Vision Research 51 (2011) 2471–2477

Contents lists available at SciVerse ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Optimizing the subjective depth-of-focus with combinations of fourth- and sixth-order spherical aberration ☆

Yohann Benard [a,b], Norberto Lopez-Gil [c], Richard Legras [a,b,*]

[a] CNRS, Laboratoire Aimé Cotton, F-91405 Orsay Cedex, France
[b] Univ. Paris-Sud, F-91405 Orsay Cedex, France
[c] Instituto Universitario de Investigación en Envejecimiento, Universidad de Murcia, 30100 Murcia, Spain

ARTICLE INFO

Article history:
Received 4 July 2011
Received in revised form 7 October 2011
Available online 14 October 2011

Keywords:
Depth-of-focus
Spherical aberration
Sixth-order spherical aberration
Presbyopia

ABSTRACT

We optimize the subjective depth of focus (DoF) with combinations of spherical aberration (SA4) and secondary spherical aberration (SA6) in various levels. Subjective DoF was defined as the visual interval for which three 20/50 high-contrast letters was perceived acceptable (objectionable blur limits). We used an adaptive optics system to dynamically correct the observer's aberrations and control their accommodation. DoF was measured with a 0.18-D step on three non-presbyopic subjects. The target seen by the subjects was modified to include 25 combinations of SA4 and SA6 (i.e. 0, ±0.15 and ±0.30 μm) for 3, 4.5 and 6 mm of pupil diameter. We found a mean DoF of 1.97 D with a 3 mm pupil size, which decreased by 28% with a 4.5 mm pupil and by 34% with a 6 mm pupil. For 6 mm pupil we found an increase of subjective DoF of 45% and 64% with the addition of 0.3 and 0.6 μm of SA4, and of 52% and 117% with the addition of 0.15 and 0.3 μm of SA6. The largest DoF measured (4.78 D) increased 3.6 times that of the naked eye and was found for a combination of opposite signs of SA4 and SA6 of 0.6 and 0.3 μm respectively. Reducing the pupil size minimized the effect of aberrations on subjective DoF. Combination of SA4 and SA6 of opposite sign could increase DoF more than three times for pupils larger than 4.5 mm. Subjective DoF is well predicted by measuring the induced variation of vergence arising in the pupil size.

1. Introduction

For several centuries now, the human being has been trying to avoid presbyopia by expanding the depth of field (DoF) of the aged eye using spectacle lenses, or more recently by means of contact lenses, intraocular multifocal or accommodative lenses, or refractive surgery (Chateau & Baude, 1997; Piers et al., 2004; Plakitsi & Charman, 1995).

Although most people would agree in defining DoF as the dioptric range of clear vision, special care has to be taken since clear vision depends on many factors such as the task, ambient light, target color and contrast. In general, DoF is associated to the interval of vision over which the visual performances exceed a certain threshold. DoF involves some compromises in the level of vision, which is measurable in terms of contrast sensitivity or visual acuity (Borish, 1988; Erickson et al., 1988; Piers et al., 2004). Visual acuity remains the main criterion used to measure the quality of vision. However, the final acceptability of a correction is mainly based on the patient evaluation of his/her quality of vision. Consequently, the subjective DoF appears to be the key factor to measure. That is the reason why some authors (Atchison, Guo, & Fisher, 2009; Atchison et al., 2005; Bénard, Lopez-Gil, & Legras, 2010) considered the DoF as the range of proximities where the vision is still judged acceptable, which is called by Atchison et al. (2005) the objectionable blur. That definition is then directly linked to final acceptance of the optics worn (e.g. a multifocal correction).

Besides the pupil size, subjective DoF could be increased by the use of multifocal artificial systems (such as multifocal intraocular lenses or contact lenses) that distribute the light energy in more than one focal point. A similar strategy used in the last decade consists in adding some high-order aberration to the eye by means of an artificial system or refractive surgery. The aberrations induced try to spread the concentration of rays along the visual axis producing a multifocality that could increase DoF. Several high-order aberrations have been studied (Bénard, Lopez-Gil, & Legras, 2010; Rocha et al., 2009), but the most used have been the primary spherical aberration, also called fourth-order spherical aberration in the Zernike polynomial expansion (SA4). SA4 causes the rays entering the eye to focalize at different

☆ Source of public and private financial support: None. No author has a financial or proprietary interest in any material or method mentioned.
* Corresponding author at: Laboratoire Aimé Cotton, Bât. 505, Campus d'Orsay, F-91405 Orsay Cedex, France. Fax: +33 1 69 41 01 56.
E-mail address: richard.legras@u-psud.fr (R. Legras).

0042-6989/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2011.10.003

distances depending on their distance from the pupil center. SA4 can be modified altering the *Q*-factor of the cornea which makes this strategy of increasing DoF very attractive in ophthalmology since it can be done in refractive surgery (Ortiz et al., 2007; Tuan & Chernyak, 2006).

In the last 5 years several studies have been carried out concerning the increase of DoF in the presence of high-order aberrations induced by means of an adaptive optics system that could also correct most of the subject's aberrations at the same time (Atchison, Guo, & Fisher, 2009; Bénard, Lopez-Gil, & Legras, 2010). In particular some authors (Bénard, Lopez-Gil, & Legras, 2010; Rocha et al., 2009) have explored the positive effect of SA4 on the DoF. Their results showed that the DoF increased by 30% when adding 0.3 μm of SA4 and by around 45% (Bénard, Lopez-Gil, & Legras, 2010) to 62% (Rocha et al., 2009) in presence of the 0.6 μm of SA4.

Bénard, Lopez-Gil, and Legras (2010) and Yi, Iskander, and Collins (2011) also studied some combinations of SA4 and secondary spherical aberration, or sixth-order spherical aberration in the Zernike polynomial expansion (SA6). They observed that a combination of the same signs of SA4 and SA6 did not change the DoF obtained with only SA4, whereas inducing certain SA6 with opposite sign than SA4 increases the DoF obtained with only SA4.

Manzanera et al. (2009) measured the subjective DoF, defined as the range of proximities where words were still readable, in presence of the various monochromatic aberrations. The estimates of DoF from optical data did not reproduce accurately the values obtained by visual testing. Bénard, Lopez-Gil, and Legras (2010), who measured the subjective DoF (i.e. objectionable blur) in presence of SA4 and SA6, confirmed these findings.

The two main limitations of using an adaptive optics system to generate the aberrations consist of the dynamic range to generate large aberrations and the impossibility to mimic retinal images generated by bifocal refractive or diffractive lenses (Bénard, Lopez-Gil, & Legras, 2010), such as contact or intraocular multifocal lenses. Applegate, Sarver, and Khemsara (2002) and Applegate et al. (2003) used an alternative method that does not have these limitations by showing the subjects a target which was already convoluted by the PSF of the aberration to be tested. They did not use any adaptive optics system, instead, the subject saw the target through a small pupil (3 mm), so the aberrations of the subjects could be neglected. Although the aberrations tested with this method can be as large as desired, the problem of using that methodology are the diffraction effects of a small pupil affects the retinal image. On the other hand, the use of targets that show computer simulated images for normal or large pupils is only a practical methodology if the eye has very little aberrations; otherwise the eye's aberrations could exceed the aberration to be tested. In a recent publication (Atchison, Guo, & Fisher, 2009), the authors used a mixed methodology in which the subject looked at an aberrated target through a pupil of 3 or 6 mm and used an adaptive optic system to correct most of the eye's aberrations. This methodology has also the advantage to test DoF and to be independent of the subject's aberrations since they are corrected. In that study (Legras, Bénard, & López-Gil, in press), the authors compared that methodology with the one in which the adaptive optics system corrects the subject's aberrations while inducing the aberration to be tested at the same time. The results showed a good agreement ($r^2 = 0.88$) between both methodologies.

The main goal of this work was to determine the combination of SA4 and SA6 that most increased the subjective DoF by using an adaptive optics system to correct the eye's monochromatic aberrations while the target seen by the subject has been previously modified by the aberrations that want to be tested.

2. Methods

2.1. General method

We measured the subjective DoF in the presence of various levels of Zernike SA4 and SA6 at three pupil sizes (i.e. 3, 4.5 and 6 mm) using simulated images. The subject viewed the simulated images on a micro-display (a white screen of 100 cd/m^2) through a dynamic (1 Hz) correction of their aberrations (i.e. residual RMS lower than 0.1 μm on a 6 mm pupil size) by means of a deformable mirror and through an artificial pupil of 6 mm conjugated to the observer's pupil. The displayed images were aberrated variants of an original image composed of three 0.4 logMAR black letters (i.e. H, E, and V), similar to the one used in other studies (Atchison, Charman, & Woods, 1997; Bénard, Lopez-Gil, & Legras, 2010; Ciuffreda et al., 2006) and close to typical letter sizes contained in books or newspapers (i.e. 0.46 logMAR letters, Legge & Bigelow, 2011).

The advantage of presenting simulated images instead of inducing the aberrations with the mirror is that it is possible to simulate larger levels of aberrations. In addition, the appearance of the target is more stable, and the measurements are much faster (i.e. less than 2 min per repetition). Both methods (mirror-controlled and object-controlled conditions) were compared in a previous study (Legras, Bénard, & López-Gil, in press) and were found to be well correlated (i.e. $r^2 = 0.88$).

The out-of-focus blur produced by the proximity of the target was simulated by a defocus term induced in the image calculation which changed in steps of 0.18 D in a range from −5 D to +5 D. Then the 56 deconvolved images were arranged according to their defocus term in a slideshow presentation.

2.2. Apparatus

We used a deformable mirror (Mirao, Imagine Eyes, France) together in closed-loop with a wavefront sensor (HASO CSO, Imagine Eyes) to dynamically correct the subject's wavefront aberration. The system optically conjugates the subject's exit pupil plane with the correcting device, the wavefront sensor and an artificial pupil. The Shack–Hartmann wavefront sensor has a square array of 1024 lenslets. The wave-aberration measurements are made at 850 nm.

The wavefront corrective device is a deformable mirror using 52 independent magnetic actuators. The control of the deformable mirror surface is accomplished by a commercially available program (HASO CSO™, Imagine Eyes) which reshapes the deformable mirror from its normally flat surface to a shape that corrects the aberrations up to the 6th order (25 Zernike coefficients) (Fernandez et al., 2006). The micro-display (eMagin, Rev2 SVGA+ White Oled Microdisplay) subtended a visual angle of 114 × 86 arcmin with a resolution of 800 × 600 pixels (pixel size = 0.143 arcmin). The display was linearized using a Topcon BM3 luminance meter. The pupil position and size was monitored using a CCD camera. The pupil center was aligned with the optical axis of the set-up. The subject's pupil was not artificially dilated since the experiments were performed in dim surrounding illumination providing a diameter higher than 6 mm.

The mirror will change its shape for any variation of the aberration pattern of the subject so the accommodative response to a stimulus will also be compensated by the mirror (Bénard, Lopez-Gil, & Legras, 2010).

2.3. Calculations of degraded images

We calculated the retinal image which was obtained by convolving the original image (0.4 logMAR high-contrast letters) with