Vision Research 224 (2024) 108476

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Editorial

Special issue: Seeing colors in nature

Color vision is present in a wide range of animals, including insects, spiders, fish, amphibians, reptiles, birds, mammals, and humans. It is fundamental to the detection, discrimination, and recognition of suitable habitats, materials, objects, and other organisms. In the laboratory, it is often studied under strongly controlled conditions with simple sets of stimuli. Yet the natural environments in which color vision has evolved and functions are often complex and challenging for any sensory system. The contributions to this Special Issue explore how both vertebrates and invertebrates address these challenges to seeing colors in nature.

Despite the complexities of natural scenes, the primary light source, daylight, is spectrally constrained (Judd et al., 1964; Peyvandi et al., 2016) as are the spectral reflectance functions of natural surfaces seen on land or underwater (Chiao et al., 2000; Griffin, 2019). This implies that the colors to which vision must adapt are also constrained. In humans, the color gamuts are smaller than the maximum theoretically possible and oriented around a yellowish-bluish axis (Burton & Moorhead, 1987; Webster & Mollon, 1997). In two articles in this Special Issue, Su, Shi, and Wachtler (2024) show how the distribution of colors in natural environments can influence hue perception, and Marques and Nascimento (2024) show that the yellow-blue bias may influence color discrimination by dichromats, particularly the orientation of the color gamut.

The spectral constraints on daylight also benefit adaptation mechanisms contributing to color constancy. In their article, Karimipour and Witzel (2024) investigate how expectations about the shifts in surface color under changing illumination conditions relate to color constancy. Ojeda, Romero, and Nieves (2023) examine the influence of the correlated color temperature of daylight on several spatio-chromatic properties of natural scenes. Another aspect of color constancy is addressed by Falkenberg and Faul (2024) in a study of how complexities of natural stimuli influence transparency perception in transparent layer constancy.

The intricate three-dimensional nature of natural scenes creates complicated lighting environments, characterized by shadows and multiple sources of indirect illumination (Endler, 1993). Shadows may be colored and their interpretation can present a challenge for both physicists and artists. Smith (2023) explores the role of shadows in paintings and how they are perceived and depicted by artists.

Despite the dominance of chlorophyll-filtered light, the interplay of lightness and chromatic variation in forests affects many behaviors of forest-dwelling species (Tedore & Nilsson, 2019). Changes in forest vegetation structure, whether through direct or indirect human intervention, can have consequences for the visual ecology of various species. Boycott, Sherrard, Gall, and Ronald (2023) model how visual signaling in a wide range of avian species in temperate deciduous forests is affected by deer management programs.

In humans, color vision is primarily mediated by cone photoreceptors, but there have been suggestions that intrinsically photosensitive retinal ganglion cells (ipRGCs) may also be involved in color perception. Barrionuevo, Salinas, and Fanchini (2024) provide a comprehensive review of the hypotheses and evidence for this involvement. They consider how ipRGC signals might encode natural image statistics and contribute to maintaining color constancy under varying lighting conditions.

The phenomenon of infrared vision in humans and other animals by a process of two-photon absorption is reviewed by Komar (2024). It was discovered in the 1960s, though it was not explained until around 50 years later. This article sets out our current knowledge of the phenomenon and its clinical and other applications.

The evolution of visual opsin genes underpins our understanding of color vision development across species. Opsins have been lost and new opsins evolved in many animal groups (e.g. Kelber & Jacobs, 2016), and it is generally assumed that the diversity of color coding reflects evolutionary adaptation and resource optimization. Lin, Wang, Chung, and Wang (2024) identify the locations of visual opsin genes, their neighbors, and tuning sites in 39 amphibian genomes and suggest that missing genes in some species may be correlated with their cryptic lifestyles. Ramirez (2023) considers the theoretical optimization of color information encoding in retinae that use colored oil droplets, such as those found in birds, coupled with clever retinal circuitry to encode spectral information, as found in zebrafish. It is argued that the presence of colored oil droplets may compromise spectral encoding efficiency.

Iwanicki, Steck, Bracken-Grissom, and Porter (2024) examine the visual opsins in several species of pelagic shrimp from the superfamily Oplophoroidea, and provide molecular evidence of opsin protein localization in ocular tissues. Also with a study of opsin protein components in jumping spiders (Salticidae), Steck, Hanscom, Iwanicki, Sung, Outomuro, Morehouse, and Porter (2024) show that the spiders' secondary eyes have the potential for color vision, with differences between species probably linked to different ecologies and task requirements.

These contributions to this special issue address seeing color at multiple levels: perceptual, aesthetic, ecological, physiological, and genetic-molecular. They consider how the spectral and chromatic properties of natural scenes and natural lighting influence color discrimination, hue perception, color constancy, and the perception and artistic representation of shadows. They show how human action can change the visual ecological balance; how other processes such as two-photon absorption and intrinsically photosensitive retinal ganglion cell activity can expand visual experience; and how the evolution of visual

https://doi.org/10.1016/j.visres.2024.108476

opsins and their location provide cues to how different species adapt to differing visual environments. Overall, they demonstrate the extraordinary flexibility of color vision in accommodating the challenges of the natural world.

References

Barrionuevo, P. A., Sandoval Salinas, M. L., & Fanchini, J. M. (2024). Are ipRGCs involved in human color vision? Hints from physiology, psychophysics, and natural image statistics. *Vision Research, 217*. https://doi.org/10.1016/j.visres.2024.108378

Boycott, T. J., Sherrard, M. G., Gall, M. D., & Ronald, K. L. (2023). Deer management influences perception of avian plumage in temperate deciduous forests. *Vision Research, 213*. https://doi.org/10.1016/j.visres.2023.108312

Burton, G. J., & Moorhead, I. R. (1987). Color and spatial structure in natural scenes. *Applied Optics, 26*(1), 157. https://doi.org/10.1364/ao.26.000157

Chiao, C.-C., Cronin, T. W., & Osorio, D. (2000). Color signals in natural scenes: Characteristics of reflectance spectra and effects of natural illuminants. *Journal of the Optical Society of America A, 17*(2), 218. https://doi.org/10.1364/josaa.17.000218

Endler, J. A. (1993). The color of light in forests and its implications. *Ecological Monographs, 63*(1), 1–27. https://doi.org/10.2307/2937121

Falkenberg, C., & Faul, F. (2024). Transparent layer constancy improves with increased naturalness of the scene. *Vision Research, 221*. https://doi.org/10.1016/j.visres.2024.108423

Griffin, L. D. (2019). Reconciling the statistics of spectral reflectance and colour. *PLoS ONE, 14*(11). https://doi.org/10.1371/journal.pone.0223069

Iwanicki, T., Steck, M., Bracken-Grissom, H., & Porter, M. L. (2024). Localization of multiple opsins in ocular and non-ocular tissues of deep-sea shrimps and the first evidence of co-localization in a rhabdomeric R8 cell (Caridea: Oplophoroidea). *Vision Research, 219*. https://doi.org/10.1016/j.visres.2024.108403

Judd, D. B., MacAdam, D. L., Wyszecki, G., Budde, H. W., Condit, H. R., Henderson, S. T., & Simonds, J. L. (1964). Spectral distribution of typical daylight as a function of correlated color temperature. *Journal of the Optical Society of America, 54*(8), 1031. https://doi.org/10.1364/josa.54.001031

Karimipour, H., & Witzel, C. (2024). Colour expectations across illumination changes. *Vision Research, 222*. https://doi.org/10.1016/j.visres.2024.108451

Kelber, A., & Jacobs, G. H. (2016). Evolution of Color Vision. In J. Kremers, R. C. Baraas, & N. J. Marshall (Eds.), *Human Color Vision* (pp. 317–354). Springer International Publishing. https://doi.org/10.1007/978-3-319-44978-4_11.

Komar, K. (2024). Two-photon vision – Seeing colors in infrared. *Vision Research, 220*. https://doi.org/10.1016/j.visres.2024.108404

Lin, J. J., Wang, F. Y., Chung, W. Y., & Wang, T. Y. (2024). The genomic evolution of visual opsin genes in amphibians. *Vision Research, 222*. https://doi.org/10.1016/j.visres.2024.108447

Marques, D. N., & Nascimento, S. M. C. (2024). How the orientation of the color gamut of natural scenes influences color discrimination in red-green dichromacy. *Vision Research, 222*. https://doi.org/10.1016/j.visres.2024.108435

Ojeda, J., Romero, J., & Luis Nieves, J. (2023). Understanding the effect of correlated colour temperatures on spatio-chromatic properties of natural images. *Vision Research, 208*. https://doi.org/10.1016/j.visres.2023.108234

Peyvandi, S., Hernández-Andrés, J., Olmo, F. J., Nieves, J. L., & Romero, J. (2016). Colorimetric analysis of outdoor illumination across varieties of atmospheric conditions. *Journal of the Optical Society of America A, 33*(6), 1049. https://doi.org/10.1364/josaa.33.001049

Ramirez, L. (2023). Trade-off between coding efficiency and color space in outer retinal circuits with colored oil droplets. *Vision Research, 208*. https://doi.org/10.1016/j.visres.2023.108224

Smith, P. (2023). Painting coloured shadows: An introduction. *Vision Research, 209*. https://doi.org/10.1016/j.visres.2023.108225

Steck, M., Hanscom, S. J., Iwanicki, T., Sung, J. Y., Outomuro, D., Morehouse, N. I., & Porter, M. L. (2024). Secondary not subordinate: Opsin localization suggests possibility for color sensitivity in salticid secondary eyes. *Vision Research, 217*. https://doi.org/10.1016/j.visres.2024.108367

Su, Y., Shi, Z., & Wachtler, T. (2024). A Bayesian observer model reveals a prior for natural daylights in hue perception. *Vision Research, 220*. https://doi.org/10.1016/j.visres.2024.108406

Tedore, C., & Nilsson, D. E. (2019). Avian UV vision enhances leaf surface contrasts in forest environments. *Nature Communications, 10*(1), 238. https://doi.org/10.1038/s41467-018-08142-5

Webster, M. A., & Mollon, J. D. (1997). Adaptation and the color statistics of natural images. *Vision Research, 37*(23), 3283–3298. https://doi.org/10.1016/S0042-6989(97)00125-9

Sérgio M.C. Nascimento*
Physics Center of Minho and Porto Universities (CF-UM-UP), Portugal

David H. Foster
The University of Manchester, Department of Electrical and Electronic Engineering, United Kingdom

Almut Kelber
Lund University, Lund Vision Group, Department of Biology, Sölvegatan 35, S223 62 Lund, Sweden

Hidehiko Komatsu
Tamagawa University, Brain Science Institute, Japan

* Corresponding author.
E-mail address: smcn@fisica.uminho.pt (S.M.C. Nascimento).