Correcting the aberrations of the eye in a retinal imager with a variable Zernike corrector

Schematic eye with an aberrated cornea, 3 mm pupil, 840 nm; corrector plate with 12 Zernike terms; ICNIRP exposure check

The design problem

When an instrument images the retina through the pupil, the aberrations of the eye blur the image of each photoreceptor. Adaptive optics corrects them, usually with a deformable mirror driven by a wavefront sensor, a large and expensive assembly. A variable refractive corrector inside the instrument, such as a phase plate, a liquid lens or an Alvarez pair, is a cheaper alternative. The design must keep the wavefront error left by the corrector small for each eye, and the light dose on the retina within the safety limits.

How the system is modelled

The eye is the schematic eye of Navarro [1] in its wide-angle version [2]. Its anterior cornea carries two Zernike terms of surface height, 2 µm and 1 µm, which add to the aberrations of the eye itself. The eye, aberrated cornea included, is a fixed input, and only the plate changes during the design. As in an ophthalmoscope, light leaves a point of the retina, crosses the eye and the corrector plate, and an ideal camera lens, which adds no aberration, images it on a detector. The corrector is a flat glass plate whose front surface carries the Zernike terms OSA j = 3 to 14, which run from astigmatism and defocus to the fourth-order terms. The optimizer adjusts these 12 terms alone, with the RMS wavefront error at 840 nm as merit function.

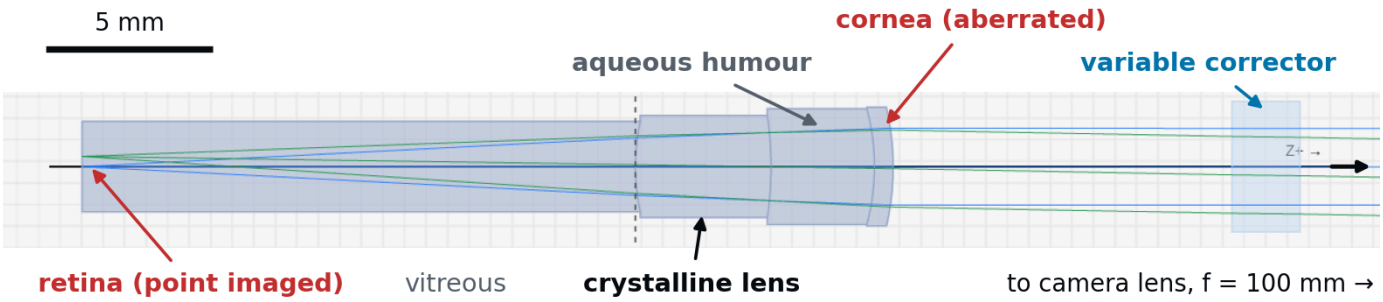


Figure 1. The eye and the corrector in the 2D view of etendue, at true scale. Light from a point of the retina crosses the eye, then the corrector plate; the camera lens and the detector lie further to the right.

What the analysis shows on the starting design

Before correction, the RMS wavefront error of the eye is 0.276 waves at 840 nm, and the Strehl ratio computed from the point spread function is 0.16. The largest terms are astigmatism, 0.17 waves, and secondary astigmatism, 0.12 waves. After one optimization of the corrector, the wavefront error falls to 0.0028 waves and the Strehl ratio rises to 0.9997. The twelve corrected terms keep a residual of 0.0009 waves RMS. Terms beyond j = 14, which the plate cannot reach, contribute 0.0026 waves, and the two add in quadrature to the total. Figure 2 shows the resulting image of a retinal point.

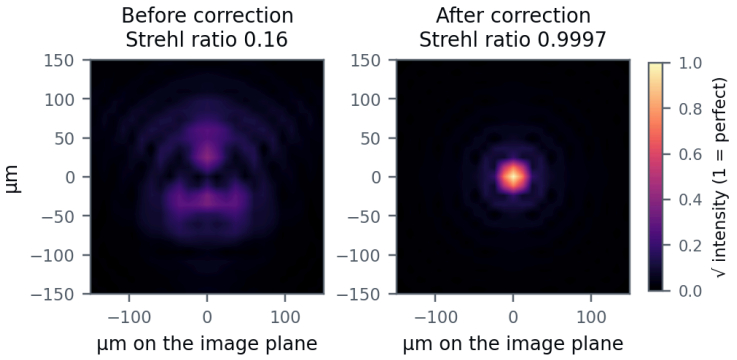


Figure 2. Image of a point of the retina formed through the eye and the camera lens, before and after correction. Point spread functions computed by etendue, shown as the square root of the intensity, on a scale where 1 is the peak of a perfect, diffraction-limited image.

Safety of the retinal illumination

The exposure calculator of etendue compares the light sent into the eye with the exposure limits of the ICNIRP guidelines [5, 6]. A 1 mW source at 840 nm that lights a 3° field on the retina for 10 s reaches 1.2 % of the retinal thermal limit. As a worst case, the same 1 mW is focused on one spot, a source of 1.5 mrad apparent size, the smallest the guidelines consider, through a pupil dilated to 7 mm as during an examination, for 30 s. The retina then receives 2.0 times the thermal limit set for ophthalmic instruments [6]. The calculator follows these guidelines; conformity with ISO 15004-2 [7], the regulatory standard for ophthalmic instruments, is a separate assessment.

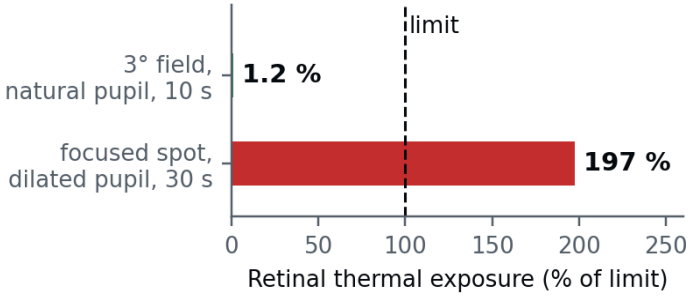


Figure 3. Retinal thermal exposure of the two illuminations, as a share of the ICNIRP limit, from the exposure calculator of etendue.

From the model to a real corrector

The optimized plate is described by 12 Zernike coefficients of surface height, the largest of which is 4.7 µm. A freeform phase plate would be made to these coefficients, and a programmable corrector would be set to them for this eye.

Reliability of the results

The table compares the eye models and the wavefront criteria with published results or exact formulas, and gives the largest differences. Outside the table, the largest gap is on the off-axis astigmatism of the wide-angle eye, 15 % of the published value at 20° [2]; this note uses the axis only. One worked example is not reproduced because the guideline text contradicts itself. It prints 50 W/cm² as the retinal limit for a 26 µm image [6], while its own formula gives 46.2 W/cm².

CHECK	RESULT	SOURCE
Power of the Navarro eye at 589 nm	60.40 D against 60.4 D published	[1]
Chromatic aberration of the eye from 450 to 900 nm	largest difference 0.11 D from the chromatic eye of [3]	[3]
RMS wavefront of a Zernike surface of known height	largest difference 0.24 % from the exact value	exact formula
Strehl ratio for $\sigma \le 0.1$ wave RMS	largest difference 0.08 % from $\exp(-(2\pi\sigma)^2)$	[4]
Worked examples of the exposure limits	12 of 13 reproduced	[5, 6]

D: dioptres.

Limitations

One optimization run is limited to 9 minutes of computing time, and the result above used this full time on a workstation. There is no ready-made liquid lens or Alvarez component in etendue; they are built from a surface of variable curvature or from two polynomial plates moved sideways. This note treats one eye. Several eyes are handled as copies of the system that share the instrument and differ by the eye and by the corrector terms.

Use in teaching

The case is used as a design exercise in five stages. One loads a published eye, adds the aberrations of a measured eye, builds the instrument around it, optimizes the corrector on the wavefront and checks the illumination against the exposure limits.

References: [1] R. Navarro, J. Santamaría, J. Bescós, J. Opt. Soc. Am. A 2(8), 1273–1281 (1985). [2] I. Escudero-Sanz, R. Navarro, J. Opt. Soc. Am. A 16(8), 1881–1891 (1999). [3] L. N. Thibos, M. Ye, X. Zhang, A. Bradley, Appl. Opt. 31(19), 3594–3600 (1992). [4] V. N. Mahajan, J. Opt. Soc. Am. 73(6), 860–861 (1983). [5] ICNIRP, Health Phys. 105(1), 74–96 (2013). [6] ICNIRP, Appl. Opt. 44(11), 2162–2176 (2005). [7] ISO 15004-2:2024, ophthalmic instruments.

Wavefront from real-ray tracing; Strehl ratio from the FFT point spread function.