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The number of discernible colors perceived by dichromats in natural scenes and the effects of colored lenses

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Abstract

The number of discernible colors perceived by normal trichromats when viewing natural scenes can be estimated by analyzing idealized color volumes or hyperspectral data obtained from actual scenes. The purpose of the present work was to estimate the relative impairment in chromatic diversity experienced by dichromats when viewing natural scenes and to investigate the effects of colored lenses. The estimates were obtained computationally from the analysis of hyperspectral images of natural scenes and using a quantitative model of dichromats' vision. The color volume corresponding to each scene was represented in CIELAB color space and segmented into cubes of unitary side. For normal trichromats, the number of discernible colors was estimated by counting the number of non-empty cubes. For dichromats, an algorithm simulating for normal observers the appearance of the scenes for dichromats was used, and the number of discernible colors was then counted as for normal trichromats. The effects of colored lenses were estimated by prior filtering the spectral radiance from the scenes with the spectral transmittance function of the lenses. It was found that in dichromatic vision the number of discernible colors was about 7% of normal trichromatic vision. With some colored lenses considerable improvements in chromatic diversity were obtained for trichromats; for dichromats, however, only modest improvements could be obtained with efficiency levels dependent on the combination of scene, lens and type of deficiency.

Keywords: Color vision, Dichromacy, Discernible colors, Colored lenses

Introduction

How many discernible colors can be perceived by normal trichromatic observers is a classical question in color vision research (Judd & Kelly, 1939; MacAdam, 1947; Nickerson & Newhall, 1943). Although some early estimates refer to the number of different chromaticities that can be perceived in a constant luminance plane (MacAdam, 1947) recent estimates considered the three-dimensionality of color perception and have been based on the representation of the theoretical object-color solid in uniform color spaces (Martinez-Verdu et al., 2007; Perales et al., 2006; Pointer, 1998; Pointer & Attridge, 1998) or on the analysis of hyperspectral imaging data obtained from natural scenes (Linhares, 2005; Linhares et al., 2004). Estimates reported vary over a wide range but a number around two million is common to several recent studies (Martinez-Verdu et al., 2007; Pointer & Attridge, 1998).

Dichromats lack one cone pigment (Sharpe et al., 1999) and although they may be more efficient in some specific tasks, e.g., in discrimination of color-camouflage (Morgan et al., 1992; Saito et al., 2006) and detection of some stimuli at high temporal frequencies (Sharpe et al., 2006), their color discrimination is significantly impaired in relation to normal trichromats (Ruddock, 1991). But how much this reduction in color discrimination affects the number of discernible colors they perceive? Even though color confusions lines for dichromats are well characterized (Wyszecki & Stiles, 1982), the unavailability of uniform color spaces representing their color perception poses difficulties in generalizing to dichromatic vision previous estimates obtained for trichromats. It is possible, however, based on some assumptions concerning dichromatic color vision to infer plausible color appearance (Vienot et al., 1995) and use quantitative algorithms to simulate for normal observers the appearance of the scenes for dichromats (Brettel et al., 1997). This model is known to represent dichromatic vision incompletely (Wachtler et al., 2004) but has been used to obtain approximated descriptions in real-world scenes (Mollon & Regan, 2001) and in practical applications (Kovalev, 2006; Rasche et al., 2005; Vienot et al., 1999). By converting dichromatic color vision to perceptions experienced by normal trichromats, an indirect representation of dichromatic color perception in uniform color spaces becomes possible and an estimate of the number of discernible colors can then be obtained.

Another issue regarding dichromats is the possibility of improving color vision by increasing chromatic diversity through the use of colored filters. For normal trichromatic observers, the

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number of discernible colors that can be perceived in a scene is influenced by the spectral composition of the illumination (Martinez-Verdu et al., 2007; Pinto et al., 2006) and by observation through colored lenses (Linhares et al., 2005). For anomalous trichromats, variations in the optical density of macular pigment was found to improve discrimination (Moreland & Westland, 2006) and it has been suggested that specific color filters may enhance their vision in particular circumstances (Kovacs et al., 2001). It is, however, unclear how much the use of colored lenses may improve the chromatic diversity experienced by dichromats when viewing natural scenes.

The purpose of the present work was to estimate the relative impairment in chromatic diversity experienced by dichromats when viewing natural scenes and to investigate the effects of colored lenses. The estimates were obtained computationally from the analysis of hyperspectral images of natural scenes and using a quantitative model of dichromat's vision. Hyperspectral images combine spectral and spatial information and have been used in the characterization of the spectral and chromatic properties of natural scenes (Foster et al., 2006; Linhares, 2005; Linhares et al., 2004; Nascimento et al., 2002, 2005). The color volume corresponding to each scene was represented in CIELAB space and segmented in cubes of unitary side. For normal trichromats, the number of discernible colors was estimated by counting the number of non-empty cubes. For dichromats, an algorithm (Brettel et al., 1997) modeling dichromatic vision was applied. The effects of colored lenses were estimated by prior filtering the spectral radiance from the scenes with the spectral transmittance function of the lenses. It was found that in dichromatic vision the number of discernible colors was about 7% of that perceived in normal trichromatic vision. With some colored lenses considerable improvements in chromatic diversity were obtained for trichromats; for dichromats, however, only modest improvements could be obtained.

Materials and methods

A database with hyperspectral images from 50 natural scenes was used in the computational analysis. The scenes were from rural and urban environments and were all from the Minho region of Portugal. The hyperspectral system used a low-noise cooled digital camera with a spatial resolution of 1344×1024 pixels (Hamamatsu, model C47542-95-12R, Hamamatsu Photonics K.K., Hamamatsu City, Japan) with a fast tunable liquid-crystal filter (VariSpec, model VS-VIS2-10-HC-35-SQ, Cambridge Research & Instrumentation, Inc., Woburn, MA) mounted in front of the lens, coupled with an infrared blocking filter. Images were acquired from 400 to 720 nm in 10 nm steps and particular care was taken to avoid scenes containing movement. The spectral radiance from each point of the scenes was estimated by calibrating the images using the reflected spectrum from a small flat gray (Munsell N7) reference surface present in the scene measured with a telespectroradiometer (SpectraColorimeter, PR-650, Photo Research Inc., Chatsworth, CA). Detailed description of the system, image processing and properties of the scenes is provided elsewhere (Foster et al., 2004, 2006).

Scenes were represented in the approximately uniform CIELAB color space (CIE 2004). As the issue here was to evaluate just noticeable color differences a perceptual space rather than a cone space was used in the analysis. To obtain the CIELAB color coordinates from the radiance spectrum of each image pixel the CIE 1931 Standard Observer was used to compute the tristimulus values which were then converted into CIELAB coordinates. The white reference was obtained from the spectrum reflected from the gray reference present in the scene.

To simulate for normal trichromatic observers the colored images seen by dichromats the algorithm described by Brettel et al. (1997) was applied. The algorithm is based on assumptions concerning the hues that appear the same to dichromats and normal trichromats, namely that neutrals and some specific monochromatic lights are perceived in the same way for both type of observers (Judd, 1948). These assumptions allow the definition of flat stimuli surfaces in LMS space, L, M, and S representing the quantum catches for the long-, medium-, and short-wavelength-sensitive cones, respectively; the principle of the algorithm relies in attributing to the undetermined cone signal a value obtained by projecting the (L, M, S) vector in the corresponding reduced stimulus surface.

Using the tristimulus values obtained from the radiance data as describes above, the (L, M, S) coordinates were computed using the Vos (1978) transformation and the Smith and Pokorny's (1975) fundamentals. In these transformations Judd's modified photopic luminous efficiency function was assumed to coincide with the non-modified function. For protanopes, deuteranopes and tritanopes, the simulated (L', M', S') coordinates were obtained by replacing the undetermined cone signal by the corresponding value on the respective reduced stimuli surface (Brettel et al., 1997). The coordinates obtained in this way were then converted back into CIELAB coordinates using the inverse Vos transformation. In this process a small number of colors could not be transformed into meaningful cone quantum catches by the algorithm; these represented on average less than 1% of the pixels in the images and were excluded from the analysis.

As an illustration of the results of this computations, Fig. 1 shows on the left the pictures displaying the colors perceived by normal trichromats (1), by protanopes (2), by deuteranopes (3) and by tritanopes (4), when viewing one of the scenes of the database. On the right are represented the corresponding color volumes in the CIELAB color space. For visual clarity only a fraction of the colors was represented in the three-dimensional graphs. Notice that the color volume for the normal trichromats transforms into surfaces projecting lines in the CIELAB (a^*, b^*) plane.

The number of discernible colors was estimated for each scene as follows. The CIELAB color volume was segmented into cubes of unitary side and the number of colors was counted as the number of non-empty cubes. This methodology gives an approximate but reasonable estimate (Pointer & Attridge, 1998) and was preferred over more complex approaches such as spherical segmentation (Martinez-Verdu et al., 2007; Perales et al., 2006) for its moderate demanding computational power.

To study the influence of colored lenses the radiance spectra of each image pixel was multiplied by the transmittance spectra of each colored lens tested, returning a spectral image as if seen through the lens. The CIELAB color volume was then computed and the number of discernible colors estimated as without lenses. The transmittance spectra of the 10 colored lenses used in the analysis are represented in Fig. 2. Spectral transmittance functions were measured with a spectrophotometer (Shimadzu, model UV-3101PC, Shimadzu Japan), from 400 to 720 nm in 1 nm steps. Nine lenses were commercial sunglasses colored lenses but lens number eight was an idealized lens which spectral transmittance function was obtained computationally by an optimization routine to maximize the number of discernible colors perceived by normal trichromats when seeing the natural scenes of the database through it.

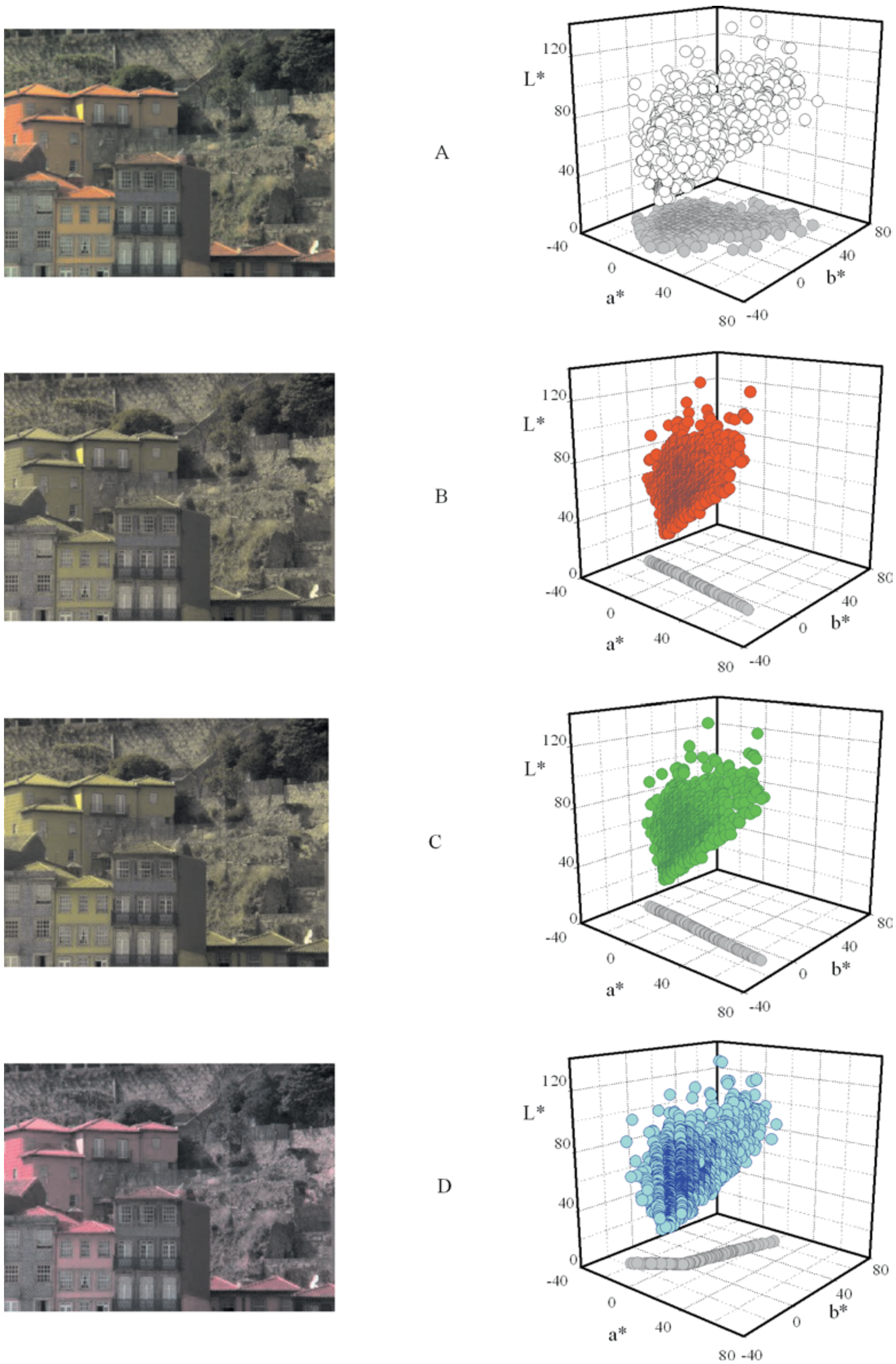

Fig. 1. Left: pictures displaying the colors perceived by normal trichromats (A), by protanopes (B), by deuteranopes (C), and by tritanopes (D), when viewing one of the scenes of the database. Right: the corresponding color volumes in the CIELAB color space. For clarity only a fraction of the colors was represented in the three-dimensional graphs.

Results

Fig. 3 shows the fraction of discernible colors perceived by protanopes, deuteranopes and tritanopes when compared to normal trichromats viewing the same scenes. Data represent mean across scenes and error bars represent sample standard deviation. The mean reduction in chromatic diversity experienced by the three types of dichromats is similar and to about 7%. For individual

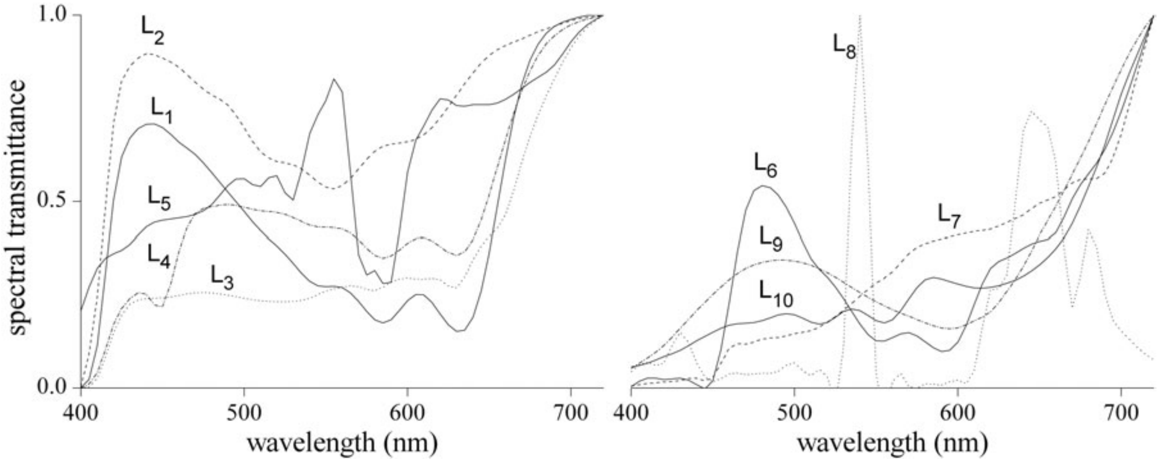

Fig. 2. Spectral transmittance functions of the 10 colored lenses tested. All lenses except number 8 were commercial sunglasses lenses. Lens number 8 was an idealized lens (see text for details).

scenes the larger impairment corresponded to 4% and the smaller to 15%, also similar for the three types of deficiencies. The impairment corresponding to the scene represented in Fig. 1 was of 6% for protanopes and deuteranopes and of 7% for tritanopes.

Fig. 4 represents for each colored lens the relative variations obtained when comparing the number of discernible colors obtained with and without lenses. Data represent mean across scenes and error bars represent sample standard deviation. Negative values indicate a reduction in the number of discernible colors with lenses and positive values an enhancement. More detailed information about the effect of colored lenses is shown in Table 1. For each colored lenses are represented the minimum, maximum and mean value across scenes of the ratio between the number of discernible colors obtained with lenses and the number of discernible colors obtained without lenses. Values larger than 1 indicate an increment in the number of colors and smaller than 1 a decrement. On average, the effects of the lenses on normal trichromats indicate a small enhancement corresponding to 1.07; for protanopes and deuteranopes a small impairment corresponding to 0.96 and 0.99, respectively; and a considerable enhancement for the tritanopes corresponding to 1.11. For particular combinations scene-lens larger values can be obtained, e.g., with lens number eight.

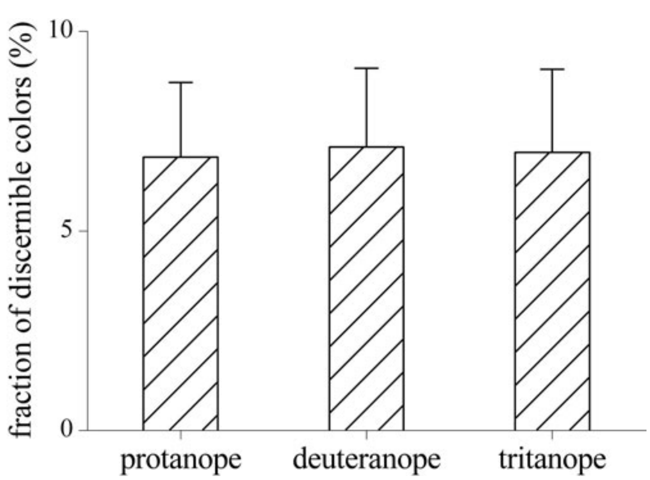

Fig. 3. Fraction of discernible colors perceived by protanopes, deuteranopes and tritanopes when compared to normal trichromats viewing the same scenes. Data represent mean across the scenes of the database and error bars represent sample standard deviation.

Discussion

The computations reported here suggest that dichromats can perceive on average about 7% of the colors that normal trichromats do. Although attempts to model dichromatic color perception have been reported (Brettel et al., 1997; Mollon & Regan, 2001; Vienot et al., 1995; Wachtler et al., 2004) the question of how much impaired is chromatic diversity experienced by dichromats has not been addressed. It can be argued that the number obtained here is too low given that dichromats do not seem so much impaired in practical everyday life. But such reduction does not seem to affect the ability to perceive the main features of the scenes as suggested by Fig. 1 which represents impairments of 6% for protanopes and deuteranopes and of 7% for tritanopes.

This study was based on the analysis of hyperspectral images of 50 natural scenes. In spite of the limited number of scenes the set contained considerable diversity, with close-up and distant scenes of urban and rural environments, and therefore may be a representative sample of most of the color stimuli humans are exposed to.

The comparison of chromatic diversity obtained with and without colored lenses shows that their use may in some cases improve the chromatic diversity experienced by normal trichromats and dichromats. These findings generalize the results of Moreland and Westland (2006) for macular pigment and anomalous trichromats. Improvements obtained here were, however, modest, especially for dichromats and suggest that a general improvement in dichromats vision may be difficult, although it can be achieved for specific scenes. Whether these improvements can be perceived by observers as better vision is an open question. In a psychophysical experiment with normal trichromatic observers (Pinto et al., 2006) chromatic diversity of artistic paintings was systematically varied by altering the spectral composition of the illumination. It was found that changes of only a few percent in chromatic diversity

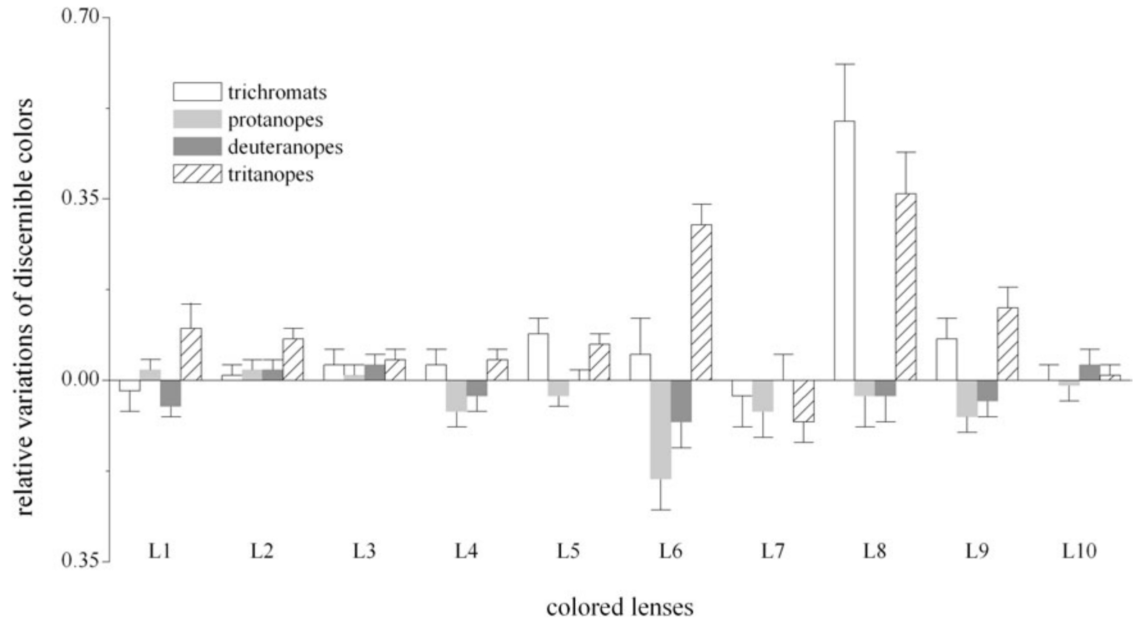

Fig. 4. Relative variations obtained when comparing the number of discernible colors obtained with and without lenses. Data represent mean across the scenes of the database and error bars represent sample standard deviation. Negative values indicate a reduction in the number of discernible colors and positive values an enhancement.

produced significant changes in observers' preferences a result that may indicate that the small improvements reported here may be visually relevant.

The lens producing the larger increase in chromatic diversity for normal trichromats was a lens with narrow peaks in some regions of the spectrum (lens number eight). This may seem puzzling and inconsistent with some data suggesting that narrowing the spectrum of the light reaching the eye tends to produce impairing of color discrimination (Vienot et al., 2005). The effects reported here, however, concern an expansion of the color volume and are not easily related with data obtained from standard testes designed for daylight. To illustrate the effect of lens 8 the CIELAB representation of the set of 1269 samples from the Munsell Book of Color (Munsell Color Corporation, 1976) assuming rendered under the equi-energy illuminant viewed with and without the lens eight was computed. The spectral reflectances were used as tabulated by the University of Joensuu Color Group (http://spectral.joensuu.fi/). Results are represented in Fig. 5 in the plane (a^*, b^*). Data obtained without the lens is represented on the left and data obtained with the lens is represented on the right.

Segmenting the CIELAB color space into cubes of unitary side to estimate the number of discernible colors is a methodology often applied (Martinez-Verdu et al., 2007; Pointer & Attridge, 1998) but relies on the assumption that all colors represented inside the same cube cannot be discriminated even though some pairs may have a color difference $\Delta E^*_{ab} > 1$, that is, larger than the just noticeable difference. A segmentation of the color space in spheres partially overcomes this problem and estimates consistently about the double number of colors (Linhares, 2005). This suggests that the relative estimates of the present study are robust

Table 1. *The minimum, maximum and mean value across scenes of the ratio between the number of discernible colors obtained with lenses and the number of discernible colors obtained without lenses*

Lens	Trichromats			Protanopes			Deuteranopes			Tritanopes		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	0.91	1.15	0.98	0.94	1.08	1.02	0.89	1.04	0.95	1.00	1.25	1.10
2	0.96	1.12	1.01	0.97	1.10	1.02	0.96	1.09	1.02	1.03	1.15	1.08
3	0.97	1.12	1.03	0.96	1.09	1.01	0.96	1.09	1.03	1.00	1.11	1.04
4	0.98	1.16	1.03	0.89	1.03	0.94	0.92	1.05	0.97	1.00	1.14	1.04
5	1.02	1.20	1.09	0.92	1.04	0.97	0.93	1.06	1.00	1.02	1.15	1.07
6	0.92	1.25	1.05	0.68	0.96	0.81	0.85	1.04	0.92	1.18	1.40	1.30
7	0.86	1.11	0.97	0.84	1.07	0.94	0.90	1.11	1.00	0.83	1.05	0.92
8	1.28	1.74	1.50	0.80	1.19	0.97	0.88	1.10	0.97	1.20	1.51	1.36
9	1.01	1.22	1.08	0.87	1.03	0.93	0.91	1.05	0.96	1.05	1.24	1.14
10	0.95	1.08	1.00	0.93	1.08	0.99	0.95	1.09	1.03	0.96	1.07	1.01

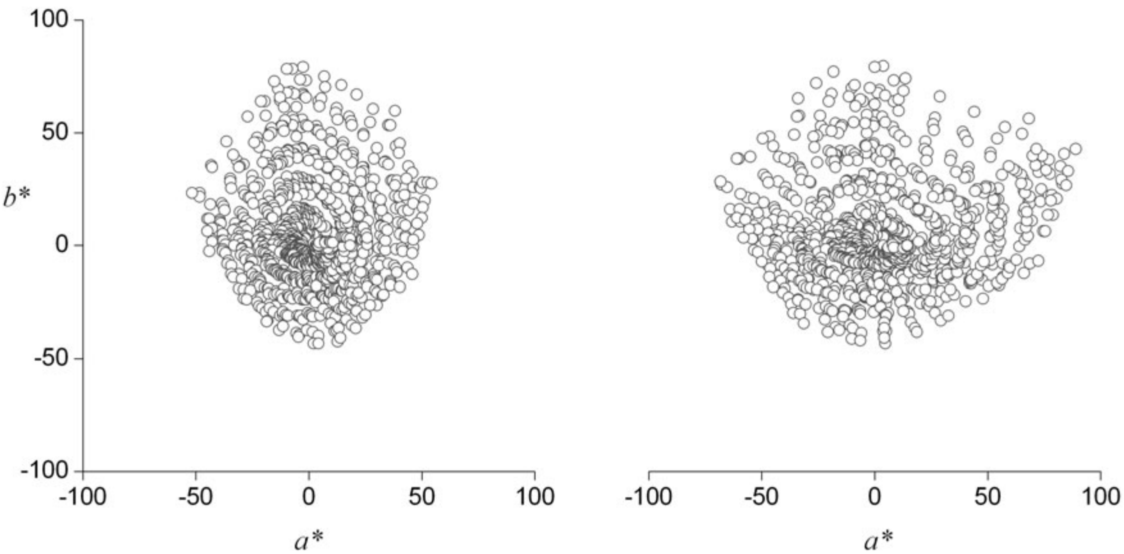

Fig. 5. CIELAB representation of the set of 1269 samples from the Munsell Book of Color assuming rendered under the equi-energy illuminant and viewed with (right) and without (left) lens 8.

in relation to more accurate methodologies to estimate the number of discernible colors.

The CIELAB color space is of limited uniformity (Luo & Rigg, 1986) and other more uniform spaces are available (Fairchild, 2005; Luo et al., 2001). In addition, color effects like assimilation, induction and the variations of visual sensitivity with spatial structure (Aldaba et al., 2006; Zhang et al., 1997) are not embodied in CIELAB. The implementation of more advanced color representations, however, can only be carried out with considerable computational cost and it is not likely to affect critically the results presented here.

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