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ORIGINAL ARTICLE

Eccentric Correction for Off-Axis Vision in Central Visual Field Loss

JÖRGEN GUSTAFSSON, OD and PETER UNSBO, PhD

Certec, Division of Rehabilitation Engineering Research, Department of Design Sciences, Lund University, and Biomedical and X-ray Physics, Royal Institute of Technology, Stockholm, Sweden

ABSTRACT: *Background.* Subjects with absolute central visual field loss use eccentric fixation and magnifying devices to utilize their residual vision. This preliminary study investigated the importance of an accurate eccentric correction of off-axis refractive errors to optimize the residual visual function for these subjects. *Methods.* Photorefraction using the PowerRefractor instrument was used to evaluate the ametropia in eccentric fixation angles. Methods were adapted for measuring visual acuity outside the macula using filtered optotypes from high-pass resolution perimetry. Optical corrections were implemented, and the visual function of subjects with central visual field loss was measured with and without eccentric correction. *Results.* Of the seven cases reported, five experienced an improvement in visual function in their preferred retinal locus with eccentric refraction. *Conclusions.* The main result was that optical correction for better image quality on the peripheral retina is important for the vision of subjects with central visual field loss, objectively as well as subjectively. (Optom Vis Sci 2003;80:535–541)

Key Words: aberrations, oblique astigmatism, central scotoma, central visual field loss, central field loss, eccentric correction, eccentric fixation, preferred retinal locus,

Peripheral vision is invaluable for people with reduced central vision. It can never replace direct or central vision, but people with a central visual field loss (CFL) (central scotoma) can, despite this and to a limited extent, read, do needlework, and watch television with magnification devices. No real efforts beyond the use of magnification have ever been attempted to optically improve their peripheral vision. It has often been assumed that such efforts would make no difference anyway because the peripheral portion of the retina has limited resolution capacity. At the same time, it has been obvious to clinicians and others who work in the area of low-vision rehabilitation that people with central scotomas actively make use of their peripheral vision. This is evident from how they fixate eccentrically in orientation and discrimination of objects and text. Reading training with magnifying devices has been used in low-vision rehabilitation for many years.[1, 2] Different ways of training eccentric fixation with the help of new technology have also been introduced.[3–5]

A number of researchers have measured the off-axis optical aberrations in the eye,[6–10] and there have been some attempts to correct them in healthy eyes, but little or no visual improvement has been found for the most part.[10–13] Two exceptions are the improvements in motion detection and orientation that seem to be limited by the refractive errors in the peripheral optics of the eye.[14, 15] It has also been shown that there are optical limitations to the detection of sinusoidal gratings in peripheral vision.[16] Recent experiments have indicated that detection acuity varies strongly with defocus, whereas resolution acuity for high-contrast targets is robust against refractive blur in the periphery.[17] The dominating optical aberrations in the peripheral eye for large angles are field curvature and oblique astigmatism. These aberrations result in an effective eccentric refractive error. The most prominent difference compared with central refraction is an induced astigmatism in the periphery. The aim of this study was to investigate whether eccentric correction of refractive errors is important for the visual function in CFL subjects who use eccentric fixation.

METHODS

Subjects

Peripheral refraction was measured in 38 CFL subjects, and seven subjects were selected for peripheral correction. The selection was based on the following criteria: the subjects had been visually impaired for a long time, they had large total CFL in both eyes, and they were using one preferred retinal locus (PRL) with a conscious eccentric fixation and with an oblique astigmatism >1.0 D at the PRL. The age of the seven subjects ranged from 17 to 72 years. Four subjects had macular degeneration: age-related in subjects 4 and 5 and hereditary in the two younger subjects 1 and 2.

had hereditary degeneration. The diagnosis in subject 6 was Stargart's disease, and subjects 3 and had 7 Leber's opticus atrophy. The subjects had a CFL from about 10° to 30° in radius.

The study followed the tenets of the Declaration of Helsinki and was approved by the local research ethics committee. All subjects gave informed consent before participation.

Eccentric Refraction

The peripheral refractive errors were measured with the PowerRefractor instrument (Multi Channel Systems GmbH, Tübingen, Germany). The measurement principle is based on photorefraction where the light from a small source near a camera's objective is reflected from the retina. Six segments with infrared LED's are mounted in a circle around a camera objective. The instrument software analyzes the illumination of the pupil and calculates the refractive error. The measurement takes place in real time at a working distance of 1 m. Unlike many autorefractors, the PowerRefractor is able to carry out measurements even when the fixation is not central. Changes in astigmatism are clearly seen between different fixation points. The instrument can measure from the optical axis and to about a 30° eccentric angle. The reliability of the measurement values is documented and has proven to be particularly accurate for astigmatism.[18]

To guide and stabilize the gaze direction for CFL subjects with no central vision, a fixation pattern with large, concentric rings and support lines vertically and horizontally was used (Fig. 1). This target was designed with the help and experience of several subjects with CFL. The fluorescent pattern was centered around the camera head of the PowerRefractor and was illuminated by ultraviolet light that does not interfere with the infrared-sensitive camera. The rings cover a field of view of 25° in radius, with the five rings placed at 5°, 10°, 15°, 20°, and 25°. The measurements were performed with natural pupils under reduced room light conditions.

To keep the eye in a stable eccentric fixation direction, the participants were encouraged to look sideways at the angle that they usually use to see straight ahead, i.e., to try to look at the camera using their normal eccentric fixation and thus put the image of the camera at their PRL. For those who were already aware of how they fixated and only had one habitual fixation point, it was easy to place the scotoma 20° upward, for example. At this point, the fourth ring from the center meets the vertical line and the subject redirects his gaze to not see this juncture. The eccentric angle of fixation is registered in the PowerRefractor in relation to the optical axis of the eye. Fig. 2 shows an almost central PowerRefractor measurement (left) and a measurement at approximately 20° upward fixation (right)

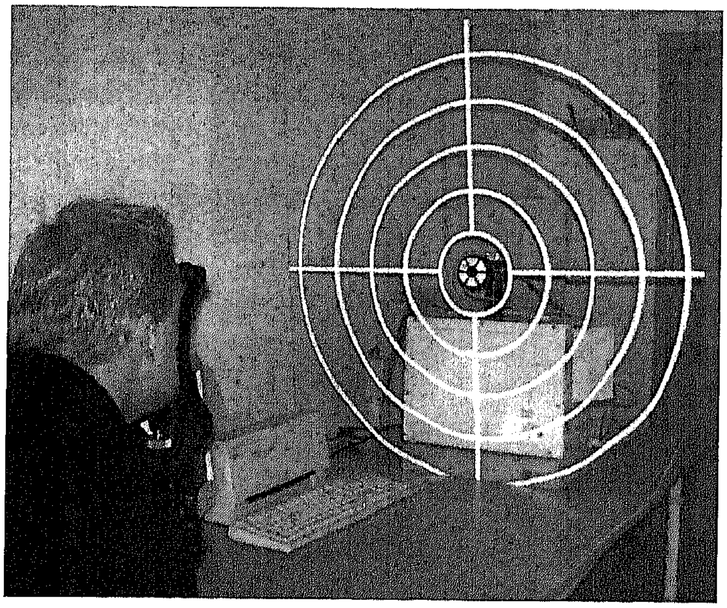

FIGURE 1.

Measurement of eccentric refraction with the PowerRefractor. The yellow fluorescent fixation rings help to keep the subject's gaze stable. The subject-screen distance is 1 m.

Eccentric Correction

In all subjects, the dominant eye with highest acuity was measured. The other eye, which was worse in all subjects, was not used for anything more than orientation, and mobility and was not corrected. The mean value of the refractive error from at least three different measurements was used for the correction. The prescribed eccentric correction was mounted in normal spectacle frames for one angle of oblique fixation. For the majority of the cases, this was the habitual fixation angle and corresponded to the preferred retinal locus.

Measurements of Acuity

To control the fixation direction, it was desirable to implement an acuity measurement in a situation similar to the refraction measurements. This called for individually presented targets. The standard ring targets from high-pass resolution perimetry (HRP)[19,20] were chosen to accurately measure the peripheral acuity. Such rings have previously been used to measure peripheral acuity in two healthy eyes out to 50°.[21] A computer screen with calibrated luminance replaced the PowerRefractor camera in the center of the fixation rings, and a single ring-shaped high-pass spatial frequency filtered target was presented (Fig. 3). The subjects placed their scotoma on the same fixation ring as when their eyes were measured for refractive error. The distance to the computer screen was again 1 m. Special software was used to display the ring targets on the screen and to calculate the acuity. The rings were set to flash only one time for 165 ms, with a constant contrast level of 0.9 (90%), at a background luminance of 20 cd/m^2. The rings can be displayed in 22 different sizes corresponding to an acuity from 20/90 (1/4.5) to 20/1400 (1/70).

A set of 50 rings with sizes close to the estimated acuity level was displayed. Size was varied by 0.05 log units in a pseudo-random sequence. The subject reported each time he/she detected a ring. The 50% thresholds and 95% confidence intervals for the minimum resolved angle were obtained by probit analysis in minutes of arc. The acuity measurement was performed in reduced room light conditions with natural pupils. Ring target acuity, both with the habitual central correction or uncorrected and with eccentric correction, was measured with reasonable precision on three different occasions for all subjects.

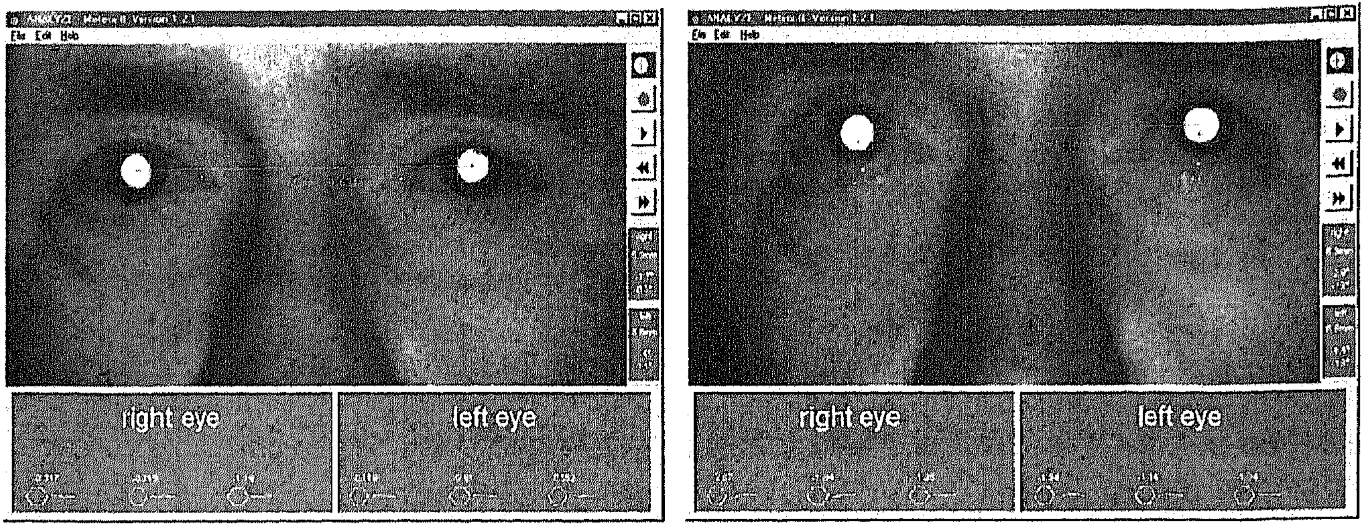

FIGURE 2.
Measurements of central refraction (left) and eccentric refraction (right) about 20° eccentric fixation in an upward direction. The fixation direction (displayed on the right in each picture) is registered at the same time as the refractive error.

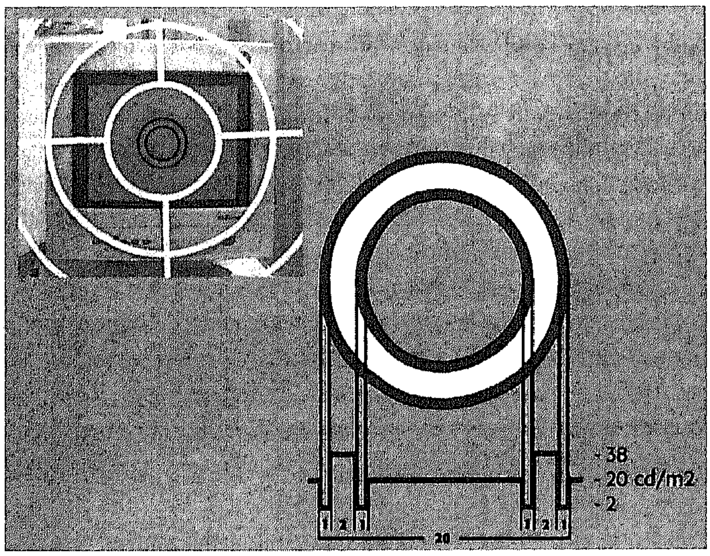

FIGURE 3.
HRP target proportions and luminance distribution at 0.9 contrast. The subject's task was to signal all rings seen. Nonresolved rings become invisible because the average luminance of the ring target is the same as the background.

Contrast Sensitivity

The Pelli-Robson test[22] was used to estimate the contrast sensitivity function in log contrast sensitivity units. The test distance was 1 m, but for one of the subjects, it was necessary to use a shorter distance. The letters with higher contrast in the upper part of the test charts were mainly used for these subjects. The measurement was carried out with natural pupils in a bright room, one time with the subject wearing central correction, and one time with eccentric correction. The contrast sensitivity function test in this preliminary study was not intended to give detailed quantitative measures, but rather to show another important aspect of eccentric correction vs. central correction.

RESULTS

There is a substantial amount of astigmatism induced by eccentric fixation that generally increases with the oblique angle. Table 1 shows the eccentric correction for all seven subjects, based on the mean value from at least three different measurements of the refractive error. All subjects except 3 and 6 also had a central refractive error with a previously prescribed spectacle correction. In subjects 3 and 6, there was only a small astigmatism in the central refraction, about 0.5 DC, with axis approximately 90° against the eccentric refraction. The subjects who previously had a central correction almost never used them with the exception of subject 2.

It was possible to demonstrate statistically significant visual improvements in five of seven corrected subjects with the ring target acuity test. The measurements were repeated three times to con-

TABLE 1.
Central and eccentric corrections for the most-used eye in the seven subjects who were corrected.[a]

Subjects	Eye	Central Correction	Eccentric Fixation Angle	Eccentric Correction
1	OD	+2.00 −1.00 × 25	30° right	+4.00 −4.00 × 90
2	OS	−3.75 DS	18° right	−2.00 −3.00 × 90
3	OD	none	13° up	+3.00 −1.50 × 160
4	OD	+2.00 DS	20° right	+5.00 −5.00 × 90
5	OD	−1.25 DS	20° right and 8° up	−1.00 −4.00 × 90
6	OD	none	22° right	−1.00 −2.00 × 80
7	OS	−1.50 DS	20° up	−1.00 −2.00 × 175

[a] Central correction was almost never worn except in subject 2. For all subjects there was a higher and different astigmatism in the eccentric direction.

firm the results. Table 2 shows the results and the reproducibility of the measurements. All subjects except 4 and 7 showed an improvement. Despite the large eccentric astigmatism of 5 DC in subject 4, no change in acuity was found. In subject 7, eccentric astigmatism 2 DC, there was also no change in acuity, but there was a small improvement in contrast sensitivity.

A majority of the test subjects, again five of seven, showed improved contrast sensitivity with the Pelli-Robson test (Table 3). These five are the same as the ones who showed improvement in acuity with one exception; in subject 6 there was only an improvement in acuity, whereas subject 7 only showed improved contrast sensitivity. Subject 4 showed no change in acuity and also no improvement in contrast sensitivity. In subjects 3 and 5, the improvement in contrast sensitivity was larger, two steps on the Pelli-Robson chart.

The subjective experiences of the subjects involved in this study were interesting in many ways. One of the most encouraging was that guide vision ability (mobility) improved in two of them. The improvement in visual function obviously influenced daily living activities. Some reported positive effects that we were unable to measure, such as improved balance. Two of the subjects reported improved stability when walking. All subjects described how they could see better when watching television and, for some, even when using the computer. The eccentric corrections made it possible for four subjects to better recognize faces. Table 4 summarizes the results of the subjective experiences and the outcome of the acuity and contrast sensitivity measurements for the seven test subjects. Several persons in the larger group of 38 subjects were able to find a better fixation after receiving simple guidance and have become considerably more aware of possible directions of fixation that enable them to make better use of their remaining vision. However, the results in the seven subjects presented compared the use of central and eccentric correction in a single PRL and were not an effect of finding a better PRL. These seven subjects had a conscious eccentric fixation for many years and a well-established PRL.

TABLE 3.
Changes in contrast sensitivity with and without eccentric correction measured in log contrast sensitivity units using the Pelli-Robson chart at a distance of 1 m (subject 1, 50 cm).

Subject	Central Correction	Eccentric Correction
1	0.30	0.45
2	0.90	1.05
3	0.45	0.75
4	1.05	1.05
5	0.30	0.60
6	1.05	1.05
7	0.90	1.05

DISCUSSION

The most important result of this study is that the limitation of peripheral vision, for the present group of seven CFL subjects, is not entirely on the neural level. The optical corrections and the improvements in visual function that they produced show that it is important to measure and correct off-axis refractive errors in the direction of the trained eccentric fixation. Persons with CFL who actively use eccentric fixation are the ones who can benefit the most from a better image quality outside the macula. During the screening to find the subjects for this study, it was clear that if subjects with large CFL have any distance correction, it has been prescribed using central (foveal) refraction. In the larger group of 38 subjects,

TABLE 2.
Visual acuity with and without eccentric correction for the seven subjects measured on three occasions.[a]

Subject	Visual Acuity					
	Measurement 1		Measurement 2		Measurement 3	
	Central Correction	Eccentric Correction	Central Correction	Eccentric Correction	Central Correction	Eccentric Correction
1	1/40 (1/43–1/35)	1/26 (1/29–1/23)	1/43 (1/45–1/38)	1/30 (1/31–1/26)	1/45 (1/47–1/40)	1/32 (1/37–1/28)
2	1/18 (1/19–1/17)	1/16 (1/17–1/15)	1/19 (1/21–1/18)	1/14 (1/17–1/13)	1/20 (1/21–1/18)	1/14 (1/16–1/13)
3	1/35 (1/41–1/30)	1/24 (1/29–1/22)	1/30 (1/31–1/28)	1/21 (1/26–1/17)	1/33 (1/37–1/30)	1/23 (1/25–1/21)
4	1/18 (1/21–1/16)	1/18 (1/22–1/17)	1/20 (1/23–1/17)	1/21 (1/24–1/18)	1/18 (1/20–1/16)	1/19 (1/21–1/16)
5	1/32 (1/36–1/29)	1/21 (1/23–1/19)	1/30 (1/32–1/28)	1/21 (1/23–1/19)	1/32 (1/34–1/28)	1/19 (1/21–1/18)
6	1/16 (1/17–1/14)	1/12 (1/13–1/11)	1/16 (1/16–1/14)	1/13 (1/15–1/12)	1/14 (1/15–1/10)	1/11 (1/12–1/9)
7	1/17 (1/18–1/15)	1/17 (1/17–1/16)	1/23 (1/30–1/19)	1/21 (1/23–1/17)	1/20 (1/24–1/15)	1/18 (1/19–1/15)

[a] The values in parentheses show the 95% confidence interval. All values are converted from the minimum angle resolved in minutes of arc to equivalent fractional acuity values for a testing distance of 1 m.

TABLE 4.
Subjective experiences and measured improvements in the seven subjects are marked with an X.

Subject	Improved Guide Vision	Easier to Watch Television	Easier to See Faces	Detect Objects Further Away	More Stable Gait	Improved Acuity	Improved Contrast Sensitivity
1	—	X	—	X	—	X	X
2	X	X	X	—	X	X	X
3	—	X	X	X	—	X	X
4	—	X	—	—	—	—	—
5	X	X	X	X	X	X	X
6	—	X	X	X	—	X	—
7	—	X	—	X	—	—	X

only one or two had optical corrections similar to the eccentric correction that was found. In the group with an eccentric angle >10 to 15°, we did not find a single subject who had been prescribed correction for the oblique astigmatism. The reason for these findings can be a widespread ignorance of the difference between central and eccentric refraction and, thus, the importance of a well-controlled eccentric fixation. Objective refraction of an eye with CFL always requires that the clinician consciously measures in the direction of the PRL. Ideally, on the other hand, a careful subjective refraction of the CFL subject would automatically give the right eccentric correction because the subject would use his/her PRL during the examination. However, most CFL subjects do not have a stable, well-defined PRL. The fixation and, consequently, the refractive error will therefore vary during the refraction process, and the values will be unreliable. Furthermore, it can be difficult to carry out accurate subjective refraction in larger eccentric angles due to the simple fact that it is harder for the subject with a large CFL to judge the best focus.

The PowerRefractor instrument has been most useful for this work. It readily gives information about how the refractive state changes with fixation direction, and it also works as an eye tracker. The ability to check the angle of fixation in relation to the optical axis of the eye makes it possible to carry out repeated measurements in the same oblique angle. The fixation target surrounding the photorefraction camera in the current setup also makes it easier for the subject to have a stable eccentric fixation. In comparison, many of the clinically used autorefractors have a closed-field design and thus have limited possibilities to allow eccentric fixation targets. Retinoscopy is otherwise one of the most common objective methods for measuring refractive errors. Rempt et al.[9] used retinoscopy for eccentric refraction in a large group of subjects in oblique angles to 60°. The method works very well for central vision and for lower eccentricities. In larger off-axis angles, the oblique aberrations may split the reflex and make it more complex to interpret.[9] Other possible objective methods for eccentric refraction include (old) manual optometers (refractometers), open-field autorefractors and new technologies such as wavefront sensing. Manual optometers have been used in several investigations of off-axis refractive errors, demonstrating that astigmatism is common if the light enters the eye at an oblique angle.[6, 8, 23]

More recent studies on peripheral refraction and aberrations have often been based on the double-pass method.[24] Although this method has not yet been implemented as a clinical instrument, it has provided insight into the peripheral optics of the eye. A study of 20 emmetropic eyes showed that even in eyes with central emmetropia, there are great individual variations in the periphery. At an eccentric angle of 60° there are individual differences up to 10 D of astigmatism.[25] This means that it is not possible to simply calculate the eccentric correction from the central refraction and the fixation angle. From double-pass measurements, it is also clear that there can be a considerable amount of coma and other higher-order aberrations in the peripheral eye.[26]

A large amount of coma, for example, will make the PowerRefractor readings less reliable. This could be one explanation for the variation in the outcome of the implemented eccentric corrections. In this respect, it would be interesting to compare the PowerRefractor results with subjective refraction and complete aberration measurements with wavefront sensing.[27] Another factor that affects the influence of eccentric refractive correction is the pupil size. The larger the pupil, the more blurred the optical image for a given amount of ametropia. Thus, the visual benefits of eccentric correction are strongly dependent on pupil size. In this study, however, the pupil size was not controlled or registered.

The acuity measurement with HRP is a simple detection task, but it was originally asserted that the special filtered target has very similar detection and resolution thresholds.[21, 28] The argument is that when the target no longer can be resolved, it also vanishes due to the pseudo high-pass filtering, which eliminates the overall luminance cue. This argument is valid as long as resolution is limited by the level of retinal contrast produced by the optical system of the eye. Although this is the case in foveal vision, several authors have shown that detection thresholds are higher than resolution thresholds in the peripheral eye due to the fact that resolution is instead limited by the sampling density of the retinal ganglion cells.[17, 29] However, the magnitude of the difference between the two thresholds depends on stimulus properties. A decrease in the number of cycles, the contrast, or the luminance levels in the stimulus will reduce the detection threshold to a point where it eventually aligns with the resolution threshold, and both will be contrast limited.[29, 30] Due to its construction, the HRP stimulus itself cannot be used as a discrimination task. But recently, it has been suggested that at the normal 25% stimulus contrast and 20 cd/m^2 background luminance, the HRP threshold may be regarded as equivalent to a theoretical resolution threshold.[30] In the present study, the normal conditions for HRP were used, except that the stimulus contrast was 90%. At this increased contrast level, it is not clear whether the measured thresholds can be considered equivalent to resolution.

In the assessment of acuity, five of the seven selected subjects displayed an improvement on the ring target test with eccentric correction compared with central correction. These five have also expressed more extensive subjective improvements of their visual function. Considered as a measure of resolution threshold, the improvement in ring target acuity seems to be in conflict with the results in healthy eyes with intact central vision, as determined by Wang et al.[17] They found that peripheral detection acuity varies with defocus, whereas peripheral resolution acuity is largely unaffected by defocus. However, the study by Wang et al.[17] used large sinusoidal grating patches corresponding to 15 to 40 cycles at the detection limit, a background luminance of 55 cd/m^2, and a subject-controlled viewing time. The HRP stimuli correspond to about one or two cycles. The present study also used a 20-cd/m^2 background and a 165-ms exposure. Both studies used high-contrast stimuli. The results of the different settings are clear when the detection and resolution thresholds of the two studies are compared. At 20° eccentricity, the gratings showed a detection threshold of about 15 cpd with optimal focus and a sampling limited resolution threshold of about 4 cpd. At 30°, the corresponding values were about 8 cpd and 2.5 cpd. In comparison, with optimal eccentric correction, the HRP detection/resolution acuities found in the present seven subjects are equivalent to about 1 to 2.5 cpd. It is then possible that the HRP detection threshold is aligned with the resolution threshold and that both are below the theoretical sampling limit and both contrast limited.

Compared with the variation in detection acuity with defocus found by Wang et al.,[17] the measured improvements in HRP acuity with eccentric correction are low, considering the large difference in central and eccentric refraction in the seven subjects. For example, if 4 DC of eccentric astigmatism is considered equivalent to 2 DS spherical defocus, one would expect an improvement in acuity with a factor of about 2 to 2.5 given the results of Wang et al.[17] However, there was only an improvement of about 50% in subject 5. This could be explained by the fact that the symmetric HRP stimulus may be very robust to astigmatic errors. The possible benefit of eccentric refraction and correction for the individual subject will then be underestimated.

The problem with much of the older literature on peripheral refractive correction[10–13] is that it did not differentiate between resolution and detection tasks. To an even lesser extent, did it consider whether a given resolution task was contrast limited or sampling limited and, therefore, whether the corresponding detection task could be considered as an equivalent measure of resolution or whether the stimulus would be detected through aliasing in the retinal sampling process. This can explain why some earlier studies found little or no visual improvement with peripheral refractive correction. Clearly, any contrast limited task, such as the one used in this study, will show an improvement with correction, whereas a sampling-limited task will not.

Contrast sensitivity, which is important in daily living, improved for five of the seven subjects. It is interesting to note that four of the seven subjects also claimed to be better able to recognize faces, a task that is strongly dependent on the contrast sensitivity function. Perhaps this is the most important visual function to evaluate when central vision is lost.

One possible explanation as to why all subjects expressed an improvement in watching television can be that they are stationary while doing so. In this very controlled situation, they made use of their vision only in the direction for which the eccentric correction was measured. This correction can, however, be entirely wrong in other directions of fixation. The eccentric corrections produced the best results for the two subjects who only had a single direction of eccentric fixation all the time. These two people wore their glasses with eccentric correction all day. When there are several eccentric fixation angles and the person alternates between them, more advanced ways of correcting the oblique astigmatism and defocus need to be developed.

In addition to the eccentric refractive corrections of the seven selected subjects, this study also resulted in a number of other subjects becoming aware of how they should fixate to make better use of their remaining vision. It is reasonable that methods should be developed in low-vision rehabilitation that enable as many patients as possible to discover their best direction of eccentric fixation.

This limited study shows that in low-vision rehabilitation of CFL subjects, a category that actively relies on eccentric fixation, it is important to recognize the difference between central and eccentric refraction/correction. There are large individual variations in peripheral refraction and the use of refractive correction for foveal vision may result in a significant refractive error in the PRL that negatively affects the residual visual function. To confirm the results, several more CFL subjects need to be measured and corrected. There is also a need to develop more precise measurement techniques, especially for the optical measurements in the peripheral eye, as well as for assessing the remaining visual function outside the macula. Wavefront sensing techniques can be used to study the higher-order aberrations, and the effects of eccentric correction on reading with magnifying devices could be one important evaluation of the visual benefit.

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Jörgen Gustafsson
Certec, Division of Rehabilitation Engineering Research.
Department of Design Sciences
Lund University
P.O. Box 118
221 00 Lund
Sweden
e-mail: jorgen.gustafsson@certec.lth.se