Does melanopsin help to explain color constancy in natural environments?

Pablo A. Barrionuevo[a]*, Dingcai Cao[b]

[a] Instituto de Investigación en Luz, Ambiente y Visión, CONICET - UNT, Tucumán, Argentina
[b] Department of Ophthalmology and Visual Sciences, University of Illinois, Chicago, IL, USA
* pbarrionuevo@herrera.unt.edu.ar

ABSTRACT

The aim of this work was to assess whether melanopsin excitation could help to achieve a better color constancy in natural environments.

Data from hyperspectral natural images and 21 daylight illuminants were used to compute L-, M-, S-cone and melanopsin excitations for each pixel. The geometrical distance in the cone chromaticity diagram [L/(L+M) and S/(L+M)] was computed between daylight illuminants and the reference illuminant (D65) for each pixel in each image. These distances were related to melanopsin excitation. Our analysis showed that to achieve a better color constancy, melanopsin contribution to afferent chromatic pathways depends on the correlated color temperature (CCT) of illuminants. For CCT values related to clear sky conditions, signals in the S/(L+M) axis need a positive melanopsin contribution, and the L/(L+M) axis a negative contribution. Instead, scenes such as those related with dawn and dusk, have worse constancy when melanopsin is considered.

Keywords: *color constancy, melanopsin, natural environment*

INTRODUCTION

Human color vision in photopic conditions is mediated by three cone types (L, M and S). The cone excitations are conveyed by three post-receptoral pathways, including magnocellular (MC), parvocellular (PC) and koniocellular (KC) pathways, reviewed by Lee (2004). The MC-pathway combines L- and M-cone signals with the same sign to mediate luminance information. The PC-pathway combines L-cone and M-cone signals with opposite signs to provide red-green chromatic information. Finally, the KC-pathway combines S-cone signals in opposition to L- and M-cone signals to provide blue-yellow chromatic information.

Cones are not exclusive retinal photoreceptors detecting light in photopic conditions. In the beginning of this century, it was demonstrated that a group of retinal ganglion cells (ipRGCs) are intrinsically photosensitive (Berson et al. 2002, Hattar et al. 2002). These cells express the photopigment melanopsin (Provencio et al. 2000). IpRGCs projections include centers for non-image forming functions, but also the Lateral Geniculate Nucleus (LGN) and superior colliculus that are involved in image-forming visual processes (Hattar et al. 2003).

Color constancy is a perceptual ability by which we are able to maintain a relatively stable color perception to objects despite of changes in illumination (Foster 2011). This ability is important since color provides information about object properties (Brainard and Radonjić 2014).

Several models have been proposed trying to understand how the visual system achieves color constancy. These models can be classified as so-called lightness algorithms, estimators of the illumination spectrum, low-dimensional linear models, or Bayesian models, for a review see Foster (2011). However, most of the existing research thus far didn't focus on the statistical properties of natural environments (Arend 2001, Foster 2011).

Mice studies showed that melanopsin activation not only improves the LGN capacity to codify natural visual information and to work as an independent irradiance measurement to control visual adaptation in retinal level (Allen et al. 2014), but also a subset of LGN units can detect modest changes in irradiance employing melanopsin signals (Davis et al. 2015). Furthermore, macaque studies showed an important feature of melanopsin as an irradiance meter (Dacey et al. 2005). Therefore melanopsin may be a potential candidate for being involved in color constancy in natural environments. The objective of this exploratory analysis is to assess how melanopsin activation could help to achieve a better color constancy in natural environments.

METHODS

Natural images and illuminants

The excitation of each type of photopigment was computed from the combination of the reflectance of hyperspectral images with natural illuminants. Four hyperspectral images of rural scenes were downloaded from the website of Dr. David Foster's laboratory (http://personalpages.manchester.ac.uk/staff/david.foster/default.htm) (Foster et al. 2006). These images contain primordial foliage information and spectral reflectance information at each pixel. The scenes were acquired using a tunable bi-refringent filter mounted in front of the lens of a progressive-scanning monochrome digital camera (Nascimento et al. 2002), with image sizes of 820 pixels × 820 pixels. For this exploratory analysis we used a central patch of 800 pixels × 800 pixels (Figure 1a).

Natural daylight illumination was represented by 21 "D" illuminants with correlated color temperature (CCT) from 3600 K to 25,000 K (Linhares and Nascimento 2012), covering different phases of the day, from moon light to sun light (Wyszecki and Stiles 2000: 11, Stair and Johnston 1953). The spectral power distributions of the illuminants were normalized with the peak values of 1. The normalized illuminant spectral distributions are shown in Figure 1b.

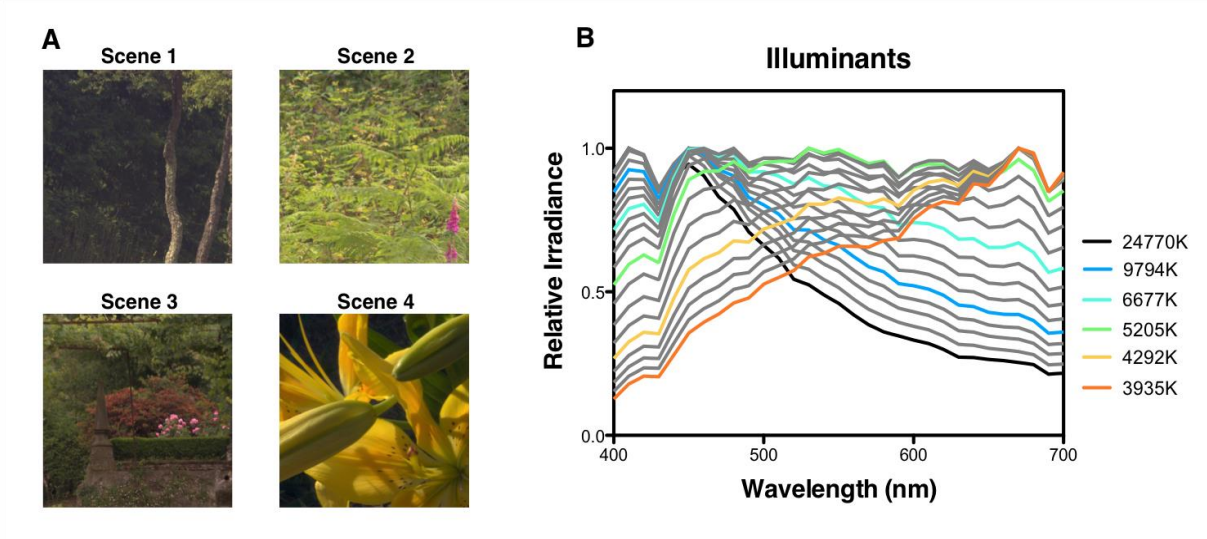

Figure 1:
a) Scenes used for the computation of the cone and melanopsin chromaticities.
b) Normalized daylight illuminants spectrum.

Analysis

For each combination of illuminant and scene, the illuminant power was multiplied by the reflectance value at each wavelength between 400-700 nm in 10 nm steps to obtain the spectral radiance values at each pixel. We then computed the L-cone, M-cone, S-cone, and melanopsin-mediated ipRGC excitations for each pixel. The cone excitations (L, M, S) were computed based on the Smith and Pokorny (1975) cone fundamentals applied for the CIE 1964 10° standard observer.

The melanopsin-mediated ipRGC excitation (I) was computed according to the melanopsin spectral sensitivity function (Enezi et al. 2011). The photoreceptor spectral sensitivity functions were normalized such that the areas under the curves were equal to 1.

We also computed the quantities l = L/(L+M), s = S/(L+M) and i = I/(L+M). Note that l and s are two cardinal axes in a MacLeod & Boynton equiluminant cone chromaticity space (MacLeod and Boynton 1979), corresponding to the PC- and KC-pathways, respectively (Lee et al. 1990, Derrington et al. 1984). In such a space, luminance is specified as L+M because S-cones do not contribute to $V(\lambda)$. We used the same approach to normalize melanopsin excitations by cone luminance at each pixel.

Using D65 illuminant as a reference, the geometrical distance d in the cone chromaticity diagram (l vs s) was computed between daylight illuminants and the reference illuminant for each pixel in each image. We also used an equal energy spectrum (EES) illuminant as the reference for a control purpose, which allowed representing the chromaticities of the objects in the scene. Distance d data were correlated to melanopsin chromaticities (i) using different multiplicative coefficient for each cardinal axis. All of the analyses were carried out in MATLAB (Mathworks Inc.).

RESULTS

Rationale

Chromaticity values *l* and *s* for scene 1 are shown in Figure 2. Chromaticities considering the 21 illuminants form the blue data cloud (l_b, s_b). While the red data cloud represent chromaticities (l_r and s_r) considering only D65 illuminant (Figure 2, left) or EES illuminant (Figure 2, right). Therefore, a pixel (p_{xy}) has one representation in the red cloud but 21 representations in the blue cloud. In order to achieve color constancy the illuminant effect should be discounted. The distance (*d*) in the chromaticity diagram between a blue point for one illuminant (*j*) and a red point for pixel (p_{xy}) can be computed as $d_l = l_{bi} - l_r$, and $d_s = s_{bj} - s_r$. If melanopsin helps to achieve color constancy discounting the illuminant effect, then *d* should be function of melanopsin excitation removing luminance (d = f(i_b), Figure 3). We tested only the assumption that *d* is linearly related to melanopsin chromaticity. Therefore *d* and *i* are related by scaling factors F, i.e., $d = F * i_b$.

Then: $l_b = F_l * i_b + l_r$ (Eq. 1)

and $s_b = F_s * i_b + s_r$ (Eq. 2)

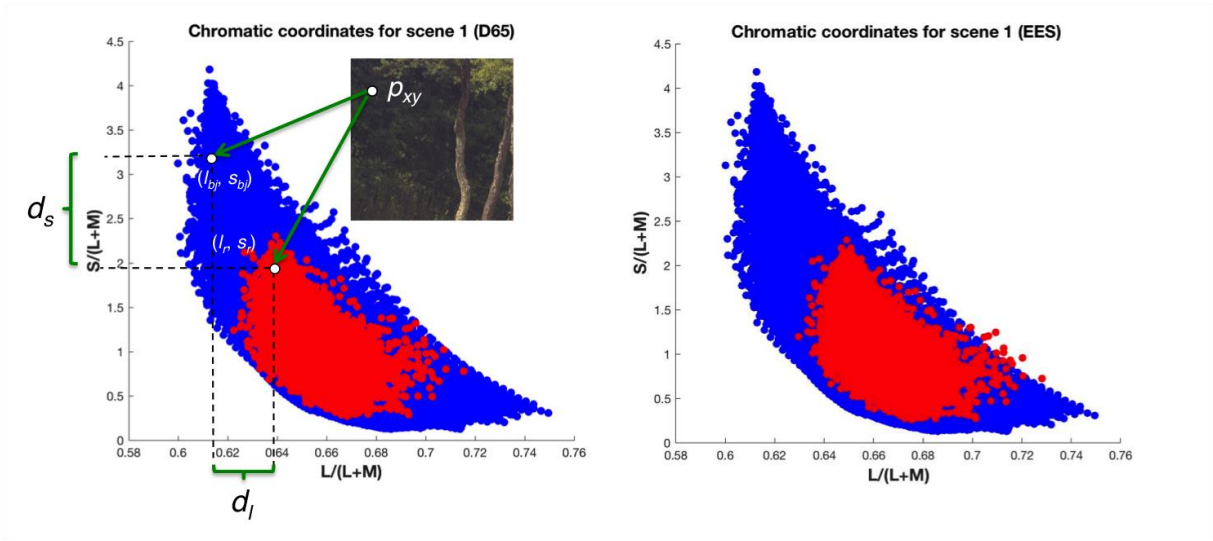

Figure 2:
Blue dots represent chromaticities for all illuminants computed by the reflectance of each pixel.
Red dots represent chromaticities computed considering only one illuminant, D65 or EES.

Melanopsin excitation

Melanopsin excitation normalized by luminance (*i*) results for the four scenes considering the 21 illuminants from lowest CCT value to highest CCT value are shown in Figure 3. As expected, the normalized melanopsin excitation increased in function of CCT of the illuminant for the four scenes.

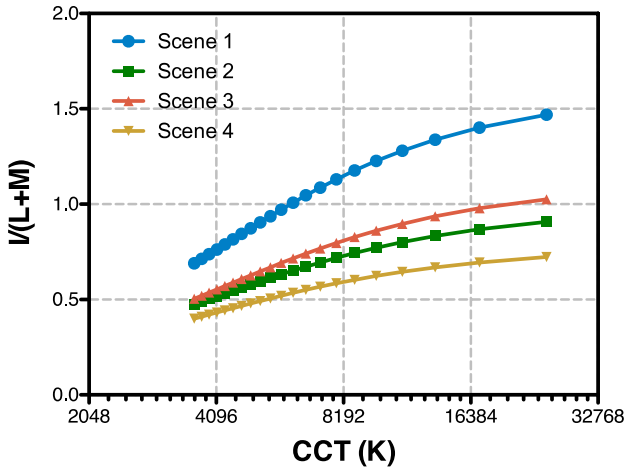

Figure 3:
Averaged data of melanopsin excitation normalized by luminance in each pixel. Error bars are standard errors. Each panel represents the data for each scene.

Factors

Factors F_s and F_I were computed for each scene following equation 1 and 2 respectively, considering D65 illuminant and EES illuminant as references (I_r , s_r). Results are shown in Figure 4. For the four scenes, with increasing CCT value, the value of F_I that is needed in the *I* coordinate is reduced from positive to negative values, while the value of F_s factor increased from negative to positive values. Of course the zero value for F_I or F_s indicated when red points were equal to blue points in Figure 2.

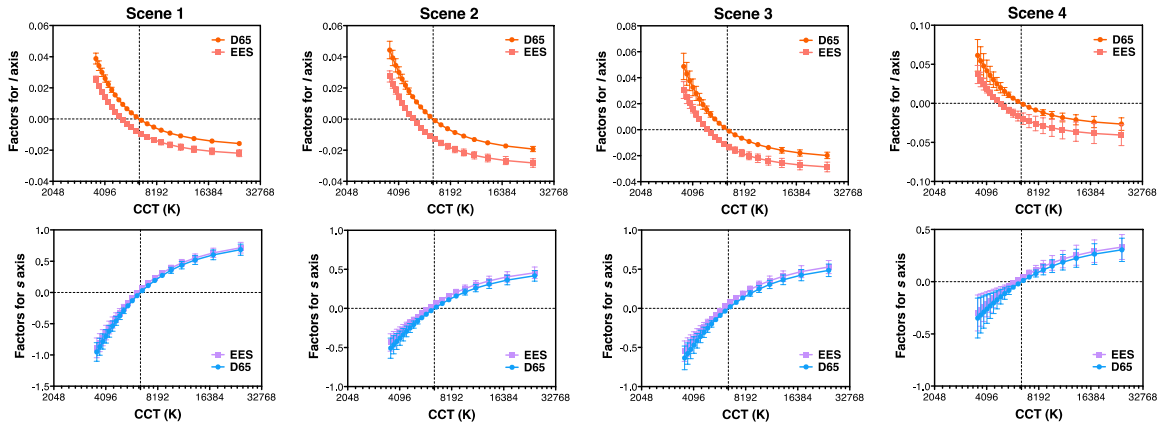

Figure 4:
Factors for D65 and EES illuminants as references. Upper row panels contain factor values for *I* axis. Lower row panels contain factor values for *s* axis. Error bars are standard deviations.

DISCUSSION

We showed that potential linear contribution of melanopsin to color constancy should affect in opposite ways the KC- and PC-pathways, but the sign depends on the CCT of the illuminant. For high CCT, a better color constancy requires that melanopsin has a positive contribution to the KC-pathway

but a negative contribution to the PC-pathway. For low CCT illuminants, however, a better color constancy requires that melanopsin has a negative contribution to the KC-pathway but a positive contribution to the PC-pathway. These results are similar either considering as reference a D65 Illuminant, which represents roughly a midday natural lighting conditions; or Equal energy spectrum illuminant, which give information about the spectral reflectance of the scene objects.

Part of this simple analysis is supported by previous studies. It has been shown that most of the reflectance variability in natural scenes is related to changes in luminance and in KC-signals (Ruderman et al. 1998, Barrionuevo and Cao 2014). We previously showed that melanopsin contributes positively to the MC and KC pathways (Barrionuevo and Cao 2014). Linear relation between melanopsin and KC-signals was demonstrated for pupil control (Barrionuevo and Cao 2016). According to these antecedents it is possible to think that melanopsin helps to achieve color constancy with high CCT illuminants, such as clear sky conditions.

Explanations about color constancy consist on cognitive, sensorial and computational components (Smithson 2005), suggesting that this visual ability is a multi-stage process. From an evolutionary perspective it is important to consider how illuminant changes in natural environments can be discounted, since constancy is better achieved under natural than artificial illumination (Lucassen and Walraven 1996). One possible explanation is considering melanopsin intrusion, since it has photon-counting properties (Dacey et al. 2005). Our exploratory analysis provides the possibility of the involvement of melanopsin in color constancy.

ACKNOWLEDGEMENTS

Agencia Nacional de Promoción Científica y Tecnológica PICT 2016-3312 (PB). Consejo Nacional de Investigaciones Cientificas y Técnicas P-UE 0114 ILAV (PB). Fulbright Visiting Scholar Program (PB). UIC core grant for vision research P30-EY001792, Unrestricted Departmental Grant (DC).

REFERENCES

Allen, A., R. Storchi, F. Martial, R. Petersen, M. Montemurro, T. Brown, and R. Lucas. 2014. Melanopsin-driven light adaptation in mouse vision. *Current Biology* 24 (21): 2481-2490.

Arend, L. 2001. Environmental challenges to color constancy. In: *Human Vision and Electronic Imaging VI*, 4299. International Society for Optics and Photonics, 392-399.

Barrionuevo, P., and D. Cao. 2014. Contributions of rhodopsin, cone opsins, and melanopsin to postreceptoral pathways inferred from natural image statistics. *Journal of the Optical Society of America A* 31 (4): 131-139.

———. 2016. Luminance and chromatic signals interact differently with melanopsin activation to control the pupil light response. *Journal of Vision* 16 (11): 29.

Berson, D., F. Dunn, and M. Takao. 2002. Phototransduction by retinal ganglion cells that set the circadian clock. *Science* 295 (5557): 1070-1073.

Brainard, D., and A. Radonjić. 2014. Color constancy. In: *The new visual neurosciences*, J. S. Werner and L. M. Chalupa, eds. Cambridge, MA: The MIT Press, 545-556.

Dacey, D., H. Liao, B. Peterson, F. Robinson, V. Smith, J. Pokorny, K. Yau, and P. Gamlin. 2005. Melanopsin-expressing ganglion cells in primate retina signal colour and irradiance and project to the LGN. *Nature* 433 (7027): 749-754.

Davis, K., C. Eleftheriou, A. Allen, C. Procyk, and R. Lucas. 2015. Melanopsin-derived visual responses under light adapted conditions in the mouse DLGN. *PLOS ONE* 10 (3): e0123424.

Derrington, A., J. Krauskopf, and P. Lennie. 1984. Chromatic mechanisms in lateral geniculate nucleus of macaque. *The Journal of Physiology* 357 (1): 241-265.

Enezi, J., V. Revell, T. Brown, J. Wynne, L. Schlangen, and R. Lucas. 2011. A 'melanopic' spectral efficiency function predicts the sensitivity of melanopsin photoreceptors to polychromatic lights. *Journal of Biological Rhythms* 26 (4): 314-323.

Foster, D. 2011. Color constancy. *Vision Research*, Vision Research 50th Anniversary Issue: Part 1, 51 (7): 674-700.

Foster, D., K. Amano, S. Nascimento, and M. Foster. 2006. Frequency of metamerism in natural scenes. *Journal of the Optical Society of America A* 23 (10): 2359-2372.

Hattar, S., H. Liao, M. Takao, D. Berson, and K. Yau. 2002. Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity. *Science* 295 (5557): 1065-1070.

Hattar, S., R. Lucas, N. Mrosovsky, S. Thompson, R. Douglas, M. Hankins, J. Lem, M. Biel, F. Hofmann, R. Foster, and K. Yau. 2003. Melanopsin and rod–cone photoreceptive systems account for all major accessory visual functions in mice. *Nature* 424 (6944): 75-81.

Lee, B. 2004. Paths to colour in the retina. *Clinical and Experimental Optometry* 87 (4-5): 239-248.

Lee, B., J. Pokorny, P. Martin, A. Valberg, and V. Smith. 1990. Luminance and chromatic modulation sensitivity of macaque ganglion cells and human observers. *Journal of the Optical Society of America A* 7 (12): 2223-2236.

Linhares, J., and S. Nascimento. 2012. A chromatic diversity index based on complex scenes. *Journal of the Optical Society of America. A, Optics, Image Science, and Vision* 29 (2): A174-181.

Lucassen, M., and J. Walraven. 1996. Color constancy under natural and artificial illumination. *Vision Research* 36 (17): 2699-2711.

MacLeod, D., and R. Boynton. 1979. Chromaticity diagram showing cone excitation by stimuli of equal luminance. *Journal of the Optical Society of America* 69 (8): 1183-1186.

Nascimento, S., F. Ferreira, and D. Foster. 2002. Statistics of spatial cone-excitation ratios in natural scenes. *Journal of the Optical Society of America. A, Optics, Image Science, and Vision* 19 (8): 1484-1490.

Provencio, I., I. Rodriguez, G. Jiang, W. Hayes, E. Moreira, and M. Rollag. 2000. A novel human opsin in the inner retina. *The Journal of Neuroscience* 20 (2): 600-605.

Ruderman, D., T. Cronin, and C. Chiao. 1998. Statistics of cone responses to natural images: implications for visual coding. *Journal of the Optical Society of America A* 15 (8): 2036-2045.

Smith, V., and J. Pokorny. 1975. Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm. *Vision Research* 15 (2): 161-171.

Smithson H. 2005. Sensory, computational and cognitive components of human colour constancy. *Philosophical Transactions of the Royal Society B: Biological Sciences* 360 (1458): 1329-1346.

Stair, R., and R. Johnston. 1953. Ultraviolet spectral radiant energy reflected from the Moon. *Journal of Research of the National Bureau of Standards* 51: 81-84.

Wyszecki, G., and W. S. Stiles. 2000. *Color science: concepts and methods, quantitative data and formulae*, 2nd ed. New York: John Wiley & Sons.