Effect of optical correction and remaining aberrations on peripheral resolution acuity in the human eye

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Abstract: Retinal sampling poses a fundamental limit to resolution acuity in the periphery. However, reduced image quality from optical aberrations may also influence peripheral resolution. In this study, we investigate the impact of different degrees of optical correction on acuity in the periphery. We used an adaptive optics system to measure and modify the off-axis aberrations of the right eye of six normal subjects at 20° eccentricity. The system consists of a Hartmann-Shack sensor, a deformable mirror, and a channel for visual testing. Four different optical corrections were tested, ranging from foveal sphero-cylindrical correction to full correction of eccentric low- and high-order monochromatic aberrations. High-contrast visual acuity was measured in green light using a forced choice procedure with Landolt C's, viewed via the deformable mirror through a 4.8-mm artificial pupil. The Zernike terms mainly induced by eccentricity were defocus and with- and against-the-rule astigmatism and each correction condition was successfully implemented. On average, resolution decimal visual acuity improved from 0.057 to 0.061 as the total root-mean-square wavefront error changed from 1.01 µm to 0.05 µm. However, this small tendency of improvement in visual acuity with correction was not significant. The results suggest that for our experimental conditions and subjects, the resolution acuity in the periphery cannot be improved with optical correction.

OCIS codes: (010.1080) Adaptive optics; (330.7310) Vision; (330.6130) Spatial resolution; (330.1070) Acuity; (330.5510) Psychophysics

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1. Introduction

In the peripheral field of view the ability of the human eye to discriminate small objects decreases rapidly with the angle of eccentricity. This reduction can be due to both optical and neural limitations: the eccentric angle induces optical aberrations, which lower the contrast of the image on the retina; and the density of cones and ganglion cells decline with eccentricity, resulting in sparse sampling of the image. Foveal vision is generally limited by the on-axis optical properties of the eye and the foveal sampling density poses no restrictions under normal viewing conditions. In peripheral vision, however, the limited neural function can lead to situations where, e.g., a grating is detected even though its orientation cannot be identified, i.e. the threshold of resolution acuity is worse than the threshold of detection acuity. This is a result of the aliasing phenomena, which means that a coarse neural sampling density mis-interprets spatial frequencies above the Nyquist criterion as lower, distorted frequencies [1-3].

Optical errors will reduce the contrast of the high-spatial frequencies present in the image on the retina. The aliasing effect will thereby decline and the peripheral resolution acuity may eventually become limited by the contrast of the retinal image. It is well known that large oblique angles in an optical system induce aberrations, mainly field curvature and oblique astigmatism, which result in an effective eccentric refractive error [4,5]. Peripheral aberrations can, e.g., affect the emmetropization process [6], the results of perimetry, and the remaining vision for people with central visual field loss [7]. A number of studies have therefore investigated the influence of optical correction on peripheral vision. These studies found no

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difference in peripheral resolution acuity when the eye was uncorrected compared to when refractive correction was used [8-11]. However, it should be noted that the difference between foveal and eccentric refractive correction varies for individual subjects and that retinoscopy, which was used to determine the refractive error, has been found to be difficult to use off-axis [12,13]. A few studies have investigated how peripheral resolution acuity change with optical defocus [11,14,15]. Wang et al. [11] measured detection and resolution acuity with sinusoidal gratings and letter discrimination acuity with tumbling-E's in 20º eccentricity on three subjects. They found that grating detection varied with spherical defocus whereas resolution of both gratings and tumbling-E's was robust to defocus and generally unaffected by spherical defocus of ±3 diopters (D). Similar experiments were performed by Anderson [14]; grating resolution was robust to about 2 D of defocus in 30º eccentricity on one subject. These results are not in agreement with some of the measurements by Rovamo et al. [15], who found that grating resolution varied with the power of a cylinder lens on one subject in 25º eccentricity. This discrepancy might be explained by the fact that there are large individual variations in the amount of peripheral optical errors. For example, in 30º eccentricity the astigmatism in a foveally emmetropic population is between 2.5 and 5 D [16].

Large high-order aberrations could possibly mask the effect of moderate changes of defocus on resolution acuity. However, the amount of optical errors needed to change peripheral resolution from sampling limited to aberration limited is not known. To our knowledge, no previous study has examined peripheral resolution acuity in relation to the amount of remaining optical refractive errors and high-order aberrations. The purpose of this study is to investigate the correlation between peripheral resolution acuity and total remaining optical aberrations of the eye in an eccentric angle with different optical corrections.

2. Methods

The off-axis monochromatic wavefront aberrations of six subjects were measured and corrected to different degrees with the adaptive optics visual simulator of the Laboratory of Optics at the University of Murcia. The system is an upgraded version of previous apparatuses [17,18], modified to allow eccentric fixation. The measurements were performed monocularly on the right eye, with the left eye covered. No cycloplegia was used and therefore the background illumination in the room was low to achieve naturally large pupils. All subjects had normal vision with a monocular best corrected decimal acuity of 1.0 or better. The foveal refractive errors ranged from 0 D to -3.75 D in spherical equivalent and up to 0.5 D in cylinder. The age was between 27 and 34 years. The study followed the Declaration of Helsinki and the subjects gave informed consent prior to participation.

The principle and basic components of the optical setup are shown in Fig. 1. The foveal fixation target was a cross illuminated by a green diode. It was placed horizontally 20º to the right of the measurement axis with the help of a mirror. A lens in front of the fixation target was adjusted to place the cross in the far-point of the eye as a target to keep steady foveal accommodation. The off-axis wavefront was measured with infrared light (780 nm) using a Hartmann-Shack sensor [19] and reconstructed with Zernike polynomials up to the seventh radial order. A Xinetics deformable mirror with 97 piezoelectric actuators was used in closed-loop with the wavefront sensor to achieve different optical corrections. The resolution acuity was evaluated with specially developed software, based on the standard Cambridge Research System libraries, and used rotating Landolt C's in green light. These stimuli were presented on a calibrated monitor that was placed at a distance of approximately 3 m from the setup. The subject viewed the monitor via the deformable mirror, with the head stabilized by a bite bar.

In oblique angles the pupil will appear elliptical in shape, which implies that the Zernike coefficients, defined over a circular pupil, do not directly describe the true root-mean-square (RMS) wavefront error [20]. To avoid this difficulty, the wavefront measurements and the optical corrections were performed over an artificial circular pupil of 5 mm in diameter centered on the real elliptical pupil. Accordingly, the visual evaluation was also performed with an artificial pupil; the monitor was viewed through an aperture that corresponded to a

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circle of 4.8 mm in diameter in the pupil plane. The following two sections describe the procedure of the optical correction and the visual evaluation.

2.1 Optical measurements and corrections

For each subject the optical errors at 20º to the left in the horizontal visual field were corrected to different degrees. The experimental session started with the determination of the foveal sphero-cylindrical correction by a hybrid subjective-objective method. The foveal defocus was subjectively corrected: the subject viewed a letter on the monitor along the measurement axis via the flat deformable mirror, which means that no modifications to the wavefront were introduced, and was given control of the motorized Badal defocus system to search for his/her subjective best focus in 0.05 D steps. The final setting was used all throughout the experiment. Subsequently, the on-axis aberrations of the subject were measured with the Hartmann-Shack sensor. The second order Zernike coefficients were retained; $C(2,-2)_{foveal}$, and $C(2,2)_{foveal}$ correspond to the foveal cylinder, while $C(2,0)_{foveal}$ is the residual foveal defocus that can be attributed to the difference between objective and subjective refraction as well as to the chromatic difference between the target on the monitor and the IR laser diode used for the wavefront measurements [21,22]. The value of $C(2,0)_{foveal}$ was used as the reference for defocus, i.e., it was subtracted from the eccentric defocus measurements to obtain the sphere effectively introduced by the eccentricity. The subject then turned his/her eye towards the oblique fixation target and the eccentric wavefront aberrations at 20º eccentricity were measured with no changes of the optical setup. Once again, the second order Zernike coefficients were collected to quantify the eccentric sphero-cylindrical correction.

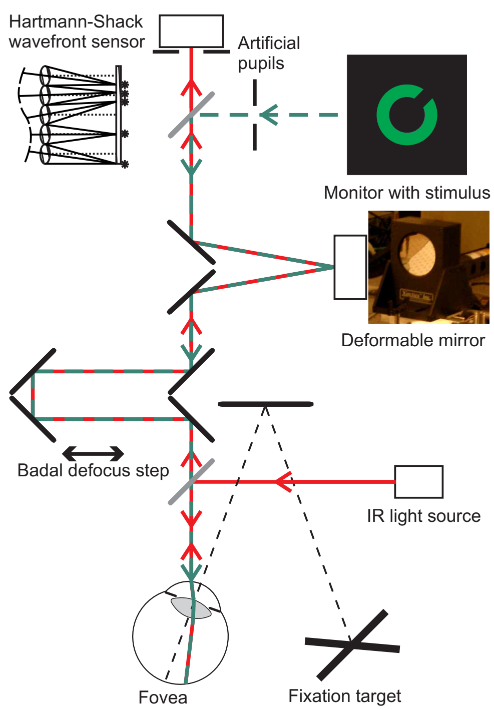

Fig. 1. Main components of the optical setup. The entrance pupil of the eye is conjugated to the deformable mirror and the wavefront sensor via telescopes. For the sake of clarity, lenses and some mirrors have been excluded and the setup is not drawn to scale.

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After these preliminary procedures, the adaptive optics system was switched on to achieve the desired correction conditions with the eye still fixating at 20º eccentricity:

A) Foveal sphero-cylindrical correction: Since the Badal system setting corrects for the foveal sphere, the adaptive optics system was used to correct only for the foveal cylinder. The rest of the Zernike coefficients were set to remain constant.

B) Eccentric defocus correction: The adaptive optics system was set to correct for foveal astigmatism, as in the previous case, but now the defocus coefficient was also modified in order to compensate the eccentric defocus. The other coefficients were set to remain constant.

C) Eccentric sphero-cylindrical correction: The adaptive optics system was set to correct the eccentric defocus and astigmatism without modifying the other Zernike coefficients.

D) Full eccentric aberration correction: All the Zernike coefficients were considered for correction by the adaptive optics system.

The settings of the deformable mirror were then saved and the visual function was evaluated with the mirror set to static correction for the cases A to D. For each subject the order of the corrections was random and the subject was not informed.

2.2 Visual function evaluation procedure

The peripheral resolution threshold for high-contrast Landolt C's was measured for each correction condition. The stimuli were green (λ_{peak} = 532 nm with a half-width of 70 nm, luminance 84 cd/m^2) Landolt C's displayed by the monitor on a black background. The gap of the C's occurred in four oblique angles (45º, 135º, 225º, and 315º) to have equal visibility of the stimuli in spite of the horizontal-vertical astigmatism induced by the horizontal angle. The contrast was higher than 99 %.

The psychophysical evaluation started by letting the subject adjust the size of a Landolt C until the direction of the gap was barely visible. This adjustment method served as an opportunity for the subject to get used to the test and the achieved threshold was used as a starting value. Because many subjects found the adjustment to be very difficult, one short training-test was made and, if necessary, the starting value was modified. Landolt C's with random orientation were then presented in a four alternative forced-choice paradigm according to the method of constant stimuli. Five object sizes were tested in steps of approximately 0.75 LogMAR around the starting value and each object size was tested 12 times, totaling 60 presentations. The duration of each stimulus presentation was 300 ms and the subject used a computer keyboard to indicate the perceived orientation and to trigger the next presentation. The frequency-of-seeing values for each object size were then used to make a least-square-fit of the constants t_0 and Δt of a Boltzmann sigmoidal function:

$$\text{freq. of seeing} = \frac{100\% - 25\%}{1 + e^{(t-t_0)/\Delta t}} + 25\% \cdot$$

Here t denotes the object size (i.e. gap-width) in arc minutes and the guessing rate is 25 %. From this curve the threshold value was defined as the 62.5 % frequency of seeing level. One evaluation session took around three minutes and was repeated three times for each correction condition. The subject was allowed to rest from the bite bar between the sessions. The combined time-span for each correction condition, including the adaptive optics loop and the series of three psychophysical sessions, was 45 minutes approximately. The whole experimental session lasted around four hours per subject.

3. Results

The adaptive optics system was successful in implementing the four different correction levels for peripheral vision. Fig. 2 shows the remaining second order Zernike coefficients and the RMS wavefront error of high-order aberrations for the six subjects for a 4.8 mm pupil, together with the mean values. The coefficients have been recalculated from 780 nm in wavelength to 532 nm according to equation 1 in the paper by Salmon et al. [23] and the residual foveal defocus obtained after the subjective best focus search has been subtracted from the C(2,0) term. A number of characteristics are to be noted: 1) With foveal sphero-cylindrical correction the oblique angle of fixation introduced a slight hyperopic shift of

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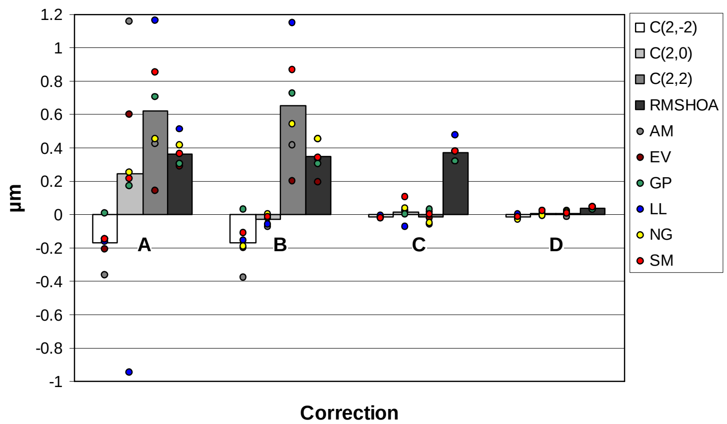

Fig. 2. Remaining peripheral aberrations for each correction level: A - Foveal sphero-cylindrical correction, B - Eccentric defocus correction, C - Eccentric sphero-cylindrical correction, D - Full eccentric aberration correction. The columns show the average defocus, C(2,0), oblique astigmatism, C(2,-2), horizontal/vertical astigmatism, C(2,2), and the root-mean-square error of high-order wavefront aberrations, RMSHOA. The colored dots are the values for each individual subject. All values are given in µm over a circular pupil of 4.8 mm in diameter (λ = 532 nm).

defocus, C(2,0), a negative cross-cylinder in 180º (positive C(2,2), i.e. against the rule astigmatism), and a positive cross-cylinder in 45º (negative C(2,-2)) compared to the foveal optics. 2) Correction of eccentric defocus clearly reduces C(2,0) whereas the astigmatic terms and high-order aberrations are unchanged. 3) Eccentric sphero-cylindrical correction reduced the mean value of all second order Zernike terms to less than 0.02 µm, with the high-order RMS remaining stable at an average of 0.36 µm. 4) Finally, the full eccentric aberration correction reduced also the high-order RMS down to less than 0.04 µm. The total RMS wavefront error, including defocus and astigmatism, was on average 1.01 µm, 0.78 µm, 0.38 µm, and 0.05 µm for the four degrees of correction, respectively. As an illustration of the effect of the adaptive optics correction, Fig. 3 shows the measured eccentric wavefront maps and the corresponding calculated point-spread functions (PSF) for one subject.

The peripheral resolution acuity showed no statistically significant improvement with the different optical corrections. However, a small tendency to better resolution acuity with optical correction can be seen in the four cases: foveal sphero-cylindrical correction gave a decimal visual acuity of 0.057 averaged over the six subjects; eccentric defocus correction gave 0.058; eccentric sphero-cylindrical correction 0.059; and full eccentric correction 0.061. The results of the individual subjects are plotted for the four correction levels in Fig. 4. Although there is a slight tendency to better acuity with subsequent correction levels, no subject showed acuity improvements larger than 0.01 between foveal and full eccentric aberration correction and subject AM showed a decrease in acuity for full correction.

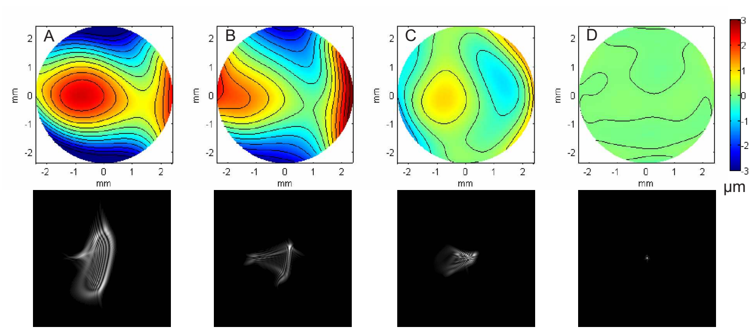

Fig. 3. Wavefront map and associated PSF for subject LL for each correction level (A-D, same as in Fig. 2). The brightness of the PSFs has been increased.

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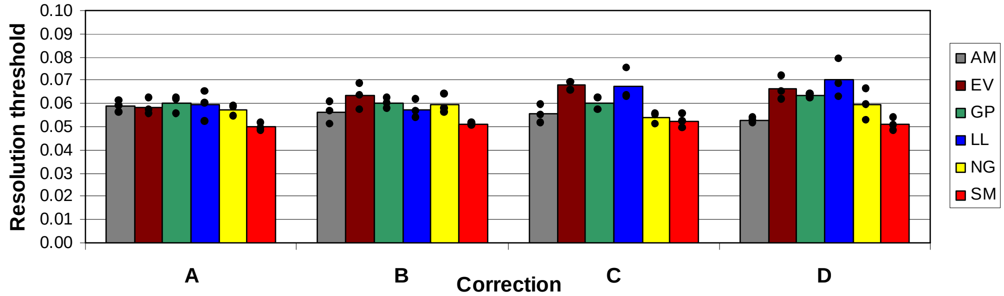

Fig. 4. Peripheral resolution threshold values in decimal visual acuity for the six subjects (SM, NG, GP, LL, EV, and AM) with the same optical corrections (A-D) as in Fig. 2. The bars are the average of three visual evaluation measurements, which are also shown individually by the black dots.

No correlation between peripheral resolution acuity and the remaining total wavefront RMS error was found (see Fig. 5). The PSF and the modulation transfer function (MTF) were calculated from the wavefront measurement, but also here no significant correlation was found neither between resolution and the Strehl ratio (normalized peak value of the PSF), nor between resolution and the volume under the two-dimensional MTF curve, which was tested with four different cut-off frequencies: 60, 30, 10, or 3 cycles/degree, respectively.

4. Discussion

The adaptive optics system worked satisfactorily and the remaining aberration data shown in Fig. 2 is in agreement with earlier studies [6,24] (note that our study included more myopes, who generally show a hyperopic defocus shift in the periphery, than emmetropes, who often have a myopic shift). However, it has to be pointed out that the eye is a living system and the ocular aberrations during the visual testing might be somewhat larger than those presented in Fig. 2, which correspond to the endpoint of the adaptive optics loop. Three factors can be mentioned. First, the correction of defocus relied on the adjustment of the Badal defocus step; a small error, e.g. if the subject accommodated while performing the adjustment, would add to the wavefront error in all four correction cases. Second, many subjects reported difficulties with keeping a stable fixation of the foveal target at the same time as they concentrated on the peripheral stimulus, which might have induced involuntary eye movements and small accommodation changes. The third potential factor is the temporal variability of the ocular aberrations [25], both from fluctuations of the ocular media and from head and body movements resulting in a decentration of the natural pupil relative to the measurement axis. The data presented in Fig. 2 correspond to the wavefront aberrations at the end of the closed loop session, i.e. during optimal correction. To get an estimate of the potential variations in the aberrations during the visual testing, the wavefront was measured at the end of each visual evaluation session. The full eccentric aberration correction was obviously the most clearly affected by this effect: on average the total RMS changed from 0.05 µm directly after the closed loop to 0.25 µm after the psychophysical session (0.16 µm excluding defocus).

The measured resolution thresholds in this study were lower than what can be predicted from anatomical data with the Nyquist criterion; the ganglion cell density in 20º off-axis can allow decimal visual acuities of up to approximately 0.18 [3,26]. The thresholds are also lower than reported earlier by Wang et al. [11], who found resolution acuities of approximately LogMAR 1.0 (decimal visual acuity 0.1) in the same eccentricity. This is mainly because we used inverted stimuli, i.e. green C's on a black background. The black background was chosen to achieve natural pupils larger than the artificial pupil in the setup. To verify that our subjects had resolution thresholds comparable to the previous study, additional non-inverted measurements with black C's on a green background were made on two of the subjects, who had large pupils also for this setup. Under these conditions subject

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NG had a resolution threshold of 0.13 for foveal sphero-cylindrical correction and the same value for full eccentric correction, consistent with his results for inverted C's. Subject LL also showed the same trend as with inverted stimuli: the resolution for non-inverted C's increased to 0.11 and 0.16 for foveal sphero-cylindrical and full eccentric aberration correction, respectively. Additionally, our study used artificially circular pupils, which differs from earlier studies and from how peripheral vision is used in everyday life.

We could not find significant differences between the four degrees of correction nor any significant correlation between the remaining optical errors and the peripheral resolution threshold. That is, for these six subjects the total eccentric RMS wavefront error could on average be as high as 1.0 µm for a 4.8 mm pupil without any significant reduction in resolution acuity for high-contrast, inverted Landolt C's, which suggests a neural limitation. However, a slight trend of improvement can be seen and subject LL, who experienced the largest resolution improvements, could subjectively tell the difference between a better (eccentric sphero-cylindrical and full eccentric aberration correction) and a worse correction (foveal sphero-cylindrical and eccentric defocus correction) even when she did not know which correction was used. Additionally, the test with non-inverted black Landolt C's on a green background suggests that larger improvements can be found with other kinds of stimuli, e.g., with lower contrast levels or polychromatic light. The results might also be different on other subject groups, for other visual tasks, or in other eccentric viewing angles.

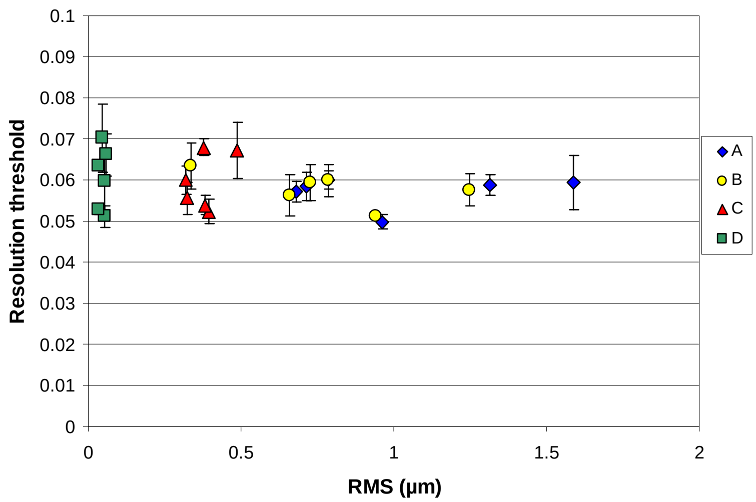

Fig. 5. Mean peripheral resolution threshold values plotted against the aberration root-mean-square (including defocus and astigmatism). The different markers denote the four optical corrections presented in Fig. 2 (A-D). The error bars are the standard deviation of the three visual testing runs.

5. Conclusion

To our knowledge this paper presents the first investigation on the peripheral resolution acuity in relation to the low- and high-order eccentric optical aberrations of the eye. On average the remaining RMS error was changed from 1.01 µm to 0.05 µm and a small, but not significant, improvement in resolution threshold was found. These results suggest that correction of the peripheral optics of the eye has a limited impact on the eccentric resolution acuity in young and healthy subjects for the experimental conditions of this study. However, the results do not rule out the possibility of improvements for other visual tasks, contrasts, stimuli, or subjects.

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