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ORIGINAL ARTICLE

Objectively Determined Refraction Improves Peripheral Vision

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ABSTRACT

Purpose. The purpose of this study was twofold: to verify a fast, clinically applicable method for determining off-axis refraction and to assess the impact of objectively obtained off-axis refractive correction on peripheral low-contrast visual acuity.

Methods. We measured peripheral low-contrast resolution acuity with Gabor patches both with and without off-axis correction at 20 degrees in the nasal visual field of 10 emmetropic subjects; the correction was obtained using a commercial open-field Hartmann-Shack wavefront sensor, the COAS-HD VR aberrometer. Off-axis refractive errors were calculated for a 5-mm circular pupil inscribed within the elliptical wavefront by COAS using the instruments' inbuilt ''Seidel sphere'' method.

Results. Most of the subjects had simple myopic astigmatism, at 20 degrees in the nasal visual field ranging from −1.00 to −2.00 DC, with axis orientations generally near 90 degrees. The mean uncorrected and corrected low-contrast resolution acuities for all subjects were 0.92 and 0.86 logMAR, respectively (an improvement of 0.06 logMAR). For subjects with a scalar power refractive error of 1.00 diopters or more, the average improvement was 0.1 logMAR. The observed changes in low-contrast resolution acuity were strongly correlated with off-axis astigmatism (Pearson $r = 0.95$; $p < 0.0001$), the J_{180} cross-cylinder component (Pearson $r = 0.82$; $p = 0.0034$), and power scalar (Pearson $r = -0.75$; $p = 0.0126$).

Conclusions. The results suggest that there are definite benefits in correcting even moderate amounts of off-axis refractive errors; in this study, as little as −1.50 DC of off-axis astigmatism gave improvements of up to a line in visual acuity. It may be even more pertinent for people who rely on optimal peripheral visual function, specifically those with central visual field loss; the use of open-field aberrometers could be clinically useful in rapidly determining off-axis refractive errors specifically for this patient group who are generally more challenging to refract.
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Key Words: visual acuity, low-contrast resolution acuity, off-axis refractive errors, peripheral vision, off-axis astigmatism, macular degeneration, AMD

The visual environment is enormously complex, consisting of stationary and dynamic stimuli in a multitude of sizes, hues, and contrast levels. As such, the human eye has evolved to make use of many of these attributes. The fovea is specialized in the resolution and identification of fine details in stationary objects, whereas the role of the peripheral retina in comparison is to detect changes occurring within the field of view. However, for approximately 2 million citizens in the United States,[1] and 33 million individuals worldwide with central visual field loss (CFL) subsequent to age-related macular degeneration,[2] the peripheral retina must also be used for resolution tasks. Peripheral resolution is a functional requirement for CFL patients who must rely on eccentric viewing angles (peripheral vision) for all visual tasks.[3]

Limitations to Visual Performance in the Peripheral Visual Field

It is widely accepted that the limiting factor for visual resolution in the fovea is the optical quality of the eye[4–10]; relatively small errors in the refractive state of the eye result in reduced visual performance. In the peripheral retina, it has been determined that visual performance, in particular high-contrast resolution acuity, is constrained by neural sampling; the spacing between ganglion cell receptive

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fields ultimately limits most visual tasks.[4,5,11–15] Because of these factors, peripheral high-contrast resolution acuity is relatively insensitive to optical defocus, requiring several diopters of defocus before resolution diminishes significantly.[16–20]

Traditional tests of visual function generally use high-contrast stimuli, although most visual tasks in a "real-world" setting involve the resolution of low-contrast objects.[21] Testing the visual performance solely using high-contrast tests may therefore give an inadequate representation of true visual performance, especially in the peripheral visual field. This has also been demonstrated by Rosén et al.[22] who showed that spherical defocus has a detrimental effect on peripheral low-contrast resolution acuity but not on high-contrast resolution. This insensitivity to defocus on high-contrast resolution acuity has been well documented.[12,16,18,20,22–24] On the other hand, a number of studies have shown that correction of off-axis refractive errors in patients with CFL can provide improved resolution acuity.[25,26] Such improvements are more readily seen in CFL subjects when using low-contrast stimuli as opposed to high-contrast stimuli.[26,27]

The image on the peripheral retina is often more affected by optical errors than the image in the fovea.[28,29] In particular, astigmatism is known to increase with increasing retinal eccentricity,[30,31] this increase being greater in the nasal visual field than in the temporal visual field.[31–33] The mean off-axis astigmatism at 20 degrees in the nasal visual field of 20 emmetropic subjects in the study by Gustafsson et al.[31] was -1.75 DC, which is predominantly "against the rule," as expected when measuring along the horizontal visual field. The spherical component was -0.325 diopters (D), showing that the mean spherical equivalent (M) was -1.20 D. Comparable values of sphere and cylinder at the same eccentricity, and likewise in emmetropic subjects, were also reported in a study by Atchison et al.[34]

Before the advent of Hartmann-Shack aberrometers and open-field autorefractors, the measurement of peripheral refractive errors and aberrations was difficult and time-consuming. Atchison[35] and Lundström et al.[26,36] showed that the method of choice for measuring off-axis refractive errors is wavefront aberrometry, using a Hartmann-Shack sensor. They found that off-axis retinoscopy was inherently difficult at larger off-axis angles, because of the presence of large aberrations. In this study, we use COAS-HD VR, an open-field Hartmann-Shack wavefront aberrometer from WaveFront Science (Albuquerque, NM). Cheng et al.[37] and Salmon and van de Pol[38] found the COAS aberrometer agreeing with subjective refraction for on-axis measurements to within approximately 0.25 D for lower refractive errors. Similarly, measurement of off-axis higher-order aberrations has also been found to be repeatable.[39] It is also advantageous that the COAS-HD VR permits unobstructed natural binocular-viewing conditions over a large area of the visual field, thus making it suitable for peripheral refractive error measurements.[39]

Aims of the Present Study

One commonality shared by many recent studies examining the effects of optics on peripheral visual function is that optical corrections were psychophysically determined by evaluating visual performance with varying amounts of optical defocus.[20,22,40] This is a tiring and time-consuming procedure that is difficult to achieve in a clinical setting; therefore, we chose a commercially available open-field aberrometer to rapidly determine peripheral refractive errors. With the objectively determined refractive error correction, we compared both corrected and unaided peripheral low-contrast resolution acuity in a group of emmetropes. The aims of this study were to verify this fast, clinically applicable method for improving peripheral visual function and to assess the impact of objectively obtained off-axis correction on peripheral low-contrast visual acuity. This could be beneficial when refracting and evaluating CFL patients who rely on areas in the peripheral field for all visual tasks, particularly for those with large eccentric viewing angles where refractive errors differ from those in the fovea.

METHODS

Subjects

Ten subjects (mean [±SD] age, 22 [±2] years; range, 19 to 24 years) participated in this study. All had right eyes that were emmetropic centrally, with unaided logMAR visual acuities of 0.0 or better, no known ocular disease, and no strabismus or significant distance phorias. Written informed consent was obtained from each subject after the nature and purpose of the experiment had been explained. The tenets of the Declaration of Helsinki were followed and the research was approved by the local ethics committee (Etikkommittén Sydost diary number: FEK-2007-16).

Measurement of Refractive Errors

Before acuity measurement, central and peripheral refractive errors were acquired on the right eyes of the subjects using an open-field COAS-HD VR aberrometer. Measurements were taken under dim room illumination, so as to allow the use of natural pupils. Subjects were instructed to fixate a central red light-emitting diode (LED) during measurement of on-axis refraction and to turn their eye to fixate a second LED situated 20 degrees to the right for off-axis measurements (thus measuring in the temporal retina, which corresponds to the nasal visual field). The mean of three measurements was rounded to the nearest 0.25 D and given as the off-axis correction. The distance from the subject to the LED was kept constant at 3.0 m. Off-axis refractive errors were calculated for a 5-mm circular pupil inscribed within the elliptical wavefront by COAS using the "Seidel sphere" method. The Seidel sphere method in COAS determines spherical error (M) by paraxial curvature matching the lower-order defocus term (C_2^0) and the higher-order spherical aberration term (C_4^0), whereas cylindrical error (J_{45} and J_{180}) is determined from the lower-order aberration terms (C_2^{-2} and C_2^2) as described by Thibos et al.[41] and Salmon et al.[42]

Subject Alignment during Acuity Measurements

Subjects were seated a distance of 3.0 m from the stimulus monitor and instructed to observe a fixation target (a cross subtending 0.5 degrees in the visual field), which was displayed on a small LCD display 20 degrees to the right. The position and correct alignment of the subject were ensured by using a chin and forehead rest.

Two septums made of thin sheets of anodized aluminum were positioned so as to obscure the stimulus screen from the left eye, while still enabling the left eye to view the fixation target. In a similar fashion, the right eye was able to see the stimulus screen but was prevented from seeing the fixation cross (Fig. 1). These measures, in combination with the exclusion of subjects with significant distance phorias, were taken to ensure both fixation and accommodation stability.

Stimuli

Stimuli used for the measurement of resolution thresholds consisted of low-contrast (10%) Gabor patches with a contrast reduction factor of $1/e^2$ (13.5%) at a diameter of 2 degrees. They were presented on a 17-inch CRT screen (Nokia 447Pro) that was positioned 20 degrees to the left of the fixation display. Gabor patches were chosen as they have well-defined spatial frequency, are luminance neutral, and can be presented at distinct locations in the visual field. The mean luminance of the CRT screen was 31 cd/m^2. The display had previously been calibrated and gamma-corrected with an i1Display 2 colorimeter from X-Rite. The mean luminance of the LCD fixation screen was 32 cd/m^2.

Stimuli (Gabor patches) were generated using Matlab software with extensions supplied with the Psychophysics Toolbox.[43,44]

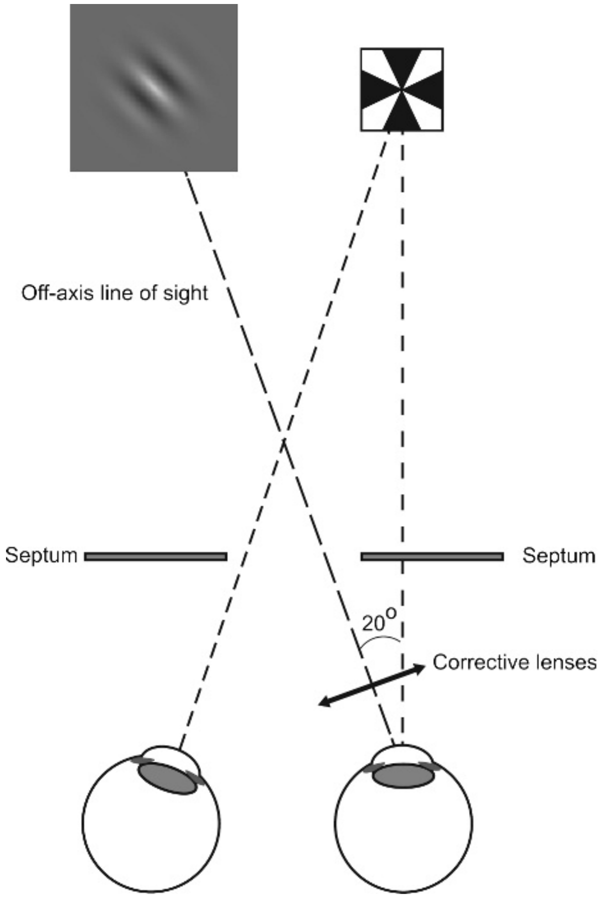

FIGURE 1.
Schematic representation of the experimental setup. The distance from the subject to the fixation target and stimulus screen was 3.0 m. A septum was adjusted to partially occlude the right eye while still allowing unhindered viewing of the stimulus screen; a second septum was also positioned so that only the fixation screen was visible to the left eye. Corrective lenses were inserted in a modified lens holder, mounted on the forehead rest and normal to the off-axis line of sight.

The Gabor patches were orientated obliquely, leaning either +45 or −45 degrees from the vertical so as to reduce the orientation-specific blurring effects of axis orientation of peripheral astigmatism in the horizontal visual field, as well as to minimize the superiority in resolution of horizontal gratings over vertical gratings along the horizontal meridian.[19,45,46] It should be noted that, by choosing these oblique orientations of the gratings, the psychophysical methodology will be less sensitive to J_{45} errors.

Optical Correction

Off-axis sphero-cylindrical refractive errors, as measured with the COAS-HD VR aberrometer, were corrected with full-aperture trial lenses after rounding to the nearest 0.25 D. These were inserted in a modified lens holder, mounted on the forehead rest and normal to the off-axis line of sight. The vertex distance from the right eye was 20 mm.

For statistical analysis, the refractive errors, sphere (S), cylinder (C), and axis (Θ) were converted into their vector components (M, J_{180}, and J_{45}) as described by Thibos et al.[13]:

$$M = S + \frac{C}{2} \quad J_{180} = -\left(\frac{C}{2}\right)\cos(2\Theta) \quad J_{45} = -\left(\frac{C}{2}\right)\sin(2\Theta)$$

The M component is the familiar mean spherical equivalent power; the J_{180} and J_{45} components represent the powers of crossed cylinders with axes of 180 and 45 degrees, respectively. This method of specifying refractive errors allows for more simplified analysis and comparison of different refractive errors.[47]

The total scalar power (P) of the sphero-cylindrical correction, producing an equivalent amount of blur, was also calculated as the square root sum of M^2, $J_{180}{}^2$, and $J_{45}{}^2$ as described by Thibos et al.[13]:

$$P = \sqrt{M^2 + J_{180}^2 + J_{45}^2}$$

Psychophysical Methodology

Resolution acuity was measured off-axis (20 degrees nasal visual field) under four refractive conditions: (1) unaided, (2) with peripheral COAS correction, (3) peripheral COAS correction with an addition of +1.00 D sphere, and (4) peripheral COAS correction with an addition of −1.00 D sphere; the last two conditions were performed to verify the peripheral COAS correction. Two measurements were performed for each condition; these were recorded and subsequently averaged. The testing order of each refractive condition was randomized to counteract any possible learning effects.

Low-contrast resolution thresholds were determined by a two-alternative forced-choice procedure, whereby the subjects had to decide the orientation of the grating. An adaptive Bayesian algorithm as described by Kontsevich and Tyler[48] was used to calculate the probability density function for the threshold from a total of 40 trials. Full details of the psychophysical methodology are available in Rosén et al.[22] where the SD of the probability density function for the acuity threshold for 30 trials was approximately 0.05 logMAR.

Subjects initiated each measurement trial by pressing a key on a modified numerical keypad, which also served to record responses during the trial. Stimulus presentation was preceded by a sound cue followed by a delay of 500 milliseconds. To minimize saccadic fixational eye movements, stimuli remained visible for a duration of 300 milliseconds before disappearing.

RESULTS

All subjects were emmetropic centrally (subjectively) and had astigmatism at 20 degrees in the nasal visual field, ranging from −1.00 to −2.00 DC. The average uncorrected peripheral low-contrast resolution acuity was 0.92 logMAR. Following correction of off-axis refractive errors, this improved to 0.86 logMAR, a small but significant improvement of 0.06 logMAR ($p = 0.028$, paired Student *t* test). The maximum improvement in acuity observed in this study was 0.17 logMAR. Table 1 shows the measured COAS refractive errors and the averaged psychophysical results.

Most of the subjects in this study had simple myopic astigmatism with approximately similar axis orientations, as was expected from previous studies.[31,34] From a clinical perspective, it was practical to group them according to the amount of off-axis astigmatism (Table 1). The group having −1.00 DC of astigmatism showed a slight decrease in resolution acuity when their objectively determined off-axis refractive correction was introduced. The other three groups showed improved resolution acuity with increasing degrees of astigmatism; the −1.25 DC group improved by 0.05 logMAR, the acuity of the subject with −1.50 DC improved by 0.14 logMAR, and the two subjects with −2.00 DC improved on average by 0.16 logMAR.

Comparisons between the change in low-contrast resolution acuity and off-axis astigmatism, mean spherical equivalent refractive error (M), J_{180} cross-cylinder component, and power scalar (P) were also performed; the results for the power scalar (P) are shown graphically in Fig. 2 (as the J_{180} component was the major contributor to the power scalar, no separate graph for J_{180} is presented here). The observed changes in low-contrast resolution acuity were strongly correlated with off-axis astigmatism (Pearson $r = 0.95$; $p < 0.0001$), the J_{180} cross-cylinder component (Pearson $r = 0.82$; $p = 0.0034$), and power scalar (Pearson $r = -0.75$; $p = 0.0126$). There was no significant correlation between change in low-contrast resolution acuity and mean spherical equivalent refractive error (Pearson $r = 0.56$; $p = 0.0895$) or the J_{45} cross-cylinder component (Pearson $r = -0.07$; $p = 0.8376$). This lack of correlation for the J_{45} cross-cylinder component is as one would expect for subjects having cylinder axes close to 90 or 180 degrees as was the case in this study and attributed to the chosen psychophysical methodology. Note that only the subjects with higher refractive errors showed large improvements (Table 1 and Fig. 3). Of those with a power scalar refractive error of 1.00 D or more, the average improvement in resolution acuity was 0.1 logMAR, equivalent to a one-line improvement.

Measurement of acuity with an additional +1.00 or −1.00 DS (in addition to the original COAS correction) resulted in consistently poorer performance than with solely COAS correction (Table 1 and Fig. 3). The reduction in acuity was on average 0.07 logMAR following the addition of +1.00 DS and 0.04 logMAR after the addition of −1.00 DS.

DISCUSSION

Peripheral low-contrast resolution improved following the correction of off-axis refractive errors in the subjects of this study. Of those with a scalar power refractive error (P) of 1.00 D or more, the average improvement in resolution acuity was 0.1 logMAR, equivalent to a one-line improvement. This fact implies that the COAS-HD VR aberrometer was useful in assessing the off-axis refractive error. Furthermore, the addition of ±1.00 D extra spherical defocus to the COAS refraction degraded resolution for all subjects. Note that, even for those subjects who showed no improvement in vision with the COAS correction, this correction still resulted in better visual performance than a correction with ±1.00 D extra (Fig. 3). We are therefore confident that the

TABLE 1.

Distribution of off-axis (20 degrees nasal visual field) refractive error as measured with COAS and average peripheral low-contrast 10% resolution acuity (PLCRA) with and without off-axis refractive correction

Given off-axis refraction				Unaided PLCRA, logMAR	Corrected PLCRA, logMAR	Difference: corrected VA− unaided VA, logMAR	Difference/ scalar power, logMAR/D	Change from unaided PLCRA with extra +1.00 D, logMAR	Change from unaided PLCRA with extra −1.00 D, logMAR
Sphere/cylinder	M	J_{180}	J_{45}						
Plano −1.00 × 95	−0.50	−0.50	−0.09	0.89	0.91	0.02	0.03	0.08	0.03
Plano −1.00 × 100	−0.50	−0.47	−0.17	0.85	0.88	0.03	0.03	0.05	0.06
Plano −1.00 × 65	−0.50	−0.32	+0.38	0.90	0.86	−0.05	−0.06	0.06	0.04
Plano −1.00 × 80	−0.50	−0.47	+0.17	0.80	0.82	0.02	0.03	0.08	0.04
Plano −1.25 × 95	−0.63	−0.62	−0.11	0.88	0.84	−0.05	−0.05	0.01	0.07
−0.50 −1.25 × 85	−1.13	−0.62	+0.11	0.90	0.86	−0.05	−0.03	0.02	0.01
−0.75 −1.25 × 100	−1.38	−0.59	−0.21	0.94	0.87	−0.07	−0.05	0.06	0.11
Plano −1.50 × 75	−0.75	−0.65	+0.38	0.93	0.79	−0.14	−0.13	0.11	0.05
Plano −2.00 × 90	−1.00	−1.00	±0.00	1.04	0.88	−0.16	−0.16	0.13	0.05
Plano −2.00 × 95	−1.00	−0.98	−0.17	1.10	0.94	−0.17	−0.12	0.07	−0.03
Mean	−0.79	−0.62	−0.03	0.92	0.86	−0.06	−0.04	0.07	0.04

The difference between unaided and corrected resolution acuity is shown in the fourth column from the right; negative values indicate an improvement in acuity following correction of peripheral refractive errors. The difference between unaided and corrected resolution acuity divided by the scalar power (P) is shown in the third column from the right. The change in acuity following the addition of ±1.00 DS to the COAS correction, with respect to unaided PLCRA, is shown in the last two columns.

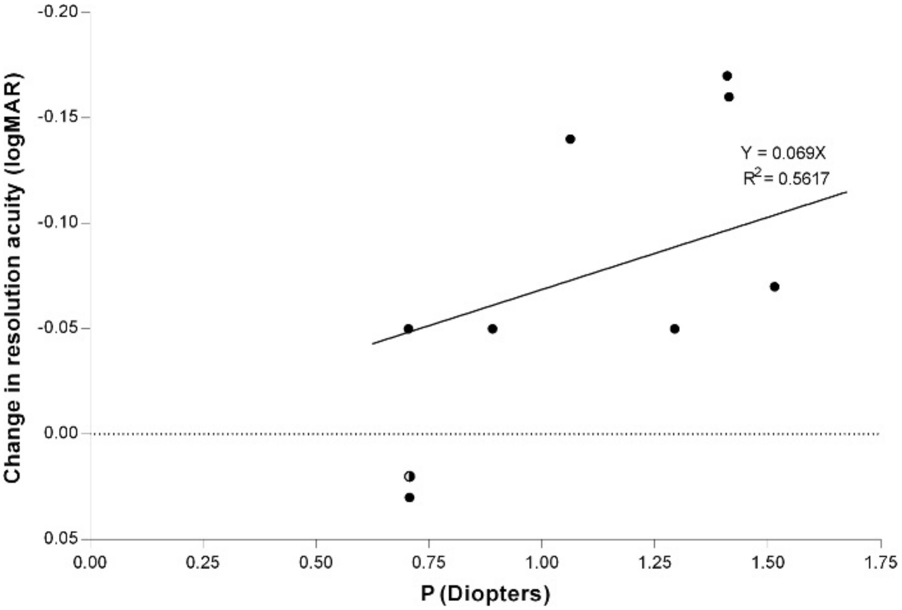

FIGURE 2.

Mean change in resolution acuity (logMAR) when subjects were grouped according to power scalar (*P*). Negative values on the ordinate axis show an improvement in resolution acuity. The regression line is fixed at the origin. Overlapping data points are represented as half-shaded circles.

aberrometer is accurate to within ±1.00 D when used for measuring off-axis refractive errors. An accuracy of 1 D is also in agreement with the fact that it was the subjects with a scalar power refractive error of 1.00 D or more who showed large improvements in acuity.

Naturally, the amount of refractive error (in this case, off-axis astigmatism) is an important factor dictating the extent of improvement following its correction; the correction of larger amounts of astigmatism provides greater improvements in resolution acuity. It is important to note that our study was limited to testing a single eccentricity in the nasal visual field and that the potential benefits of peripheral refractive corrections could vary with eccentricity as well as meridian. The improvements found in the present study are in agreement with the previous studies by Rosén et al.[22,49] who found a median change in low-contrast resolution acuity of 0.15 logMAR for every diopter of spherical defocus, which compares well with our results for those subjects with greater off-axis refractive errors. These results are further corroborated by the recent study of Atchison et al[50]; an improvement of slightly more than 0.1 logMAR/D at 20 degrees in the nasal visual field was observed. It is interesting to note that the average uncorrected low-contrast resolution was 0.92 and the corrected low-contrast acuity improved to 0.86 logMAR. This improved low-contrast resolution is in close agreement with the results of Wang et al.[20] who observed a

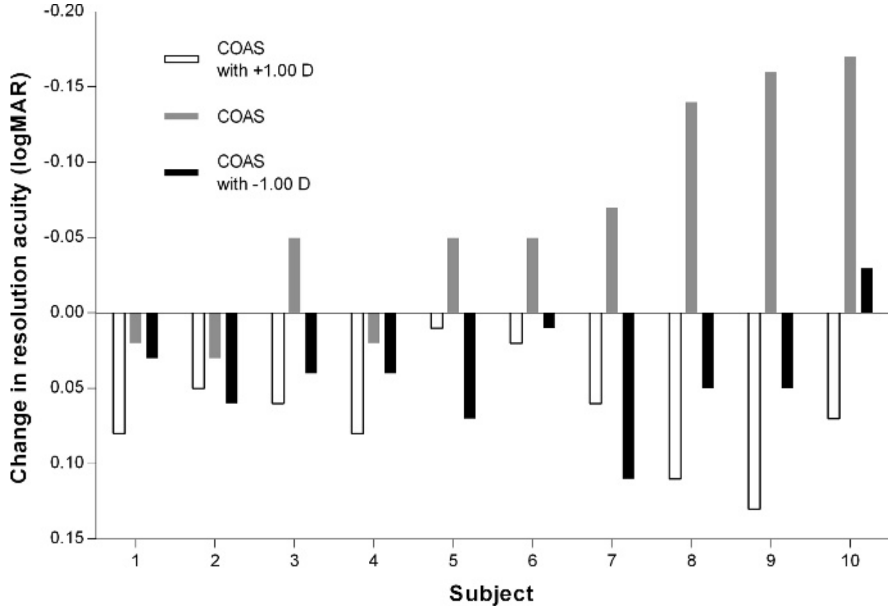

FIGURE 3.

Individual changes in resolution acuity (from unaided) with COAS correction for all subjects, as well as COAS correction with the addition of an extra ±1.00 DS. Note that subjects are plotted in the same order as in Table 1.

maximal visual acuity of 4 to 5 cycles/degree at 20 degrees in the nasal field for high-contrast resolution, which equates to an acuity of 0.78 to 0.88 logMAR. Consequently, by correcting peripheral refractive errors, low-contrast acuity approaches the maximum set by the neural limitations of the eye and lies close to the limit of high-contrast resolution acuity.

This study shows that the improvements in visual function produced under idealized laboratory settings with psychophysical through-focus procedure can be realized in a more clinical setting by using the Zernike refraction of a commercial wavefront sensor. The main advantages of using a wavefront sensor are that the refraction procedure is much faster than psychophysical through-focus procedures and does not rely on subjective responses; it should be kept in mind that the evaluation of peripheral resolution acuity is a very demanding task and multiple psychophysical procedures might give inconsistent results owing to fatigue, especially in elderly subjects. The subjects of this study had an average scalar power of 1.00 D and astigmatism of −1.25 DC × 89 at 20 degrees in the nasal visual field, which is comparable to other studies on more subjects; raw data from Baskaran et al.[51] on 30 emmetropes showed an average off-axis astigmatism of −1.50 DC × 90 measured with the COAS-HD VR aberrometer. Atchison et al.[34] reported approximately −1.25 DC from measurements on 22 emmetropes with the Shin-Nippon SRW5000 autorefractor and Gustafsson et al.[25] found −1.70 DC × 90 in 20 emmetropic eyes with a double-pass method. These amounts of off-axis astigmatism are also similar in subjects with central refractive errors; in the study of Lundström et al.,[52] the average astigmatism calculated from wavefront aberrations was −1.50 DC × 96 in the 43 subjects with central refractive errors ranging from −7.50 to +2.38 D (mean spherical equivalent). Similarly, in the large study of Atchison et al.,[32] astigmatism at 20 degrees (nasal visual field) was quite stable at around −1.00 DC × 90 for the 116 subjects with central refractive errors ranging from 0.00 to −8.00 D (mean spherical equivalent), reducing slightly for larger refractive errors at greater eccentricities. It is therefore reasonable to assume that similar off-axis refractive errors will also be found in patients with macular degeneration.

Consequently, we conclude from this study that patients with scalar power refractive errors of 1.00 D or more (as measured by the COAS-HD VR aberrometer, in an off-axis angle within 20 degrees nasally) would benefit from an optical correction determined by the aberrometer. At 20 degrees in the nasal visual field, the improvement for healthy subjects corresponds approximately to one line (0.1 logMAR).

The results from an earlier study comparing subjects with normal vision to those with CFL suggest that the improvement in visual function might be even higher for people with macular degeneration.[26]

CONCLUSIONS

This study investigates the possibilities of improving peripheral low-contrast resolution acuity with a peripheral refractive error correction determined objectively using a commercial open-field aberrometer. The results suggest that even moderate amounts of off-axis optical errors, such as 1.50 D or more of off-axis astigmatism, do influence peripheral visual tasks involving low contrast and that there are definite benefits in correcting even moderate amounts of off-axis refractive errors; improvements of up to 0.17 logMAR were seen in this study. For people who rely on optimal peripheral visual function, specifically those with CFL, correction of off-axis refractive errors may be even more pertinent; the use of the COAS aberrometer can be clinically useful in rapidly determining off-axis refractive errors specifically for this patient group.

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