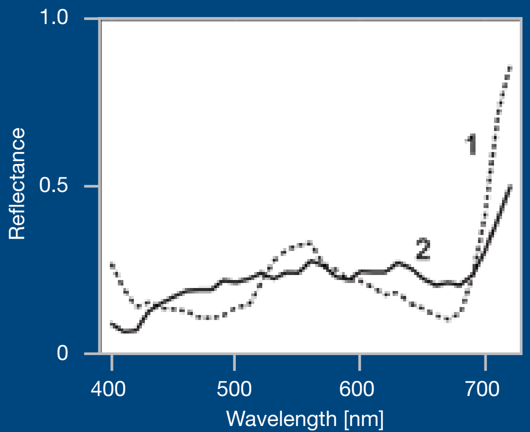
The Frequency of Metamerism in Natural Scenes

David H. Foster, Kinjiro Amano, Sérgio M.C. Nascimento and Michael J. Foster

Metamerism occurs when lights with different spectra appear the same to the eye, or, more generally, the sensor system.[1] Metamers arise because the number of degrees of freedom in a sensor system—three for the cone receptors in the normal human eye or the filters of a typical RGB camera—is smaller than the degrees of freedom needed to accurately represent light spectra.[2]

The most important example is associated with variations in surface spectral reflectances. In natural vision, these differences may be disregarded, providing that the surfaces continue to produce the same responses when the illuminant changes; visual identity is then an invariant and not an accident of viewing conditions. But metamerism becomes a problem when reflected lights become distinguishable with an illuminant change. The practical question, then, is whether metamers are common in natural scenes.

Despite speculation that natural metamers are rare,[3,4] few data have been available on their frequency. This is not surprising, since the spatial density of any particular spectral reflectance or class of reflectances in natural scenes is generally unknown. Moreover, any estimate of a spatial density must be compatible with the spatial resolution of the eye; this sets a natural limit on the extent to which spectral reflectances may be treated as unmixed. If two surfaces with different spectral reflectances cannot be spatially resolved, they are visually interchangeable with a single surface whose spectral reflectance is a mean of the two.



Two metameric surfaces from a natural scene. The surface spectral reflectances at points 1 and 2 in the scene are different but, when illuminated by skylight, produce the same patterns of excitations in the cone receptors of the eye.

We undertook a numerical evaluation of the visual discriminability of 150,000 different surfaces under different phases of daylight.[5] Using a high-resolution hyperspectral imaging system, we obtained spectral-reflectance data from 50 natural vegetated and non-vegetated scenes representing the main land-cover classifications. The frequency of metamers in each scene was estimated by the number of pairs of surfaces for which color differences were below a threshold value under one phase of daylight and above a multiple of this threshold value under another phase.

The relative frequency of metameric pairs, expressed as a proportion of all the pairs of surfaces from a scene, was found to be very low, from about 10^{-6} to 10^{-4} for the largest illuminant change tested, from skylight of correlated color temperature 25,000 K to direct sun and skylight of correlated color temperature 4000 K. Therefore, metamers are rare in natural scenes.

There is, however, another way to interpret the data—as a conditional relative frequency. When expressed as a proportion of just those pairs of surfaces that were indistinguishable under one of the phases of daylight, the relative frequency of metameric pairs was much higher, from about 10^{-2} to 10^{-1}. In this special sense, metamers are relatively common, implying that visual identity may not always be a reliable guide to material identity in natural scenes. ◭

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A New Intraocular Lens to Correct Corneal Coma

Juan Tabernero and Pablo Artal

The aberrations of the eye tend to be well balanced among optical components of the ocular system, the cornea and the crystalline lens.[1,2] This means that a high level of corneal aberrations is usually compensated with a high level of opposite sign aberrations generated by the crystalline lens. This is a well-studied effect in the case of spherical aberration. Corneal spherical aberration is usually positive while lens spherical aberration tends to be negative. The result of these extensive investigations was a new generation of aspheric intraocular lenses with negative spherical aberration that replace the lens after cataract surgery.[3]

Apart from spherical aberration, other aberrations, such as coma, are well balanced in the eye.[4] The mechanism responsible for this effect has been recently studied,[5] revealing that the eye's optical characteristics are very similar to an aplanatic optical system, corrected for off-axis coma and on-axis spherical aberration.

Our main concern was that, after crystalline lens extraction in cataract surgery, the best intraocular lens design should imitate the optimal optical characteristics of the normal eye. However, the conventional intraocular lens designs have the same shape factor for a whole range of physiological optical powers (from 10 to 30 diopters). In many cases, these fixed shape factors (usually equibiconvex) are far from the optimized solutions. Therefore, we improved the intraocular lens designs according to the compensation of aberrations found in normal eyes.

Our target was to obtain an intraocular lens that compensates the average corneal spherical aberration and corneal off axis coma in the eye. We used two variables for the design: the shape factor of the intraocular lens that controlled the offaxis coma and the aspheric coefficients of both lens surfaces that controlled the level of spherical aberration.[6]

Two procedures were tested for design. First, an *ab initio* solution was obtained from Seidel aberration theory. This solution was used as the starting point for an optimization procedure performed with ray tracing software through schematic eye models. Finally, simulations were also performed using real eye models, with the corneal surface measured from topography, to check the real performance of the solution.

The resulting shape factors of the intraocular lens solution were meniscus bended toward the retina (for the lower powers) evolving to biconvex shapes with the increase of intraocular lens power. The aspheric coefficients in both surfaces generated negative spherical aberration opposite to the normal positive values of the cornea.

In conclusion, we designed a new generation of very promising intraocular lenses by mimicking the natural optimal situation found in the normal eye. Simulations using data of real measured aberrations indicated that a significant improvement in optical quality can be expected with respect to conventional intraocular lens implants.

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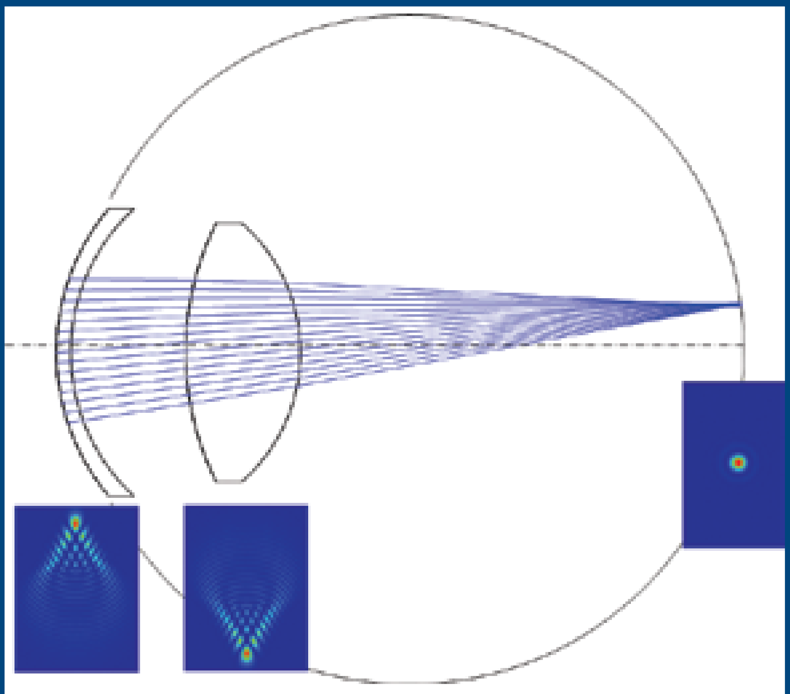

Coma is well balanced in the normal eye