Introduction

The eye as an optical system suffers from both longitudinal chromatic aberration (LCA) and transverse chromatic aberration (TCA). In the presence of polychromatic light, these two types of chromatic aberrations have an impact on the retinal image. Studied isolated, both the LCA and the TCA have been theoretically shown to be a major optical factor limiting the retinal image quality.

The purpose of this study was to see if we can reduce the LCA and hence improve visual acuity.

Methods

1. Software modeling of the eye and LCA corrector

We designed a two-triplet air-spaced system, using glasses for the range of 405-1060 nm as provided in the optimization software (Zemax Development Corporation, Bellevue, WA, USA). The chromatic eye model was added to the simulation, and optimization was performed to obtain a minimum LCA without introducing additional monochromatic aberrations, while keeping a reasonable field of view. The variables for the optimization were the internal curvatures of the triplets, the thickness of the glasses and the distance between the two triplets. After obtaining a satisfying correction of LCA, with a unit magnification for all wavelengths, we examined the optical quality of the corrector with a wide-angle eye model.

2. Hartmann-Shack wave-front sensor

Aberrations of the corrector were examined with a system based on a Hartmann-Shack wave-front sensor (Fig. 1). The illumination source is a white-light Xenon lamp (Hamamatsu L2274). The monochromatic aberrations for different wavelengths were measured by inserting the appropriate 10-nm bandwidth interference filter (FI) in front of the lamp (wavelengths, 440, 488, 532, 633, and 694 nm).

3. Subjective measurements of the eye’s LCA

Subjective measurements of the eye’s LCA were performed, with and without the corrector (Fig. 2). For these measurements, a mirror is used to allow the subject fixating to a target slide with high spatial frequency features. This slide is illuminated with different wavelengths used to allow the subject fixating to a target slide with high spatial frequency features. This slide is illuminated with different wavelengths (440, 488, 532, 633, and 694 nm).

4. Subjective measurements of Visual acuity (VA)

Visual acuity (VA) tests were performed (Fig. 2). The subject’s task is to determine the orientation of the letter E. From the responses, we obtain the psychometric function and the VA. The VA is measured with and without the corrector in front of the eye.

Results

Optimization results

A layout of the modeled eye with the final corrector is presented in Fig. 3. Manufacturing hardware constraints slightly changed the parameters of the final design. A practical advantage of this design is that each of the triplets is symmetric, so flipping an element does not change the optics of the system. Fig. 4 presents the spot diagrams of the modeled eye with and without the corrector.

Corrector aberrations

The individual Zernike coefficients (defocus excluded) are presented in Fig. 5, showing that no systematic aberration pattern is introduced. The wrapped wave-front maps are displayed in Fig. 6 and are basically flat for every wavelength.

Conclusions:

• A new design of achromatizing correcting lens optimized for a wide field has been presented. Theoretical analysis of the design predicts a good chromatic aberration correction and a potential improvement of retinal image quality for polychromatic light.

• The optical quality of the corrector alone was tested for different wavelengths with a Hartmann-Shack wave-front sensor, showing only small amounts of aberrations.

• The performance of the device for LCA correction was checked on three subjects and is in agreement with the predictions.

• One of the subjects showed an improvement in the monochromatic VA that can be attributed to the correction of LCA, while for the other subject the results are not clear. The potential benefits of chromatic aberration correction alone can be thwarted by the interaction with monochromatic aberrations and, therefore, will probably be more apparent when the corrector is used as an element on a system for global compensation of both monochromatic and chromatic aberration such as, e.g., an adaptive optics apparatus.

Visual acuity measurements

The VA estimates for the two subjects can be seen graphically in Fig. 8. Without the corrector, the monochromatic VA is slightly better than the polychromatic VA for both subjects, although these differences has marginal statistical significance. This effect can be produced by the chromatic aberrations (both LCA and TCA) of the eye, and may indicate that there is room for some improvement in visual performance by correction of the LCA.

Three young subjects with normal vision participated in the experiment: PA, PP and YB. The experiment was performed both with the corrector in front of the subject's eye and with the naked eye. Fig. 7 presents the differences in focus with respect to a reference wavelength (532 nm), which can be taken as an estimate of the subject's LCA.

Figure 1: Experimental apparatus for measuring the monochromatic aberrations introduced by the corrector for different wavelengths.

Figure 2: Experimental apparatus for measuring the ocular LCA and performing VA tests with and without the corrector.

Figure 3: Schematic diagram of the corrector and the wide-angle eye model used for the optimization process.

Figure 4: Spot diagrams for 0 deg and 6 deg of the modeled wide-angle eye (top) and the modeled eye after adding the corrector (bottom), for 6 mm pupil.

Figure 5: Wrapped phase maps of the corrector aberrations for the five selected wavelengths.

Figure 6: Zernike coefficients (OSA standard order) of the corrector aberrations over a 5.0 mm pupil for a set of wavelengths. The defocus term is not included.

Figure 7: Longitudinal chromatic aberration for the naked eye (solid circles) and after LCA correction with the two-triplet system (open triangles) for three subjects.

Figure 8: Visual acuity estimates for two subjects, SM (-3 D) and YB (-3.5 D).