4th International Congress of Wavefront Sensing and Aberration-free Refractive Correction

(Supplement to the Journal of Refractive Surgery; June 2003)

ADAPTIVE OPTICS FOR VISION: THE EYE'S ADAPTATION TO ITS POINT SPREAD FUNCTION

Pablo Artal, Li Chen*, Enrique J. Fernández, Ben Singer*, Silvestre Manzanera and David R. Williams*

Laboratorio de Optica, Departamento de Física, Universidad de Murcia, Campus de Espinardo (Edificio C), 30071 Murcia, Spain.

* Center for Visual Sciences, University of Rochester, Rochester NY 14627, USA.

Phone: 34-968367224; Fax: 34-968367667; E-mail address: pablo@um.es

ABSTRACT

Despite ocular aberrations blur the retinal images, our subjective impression is that the visual world is sharp what may suggest that the visual system compensates for their subjective influence. If the brain adjusts for the specific aberrations of the eye, vision should be clearest when looking through the normal wave aberration rather than through an unfamiliar one. The use of adaptive optics techniques to control the eye's aberrations allows performing experiments to evaluate this hypothesis. We used adaptive optics to produce point-spread functions (PSFs) that were rotated versions of the eye's usual PSF by angles in 45 degrees intervals. Five normal subjects were asked to view a stimulus with their own PSF or with a rotated version. The subject's task was to adjust the magnitude of the aberrations in the rotated case to match the subjective blur of the stimulus to that seen when the wave aberration was in the normal orientation. The magnitude of the rotated wave aberration required to match the blur with the normal wave aberration was 20 to 40% less, indicating that the subjective blur for the stimulus increased significantly when the PSF was rotated. These results support the hypothesis that the neural visual system is adapted to the eye's particular aberrations. This result has important implications for methods to correct higher order aberrations with customized refractive surgery or contact lenses because the full visual benefit of optimizing the correction optically requires that the nervous system can compensate for the new correction.

The quality of the retinal images is affected by optical aberrations[1,2] that cannot be corrected with ordinary spectacles or contact lenses. These aberrations are different in every eye, blur the retinal image and ultimately limit spatial vision. The lower order aberrations: defocus and astigmatism, are widely known and corrected routinely in the clinical practice. The presence in the eye of higher order aberrations, beyond defocus and astigmatism, has been well known for researchers for more than 150 years, but only in the last decade wave-front sensors instruments were well developed to allow a routine estimation of the eye's aberrations. From the aberrations we can simulate[3] how are the retinal images, however we do not know yet how to go one step further and predict the quality of vision from aberration measurements. Adaptive Optics (AO), a technique previously used in Astronomy to remove the effect of atmospheric turbulence in telescope images, allows real-time correction of the aberrations. When AO is applied to the eye[4-7], high-resolution retinal images are obtained after removing the ocular aberrations. In addition, AO permits controlled modification of the ocular optics to perform new experiments to better understand the impact of the ocular optics in vision and in particular to explore the possible role of the neural system sharpening the retinal images. Some previous experiments indicated that not every aberration might have the same impact in vision[8]. In addition, visual acuity was found consistently higher for the normal aberrations[9], when measured in the same subject with aberration patterns that were different in shape but similar in magnitude. These antecedents lead to the question if the visual system is adapted to the optical aberrations of its own eye. To better understand this problem, we performed an experiment of subjective blur matching with the normal and rotated aberrations produced using an AO apparatus.

An AO system consists of a wave-front sensor to measure the aberrations in real time[10] and a correcting device, typically a deformable mirror, to modify the aberrations. The AO system used in this work is the second-generation Rochester AO apparatus[7] that uses a Hartmann-Shack wavefront sensor to measure the eye's aberrations. A narrow infrared beam produced by a superluminescent diode is projected into the subject's retina acting as a beacon source. In the second pass, after the light is reflected in the retina and passes through the complete system, a microlenses array, optically conjugated with the subject's pupil plane, produces an image of spots on a CCD camera. The locations of the spots in this image provide the local slopes of the ocular aberrations. A 97-channel deformable mirror (*Xinetics)* was used as the wave-front correcting device. It is placed in the system conjugated both with the subject's pupil plane and the wave-front sensor, by using appropriate lenses and two off-axis parabolic mirrors. In this experiment, besides removing the higher order aberrations in the eye, the deformable mirror also acted as an aberration generator to blur the subject’s vision either with the subject’s own aberrations or his rotated aberrations. Eight different aberration pattern were produced in each case: the normal average aberrations, that were first corrected and then induced again, and seven similar versions rotated by 45 degrees intervals. Figure 1 shows an example of the eight PSF patterns for one the subjects. Subjects viewed a binary noise stimulus through the AO system. The stimulus contained sharp edges at all orientations and subtended 1 degree of visual angle and was viewed in 550 nm monochromatic light. The subject viewed the stimulus for 500 ms immediately after the deformable mirror generated the subject’s own aberrations or his rotated. At other times, the subject viewed a uniform field. During the matching experiment measurement, the subject's head was stabilized with a bite bar, and the subject's pupil was dilated and accommodation paralysed with cyclopentholate hydrochloride (2.5%). The experiment was performed for an artificial pupil of 6 mm diameter

Figure 2 shows the average values of the relative subjective blur for the normal aberrations (0 angle) and the seven rotations. The relative subjective blur with the rotated aberrations increases between 20 to 40%. These results support the hypothesis that the neural visual system is adapted to the eye’s particular aberrations, so that edges appear sharp despite the modest blur in the normal retinal image. Although as far as we know this is the first time that a strong evidence for an adaptation to monochromatic aberrations is reported, adaptability in the visual system is well known. For example, the neural visual system remarkably adapts to prismatic distortions and to the optical aberrations[11] present in power progressive lenses used to correct presbyopia.

This adaptation phenomenon may have important implications for vision correction. In particular in the area of wave-front guided customized refractive surgery or customized contact lenses, this effect will reduce the immediate benefit for the patient of attempts to produce diffraction-limited eyes. If the brain is adapted to a particular aberration pattern, when this is changed by the surgery or contact lens, the neural compensation will remain adjusted to the first aberration pattern for some time. However the practical importance of this will depend on the time required to reverse the previous adaptation that we do not know yet.

Acknowledgments

This research was supported in part by grants from *MCyT BFM2001-0391(Spain)* to PA and *NSF_CfAO AST-9876783, NIH EY0436, EY0139* (USA) to DRW.

References

1. Liang J. and Williams D.R., Aberrations and retinal image quality of the normal human eye. J. Opt. Soc. Am. A **14**, 2873-2883 (1997).

2. Artal P., Guirao A., Berrio E. & Williams D. R., Compensation of corneal aberrations by internal optics in the human eye. Journal of Vision, **1**, 1-8 (2001).

3. Artal P., Calculations of two-dimensional foveal retinal images in real eyes. J Opt Soc Am A. **7**, 1374-1381 (1990).

4. Liang J., Williams D. R. & Miller D. T., Supernormal vision and high-resolution retinal imaging through adaptive optics, J. Opt. Soc. Am. A. **14**, 2884-2892 (1997).

5. Vargas-Martin F., Prieto P., & Artal P., "Correction of the aberrations in the human eye with liquid crystal spatial light modulators: limits to the performance", J. Opt. Soc. Am. A. **15**, 2552-2562 (1998).

6. Fernández E. J., Iglesias I., & Artal P., "Closed-loop adaptive optics in the human eye", Opt. Lett. **26**, 746-748 (2001).

7. Hofer H., Chen L., Yoon G. Y., Singer B., Yamauchi Y., & Williams D. R., "Improvement in retinal image quality with dynamic correction of the eye's aberrations", Opt. Exp. **11**, 631-643 (2001).

8. Applegate R.A., Sarver E.J., Khemsara V. Are all aberrations equal? J. Refract. Surg.; **18**, S556-62 (2002).

9. Fernández E. J., Manzanera S., Piers P., Artal P., Adaptive optics visual simulator. J. Refract. Surgery, **18**, S634-S638 (2002).

10. Hofer H. J., Artal P., Singer B., Aragón J. L. and Williams D. R., Dynamics of the eye's wave aberration. J. Opt. Soc. Am. A. **18**, 497-506 (2001).

11. Villegas E. A. & Artal P., Spatially resolved wavefront aberrations of ophthalmic progressive-power lenses in normal viewing conditions. Optom. Vis. Sci., **80,** 106-114 (2003).

Caption to Figures

Figure 1

Example of the normal PSF (0) and the seven orientations PSFs for one of the subjects that participated in the experiment. The numbers represented the rotated angle. The AO system permitted to rotate the normal aberrations by the desired angles.

Figure 2

Average relative subjective blur for the five subjects as a function of the orientation of the aberrations (in degrees). Error bars represent standard deviation of responses across subjects.

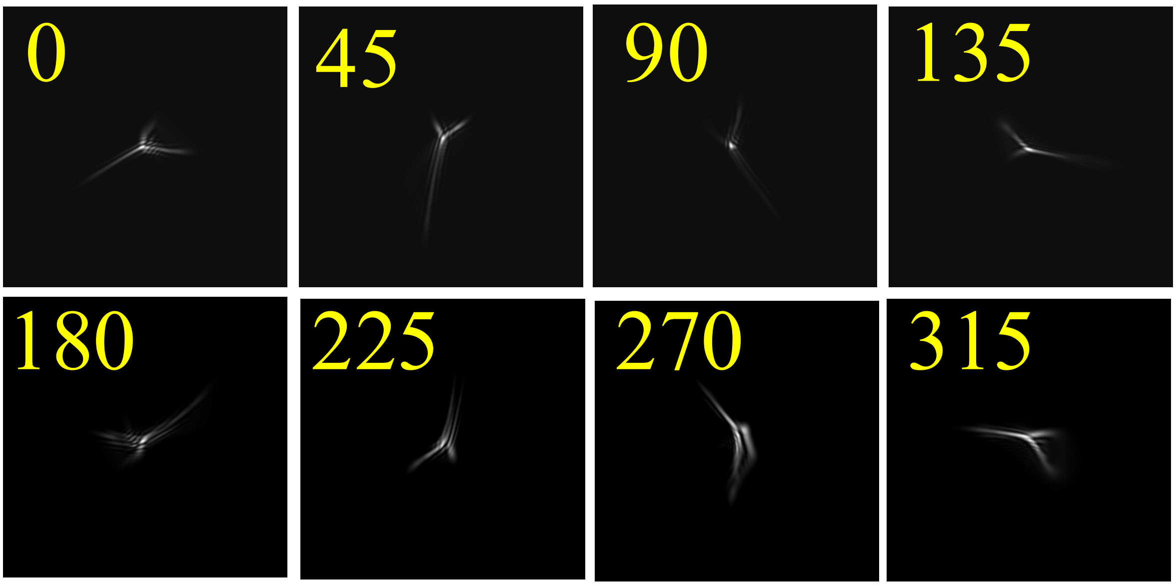

Figure 1

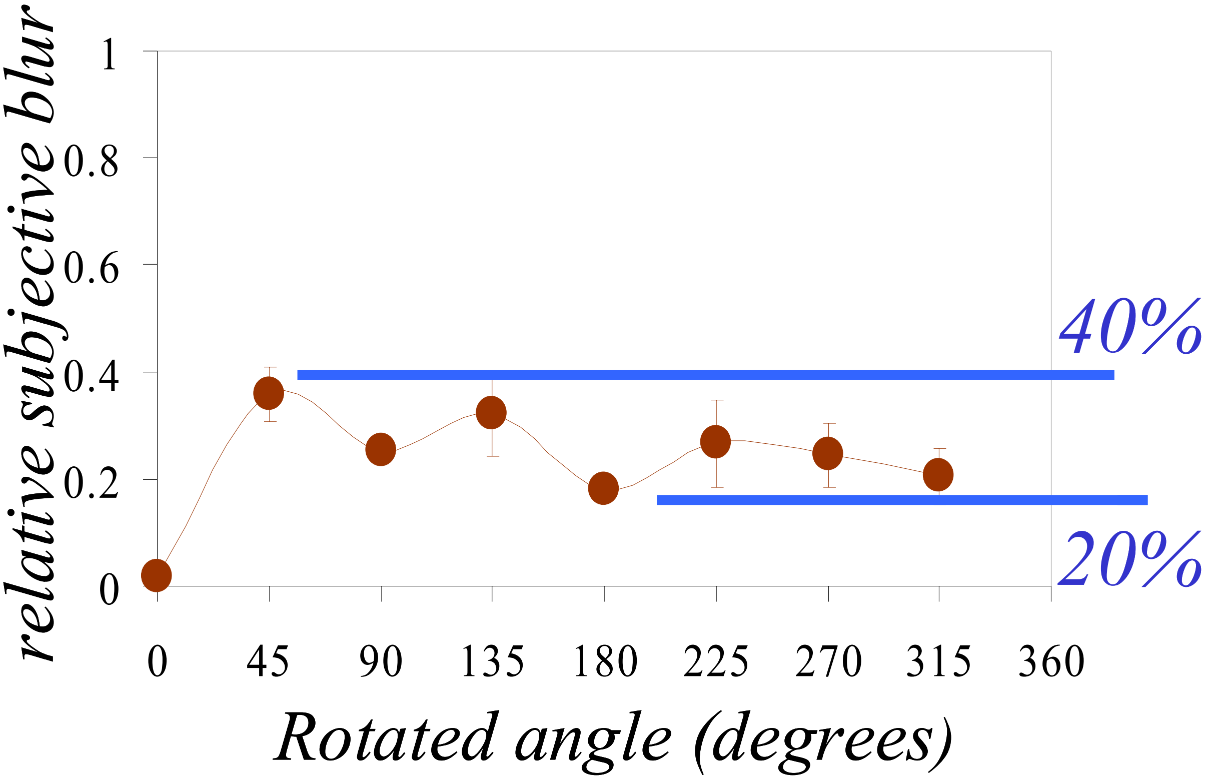
relative subjective blur
1
0.8
0.6
0.4
0.2
0
0
45
90
135
180
225
270
315
360
Rotated angle (degrees)
40%
20%

Figure 2