Binocular adaptive optics visual simulator

Enrique J. Fernández, Pedro M. Prieto, and Pablo Artal*

Laboratorio de Óptica, Centro de Investigación en Óptica y Nanofísica (CiOyN), Universidad de Murcia, Campus de Espinardo, 30071 Murcia, Spain

**Corresponding author: pablo@um.es*

Received June 26, 2009; accepted July 24, 2009;
posted August 5, 2009 (Doc. ID 113419); published August 25, 2009

A binocular adaptive optics visual simulator is presented. The instrument allows for measuring and manipulating ocular aberrations of the two eyes simultaneously, while the subject performs visual testing under binocular vision. An important feature of the apparatus consists on the use of a single correcting device and wavefront sensor. Aberrations are controlled by means of a liquid-crystal-on-silicon spatial light modulator, where the two pupils of the subject are projected. Aberrations from the two eyes are measured with a single Hartmann–Shack sensor. As an example of the potential of the apparatus for the study of the impact of the eye's aberrations on binocular vision, results of contrast sensitivity after addition of spherical aberration are presented for one subject. Different binocular combinations of spherical aberration were explored. Results suggest complex binocular interactions in the presence of monochromatic aberrations. The technique and the instrument might contribute to the better understanding of binocular vision and to the search for optimized ophthalmic corrections.

OCIS codes: 010.1080, 330.4460, 330.5370.

First limits of vision are imposed by the quality of retinal images, characterized by ocular aberrations. The interest on measuring and understanding their impact in vision has been a field of intensive research in the past few years [1–3]. Adaptive optics (AO) allows for correcting, and in general manipulating, ocular aberrations [4]. Among the many applications of AO in the context of the study of the eye, the technique has been successfully demonstrated for visual simulation [5,6]. However, studying the impact of aberrations in monocular vision, the most extended approach so far, is incomplete, since our everyday vision is binocular. Visual perception is different under normal binocular conditions [7]. Consequently, a natural step in the field would be to study the impact of aberrations under binocular vision [8]. In this direction, systems for simultaneously measuring the ocular aberrations from the two eyes have been reported recently [9,10]. A further advance would be the extension of the concept of adaptive optics visual simulation, simultaneously correcting or modifying the aberrations in both eyes to study their effect in binocular vision. In this Letter an AO system is presented for the characterization of binocular vision in presence of controlled amounts of aberrations in the two eyes. The apparatus is capable of measuring and manipulating the aberrations from the two eyes simultaneously for the first time to our knowledge. An additional relay is incorporated for the binocular presentation of stimuli and visual tests through the modified optics. Independent manipulation of the aberrations from each eye is possible with the system, while binocular viewing is still performed.

An important feature of our prototype consists in the fact that the measurement and manipulation of the wavefront is accomplished by means of a single wavefront sensor and a single correcting device, respectively. Figure 1 shows a schematic representation of the experimental apparatus and its main components. The illumination of the two eyes is performed with IR light from a pigtailed diode laser emitting at 780 nm. The collimated wavefront exiting the laser source is distributed into two narrow beams of 1 mm diameter each, through an opaque mask with two holes. A pellicle beam splitter, BS_1, reflects the two beams toward the subject's eyes. By means of a reflecting prism and two mirrors, shown in Fig. 1 as P, M_1, and M_2, respectively, light reaches simultaneously the two eyes' pupils. The light reflected or back scattered by the two retinas is directed back to the system by reverse path through M_1, M_2, and P. The exit pupils of the two eyes are placed at the focal plane of lens L_1. Lenses L_1 and L_2 (focal length 250 and 300 mm, respectively) conjugates the pupils of the two eyes onto the surface of the correcting device with a 1.2 magnification. The path between L_1 and L_2 can be varied by means of two mirrors mounted on a motorized stage, allowing the independent defocus control. The wavefront corrector is a liquid-crystal-on-silicon (LCOS) spatial light modulator (LCOS-SLM X10468-04, Hamamatsu Photonics, Japan). The correcting device modulates the incident light by locally varying the refractive index of the liquid crystal. The molecules of the liquid crystal are rotated

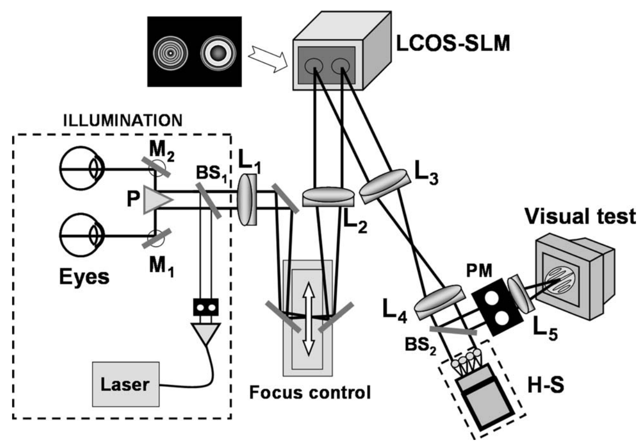

Fig. 1. Experimental apparatus showing its main components.

proportionally to the applied electrical field induced by an array of independent silicon pixels in contact with the liquid crystal. This technology has been already demonstrated for AO applications [11], showing refreshing rates up to 60 Hz, reduced diffraction losses, high resolution (800×600 pixels), and large effective stroke. We selected a pupil diameter on the LCOS-SLM of 4.8 mm, which approximately corresponds to 58,000 independent pixels for controlling the wavefront for each pupil. A second pair of lenses, L_3 and L_4 (focal length 200 and 100 mm, respectively), conjugates the plane of the corrector onto the Hartmann–Shack (H-S) sensor with a 0.5 magnification. The two pupils are spatially resolved on the sensor, allowing, through the appropriate software specifically developed for this system, the simultaneous measurement of the aberrations from each eye. The algorithms for obtaining the wavefront from the H-S images were described elsewhere [12]. The sensor microlens pitch and focal length are 0.3 mm and 6 mm, respectively. Figure 2 shows a frame produced by the wavefront sensor, with the spots from the two eyes. The corresponding pupil diameter on the wavefront plane was 2.4 mm, indicated on Fig. 2 with a solid circle, so that more that 50 microlenses sampled the incoming wavefront from each eye. Figure 2 also shows the retrieved aberration of each eye. The relay for visual tests presentation is linked to the AO system by means of a beam splitter, BS_2, placed between L_4 and the H-S sensor. The pupil size for visual testing is fixed by means of a mask, PM, with two orifices of 2.4 mm diameter, optically conjugated to the LCOS-SLM and the eye's planes. With this arrangement, the effective pupil diameter on the eye's plane is 4 mm. The relay for the presentation of visual stimuli is compounded by a positive lens of 600 mm focal length and a cathode ray tube monitor located on its focal plane. Stimuli for contrast sensitivity measurement and other visual tasks can be presented on the monitor, generated with our developed software package based on commercially available libraries for stimulus generation (Cambridge Research Systems).

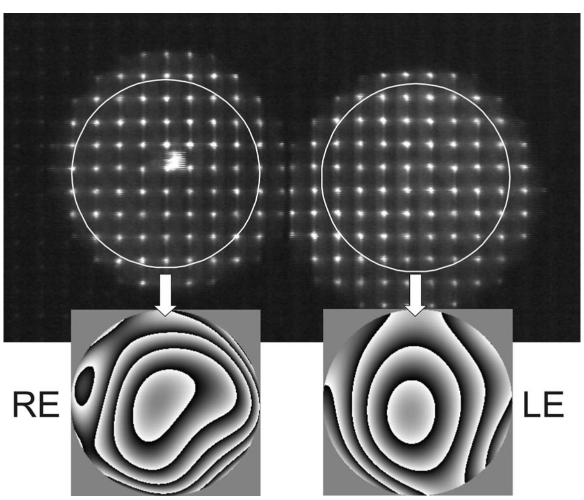

Fig. 2. H-S image depicting the spots obtained simultaneously in a single frame from each pupils of the subject. Retrieved wavefronts are also presented. RE, right eye; LE, left eye.

To test the capabilities of the instrument, measurements of contrast sensitivity were conducted in a subject. The goal of these first experiments was simply to demonstrate the potential of the binocular AO visual simulator for studying the impact of aberrations under normal vision. The subject, a 47-year-old male, mild myope ($-1.5\,D$) with normal vision, was stabilized by using his dental impression at focal distance of lens L_1. A fixation stimulus was presented, and the subject manipulated mirrors M_1 and M_2 and prism P until binocular fusion was accomplished. The procedure consisted of moving the prism to adjust the interpupillary distance, and then fine actuation over the tilts of the mirrors to avoid the perception of double image. Once binocular fusion was achieved, subjective correction of the subject's refraction was performed for each eye monocularly by varying the defocus with the LCOS-SLM in $0.1\,D$ steps. As an example of use of the binocular AO visual simulator, in this experiment we targeted to explore the impact on binocular vision of adding or subtracting 0.2 μm of spherical aberration [13] to the subject's natural aberrations. A Bayesian adaptive psychometric method [14] was used to determine contrast sensitivity for sinusoidal gratings of 7.8 c/deg in green light (green channel of the monitor) under different situations. The subject's task was to detect the presence of a sinusoidal grid of random orientation in a two-alternative forced choice between two frames presented for 500 ms. Confidence for the algorithm to obtain the contrast sensitivity was set at 75%. The stimulus subtended 1 deg, so that foveal vision was forced and isoplanatic condition [15] could be assumed during the experiment. Figure 3 presents the results obtained for the binocular contrast sensitivity when −0.2 and +0.2 μm of spherical aberration were added simultaneously to the eyes, together with the case of the subject's natural aberrations. The figure also shows the monocular results obtained for the same values and each eye separately. A decrease in the contrast sensitivity was found when adding spherical aberration, irrespectively of the sign. Binocular contrast sensitivity was systematically larger,

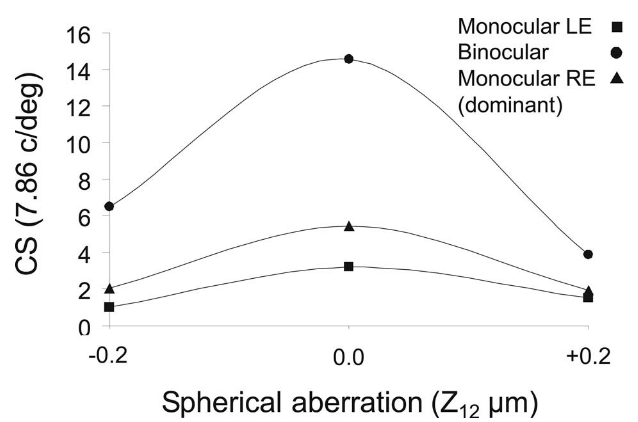

Fig. 3. Contrast sensitivity at 7.8 c/deg obtained with modified spherical aberration under binocular and monocular conditions.

as expected. However, the perceived degradation due to the addition of spherical aberration was asymmetric. Sensitivity was slightly better for the right eye, being the dominant eye for this particular subject. The system allows for the independent but simultaneous modification of the aberrations of each eye.

To exemplify this feature we tested different combinations of spherical aberration under binocular vision. The contrast sensitivity results for all possible combinations of ±0.2 μm and 0 spherical aberration are grouped in Fig. 4. The brackets in the category axis represent the programmed case ordered as (right eye, left eye). + and − stand for addition or subtraction of 0.2 μm of spherical aberration, while 0 stands for subject's natural aberrations. Error bars show the standard deviation obtained from three runs during the measurement of contrast sensitivity. Although it is not our intention to extract conclusions from a single subject, it is interesting to note that leaving the natural aberrations on the dominant eye, cases (0,0), (0,+), and (0,−), produce the best visual performance as compared with the rest of degraded situations. These results suggest a complex relationship and interaction between aberrations in binocular vision, which can be explored in the future with additional experiments using the presented device.

A possible alternative solution for the study of the impact of aberrations on binocular vision could simply consist on the duplication of the already existing monocular AO visual simulators, one for each eye. In our opinion, this is a nonefficient solution, the cost of such system would be nearly duplicated, and the complexity of its operation would probably be high. In this work we present an approach that is cost effective and relatively simple to operate from a single computer. This approach seems feasible only with the use of liquid-crystal modulators owing both to the large number of elements (pixels) and the independence between them. A constraint of liquid-crystal phase modulation is the mandatory use of polarized light, although in practice this has no effect on vision. The use of phase wrapping for controlling the wavefront also requires the employment of monochromatic light. Otherwise distinct wavelengths are differently phase modulated, which should be taken into account, perhaps with previous calibration of the device.

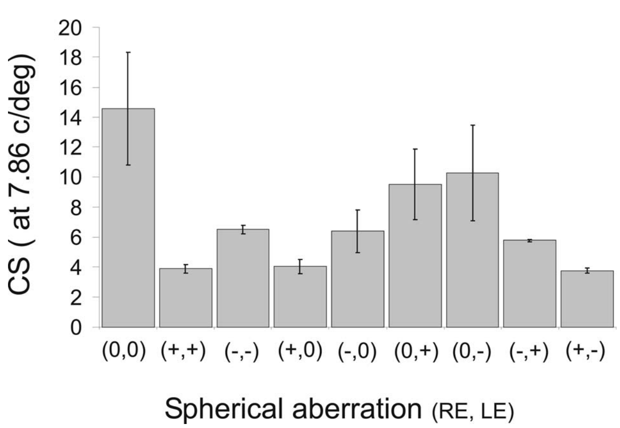

Fig. 4. Measured contrast sensitivity at 7.8 c/deg with several spherical aberration combinations under binocular vision.

The setup presented in this Letter enables for up to 58,000 independent pixels for controlling each pupil, which shows a clearly superior capability for accurately handling the wavefront than deformable mirrors. The size of the liquid crystal, 12 mm × 16 mm, allows for holding the projection of two pupils of 8 mm diameter, simply by adjusting the optics between the eyes and the correcting device. These maximum projected diameters would allow the simultaneous use of 160,000 independent pixels for each eye, which might be useful for programming also some discontinuous phase masks with high accuracy. An alternative version of the instrument could use a microelectromechanical deformable mirror for applications requiring moderate amplitude in the phase.

The instrument and technique presented here may be of help to better understand the influence and impact of aberrations in binocular vision. From a more applied perspective, the binocular AO visual simulator presents a high potential as a tool for the design of advanced or customized ophthalmic elements, and in particular for the systematic search of phase profiles extending depth of focus for correction of presbyopia.

This work has been supported by Ministerio de Educación y Ciencia, Spain (grant FIS2007-64765), and Fundación Séneca, Murcia, Spain (grant 04524/GERM/06).

References

1. J. Liang and D. R. Williams, J. Opt. Soc. Am. A **14**, 2873 (1997).
2. P. Artal, A. Benito, and J. Tabernero, J. Vision **6**, 1 (2006).
3. P. Artal, L. Chen, E. J. Fernández, B. Singer, S. Manzanera, and D. R. Williams, J. Vision **4**, 281 (2004).
4. E. J. Fernández, I. Iglesias, and P. Artal, Opt. Lett. **26**, 746 (2001).
5. E. J. Fernández, S. Manzanera, P. Piers, and P. Artal, J. Refract. Surg. **18**, 634 (2002).
6. S. Manzanera, P. M. Prieto, D. B. Ayala, J. M. Lindacher, and P. Artal, Opt. Express **15**, 16177 (2007).
7. F. W. Campbell and D. G. Green, Nature **208**, 191 (1965).
8. J. R. Jiménez, J. J. Castro, R. Jiménez, and E. Hita, Optom. Vision Sci. **85**, 174 (2008).
9. K. M. Hampson, S. S. Chin, and E. A. H. Mallen, J. Mod. Opt. **55**, 703 (2008).
10. M. Kobayashi, N. Nakazawa, T. Yamaguchi, T. Otaki, Y. Hirohara, and T. Mihashi, Appl. Opt. **47**, 4619 (2008).
11. E. J. Fernández, P. M. Prieto, and P. Artal, Opt. Express **17**, 11013 (2009).
12. P. M. Prieto, F. Vargas-Martin, S. Goelz, and P. Artal, J. Opt. Soc. Am. A **17**, 1388 (2000).
13. American National Standards Institute, *Methods for Reporting Optical Aberrations of Eyes*, Z80.28-2004 (ANSI, 2004).
14. A. B. Watson and D. G. Pelli, Percept. Psychophys. **33**, 113 (1983).
15. P. Artal and R. Navarro, Appl. Opt. **31**, 3646 (1992).