Sign-Dependent Sensitivity to Peripheral Defocus for Myopes due to Aberrations

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Purpose. Animal studies suggest that the periphery of the eye plays a major role in emmetropization. It is also known that human myopes tend to have relative peripheral hyperopia compared to the foveal refraction. This study investigated peripheral sensitivity to defocus in human subjects, specifically whether myopes are less sensitive to negative than to positive defocus.

Methods. Sensitivity to defocus (logMAR/D) in the 20° nasal visual field was determined in 16 emmetropes (6 males and 10 females, mean spherical equivalent –0.03 ± 0.13 D, age 30 ± 10 years) and 16 myopes (3 males and 13 females, mean spherical equivalent –3.25 ± 2 D, age 25 ± 6 years) using the slope of through-focus low-contrast resolution (10%) acuity measurements. Peripheral wavefront measurements at the same angle were obtained from 13 of the myopes and 9 of the emmetropes, from which the objective depth of field was calculated by assessing the area under the modulation transfer function (MTF) with added defocus. The difference in depth of field between negative and positive defocus was taken as the asymmetry in depth of field.

Results. Myopes were significantly less sensitive to negative than to positive defocus (median difference in sensitivity 0.06 logMAR/D, $P = 0.023$). This was not the case for emmetropes (median difference –0.01 logMAR/D, $P = 0.382$). The difference in sensitivity between positive and negative defocus was significantly larger for myopes compared to emmetropes ($P = 0.031$). The correlation between this difference in sensitivity and objective asymmetry in depth of field due to aberrations was significant for the whole group ($R^2 = 0.18$, $P = 0.02$) and stronger for myopes ($R^2 = 0.8$, $P < 0.01$).

Conclusions. We have shown that myopes, in general, are less sensitive to negative than to positive defocus, which can be linked to their aberrations. This finding is consistent with a previously proposed model of eye growth that is driven by the difference between tangential and radial peripheral blur. (*Invest Ophthalmol Vis Sci.* 2012;53:7176–7182) DOI: 10.1167/iovs.11-9034

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This study investigated how peripheral vision is influenced by positive and negative defocus. Peripheral vision at large eccentricities is substantially degraded compared to foveal vision.[1,2] This degradation is caused by both neural factors, in the form of decreased ganglion cell density,[3] and optical factors. Optically, the refractive errors change with angle, and large amounts of off-axis astigmatism are present for all eyes.[4–7] Furthermore, higher-order aberrations, primarily coma, are more prevalent than for foveal vision.[8–11] Whether there are neural or optical factors that limit peripheral vision is dependent on the type of psychophysical task; detection and low-contrast resolution are optically limited, whereas high-contrast resolution is neurally limited.[12–14] The image quality on the peripheral retina has been proposed to influence the development of myopia.[15–17] One difference between myopes and emmetropes lies in the relative peripheral refraction (RPR), defined as the difference between peripheral and foveal refraction; emmetropes generally have a myopic RPR, whereas myopes tend to have a hyperopic RPR.[18–27] Furthermore, animal studies have shown that imposition of refractive errors or form deprivation solely in the periphery interferes with the emmetropization process.[28–33] It is therefore important to understand how peripheral vision is influenced by refractive errors and whether systematic differences between emmetropes and myopes exist.

In a previous study describing peripheral sensitivity to defocus, the two myopic subjects stood out from the three emmetropic subjects.[14] In that study, peripheral low-contrast resolution was measured for different amounts of imposed peripheral defocus. Both positive (myopic) and negative (hyperopic) defocus were added. For myopes with peripheral refractive errors corrected, an imposition of negative defocus resulted in a lower decrease in acuity than that produced by the addition of positive defocus. Such a difference was not observed for the three emmetropes studied. If confirmed as a general phenomenon, a difference in peripheral sensitivity to defocus for myopes but not for emmetropes would be interesting for research on myopization. In order to investigate this further, the current study was designed to measure peripheral sensitivity to positive and negative defocus for myopes and emmetropes in a larger population. We will also assess the off-axis optical aberrations in order to investigate whether the phenomenon can be explained through asymmetries in the depth of field.

Methods

Experiment 1: Psychophysical Measurements

The hypothesis that myopes are less sensitive to negative than to positive peripheral defocus was tested by psychophysical measurements. We determined the sensitivity to defocus by assessing the low-contrast resolution acuities for different amounts of added defocus and interpolating the slopes in the defocus curves. The current study included 32 subjects, 28 of whom had no previous experience with

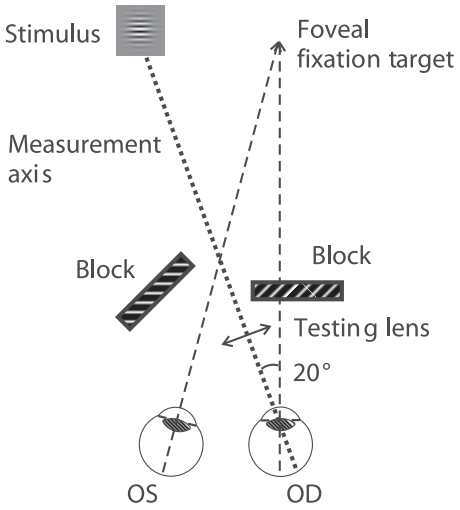

Figure 1. The experimental setup for peripheral measurements on the right eye. The foveal fixation target and stimulus screen were placed 3 m away from the subject. The left block occluded the stimulus for the left eye while the right block occluded the fixation target from the right eye, ensuring that fixation and accommodation were controlled by the left eye. Both blocks were less than 10 cm away from the subject. A custom-made lens holder, aligned by the experimenter, held the testing lens perpendicular to the measurement axis of 20° at a distance of 20 mm from the right eye of the subject. All myopic subjects wore their habitual contact lens correction on the left eye, but were uncorrected on the right eye.

peripheral psychophysical measurements. The subjects were 16 emmetropes (6 male and 10 female, ≤0.5 D absolute refractive errors, mean spherical equivalent −0.03 ± 0.13 D, age 30 ± 10 years, range 20–56 years) and 16 myopes (3 male and 13 female, mean spherical equivalent −3.25 ± 2 D, age 25 ± 6 years, range 21–44 years). Informed consent was obtained beforehand, and the study adhered to the tenets of the Declaration of Helsinki.

Measurements were conducted in the 20° nasal visual field of the right eye. Figure 1 shows the experimental arrangement used to present the stimuli. The setup was identical to that of our previous study.[14] The subject's head was stabilized in a chin rest, and the stimuli were presented 3 m away on a calibrated 19 in CRT screen with a mean luminance of 68 cd/m^2. Defocusing lenses, as well as cylindrical lenses compensating for the off-axis astigmatism, were mounted in a trial frame 20 mm from the right eye, aligned manually by the experimenters for each subject in order to be centered and perpendicular relative to the 20° off-axis direction. As a starting point, objective best peripheral defocus was determined by a Shin-Nippon autorefractor (Shin-Nippon Corp., Tokyo, Japan), which has been shown to give accurate peripheral refraction.[34] Resolution acuity was then sampled for nine different defocus values at intervals with 1 D spacing, centered on the objectively determined best peripheral defocus. Throughout the experiments, the objectively determined off-axis astigmatism was corrected. The left eye maintained stable fixation and accommodation by looking at a Maltese cross 3 m away on a mini display with a luminance of 14.5 cd/m^2. A screen blocked the right eye from seeing this foveal fixation target. This meant that the right eye did not influence the accommodative state, as peripheral stimuli beyond 15° do not trigger accommodation.[35] The myopes wore their habitual correction with soft contact lenses on their left eye for fixation but were uncorrected on their right eye. The room was dark, and the subjects had their natural pupil size.

The stimuli for the resolution acuity measurements were Gabor patches with 10% peak contrast. The Gabor patches consisted of sine-wave gratings multiplied with a Gaussian window of 0.6° standard deviation, giving an effective size of approximately 1.8°. The experiments were conducted using MATLAB (The MathWorks, Natick, MA) and the

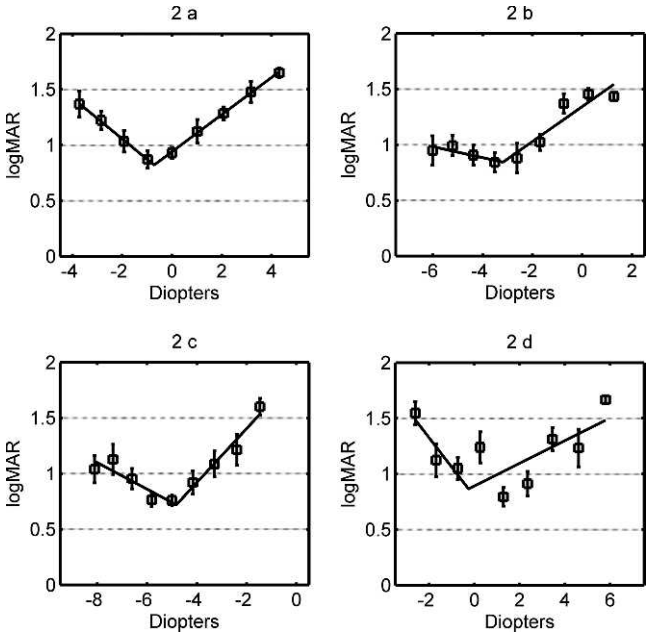

Figure 2. (**a**–**d**) Representative results from the psychophysical through-focus resolution measurements for an emmetrope (**A**, subject 5), two myopes (**b**, **c**, subjects 19 and 13), and a subject with a large fitting error (**d**, subject 29). Each square denotes the measurement of one resolution acuity threshold. *Error bars* represent standard deviation of the threshold probability density function of the single acuity measurement. The *solid lines* are least squares fit to the threshold values. See the text and Rosén et al.[14] for more information.

Psychophysics Toolbox.[36,37] The duration of stimuli presentation was 1 second, cued by sound. The size and spatial frequency of the stimuli were adjusted to compensate for the spectacle magnification: $m = 1/(1 - aF)$, with a as the vertex distance from the trial lens to the eye and F as lens power in diopters. The gratings were randomly oriented horizontally or vertically, and the psychophysical task consisted of pressing one of two possible keys on a keypad to describe the grating orientation. The threshold was found for grating resolution acuity, that is, the maximum spatial frequency at which the orientation of the gratings could be determined. We used a two-alternative forced-choice adaptive Bayesian method, which determined the threshold and the standard deviation of its probability density function in 30 trials.[38] We have previously used the same method for determining peripheral acuity.[14] The subjects received no feedback during the experiment, and the order of defocus values to be tested was random.

Experiment 1: Data Analysis

Examples of subjective data obtained from four subjects can be seen in Figures 2a–d. The data consist of resolution acuity as a function of nine different defocus values. The acuity was determined in logMAR, and the defocus values have been recalculated to correspond to actual imposed defocus, taking the vertex distance into account. For each subject, two straight lines were fitted to the data using the method of least squares regression. For the two lines, four parameters were fitted: the sensitivity to negative defocus (i.e., slope of the left line), the sensitivity to positive defocus (slope of the right line), and logMAR and defocus at the intersection of the two lines. This intersection was taken as the best subjective defocus, and any positive or negative defocus was determined relative to that point. The sensitivities to positive and negative defocus were used in the subsequent analysis, as our hypothesis is that these differ for myopes but not for emmetropes.

Peripheral psychophysical tasks can be cumbersome, especially for naïve subjects. Fatigue might lead to unreliable results at some defocus level, even if subjects are given ample time to rest between tests.

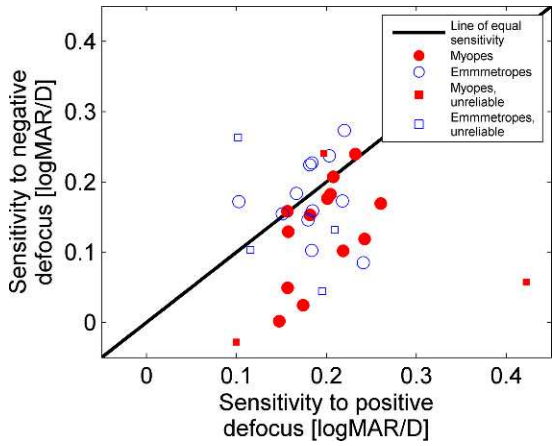

FIGURE 3. Peripheral sensitivity to positive and negative defocus for all subjects. The line shown is the theoretical line of equal sensitivity between positive and negative defocus. It can be seen that the emmetropes cluster around that line, whereas the myopes in general are located below it.

Figures 2a–c show examples of subjects for whom the linear fit is a good approximation of the data, whereas Figure 2d is an example of unacceptably large deviations. A fitting error (residual sum of squares) above 0.1 logMAR^2 was used as the threshold for unreliable estimations of sensitivity to defocus. The results were analyzed statistically both with and without these unreliable measurements included. The outliers are marked separately as squares in Figure 3.

Since we did not expect the sensitivities to defocus to be normally distributed, nonparametric statistical tests were used ($P < 0.05$ was considered statistically significant). The sensitivities to positive and negative defocus were compared within the groups of myopes and emmetropes using the paired Wilcoxon test. The difference in sensitivity to positive and negative defocus was compared between myopes and emmetropes using the Mann-Whitney test.

Experiment 2: Objective Asymmetries in Depth of Field

The optical aberrations in the 20° nasal visual field for the right eye of the subjects were measured three times for each subject using a WASCA (Carl Zeiss, Oberkochen, Germany), which is a commercially available aberrometer. The WASCA is based on the Hartmann-Shack technique, which has been used extensively for peripheral aberration measurements, for example by Lundström et al., Mathur et al., and Shen and Thibos.[10,11,39] These wavefront measurements took place 6 months after the psychophysical measurements. We contacted only subjects whose psychophysical measurements had been classified as reliable. We were able to obtain wavefront measurements from all of them except three emmetropes. In total, wavefront measurements were performed on 9 emmetropes (3 male and 6 female, mean spherical equivalent –0.06 ± 0.17 D, age 27 ± 7 years) and 13 myopes (mean spherical equivalent –3.5 ± 2 D, age 26 ± 7 years). The subjects were measured using their natural pupil in a dark room, with a small illuminated fixation target 1.5 m away. As the subjects were fixating at an object located 20° to the right of the wavefront sensor, the measured pupil was elliptical. We used the commercial software of the WASCA to reconstruct the wavefront aberrations with Zernike coefficients[40] over an inscribed circle with 4 mm diameter, which was the maximum common diameter. It was then possible to average the three measurements of each subject by averaging the Zernike coefficients.

Experiment 2: Data Analysis

A difference in sensitivity to defocus for myopes may be of optical as well as neurological origin. Here we focus on the possibility of an optical explanation—an asymmetry between the positive and negative depth of field. The depth of field was simulated through calculations of image quality as a function of added defocus, as done by Marcos et al.[41,42] The procedure was as follows. Wavefront aberrations were expressed as Zernike coefficients for a circular pupil with a diameter of 4 mm. The area under the modulation transfer function (MTF) curve was calculated out to a maximum spatial frequency of 10 cycles/degree (corresponding to an acuity of 0.5 logMAR, slightly better than the best acuity at this eccentricity) and expressed in percentage of the area under the diffraction-limited MTF. This value corresponds to the AreaMTF metric described by Marsack et al.,[43] with the addition of a maximum spatial frequency to account for the limited sampling density of the peripheral retina. In these calculations, the elliptical shape of the pupil was used. The AreaMTF was calculated for varying amounts of defocus, sampled at 0.01 D. The limit to the depth of field was set at the point where the AreaMTF had decreased to 20% of its maximum value, with the center of the field at the peak value. Asymmetry in depth of field was then calculated as the difference between negative and positive depth of field, with a positive asymmetry corresponding to a higher tolerance to imposed negative defocus. The coefficient for astigmatism C^2_2 was set to zero, as trial lenses were used to compensate for the peripheral oblique astigmatism (90°/180° meridians) during the resolution measurements performed in experiment 1. The correlation between the subjective difference in sensitivity to positive and negative defocus and asymmetry in depth of field was then determined using Spearman correlation.

RESULTS

Experiment 1

The fitted parameters of the psychophysical measurements for all subjects are listed in Table S1 (see Supplementary Material and Supplementary Table S1, http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.11-9034/-/DCSupplemental). Sample graphs in Figures 2a–d show an emmetrope (subject 5), two myopes (subjects 19 and 13), and one subject classified as unreliable (subject 29). The sensitivity to negative and positive defocus for all subjects is shown in Figure 3. As depicted, the emmetropes tended to cluster around having equal sensitivity, denoted in the figure by the line. The emmetropes had a median sensitivity of 0.18 logMAR/D to positive defocus and 0.17 logMAR/D to negative defocus. The myopes, on the other hand, were nearly all placed below that line, indicating a larger sensitivity to positive than to negative defocus, with a median sensitivity of 0.20 logMAR/D to positive defocus and 0.14 logMAR/D to negative defocus. These qualitative tendencies were confirmed by statistical analysis. First, Kolmogorov-Smirnov tests were used to see if the sensitivity to positive and negative defocus and the difference in sensitivity were normally distributed. A normal distribution was rejected for all types of sensitivities, both for myopes and emmetropes separately and for the population as a whole. Thereafter, within-group comparisons of sensitivity to defocus could be performed. For emmetropes, there was no significant difference between sensitivity to positive and negative defocus ($P = 0.382$, Wilcoxon), whereas the myopes were significantly more sensitive to positive defocus ($P = 0.023$, Wilcoxon). We also performed a between-group comparison utilizing the difference in sensitivity. For each individual subject, the difference in sensitivity was defined as the sensitivity to positive defocus minus the sensitivity to negative defocus. The difference in sensitivity for the myopes was significantly larger than for the emmetropes ($P = 0.031$, Mann-Whitney, median difference 0.06 logMAR/D for myopes, 0.00 logMAR/D for emmetropes).

As described in Methods, subjects were classified as unreliable if their linear fit had a residual sum of square error

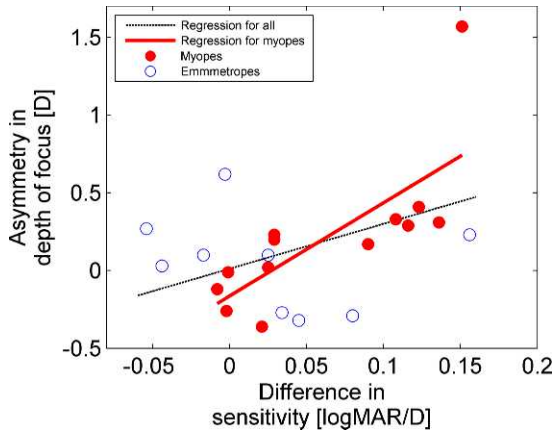

Figure 4. Asymmetry in depth of field plotted against the difference in sensitivity. The regression line is plotted for myopes ($R^2 = 0.84$, *red line*) and for all subjects ($R^2 = 0.18$, *black line*), but not for emmetropes, as there is no significant correlation there ($P = 0.87$).

above 0.1 logMAR[2]. This criterion resulted in four emmetropes and two myopes being excluded. In addition, subject 26 (myope) was classified as unreliable, since the sensitivity to positive defocus for this particular subject was sampled by only a single acuity measurement, resulting in a very large difference in sensitivity. Accordingly, 13 myopes and 12 emmetropes were classified as reliable. When we repeated the statistical tests without the unreliable subjects, our conclusions were the same: no difference within emmetropes ($P = 0.298$, Wilcoxon), significant difference within myopes ($P = 0.025$, Wilcoxon), and significantly larger difference in sensitivity between positive and negative defocus in myopes than in emmetropes ($P = 0.012$, Mann-Whitney).

Comparison of Results of Experiments 1 and 2

The aim of the objective wavefront measurements in experiment 2 was to see whether the psychophysical difference in defocus sensitivity of experiment 1 could be correlated with differences in optical properties. Normal distributions of the asymmetry in depth of field were rejected by a Kolmogorov-Smirnov test for myopes and emmetropes separately as well as together. Thus, we used the nonparametric one-tailed Spearman correlation test. The objective asymmetry in depth of field is plotted against the difference in sensitivity in Figure 4. There is significant correlation between the two values for all subjects treated as a single group ($R^2 = 0.18$, $P = 0.02$). If treated separately, there was significant correlation for myopes ($R^2 = 0.84$, $P < 0.01$) but not for emmetropes ($R^2 = 0.16$, $P = 0.87$). The correlation for myopes also remained with exclusion of subject 12, the single outlier with a very large asymmetry in depth of focus and difference in sensitivity ($R^2 = 0.8$, $P < 0.01$).

In studies on peripheral image quality, it is customary to report aberrations as Zernike coefficients and higher-order root mean square (RMS) errors using the ANSI standard.[40] In particular, spherical aberration, coma, and RMS have been of interest (see e.g., Mathur et al.).[44] Table S2 (see Supplementary Material and Supplementary Table S2, http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.11-9034/-/DCSupplemental) shows the raw data from the wavefront measurements; second- and third-order coefficients as well as spherical aberration and RMS sums up to and including sixth-order aberrations. For our subjects, the spherical aberration was on average higher for myopes than for emmetropes (mean values 0.015 μm vs. 0.004 μm), but this difference was not statistically

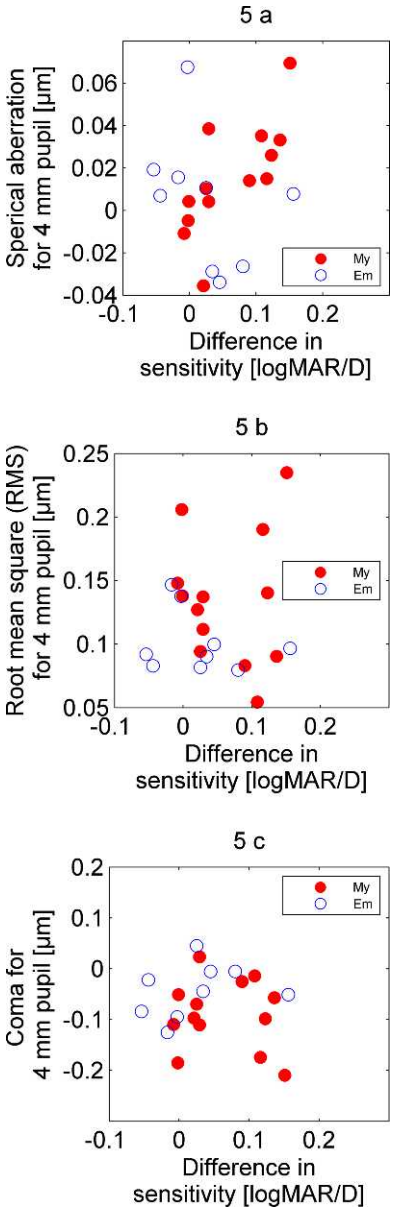

Figure 5. (**a**–**c**) Spherical aberration (**a**), root mean square error (**b**), and coma (**c**) plotted against the difference in sensitivity for each subject. Aberration data are for a 4 mm circular pupil. None of the three aberration quantities is significantly correlated with the difference in sensitivity.

significant. Myopes also had more coma than emmetropes (mean values –0.091 μm vs. –0.043 μm, $P = 0.048$, one-tailed Mann-Whitney). Spherical aberration, coma, and RMS are plotted against the difference in sensitivity in Figures 5a–c. There is correlation between difference in sensitivity to defocus and spherical aberration for the myopes ($R^2 = 0.65$, $P < 0.01$). However, for the whole group, no correlation with the difference in sensitivity to defocus was found, either for spherical aberration (Fig. 5a, $P = 0.16$, one-tailed Spearman), for RMS (Fig. 5b, $P = 0.62$), or for coma (Fig. 5c, $P = 0.55$).

To investigate the relative importance of the different Zernike coefficients for the asymmetry in depth of field, we used the wavefront data from subject 13, whose peripheral aberrations were similar to those found in the general population, as an example.[10] Figure 6 shows results of simulations of optical image quality as a function of defocus

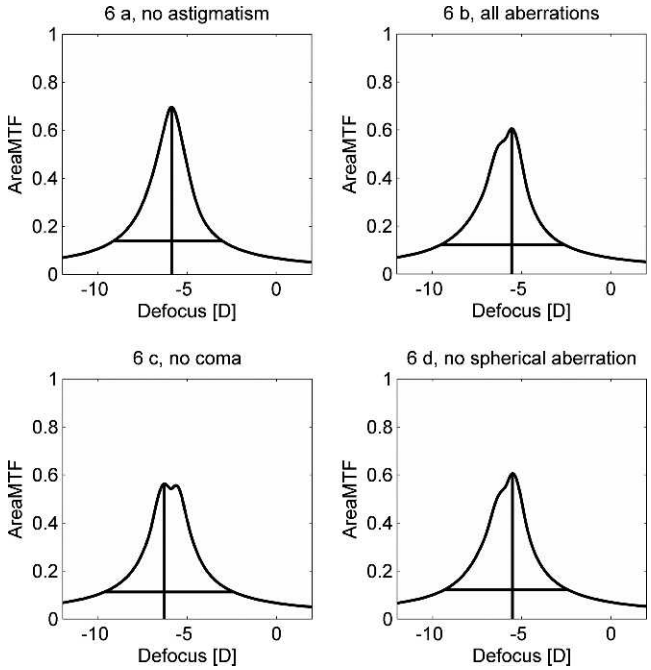

FIGURE 6. (**a**–**d**) Normalized area under MTF (AreaMTF) plotted against defocus for subject 13 (who also was the subject used for Fig. 2c). The *vertical lines* indicate the optimal points of defocus and the *horizontal lines* the limits of the depth of field, that is, the points where the image quality has decreased to 20%. The line of optimum defocus divides the depth of field into two parts, one toward more negative defocus and one toward more positive. The difference in length between these two parts is defined as the asymmetry in depth of field. In (**a**), astigmatism ($C^2_2 = 0.393$ μm) has been removed to correspond to the conditions of the psychophysical test and Figure 4 (asymmetry 0.41 D). The natural condition is shown in (**b**), with no correction of astigmatism, which makes the asymmetry larger (1.04 D, 35% of the depth of field for positive defocus). (**c**) is simulated with horizontal coma ($C^1_3 = -0.098$ μm) removed. Here, the asymmetry becomes −0.49 D, or, if the central point is taken as the mean of the two peaks, 0.15 D. (**d**) is without spherical aberration ($C^0_4 = 0.026$ μm) but includes coma, which somewhat lessens the asymmetry compared to (**b**), with a decrease to 0.71 D. All Zernike coefficients and simulations are given for a 4 mm pupil.

for this subject, with various individual aberrations removed. Figure 6a corresponds to the data presented in Figure 4, with astigmatism removed. Figure 6b shows the case in which the full wavefront is included, which increases the asymmetry in depth of field. In Figure 6c, coma (but not astigmatism) is removed, which results in the loss of the asymmetry (note that the spherical aberration remains). In Figure 6d, the spherical aberration (but neither astigmatism nor coma) is removed. This lowers, but does not eliminate, most of the asymmetry compared to Figure 6b.

DISCUSSION

This study showed that myopic subjects, in contrast to emmetropes, are generally less sensitive to negative than to positive defocus in the 20° nasal visual field in the periphery (0.14 logMAR/D compared to 0.20 logMAR/D). The difference in sensitivity to defocus is manifested as a superior acuity with imposition of negative defocus as opposed to positive defocus. A correlation was found between the difference in sensitivity and asymmetry in depth of field determined objectively from the wavefront measurements.

Similar psychophysical results showing a difference in sensitivity have previously been found foveally: Myopes were less sensitive to negative than to positive defocus, whereas emmetropes had similar sensitivity to both types of defocus.[45] The wavefront measurements presented in this study provide one explanation as to why some myopes have a larger difference in peripheral sensitivity than other myopes, as our data show a correlation between difference in sensitivity and objective asymmetry in depth of field due to aberrations. Figure 6 shows the effect of individual Zernike coefficients on the asymmetries in depth of field (plotted as the area under the MTF for different amounts of defocus). From these graphs we conclude that spherical aberration is contributing to the asymmetry but is neither necessary nor sufficient for it to occur. On the other hand, for the subject in Figure 6, coma plays a key role in causing the asymmetry in depth of field, although coma by itself is not enough to create an asymmetry; interaction with other aberrations is required,[15,46] which explains the lack of correlation between coma and the subjective difference in sensitivity in Figure 5C. Therefore, caution should be used in interpretation of results consisting of individual Zernike coefficients rather than the full image quality.

It should be noted that the aberrations measured in the current group of subjects are, on average, lower than those reported for a larger population,[10] though our population is slightly younger (average age 26.5 years compared to 31.5 years in the larger study). Moreover, our myopic subjects are also younger than our emmetropic subjects (mean age 25 and 30 years, respectively). However, as the amount of peripheral aberrations increases with age, a sample with older myopes could be expected to have more aberrations resulting in an even larger asymmetry in depth of field.[23] A potential weakness of our study is the fact that the wavefront measurements took place under different circumstances than the psychophysical measurements, 6 months later. Another shortcoming is that 7 of 32 subjects were classified as unreliable. However, some unreliable results are to be expected with naïve subjects, as peripheral psychophysical tasks are demanding. Furthermore, the results showing a larger difference in sensitivity for myopes also remained when unreliable subjects were not included. Adaptation in the periphery is not a well-understood phenomenon, but two factors make it an unlikely explanation for the differences in sensitivity observed for the myopes. First, the correlation found between the difference in sensitivity and the asymmetry caused by aberrations suggests differences in optics as a more likely explanation. Secondly, the difference in sensitivity arose from a decreased sensitivity to negative defocus. However, nearly all subjects had relative peripheral myopia or emmetropia and are therefore normally exposed to positive or no defocus, and any adaptation would be to positive defocus.

The difference in peripheral sensitivity for myopes can be understood in the broader context of emmetropization and can assist in reconciling the seemingly contradicting results from different studies. Animal studies have shown that imposition of peripheral hyperopic defocus will trigger eye growth leading to myopia.[31–33] Meanwhile, some studies on humans have shown that relative peripheral hyperopia is a consequence, not a cause, of foveal myopization.[18,21,22] Additionally, young, growing, foveally hyperopic eyes have been found to have relative peripheral myopia, which means that, with accommodation, their peripheral image will have myopic defocus.[18,20,21,47] If the peripheral refractive state can drive myopization, the eye is therefore supposed to grow under both peripheral myopia and peripheral hyperopia. Our suggestion is that a large enough peripheral defocus can trigger eye growth regardless of whether the defocus is hyperopic or myopic. In line with what was

proposed by Howland[48] and developed in a review by Charman,[49] we believe that the relationship between the blur for "tangential" and "radial" neurons may control growth. The detected blur for these neurons differs due to oblique astigmatism.[6,7] An inhibition of growth could arise when the difference in blur output from the two sets of neurons approaches zero, indicating peripheral emmetropia. The basis of this interpretation is that myopia progresses through axial elongation.[18,20,21,50,51] This would mean that an initially foveally hyperopic eye with peripheral myopia grows due to the difference in blur between the neuron groups. As the eye grows axially longer, its relative peripheral myopia decreases, eventually becoming close to emmetropia, which would then normally inhibit growth. If the peripheral image quality is less affected by hyperopic than myopic blur, due to aberrations, the growth process will have to continue longer than otherwise needed to achieve a state of equal blur.

Conclusions

Generally, myopic subjects are more sensitive to positive than to negative peripheral defocus, whereas no difference in sensitivity exists for emmetropes. The difference in sensitivity for myopes is correlated with an asymmetry in the objective depth of field caused by optical aberrations. This indicates that peripheral aberrations can result in substantial asymmetries between positive and negative depth of defocus. Further studies are needed to determine whether this difference in sensitivity is a consequence of, or exists prior to, myopia development.

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