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Adaptive optics for peripheral vision

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Understanding peripheral optical errors and their impact on vision is important for various applications, e.g. research on myopia development and optical correction of patients with central visual field loss. In this study, we investigated whether correction of higher order aberrations with adaptive optics (AO) improve resolution beyond what is achieved with best peripheral refractive correction. A laboratory AO system was constructed for correcting peripheral aberrations. The peripheral low contrast grating resolution acuity in the 20° nasal visual field of the right eye was evaluated for 12 subjects using three types of correction: refractive correction of sphere and cylinder, static closed loop AO correction and continuous closed loop AO correction. Running AO in continuous closed loop improved acuity compared to refractive correction for most subjects (maximum benefit 0.15 logMAR). The visual improvement from aberration correction was highly correlated with the subject's initial amount of higher order aberrations ($p = 0.001$, $R^2 = 0.72$). There was, however, no acuity improvement from static AO correction. In conclusion, correction of peripheral higher order aberrations can improve low contrast resolution, provided refractive errors are corrected and the system runs in continuous closed loop.

Keywords: peripheral vision; adaptive optics; off-axis wavefront aberration; low contrast resolution; visual acuity

1. Introduction

Assessment of the impact of ocular aberrations has been closely associated with the performance of vision in the fovea, the central retina corresponding to a visual field of about 5°. This paper will focus on the effect of aberrations 20° out in the less understood peripheral field. Understanding the impact of optical errors on peripheral vision is an interesting fundamental question [1,2]. Additionally, such understanding has practical implications for optical corrections for patients with central visual field loss (CFL) and for investigation into the causes of myopia development. Patients with CFL have lost their foveal vision and have to rely solely on their remaining peripheral vision, which means that any improvement by optical correction is highly important for them [3,4]. With regards to myopia development, there exist considerable data in the literature to suggest that peripheral optical errors can influence the process of emmetropization [5–9]. The mechanism of such an influence is not fully understood. Studies on the impact of optical errors on peripheral vision can help explore possible causes.

Peripheral vision is characterized by two limiting factors: coarse sampling and degraded optical quality. The coarse sampling is due to a lower density of cones and ganglion cells in the peripheral retina and is manifest for stimuli with higher spatial frequencies, since targets of high contrast can be detected but not resolved, i.e. aliasing occurs [10–19]. Degraded optical quality is caused by both lower and higher order aberrations. Lower order aberrations, defocus and astigmatism, are present even for persons with no or corrected foveal refractive errors [20]. Off-axis astigmatism is also always expected to be present to some degree [21,22], whereas spherical errors arise due to a mismatch between the optical image shell and the retina [23,24]. Frequently, foveally myopic subjects have less myopia in the periphery, whereas persons foveally emmetropic or hyperopic have a periphery that is more myopic than their central vision. Furthermore, the amount of higher order aberrations, primarily coma, is significantly larger in the periphery than in the fovea [20,25–28].

Previous studies have shown that high contrast resolution in the periphery is limited by sampling and thereby unaffected by defocus over a large dioptric range [10–19]. Conversely, peripheral high contrast detection acuity varies with the quality of the retinal image and can be notably degraded by as little as 0.5 D of defocus [19]. Accordingly, optical correction for patients with CFL would only matter for detection tasks and any role in regulation of the emmetropization process would have to rely on aliasing mechanisms. However, besides reading of high contrast letters,

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most of the visual stimuli in a normal environment consist of targets with lower contrast. We have previously shown that peripheral resolution of low (10%) contrast objects can be improved by correction of defocus errors, with an improvement of 0.15–0.20 logMAR/D [19]. In the current study, we want to explore the possible benefits of also correcting the peripheral higher order aberrations.

The correction of ocular aberrations by adaptive optics (AO) was first studied in 1997 [29]. In that study a deformable mirror was used in closed loop with a wavefront sensor to measure and correct the aberrations. Subsequently, foveal visual function with aberration correction was studied. Since then, a large number of studies have described the impact of higher order aberrations on foveal vision including normal acuity, contrast sensitivity, face recognition, and blur adaptation [29–40]. On the other hand, only one study, by Lundström et al., has used AO on peripheral vision and they found no improvements in the high contrast resolution acuity under full AO correction [41]. The current study will expand the scope to peripheral low contrast acuity, where visual benefits are more likely to be found, and investigate whether correction of the remaining higher order aberrations can further improve peripheral vision beyond best sphero-cylindrical refraction. Furthermore, the correction of ocular aberrations will be active throughout the experiment, allowing the residual aberrations to be kept to a minimum.

2. Methods

2.1. Setup

The laboratory AO system was constructed with the following aims in mind:

(1) The peripheral aberrations should be continuously corrected throughout the psychophysical session.
(2) It should be possible to compare results from best refractive correction of sphere and cylinder with full aberration correction.
(3) Large amounts of aberrations need to be corrected.
(4) Peripheral fixation needs to be kept stable.
(5) For reasons of comfort, a chin rest should be used instead of a bite bar.
(6) The continuous measurement light should not interfere with the visual task.

As the main components of the system we chose the mirao™ 52 D deformable mirror and the HASO™ wavefront sensor from Imagine Eyes™. These components have been extensively used for foveal AO correction [35,36,42–44]. In addition, the large stroke of the mirror allows for full correction of the peripheral aberrations. The schematic drawing in Figure 1 depicts the setup, while the components are listed in Table 1. The pupillary plane of the eye was made conjugate with the deformable mirror (denoted by DM in Figure 1) and the wavefront sensor (HASO) through afocal systems (L1 + L2), magnifying the pupil with a factor of 1.67 onto the deformable mirror to fully utilize its 15 mm diameter. The secondary afocal system (L3 + L5) has a magnification of 0.25 in order to ensure that the pupil will fit onto the 3.6 mm aperture of the wavefront sensor.

No artificial pupil was used to allow for natural pupil size in a dark room. The stimulus on a CRT screen (C) 2.6 m away was imaged through an afocal system (L4 + L3) which together with L2 + L1 had a total magnification of 1. Measurement light from a 830 nm laser diode (LD), in the form of a narrow collimated beam with less than 1 mm diameter and an intensity of 4.5 μW, was sent in from above through a pellicle beamsplitter. A beamsplitter (BS1) reflecting infrared but transmitting visible light allowed the separation of the measurement light without compromising the view of the stimulus.

Infrared illumination of the iris and a pupil camera (CCD) ensured that the pupil was at the front focal plane of the first lens of the first afocal system. An aperture (A) with a diameter of 5 mm, in the front focal plane of the last lens before the wavefront sensor, L5, protected against unwanted reflections. An interference filter for 830 nm before the wavefront sensor ensured that only the light from the laser diode was measured. A chin rest was used to stabilize the subject.

In this study, the peripheral vision 20° in the nasal visual field of the right eye was evaluated and the left eye was used for fixation to a Maltese cross (F) placed 2.6 m away and seen via the mirror (M). A diffuse black screen (D) eliminated any accommodative targets for the right eye. A trial lens holder (TL) in front of the right eye allowed correction of large amounts of both defocus and astigmatism simultaneously without using the deformable mirror. This configuration allowed realistic comparisons with the best sphero-cylindrical correction.

2.2. Validation

Before the initiation of the main study, preliminary validation was performed with three different procedures using three subjects. First, the correct level of defocus was determined. In foveal studies using AO, defocus is usually set by the individual subject using the method of adjustment. The method of adjustment

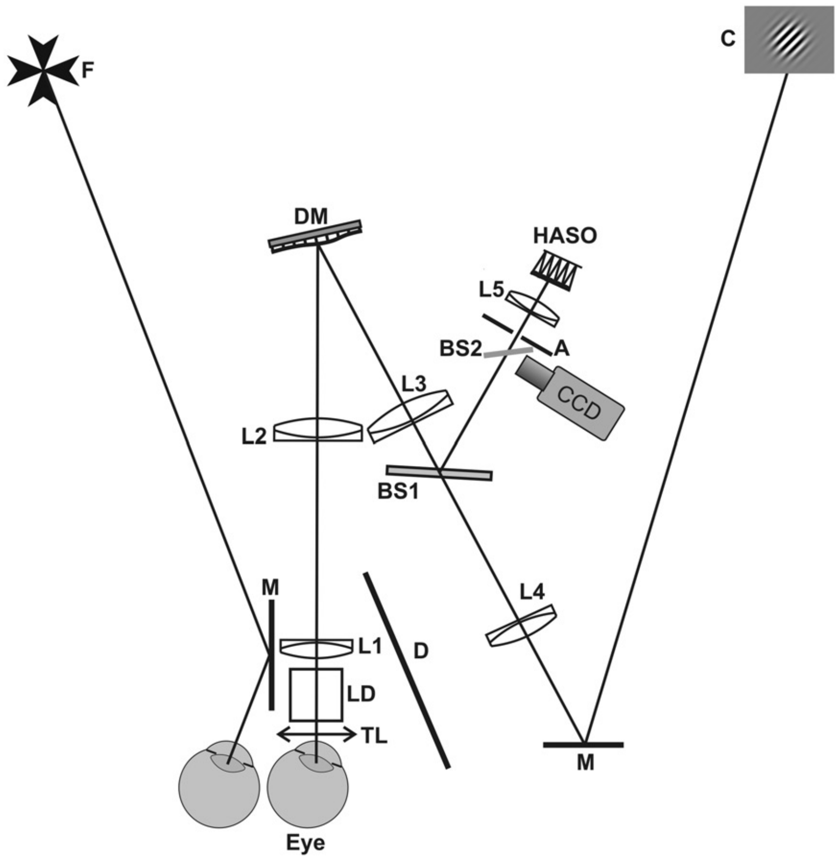

Figure 1. The adaptive optics setup seen from above. All components are listed in Table 1.

is less accurate for peripheral vision, however [45]. Instead, we used foveal through-focus resolution measurements in low contrast on the three subjects to find the optimal defocus level, as measured by the wavefront sensor. The methodology applied was identical to the one in a previous through-focus study [19]. This optimal defocus value corresponded to what was predicted by standard theory of longitudinal chromatic aberrations and the 2.6 m distance of the stimulus [46]. The optimal defocus was used as the target value for defocus for both sphero-cylindrical correction and full AO correction.

The second validation step consisted in measuring foveal low contrast acuity looking through the system with the mirror in the setting of active flat as well as when looking directly at the stimulus. No differences were found between the two sets of acuity measurements, which confirm that the optical system itself did not degrade vision.

Finally, the effect of the measurement light during peripheral visual evaluation was investigated by letting the three subjects perform low contrast resolution tests with and without the laser diode turned on. In foveal AO, the psychophysical disturbance of the measurement light is one of the reasons not to apply a closed

Table 1. Description of the components of the adaptive optics system.

LD	Laser diode, 4.5 μW at 830 nm, and a pellicle beamsplitter
TL	Trial lenses placed 20 mm from the eye
L1	Achromat f′ = 120 mm
L2	Achromat f′ = 200 mm, forms an afocal system with L1
L3	Achromat f′ = 200 mm, forms an afocal system with L2
L4	Achromat f′ = 120 mm, forms an afocal system with L3
L5	Achromat f′ = 50 mm, forms an afocal system with L3
DM	Mirao 52 D deformable mirror
HASO	HASO 32 wavefront sensor
CCD	Pupil camera
BS1	Hot mirror, reflects infrared and transmits visible light
BS2	Pellicle beamsplitter
A	5 mm aperture
M	Mirrors
C	Visual stimululs computer screen, 2.6 m from the mirror
F	Fixation target, 2.6 m from the back focal point of L1
D	Diffuse black screen

loop AO correction continuously throughout the visual evaluation. However, the measurement light was not visible for any of the subjects in their periphery, and peripheral acuity 20° in the nasal visual field of the right eye showed no difference between turning the diode on and off. The ability of the system to run continuously in closed loop for up to 10 min under normal conditions, including blinking, was confirmed.

2.3. *Acuity measurements*

A total of 12 subjects with mean age 33 ± 11 years (range 23–58 years) were measured, out of which five were females and seven were males. Only two of the subjects had previous experience with psychophysical measurements (subject 1 and 2 in the results table). There were seven emmetropes, six myopes and one hyperope. The left eye used for fixation was uncorrected for all subjects. The peripheral refractive errors of the subject's right eye were corrected for the distance to the stimulus screen by the use of trial lenses in the trial lens holder. The residual refractive errors were less than 0.12 D. The correction was kept in place throughout all measurements. The wavefront was measured in the entrance pupil of the combined trial lens–eye system and the pupil size and Zernike coefficients were evaluated in this plane. When measuring peripheral aberrations, the pupil will have an elliptical shape. The Zernike coefficients evaluated were those of an inscribed circular pupil, as described by Lundström and Unsbo [47].

Peripheral vision in the 20° nasal visual field of the right eye was evaluated using low (10%) contrast Gabor patches, i.e. sine-wave gratings multiplied by a Gaussian window with a standard deviation of 0.6°. As a two alternative forced choice psychophysical task, the subjects were asked to record the orientation of the grating, which was either 45° or 135°, via a keypad. The orientation of 45° or 135° was used in order to avoid the neural preference possible for targets oriented 90° and 180° and differential magnification of the stimuli. The acuity could be determined in 30 trials. The psychophysical algorithm and its application to peripheral vision testing has been described in detail and is identical to that described in Rosén et al. [19]. The spatial frequencies and the size of the Gabor patch were recalculated to take spectacle magnification of the trial lenses into account.

Three different types of correction were compared: *refractive correction*, with the deformable mirror set to active flat; *static closed loop*, with AO being run in closed loop until aberration correction had been achieved, after which the state of the mirror was frozen; and *continuous closed loop*, with the AO being run in closed loop during the full psychophysics procedure. Each type of correction was applied three times in random order for a total of nine acuity measurements. The subjects were allowed to rest between measurements, and the whole procedure took less than 45 min. Pupil size and wavefront data were logged during all the trials. The study had been approved by the regional ethics committee, written informed consent was obtained beforehand and the study followed the tenets of the declaration of Helsinki.

3. Results

Since natural pupils were used, the pupil diameter varied between subjects with a mean value of 4.9 ± 1.1 mm. The pupil size did not change between the three different types of correction (note that the trial lenses were in place during all measurements). Aberration data was quantified as the higher order root mean square (HORMS) wavefront error of aberrations calculated from the 3rd–6th order Zernike coefficients for the natural pupil size, which excludes defocus and astigmatism. Full closed loop correction was achieved within a few seconds for all subjects, as can be seen in Figure 2, where HORMS for one subject is plotted against time for the three correction types.

During static closed loop correction it is possible that the residual amount of HORMS can be significantly higher at the end of the trial compared to at the start, as can be seen in Figure 2. HORMS was therefore evaluated in terms of the mean amount during the whole psychophysical trial. Figure 3 plots the amount of HORMS with static and continuous

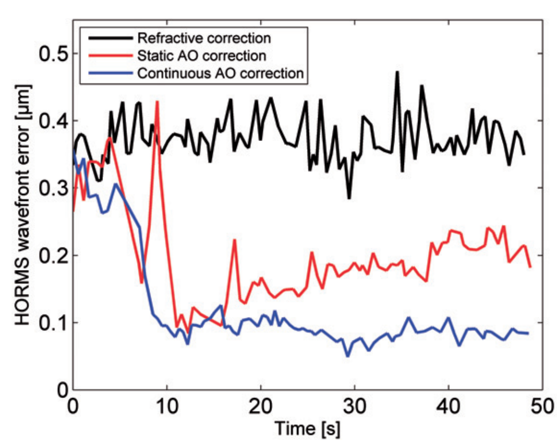

Figure 2. An example of residual root mean square higher order aberrations (HORMS) for one subject as a function of time over the course of three acuity measurements. (The color version of this figure is included in the online version of the journal.)

closed loop correction against the uncorrected HORMS with refractive correction. The amount of uncorrected HORMS varied between 0.15 µm and 1.8 µm, with an average value of 0.54 ± 0.48 µm. During static closed loop correction, the mean amount of HORMS was 0.22 ± 0.11 µm whereas it was reduced to 0.14 ± 0.04 µm during continuous closed loop correction. As can be seen in Figure 3, there is one outlier; all corrected HORMS values are below 0.3 µm for all subjects except for the person with an initial HORMS of 1.8 µm. For this subject the static closed loop correction failed to reduce the average HORMS to a value under 0.3 µm, while this level of correction proved possible with the continuous closed loop.

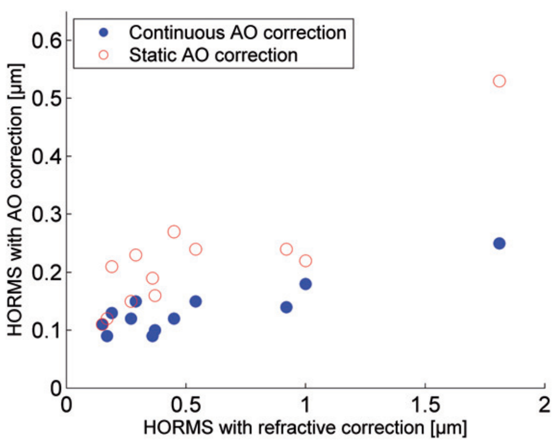

Figure 3. Residual root mean square amount of higher order aberrations (HORMS) for all subjects plotted against amount of HORMS with refractive correction. (The color version of this figure is included in the online version of the journal.)

Table 2 shows the measured low contrast visual acuities in logMAR for all 12 subjects with the three different types of correction used. Mean improvement of low contrast resolution acuity by continuous closed loop peripheral aberration correction, compared to refractive correction, was 0.04 ± 0.06 logMAR, with a maximum observed improvement of 0.15 logMAR. A static closed loop correction did not improve the average acuity (mean benefit of 0.00 ± 0.04 logMAR). A mixed effect ANOVA on acuity and correction rejects the null hypothesis of no effect from correction type ($p = 0.046$). However, as can be seen in Figure 4, the benefit depends on individual amount of aberrations, with high correlation ($R^2 = 0.72$, $p = 0.001$) between improvement of continuous closed loop correction and initial amount of HORMS. For static closed loop correction, there is no significant correlation, due to no benefit achieved for the subject with 1.8 µm of HORMS.

4. Discussion

Adaptive optics is an important tool for research on vision. We have expanded the use of that tool to include continuous closed loop correction of peripheral aberrations and shown improvements in peripheral vision as a result of that correction.

Table 2. The result of the low contrast (10%) grating resolution tests in 20° eccentricity. Each row represents one subject. The refractive correction is given in the column 'Trial lens' as sphere and cylinder in diopters and the axis in degrees. Higher order aberrations (HORMS) with refractive correction are given in µm over the natural pupil (4.9 ± 1.1 mm). The visual acuities measured under the three types of correction are given in logMAR in the following nine columns (each correction type was evaluated three times). The last column shows the average improvement in peripheral low contrast acuity (given in logMAR) when the measurements with refractive correction are compared to those with continuous closed loop correction with adaptive optics (AO).

Subj.	Trial lens	HORMS (µm)	Continuous AO correction (logMAR)			Static AO correction (logMAR)			Refractive correction (logMAR)			Improv.
1	−2.25/−2.50 × 90	0.92	0.85	0.80	0.89	0.91	0.93	0.87	0.95	0.95	0.93	0.10
2	−1.00/−1.25 × 90	0.15	1.06	1.08	1.08	1.08	1.05	1.05	1.01	1.04	1.02	−0.05
3	−0.75/−4.00 × 95	0.45	0.84	0.84	0.88	0.95	0.92	0.92	0.84	0.91	0.93	0.04
4	−1.25/−3.75 × 90	0.29	1.05	1.09	1.06	1.13	1.15	1.09	1.06	1.09	1.10	0.02
5	−0.75/−1.00 × 100	1.81	0.86	0.89	0.86	0.90	1.07	1.06	0.95	0.91	1.10	0.12
6	−6.00/−8.00 × 90	0.19	1.16	1.15	1.20	1.23	1.15	1.22	1.19	1.22	1.22	0.04
7	0.00/−1.75 × 90	0.37	0.88	0.88	0.89	0.86	0.88	0.86	0.89	0.90	0.89	0.01
8	−4.00/−2.00 × 90	0.17	0.94	1.00	0.95	1.00	0.97	1.00	0.95	0.96	0.93	−0.02
9	−0.75/−3.00 × 95	0.54	1.07	1.06	1.04	1.06	1.04	1.02	1.09	1.06	1.04	0.01
10	0.00/−2.00 × 90	0.27	0.88	0.94	0.92	0.90	0.94	0.89	0.88	0.90	0.91	−0.02
11	1.00/−1.25 × 85	0.36	0.81	0.87	0.85	0.84	0.90	0.84	0.93	0.90	0.91	0.07
12	2.00/−4.00 × 90	1.00	0.90	0.89	0.86	0.98	0.98	0.86	1.04	1.05	1.00	0.15

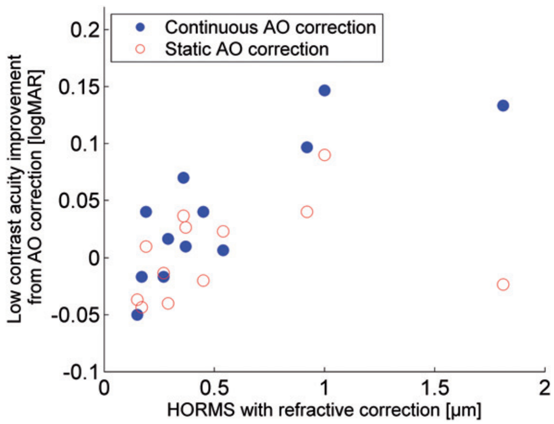

Figure 4. Improvement in peripheral low contrast resolution acuity (compared to refractive correction) for continuous and static closed loop correction plotted, against the root mean square amount of higher order aberrations (HORMS) with refractive correction. (The color version of this figure is included in the online version of the journal.)

It was possible to run the system in continuous closed loop during the visual evaluation since the low intensity measurement light did not interfere with the psychophysical tasks administered. Correction in continuous closed loop also proved to be necessary to reach residual aberrations comparable to what has been reported for foveal systems [40]. The need to use a continuous closed loop could be due to the high amount of irregular aberrations in the periphery, which means that a static aberration correction may turn out to be inadequately centered even due to small eye movements. Guirao et al. have shown that higher order corrections of foveal image quality are more sensitive to translation than refractive correction. The larger aberrations in the periphery will further exacerbate this problem [48]. No benefit from aberration correction in the periphery was reported in the previous study by Lundström et al., but then static closed loop correction was used. Furthermore, high contrast resolution acuity was tested, which is known to benefit less from optical improvements [41]. To be able to compare the intra-subject visual acuity for different correction types in the current study, the trial lenses were kept in place during all measurements. Nevertheless, the spectacle magnification caused by the trial lens correction will add uncertainty to the absolute levels of measured aberrations and visual acuity when comparing between subjects and with other studies.

The visual improvement of up to 0.15 logMAR from aberration correction for some subjects corresponds to that of correcting a spherical error of up to 1 D [19]. Correcting aberrations may therefore improve the remaining vision for people with CFL beyond what has been achieved with optimum refractive correction [3,4]. Additionally, if the emmetropization process is affected by the blur of the peripheral image, higher order aberrations that can reduce peripheral vision may also play a role in the development of myopia. Further studies of the impact of aberrations on peripheral vision can also elucidate their importance for visual tasks beyond acuity measurements, e.g. face recognition for CFL subjects.

5. Conclusion

The implemented adaptive optics system was able to reduce the peripheral higher order aberrations to levels comparable to those of foveal adaptive optics correction, when running in continuous closed loop. The aberration correction improved peripheral low contrast resolution beyond what was achieved with refractive correction. The improvement in acuity was highly correlated with the amount of higher order aberrations present.

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