Influence of Optical Defocus on Peripheral Vision

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PURPOSE. Peripheral optical corrections are often thought to give few visual benefits beyond improved detection acuity. However, patients with central visual field loss seem to benefit from peripheral correction, and animal studies suggest a role for peripheral vision in the development of myopia. This study was conducted to bridge this gap by systematically studying the sensitivity to optical defocus in a wide range of peripheral visual tasks.

METHODS. The spatial frequency threshold for detection and resolution in high and low contrast with stationary and drifting gratings were measured off-axis (20° nasal visual field) in five subjects with a peripheral optical correction that was varied systematically ±4 D.

RESULTS. All visual tasks, except high-contrast resolution, were sensitive to optical defocus, particularly low-contrast resolution with an increase of up to 0.227 logMAR/D. The two myopic subjects exhibited a very low sensitivity to defocus by negative lenses for low-contrast tasks, whereas all subjects were equally affected by myopic defocus. Contrary to expectations, drifting gratings made little difference overall.

CONCLUSIONS. Optical defocus as low as 1 D has a large impact on most peripheral visual tasks, with high-contrast resolution being the exception. Since the everyday visual scenery consists of objects at different contrast levels, it is understandable that persons with central visual field loss are helped by correction of peripheral refractive errors. The asymmetry in sensitivity to peripheral optical defocus in low-contrast tasks that was experienced by the myopic subjects in this study merits further investigation. (*Invest Ophthalmol Vis Sci.* 2011;52:318–323) DOI:10.1167/iovs.10-5623

Human visual performance degrades quickly with eccentricity. Despite this fact, normal daily tasks, such as walking, would be much more challenging without functional peripheral vision.[1] For patients with age-related macular degeneration (AMD), only the peripheral vision remains, and its optimal use is crucial.[2,3] Furthermore, peripheral refractive errors seem to induce development of myopia in animals[4,5] and have been suggested to affect human emmetropization as well.[6,7] However, the underlying nature of such a process is not yet known.

For humans, peripheral vision is limited by optical and neural factors to different degrees, depending on the type of task. It has been found that peripheral detection of pattern, movement direction, and flicker can be sensitive to optical defocus.[8–14] On the other hand, the most common way to asses foveal vision, by means of high-contrast resolution, in the periphery appears to be unaffected by spherocylindrical errors[2,9,15–19] and is not improved by adaptive optics.[17] As a result, a common conclusion of studies based on high-contrast resolution testing is that correction of peripheral optics offers few visual benefits. In contradiction of this, we present results of earlier studies of AMD patients, in which the use of customized eccentric refractive correction resulted in improved resolution and a subjective preference for the customized correction.[2,3]

The present study was performed to reconcile the seemingly conflicting conclusions between existing work on peripheral high-contrast resolution and our positive results from eccentric refractive correction. Because of the potential link between peripheral refraction and myopia, both myopes and emmetropes were included in the study. Based on our experience with AMD patients, it was expected that peripheral low-contrast resolution would depend on the amount of defocus, which forms the main hypothesis of the present study. The presence of such a dependency has not been investigated and would prove the benefit of eccentric refractive correction for AMD patients, as well as the possibility of a role for peripheral resolution in myopia development. The second hypothesis is that drifting gratings are easier to resolve, thus proving an additional benefit of moving text as a low-vision aid.[20] An unexpected result of the present study was that the myopes were found to be much more insensitive to peripheral hyperopic defocus than the emmetropes.

METHOD

Scope

We estimated the peripheral visual threshold 20° in the nasal visual field of right eyes as a function of defocus for both detection and resolution, with drifting and stationary targets in high and low contrast. The subjects maintained stable accommodation by fixating with their left eyes.

Subjects

Five subjects participated in the study. Informed consent was obtained beforehand, and the study adhered to the tenets of the Declaration of Helsinki. The ages and subjective refractions of the subjects were: (subject) PU, 43 years, −7.5 D; LL, 31 years, −3.5 D; RR, 26 years, −0.5 D; MB, 25 years, 0 D; and PS, 30 years, 0 D. None of the subjects had foveal astigmatism above 0.75 D, manifest strabismus, or other ocular diseases, and all were right eye dominant.

Experimental Arrangements

The setup is depicted in Figure 1, showing how the accommodation and fixation of the right eye was controlled with left eye fixation. The experiments were performed in a dark room with natural pupil size and a uniform background. The head of the subject was stabilized with a chin rest and turned toward the foveal fixation target. The left eye was blocked from seeing the stimulus, while the right eye was blocked
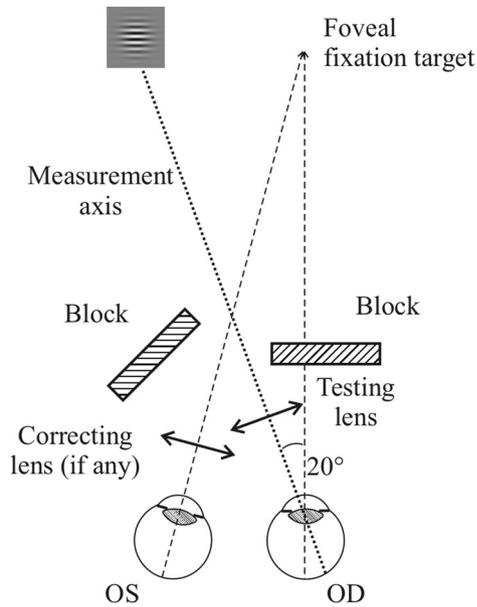
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FIGURE 1. The experimental setup. The foveal fixation target and the stimulus were at a distance of 3.15 m from the subject, and the blocks were less than 10 cm away. Two blocks occluded the stimulus for the left eye and the fixation target for the right eye, which ensured that fixation and accommodation were controlled by the left eye. Custom-made lens holders ensured proper alignment of the testing lens as well as the correcting lens that subjects LL and PU used.

from seeing the foveal fixation target. Thus, fixation and accommodation were controlled entirely by the left eye, and changing the testing lens did not affect the accommodative state of the subject. Both the foveal fixation target and the stimulus were placed at a distance of 3.15 m. The foveal fixation target was a mini display with a luminance of 14.5 cd/m^2 showing a Maltese cross. The stimuli were presented on a 19-in. CRT screen with a luminance of 68 cd/m^2, calibrated by using routines from the Psychophysics toolbox.[21,22] The two myopic subjects wore foveal correction for their left eyes. The testing lens frame was table mounted at an angle of 20° to the right eye. The distance between the testing lens and the eye was 20 mm.

To correct the off-axis astigmatism in the 20° nasal visual field, we mounted a cylindrical lens in the testing frame in addition to the spherical testing lens. The power of the cylinder was determined by an autorefractometer (PowerRefractor; Multi Channel Systems GmbH, Tübingen, Germany), which has been shown to give accurate estimations of off-axis astigmatism.[3,23–25]

Visual Stimuli

In all tasks, the stimulus consisted of a Gabor patch, a sine-wave grating multiplied with a Gaussian window of SD 0.6°, with the orientation randomly chosen to be either horizontal or vertical. The use of a Gabor patch ensured well-defined location and spatial frequency simultaneously; however, the contrast of the target and its width are less well defined.[26] These drawbacks were not a major limitation, since only high- and low-contrast, corresponding to a peak contrast of roughly 100% and 10%, were used in this study. The drifting gratings were produced by altering the phase, producing a speed of 2° per second. The Gaussian envelope remained stationary so the same retinal area was stimulated for both drifting and stationary targets. The stimuli were presented with a temporal square wave on- and offset, (i.e., there was no fading in or out). Commercial software (MatLab; The MathWorks, Natick, MA) and the Psychophysics Toolbox package were used to draw the stimuli and implement the psychophysical algorithm.[21,22]

The defocus sampling rate was 1 D, except for detection close to best focus where 0.5-D steps were used. Each visual task was tested in

a single session, but the order of the defocus values was random. Both the radius of the Gabor patch and the spatial frequency of the gratings were recalculated to take spectacle magnification into account: $m = 1/(1 - aF)$, with a as the vertex distance from the trial lens to the eye and F as lens power in diopters.

The detection tasks consisted of two-interval, forced-choice tests, with the intervals cued by sound with a presentation time of 1 second. The resolution tasks were two-alternative, forced-choice tests in which the subject had to determine the orientation of the grating. No feedback was provided, and the subjects were given ample opportunity to rest.

Psychophysical Algorithm

The psychometric function, or frequency of seeing, defined as the probability $P(x)$ of answering correctly given a stimulus of size x, was assumed to vary as a cumulative logistic function:

$$P(x) = g + \frac{(g - \delta)}{1 + e^{\frac{-(x - \mu)}{s}}}$$

The guess rate g was 0.5, as all experiments were forced choice with two options. The lapse rate δ was set to 0.02 for reasons discussed in detail by Wichmann and Hill.[27] The threshold μ and slope s were the quantities sought and x the stimulus size. All three are in logMAR units, and s was set to 0.04 logMAR, for reasons described in the Discussion section.

The psychophysical algorithm, defined as the method by which the spatial frequency of each consecutive stimulus is chosen on the basis of the previous results, was chosen to be that proposed by Konstevich and Tyler.[28] The algorithm estimates the probability density function of the threshold in 30 trials.

RESULTS

The PowerRefractor was used to measure the peripheral astigmatism and to perform a preliminary estimation of the spherical refractive error for all subjects, except PU, in whom it was impossible to measure because of the high myopia. For him, a Shin-Nippon (Tokyo, Japan) auto refractor was used instead, which has also been shown to accurately estimate off-axis refraction.[25] The results in the 20° nasal visual field of each subject was LL, −1.75 DS, −1.25 DC, axis 90; PS, −0.5 DS, −1 DC, axis 90; RR, −0.5 DS, −1 DC, axis 90; MB, −0.75 DS, −0.75 DC, axis 105; and PU, −7.5 DS, −2 DC, axis 112. The results demonstrate the well-known large cylinder with axis close to 90° that is due to the oblique incidence of the light. The optimum sphere, as determined subjectively by the spherical testing lens giving the best high-contrast detection threshold, corresponded to the sphere given by the preliminary refraction for subjects LL, MB, and RR, but not for subject PS and PU, who had optimum spheres of 0 D and −6.5 D, respectively.

Presentation

All defocus values shown in the figures were corrected for the vertex distance from the testing lens to the eye, and the defocus values were set to 0 at the subjectively determined optimum sphere for high-contrast detection acuity. Positive defocus means that the lens power was more positive than needed, which is equivalent to having myopic defocus. For comparative purposes, the data on all visual tasks for one subject are shown in Figure 2, and the data for all subjects are presented in Figure 3. In Figure 3, the results are presented as scatterplots, since the defocus induced was not identical among subjects because of the effects of the vertex distance and the differing optimum sphere. In Figures 3a–d it was
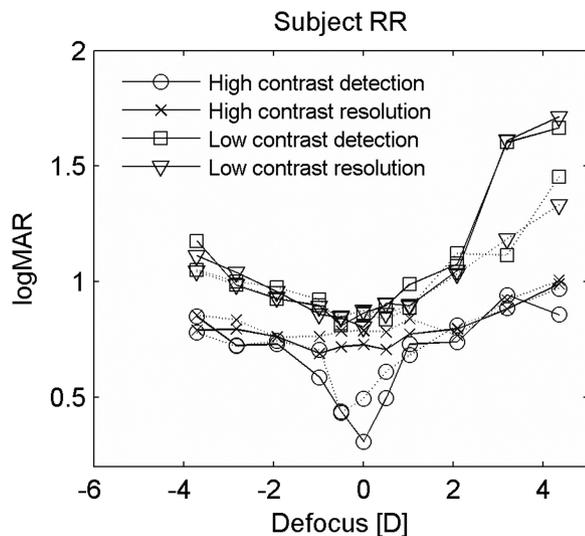
Subject RR

FIGURE 2. Acuity thresholds as a function of defocus for subject RR. Detection and resolution acuity were tested in high (close to 100%) and low (10%) contrast. *Dashed lines*: drifting gratings; *solid lines*: stationary gratings. Defocus values are corrected for vertex distance.

possible to interpolate an intersubject mean of the threshold in 0.5-D steps, which is plotted as a line. Because of the large variation between subjects in sensitivity to negative defocus, no mean is interpolated for the low-contrast tests in Figures 3e and 3f. The sensitivity to defocus was modeled in logMAR per diopter as a linear fit to the individual subject data. The results of the linear fits are shown in Table 1, giving the range of defocus sensitivity and whether the sensitivity differed in positive and negative defocus. The mean absolute residual error of the linear fit was 0.035 logMAR with an SD of 0.032 logMAR.

Defocus Affected High-Contrast Detection Acuity

All subjects exhibited a sharp, symmetric reduction in high-contrast detection acuity, with increasing defocus at an average sensitivity of 0.245 logMAR/D (Figs. 3a, 3b). At 0.8 to 1.0 logMAR, the decline leveled out, and detection acuity became more or less unaffected by defocus. On average, this effect occurred at 2-D defocus, ranging from 1 to 2.6 D. For drifting gratings, the mean sensitivity was 0.150 logMAR/D. The main difference between drifting and stationary targets was that the best corrected acuity is better for stationary gratings. Stationary gratings at best focus gave a mean detection threshold of 0.38 logMAR compared with 0.49 logMAR for drifting gratings. The leveling out around 2-D defocus occurred for drifting gratings as well.

Defocus Did Not Affect High-Contrast Resolution Acuity

The impact of defocus on high-contrast resolution acuity was asymmetric (Figs. 3c, 3d). Positive defocus gave a small reduction in acuity with a mean sensitivity to defocus of 0.08 logMAR/D. In contrast, the sensitivity to negative defocus was very low, with an average value of 0.03 logMAR/D. At high values of defocus, the curve closely followed that of high-contrast detection. On the other hand, at low values of defocus, there was a significant difference between high-contrast detection and high-contrast resolution acuity.

In Low Contrast, Positive Defocus Affected Acuity in All Subjects, but Negative Defocus Affected Acuity in Only Some Subjects

For the two persons who also tested low-contrast detection acuity, subject RR and LL, there was no difference between detection and resolution acuity, for either stationary or drifting gratings. Therefore, only low-contrast resolution acuity is presented (Figs. 3e, 3f).

For positive defocus, the acuity of all subjects behaved identically, with a mean sensitivity of 0.20 logMAR/D for stationary gratings and a mean sensitivity of 0.12 logMAR/D for drifting gratings. Contrary to high-contrast detection (where the acuity was better for stationary gratings at best focus) the low-contrast acuity was better for drifting gratings at large values of defocus and identical at best focus, resulting in the lower sensitivity of the drifting curve. No plateauing of the curve was discernable for drifting or stationary targets.

For negative defocus, the sensitivity varied highly among subjects—from hardly noticeable at 0.02 logMAR/D for subject LL to values identical with those for positive defocus for subject MB and PS. For the three subjects who were clearly affected by negative defocus (MB, PS, and RR), the impact of having the gratings drift was similar to that of positive defocus, with comparatively higher acuities at large defocus values.

DISCUSSION

Algorithmic Accuracy

There are three possible sources of algorithmic inaccuracy of the estimated thresholds: goodness of fit of the model function with the assumed lapse rate and slope of the sigmoid; the inherent uncertainty of the algorithm with a finite number of trials; and possible bias for a particular interval or grating orientation.

Normally, only the threshold μ is estimated and the slope-equivalent value s of the psychometric function is assumed a priori.[29] However, peripheral visual function has not been extensively investigated. To estimate the slope, a series of 10 experiments was therefore performed for subjects RR and LL with 300 trials (simulations showed this to be an adequate number for slope estimation) under various conditions, with the resultant slope being in the range of 0.02 to 0.08 logMAR, with a mean value of 0.04 logMAR and no task dependence. This value is comparable to the slope of the psychometric function in foveal tests[30] and corresponds to the steeper of the two peripheral slopes for one subject presented by Wang et al.[9]

With the slope fixed at 0.04 logMAR, the resultant probability density function for the threshold estimation was normally distributed, with an SD of 0.02 logMAR for 300 trials and 0.05 logMAR for 30 trials and with the fast convergence indicating an accurate estimation of the slope.

A perceptual bias for either horizontal or vertical stimuli may be the result of either inadequate correction of astigmatism or a neural preference. However, an analysis of the failed tests did not find any systematic preference for horizontal or vertical gratings, but rather a large intrasubject variation. Finally, gratings of logMAR values above 1.1 contain approximately six visible cycles within the Gabor patch, depending on the definition of its size[26] and therefore might have an increased uncertainty.[8]

Drifting Gratings

An earlier study found that discrimination of the direction of peripheral movement has a higher cutoff frequency than does resolution and, under defocus, more closely resembles the
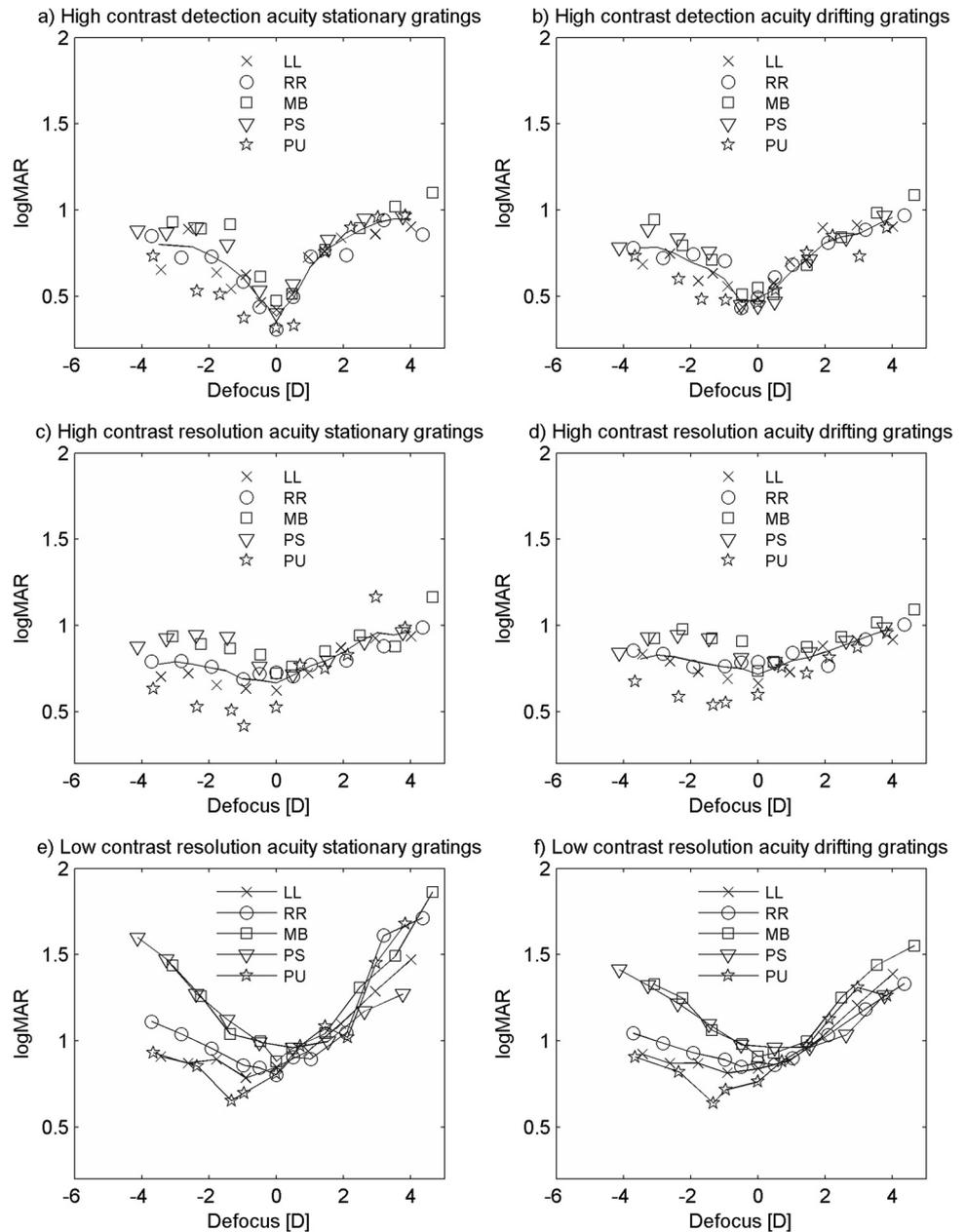
FIGURE 3. (**a–f**) Acuity thresholds as a function of defocus for all subjects under the various testing conditions. Defocus in the figure is defined as the induced peripheral defocus compared with the subjects' individual optimum sphere, as determined subjectively by the spherical testing lens giving the best high-contrast detection threshold, with the vertex distance taken into account. (**a–d**) *Solid line*: interpolated mean of all subjects. (**e, f**) The intersubject difference in sensitivity to negative defocus was >0.15 logMAR/D for the low-contrast tests, and so individual rather than interpolated mean lines are shown.

behavior of a detection task than that of a sampling-limited resolution task.[31] In addition, Artal et al.[10] found an absence of motion reversal in the peripheral field, suggesting that resolu-

TABLE 1. The Range of Sensitivity to Defocus for the Various Visual Tasks Tested

Visual Task	Sensitivity to Defocus
Detection, stationary, HC	0.175–0.315, mean 0.245
Detection, drifting, HC	0.108–0.190, mean 0.149
Resolution, stationary, HC	0.021–0.114, asymmetries
Resolution, drifting, HC	0.011–0.081, asymmetries
Detection, stationary, LC	Identical with LC resolution
Detection, drifting, LC	Identical with LC resolution
Resolution, stationary, LC	0.024–0.227, asymmetries
Resolution, drifting LC	0.020–0.170, asymmetries

Asymmetries mean that some subjects had unequal sensitivity to positive and negative defocus. Data are expressed in logMAR/D. HC, high-contrast tasks; LC, low-contrast tasks.

tion of drifting gratings may not be sampling-limited. Therefore, it was hypothesized that the movement direction cue would improve the performance of resolution tasks, even at high contrast. However, contrary to expectations, the benefit of having gratings drifting was limited to low-contrast tasks at high amounts of defocus. Conversely, detection acuity for well-corrected, high-contrast gratings had the drift, whereas in other visual tasks, the acuity for drifting and stationary gratings was identical. One explanation of why our results differ is that previous studies reporting an improvement for drifting targets have had them stimulating a larger retinal area than the corresponding stationary target, and stimulation of a larger retinal area will improve acuity.[32] Another possible explanation is that the important parameter is not the absolute velocity in degrees per second but rather the velocity relative to the grating frequency in cycles per second. For well-corrected, high-contrast detection, the grating frequency was high, and the speed in cycles per second so fast that temporal summation of the eye might be difficult. Assuming a temporal summation of 10 to 50

ms,[33] a drift of 2° per second corresponds to a movement of 0.02° to 0.1°. As logMAR 0.4 is equivalent to a line width of 0.04°, the faster-than-summation drift could explain the worse acuity. Finally, very large targets seemed to benefit from the drifting. There are two possible explanations for this: Either, a slow drift is beneficial when the drift speed is approximately 2 to 2.5 cycles per second, or the restrictions applied by the Gaussian apodization are too severe on stationary targets at such low spatial frequencies.

High-Contrast Detection Plateau

When the defocus is high enough, the detection curve plateaus and follows the resolution curve closely, as also found in other studies.[9] The fact that the detection acuity is affected by a change in defocus at low but not at high values may seem puzzling at first. However, the cessation of acuity loss with increased defocus can be understood through aliasing, which acts as a detection cue at spatial frequencies higher than the sampling limit. As previously documented,[34] detection by aliasing requires a higher retinal contrast than normal detection because of the spectral dispersion caused by irregular sampling. Therefore, there is a large dioptric zone with detection acuity at the sampling limit where the increased retinal contrast does not pay off, as it is still below the amount required by detection through aliasing.

Low-Contrast Sensitivity

The sensitivity to defocus for low-contrast resolution acuity exhibited by all subjects supported the main hypothesis of this study. This sensitivity has important clinical applications. Subjective refraction for AMD patients is traditionally performed with a high-contrast resolution task.[35] The use of the same resolution tasks in low-contrast instead has the potential to improve the accuracy and speed of subjective eccentric refraction, without altering the current refraction techniques. Furthermore, the sensitivity to defocus for low-contrast peripheral vision demonstrates the importance of accurate refractive correction, even for patients with large central scotomas.

Asymmetries

There is a weak asymmetry for high-contrast resolution, as the sensitivity to negative defocus was lower than that of positive defocus. This asymmetry is also present in the data reported by Wang et al., [9] although not discussed in their article.

For low-contrast tasks, the asymmetry was larger. The threshold data for positive defocus exhibited low intersubject variability (all were around 0.20 logMAR/D), whereas the data for the impact of negative defocus must be considered individually. Subjects MB and PS had symmetrical curves, whereas the sensitivity to negative defocus was 0.09 logMAR/D for subject RR and as low as 0.05 and 0.02 logMAR/D for subjects PU and LL. This large asymmetry is hard to understand. The results were repeatable, as retesting of the low-contrast tasks for subject LL on different days yielded identical results. The asymmetry is so large that neither induced accommodation (the asymmetry was present in the two oldest subjects) nor asymmetric depth of field (e.g., by spherical aberration) seem likely.

Speculatively, it is worth noting that the asymmetry was clearly largest for the two myopic subjects PU and LL. Similarly, an asymmetric impact of defocus for myopes but not emmetropes has been found by Radhakrishnan et al.[36] when testing foveal high-contrast resolution, although the asymmetry was not as large as in our peripheral low-contrast results. One possible explanation as to why myopes are less sensitive to negative defocus may be neural adaptation to their normal correction. In this study, the individual habitual correction for each myopic subject has been stable for more than 5 years,

with subject LL primarily wearing spectacles and subject PU contact lenses, whereas subjects RR, MB, and PS had no habitual correction. Negative lenses, which compensate for foveal myopia, tend to place the peripheral image behind the retina[37] and after years of daily wear, the visual system might have adapted more to negative than to positive defocus. However, asymmetries in the impact of defocus of different signs are generally interesting in the process of emmetropization, as it is still not understood how the eye can determine whether the image plane lies in front of or behind the retina.[7] In a recent study, Ohlendorf and Schaeffel[38] discussed the possibility of defocus-induced contrast adaptation in the fovea to act as such a cue.[38] Their results showed an asymmetry that can be understood in the light of this study; an eye that is less sensitive to blurring by negative lenses will show no or smaller contrast adaptation when exposed to blur formed by negative lenses compared with positive lenses. Although Ohlendorf and Schaeffel found asymmetric contrast adaptation in both emmetropic and myopic subjects foveally, their finding does not rule out the possibility of a difference between myopes and emmetropes peripherally. However, too little is known about the peripheral eye to determine whether an asymmetric peripheral sensitivity to defocus can actually cause an eye to grow myopic.

Conclusion

In this study we performed psychophysical measurements of the peripheral visual function for different tasks involving detection and resolution of stationary and drifting gratings in high and low contrast. The amount of optical blur was varied by spherical lenses and, contrary to the traditional belief, we found that peripheral optical errors as small as a 1 D have a large impact on most visual tasks. Actually, the indifference to optical blur evident in high-contrast resolution tasks seemed to be an exception rather than a rule. This fundamental discrepancy between high-contrast resolution and other visual tasks is important to have in mind when trying to understand the impact of peripheral optical errors on the visual system. Our everyday visual scenery consists of objects at different contrast levels, which is the reason why, for example, many persons with central visual field loss are helped by a correction of their peripheral refractive errors.[2,3] The study also revealed some new and surprising results regarding the movement of the gratings and the sign of defocus; having drifting instead of stationary gratings does not give a general improvement of the visual function and being defocused by positive instead of negative lenses seemed to degrade vision more, especially in the myopic subjects of this study. It is too early to say whether this asymmetric sensitivity to defocus can affect the emmetropization process and be linked to the development of myopia, but it shows the need for further studies on the relation between peripheral optical errors and our visual function.

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