of discernible colors is an accurate measure of the chromatic diversity of complex scenes, and comparable to the color volume[20].

The use of the number of discernible colors as a viable descriptor of chromatic diversity of complex scenes was already studied[1,2]. In the particular case of daylight illuminants, the use of the chromatic adaptation obliterated the correlation between the Munsell set and the volume of natural scenes found in the former work. The use of the chromatic adaptation shifts the maximum volume of the Munsell set into the blue and red limits of the Illuminant D, as represented in Figure 6. The minimum volume, with adaptation, occurs when a reddish illuminant D is used (chromaticity coordinate *x*=0.4) while the maximum volume occurs when a bluish illuminant D is used (chromaticity coordinate *x*=0.25), with an inflection around illuminant D65. Without the use of the chromatic adaptation such effect is not observed.

The influence of a test illuminant in a complex scene can be predicted using the Munsell set rendered under that test illuminant[20], and despite of the limitation of the present method, the data presented suggests that a new illuminant chromatic diversity index based on natural scenes could be defined using the CIELAB volume of the Munsell surfaces, with negligible influence of the chromatic adaptation.

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