Spectrum

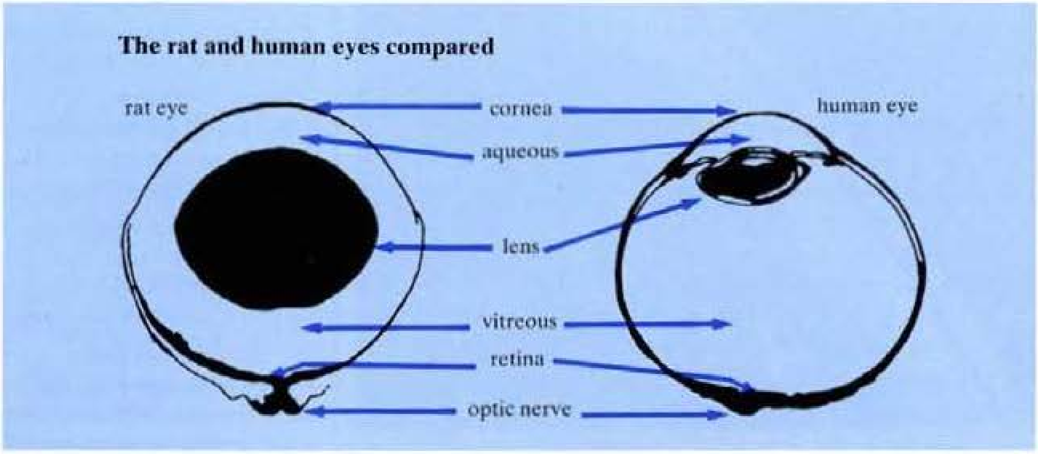
Eyeballing the eyeball

One of our society's most frequently heard replies is 'I see'. But how do we see? Despite the critical importance of the eye in our world of light, its *modus operandi* is still slightly blurred.

We know, of course, that light reflecting off the object we are looking at penetrates the eye's outer, clear, curved surface called the cornea and then passes through the curved surface of the lens. The lens and cornea successively bend the light rays so that they converge on the image-recording surface of the eye (or retina) at the back of the eyeball. The recorded image is then processed via the nerve pathway to the brain.

But why is the eye made the way it is? Theoretically, the ideal eye would have perfect spherical symmetry, with the cornea and retina forming part of the same sphere, and with the light-bending components able to eliminate any aberrations. Real eyes are not like that.

In many ways the eye is analogous to a camera. But while the camera produces a flat and undistorted image, the eye's retina has a strongly curved surface; neural processing can correct any distortion. So we can think of the eye as a precision optical system with an array of light-sensitive diodes functioning as image-detectors; neural processing would have its parallel in micro-electronics. But what about aberrations that blur the image?


The rat and human eyes compared

A comparison of the rat eye with the human eye.

Dr Peter Sands of the CSIRO Division of Computing Research, together with Dr Melanie Campbell and Professor Austin Hughes, from the Department of Physiology, John Curtin School of Medical Research, Australian National University, have been looking at ways of analysing vision using mathematical models and computer programs. They have studied imagery and image quality in a representative mammalian eye — the rat's — using optical image-analysis techniques including a computer program Dr Sands designed called Drishti — a Sanskrit word meaning 'active seeing, viewing, beholding, wisdom, intelligence'. Their 'standard rat eye' is based on data produced by Professor Hughes and Dr Campbell, who is a CSIRO Postdoctoral Fellow in the Division of Mathematics and Statistics. They had previously analysed a number of rat eyes to find average values for dimensions and properties of the cornea, lens, retina, and outer choroid layer of the eye.

Early scientists working on the classical model of a lens such as the rat's considered it to be homogeneous, refracting light only at its surfaces as do the lenses in a camera. However, an actual eye lens refracts light continuously throughout its volume. It consists of proteins in solution; as the animal ages, these tend to concentrate in the centre of the lens, causing it to harden. As a result, the refractive index — which determines the degree of light-bending — varies through the lens, from a lower value at the edge to a higher value at the centre, producing a more powerful lens than a homogeneous one.

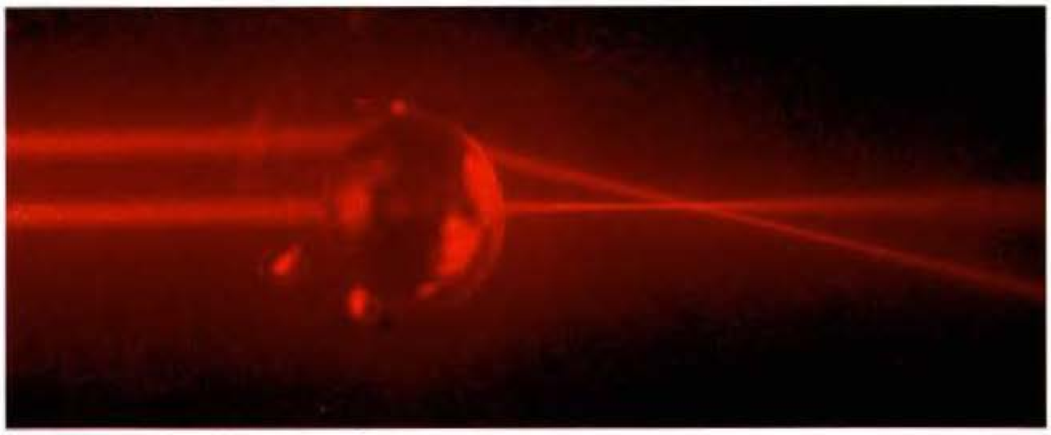
Scientists previously measured the distribution of refractive index within the rat lens by taking sections of it and measuring protein concentration. Dr Campbell has developed a method of non-destructively measuring the refractive index distribution within the lens. However, like any experimental measurement, the distribution is only known within certain bounds. Dr Sands was able to mathematically describe the most likely distribution within this experimental uncertainty, inside the rat lens.

In order to extend these analyses to the human eye, the researchers need more information on the distribution of refractive index within its lens. Dr Campbell and Dr Bob Anderssen of the CSIRO Division of Mathematics and Statistics are currently adapting their non-destructive measurement method to more complex lenses so that it may be applied to the human lens.

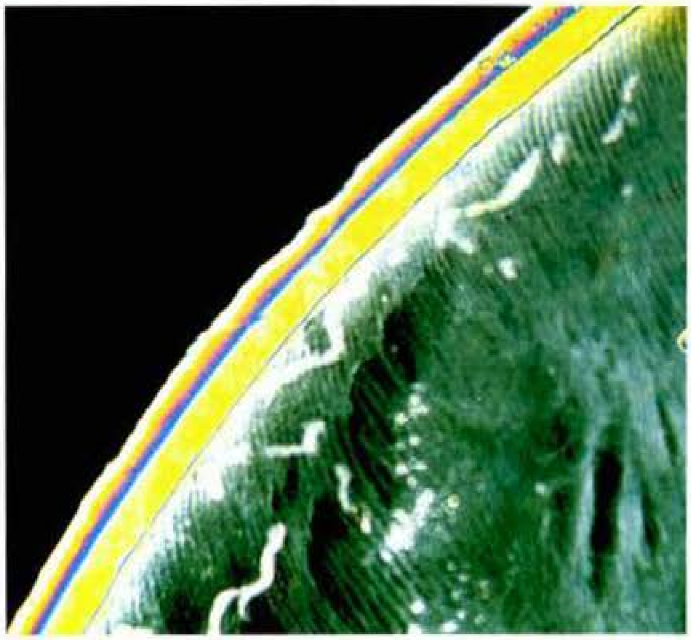
Using Drishti, Dr Sands computed a set of 'aberration coefficients' to characterize the image-forming properties of the rat-eye model. These coefficients make it easier to predict how changes in the geometry of the eye (for example, the shape and thickness of the lens) will affect the eye's performance. The next step was to modify various components of the model and determine the subsequent effect on image quality. Dr Sands examined the effects of changes in the refractive indices of the cornea, the liquids within the eye (known as the aqueous and vitreous matters), and at the lens surface and centre. He also checked what would happen if the thicknesses of the cornea or lens, the position of the lens within the eye, or the cornea shape changed.

This sensitivity analysis suggested that the rat eye has got everything right from the point of view of optimal image quality, except possibly the shape of the cornea. Making the cornea more basketball-shaped, rather than football-shaped, increased the model eye's resolution. But this meant a change in the image surface, such that the cornea and retina became more difficult to 'package' as a single unit. However, by increasing the refractive index at the lens centre, Dr Sands showed how the problem could be solved.

He also suggested why real eyes (unlike the hypothetical



Laser beams focused by a rat-eye lens.



A slice of a rat-eye lens under the interference microscope showing the layers of different density.

ideal eye), are not round. He found that, although basic optical considerations supported the ideal model, they required the use of media with refractive indices that were either too high or too low for natural biological light-refracting substances. Biological substances' refractive indices are either close to that of water (1·33) or in the range 1·36 to 1·53.

Fish eyes, much closer to the ideal shape than the rat's or any other mammal's eyes, have lenses with higher refractive indices than mammalian lenses. Why, then, doesn't the rat follow the fish's example and use material of higher refractive index, which together with a change in corneal shape should optimize its vision?

Perhaps there is some basic difference between the protein chemistries of mammals and fish, preventing mammals manufacturing high-index material. One would expect evolutionary pressure towards higher refractive indices, or towards some other means of getting a good image while using the available lens proteins.

Dr Sands' model showed that, if he started with a spherical eye and the observed refractive indices, he could reduce the aberrations by making the eye prolate (football-shaped) and the lens more oblate (shaped like the earth). He also moved the lens a little from the eye centre towards the cornea. This is just what is observed in the real eye. Dr Sands also noted that this would be a natural response to the forces of the ligaments holding the lens in place in the eye.

Thus, the basic mechanism determining the shape of the eye may be mechanical, with evolution adjusting this shape and the refractive indices to optimize the image.

But how did a lens evolve in the first place? Dr Sands' models can't answer that question; they simply show that one is needed.

Apart from these speculations on why the eye is eye-shaped, Dr Sands' modelling research has led to the refinement of Drishti, a useful tool in analysing natural and artificial optical systems, and perhaps aiding lens design procedures. Also, the geometrically described rat eyes have demonstrated the useful role that models can play in the study of complex biological systems.

Mary Lou Considine

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Checking the radioactivity of building materials

We are constantly exposed to natural nuclear radiation: from the ground, and from cosmic rays; even our bodies are weakly radioactive.

For the average person, the earth contributes most to the annual natural radiation dose. This radioactivity is mainly due to the presence of uranium and thorium, and the products of their decay. Small quantities of radioactive potassium are also sometimes present. When these atoms disintegrate, they emit penetrating *gamma* rays.

When we are inside a building we generally receive a higher dose of radioactivity than if we were outdoors. This is because materials surround us on all sides. In addition, some building materials can possess considerably greater radioactivity levels than the generally low levels found in soil (although in some localities, the ground can set Geiger counters clicking rapidly).

The OECD's Nuclear Energy Agency has suggested that the *gamma*-ray activity of building materials should be limited to a level such that any dwelling made from them should not give its occupants an additional annual radiation exposure of more than 1·5 millisieverts, corresponding to a radioactivity of 370 becquerels per kilogram. Broadly, this is equivalent to saying that any building should