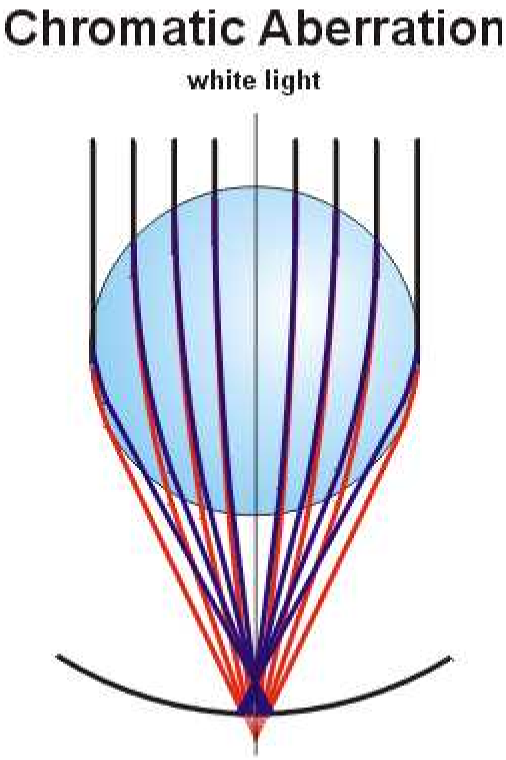
A Rank Prize for Opto-Electronics has been awarded in 2004 for the following publication:

Kröger, R.H.H., Campbell, M.C.W., Fernald, R.D. & Wagner, H.-J. (1999) Multifocal lenses compensate for chromatic defocus in vertebrate eyes. *Journal of Comparative Physiology A* 184, 361-369.

In that paper we describe how a common optical problem, chromatic aberration, is solved in animal eyes. The natural solution may inspire improved man-made optical designs. Our discovery also raises interesting questions regarding cell biology and the evolution of complex organs. Furthermore, we can explain unusual pupil shapes, such as the cat's slit pupil.

Description of the work

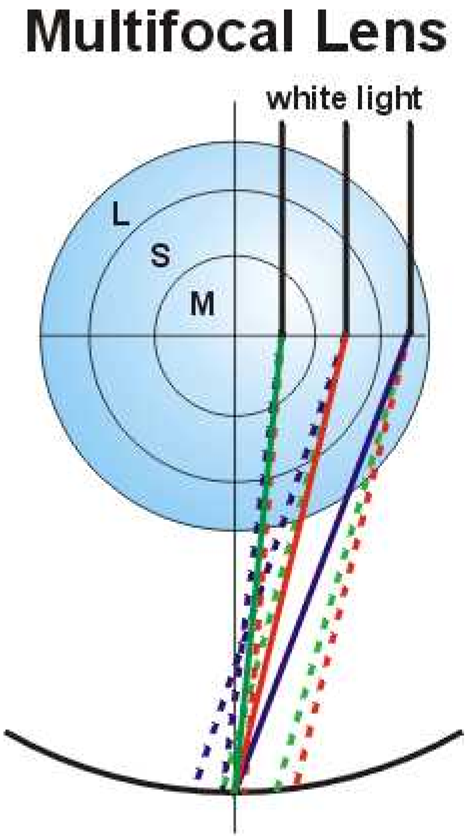


The refractive power of a lens increases with decreasing wavelength of light, i.e. from red to blue. The phenomenon is known as *chromatic aberration.* It means that different wavelengths of light are focused at different distances from the lens. As a result, some wavelengths are defocused (*chromatic defocus*).

If the optical system is designed to gather large amounts of light, the aperture (pupil in animal and human eyes) is large relative to the focal length of the system and, consequently, depth of focus is short. If chromatic defocus exceeds depth of focus, only a limited part of the visual spectrum is in focus. This is a severe problem when color images are to be created.

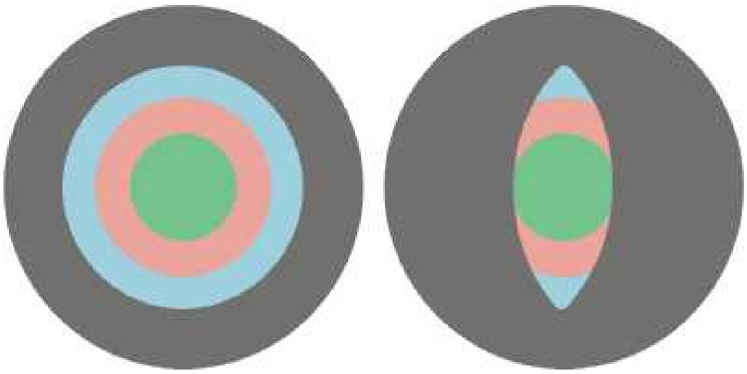
In manufactured optical systems, chromatic aberration is reduced by combining several lenses. Camera objectives are large and heavy because chromatic and other aberrations have to be minimized. The optical systems of animal eyes are much smaller and simpler. In the fish eye, a single lens creates well-focused images in full color, which in some species includes the ultra-violet (UV) part of the spectrum.

When investigating the eye of the African cichlid fish *Astatotilapia* (formerly *Haplochromis*) *burtoni*, we discovered that the lens creates three sharp images in monochromatic light (only one wavelength, e.g. red laser light). The images are located att different distances from the lens and we therefore call such lenses multifocal. Because the fish lens also suffers from chromatic aberration, the images move closer to the lens when the wavelength of light is reduced, e.g. from red to blue.



Just as humans, *A. burtoni* has three visual pigments being most sensitive to red, green, and blue light, respectively. When red, green, and blue monochromatic lights are shone through the lens of *A. burtoni*, three sets of three sharp images are created at various distances from the lens. If the used wavelengths match the maximum sensitivities of the visual pigments, one of the three images at each wavelength is created in the plane of the retina, where the cells sensitive to light are located. Well-focused color images are thus created by a single lens, an accomplishment that had been thought to be impossible because of the laws of physics.

Multifocal lenses are common in the eyes of vertebrates (animals having spinal cords), also in terrestrial species. Animals active at low light intensities, such as the cat, have eyes that collect large amounts of light through large pupils. Such species therefore need multifocal lenses. If the pupil constricts in bright light, which is not the case in most fishes, it has to have a special shape. The slit pupil of the cat, for example, allows all refractive zones of the lens to be used even when the pupil is constricted. We now understand that many unusual pupil shapes are adaptations to multifocal lenses. We have also started to investigate how other structures in the eye are adapted to multifocal lenses.



European wildcat

An animal lens may or may not have multiple focal lengths because of an exactly adjusted gradient of refractive index, which increases from the periphery of the lens to its center. As the lens grows, which it does throughout life even in humans, refractive index has to be constantly adjusted by each cell within the lens. However, most cells in a vertebrate lens have lost all major components (organelles) necessary for normal cellular function in a process similar to programmed cell death (apoptosis). To unravel how the "dead" cells of the lens can control refractive index and how it is signaled to them what index to have will keep us busy for many years to come. We expect to learn more about cell biology in general and signaling pathways within the eye in particular, as well as how complex organs such as vertebrate eyes have been brought about by natural evolution.

(Ronald Kröger, 2004)