Eccentric correction in central visual field loss

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Certec
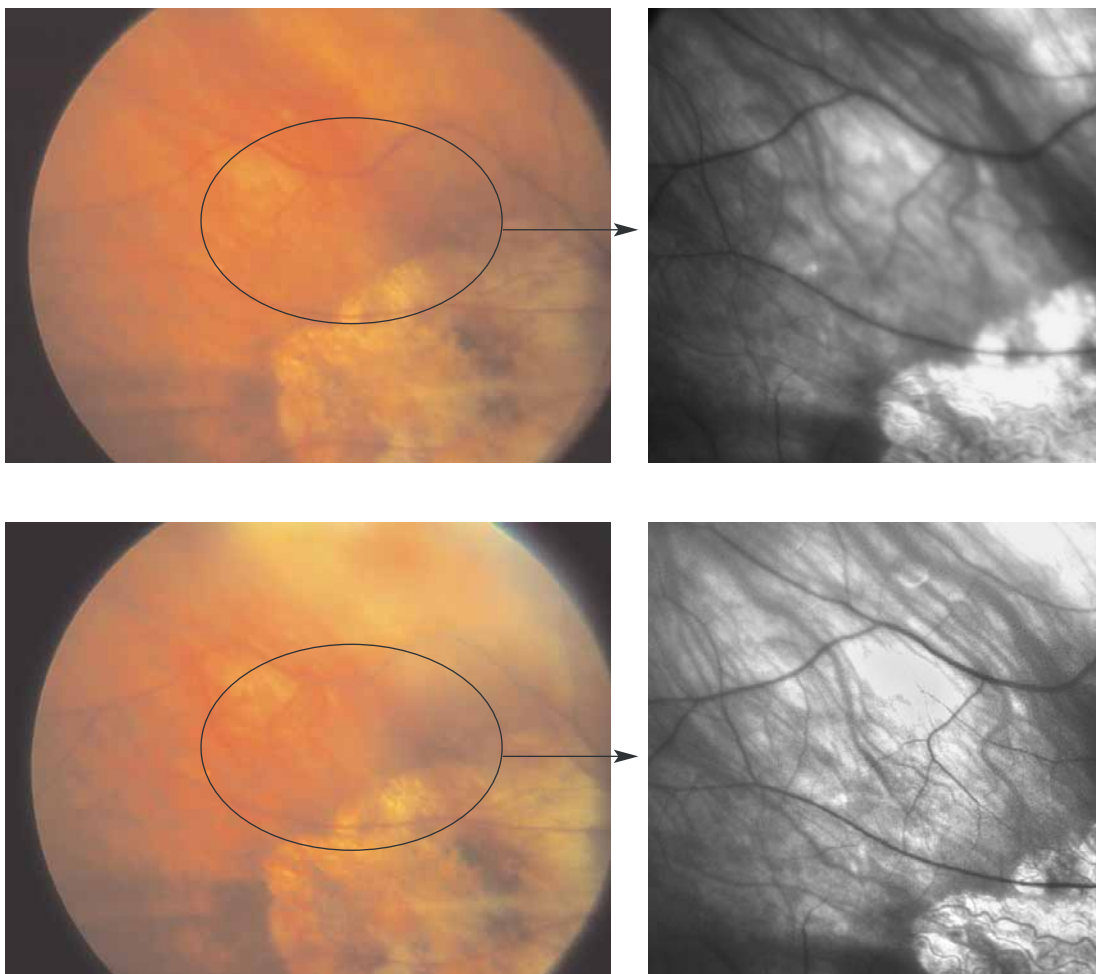
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Jörgen Gustafsson

Eccentric Correction
in Central Visual Field Loss

Preface

I never planned or even thought about the possibility of ending up in the academic world since my background is far from academic. When I first came in contact with Certec and Bodil Jönsson in my work at the Low Vision Center in Jönköping, Sweden, a new world opened up for me. Seeing these researchers and their unique ways of thinking, I couldn't resist joining up and perhaps even taking on challenges that I would never have done otherwise. Arguing against two professors in a discussion about optics means that you have to dare to stand up to and convince them. In those days all it took was practical and clinical experience as well as an interest in testing out new ideas. Because you do not know until you have tried.

When my work on the Widesight's Project became so interesting that it consumed much of my free time, I realized that it was time to concentrate on research and development. I still find it hard to believe that I am a researcher and doctoral student at a university. I have the advantage of working in a very creative climate and of receiving an incredible amount of support from my advisor and others in my surroundings.

Aspects of the project have been controversial, and there has been no lack of criticism. This has perhaps spurred us on even more, and why it is such a great joy to be able to present the first results at this time. After many years' work with visually impaired people who see for the most part with their peripheral vision, I have often contemplated why there are such great differences between individuals even though, according to their records, they have the same impairment. I have suspected for a long time that there could be optical explanations for some of these differences. Now we know that it is so, because now we can measure the optics of the eye more accurately, its limitations and its capabilities. This would not have been possible without the support we have received from people who themselves have a central visual field loss. By listening to them, the true experts, I have learned an incredible amount. I would like to take this opportunity to thank all the participants in the study, especially those who are described here, and to all the others who in different ways have contributed to the progress of this research. A special thanks goes to Krister Inde, low vision teacher, not only for being a subject but also for the many excellent suggestions and cooperation that resulted in new methods. Low vision centers, particularly those in Skåne and the one in Sundsvall (principally Dr. Marlene Lindberg, ophthalmologist), optometrists and eye clinics have helped constructively the entire time.

The biggest thanks, of course, goes to my advisor, Professor Bodil Jönsson. Because of her support, I was accepted as a graduate student in the first place. Or perhaps I should rephrase that and say that she gave me the self-confidence needed to accept the challenge. I am also

Summary

The main result of the research presented here is that optical corrections for better image quality on the retina in persons with a central vision loss can significantly improve eccentric vision, objectively as well as subjectively. Methods have been developed for measuring visual acuity outside the macula, optical corrections have been carried out and the visual function of a number of test subjects with central scotoma has been measured with and without eccentric correction.

The findings diverge from the previously held conception that optical correction outside the macula had no effect on visual function, since it was generally accepted that all loss in visual function was restricted to retinal structure. The poor optical image quality on the retina outside the macula, with its low density of receptors has been assumed to be of minor significance.

The results of this research have been made possible through the cross-disciplinary efforts of people with a variety of expertise. The field of low vision optometry has joined forces with the optics of physics; practical visual rehabilitation with the theoretical. The Lund Institute of Technology and The Royal Institute of Technology in Stockholm have worked closely together. This has not only resulted in a number of successful case studies, but also a number of new measurement methods for peripheral eye optics (and resulting correction), as well as methods for measuring eccentric vision.

This licentiate thesis is a summary of the work accomplished to date but by no means constitutes the final results. Work continues with unabated strength. The next step is measurements of peripheral optics in the eye with another method developed in an optical laboratory, with which we hope to be able to measure even further out in the periphery of the visual field. Additional case studies of eccentric optical measurement, optic corrections and measurements of visual function will be carried out. The large numbers of people with reduced central vision make it important that easier methods of measurement are also developed for use by low vision centers and optometrists in the future, as well as better possibilities for eccentric correction.

Purpose

The purpose of this research is to improve peripheral vision in people with central visual field loss (CFL). This can be broken down into three areas:

1. MODELS, MEASUREMENT METHODS AND CLINICAL MEASUREMENTS OF PERIPERIAL OPTICS

To develop methods of measurement for studying the optics of the human eye and in particular, the aberrations in eccentric fixation and peripheral imaging as well as to develop measurement methods of peripheral vision. To carry out individual measurements of the peripheral optics in the eyes of a number of people.

2. EXCENTRIC CORRECTION AND ITS EFFECTS ON VISION

To study the effects of optical correction on visual function in persons with central visual field loss (CFL) (i.e., reduced or nonexistent vision in the macula of the retina).

3. TRANSFER OF KNOWLEDGE

To bride the knowledge gap between optometrists, physicists, ophthalmologists and staff in low vision rehabilitation.

Contents

1. Introduction

When I became an optometrist 25 years ago, the training was more like that of a craftsman. This was combined with an extended period of practical experience, entirely in the master-apprentice tradition, [Jernström, 2000] alternating with classes at the school of optometry. Since 1994, training to become an optometrist takes place at the college level, and the first doctoral students with academic backgrounds in optometry are pursuing research studies. I am one of these pioneers but have also gone through the earlier basic training program, as well as receiving additional advanced training along the way.

The area of research I have chosen concerns peripheral vision. Peripheral vision is invaluable for people with reduced central vision. It can never replace direct vision, but people with a central visual field loss, also called central scotoma, can in spite of this and to a limited extent read, do needlework and watch television with magnification devices. About 80,000 people in Sweden have significantly reduced direct vision and of them about 3,000 are children. About 10,000 people are partially or completely dependent on their peripheral vision due to a total loss of central vision.

No real efforts beyond the use of magnification have ever been attempted in order to optically improve peripheral vision. It has been assumed that such efforts would make no difference anyway, since the peripheral portion of the retina has always been thought to have very limited resolution capacity. At the same time, it has been obvious to optometrists and all who work in the area of visual rehabilitation that people with central scotoma actively make use of their peripheral vision. This is evident from how they fixate eccentrically, in orientation and discrimination of objects and text. Yet, they have never been offered any kind of optical correction to help them see better at oblique angles.

Reading training with eccentric fixation was something new in the mid 1970s [Inde, 1978] [Bäckman and Inde, 1979]. The people involved practiced reading with optics that provided magnification for very short reading distances. For most, it became apparent that upward fixation, that is, placing the text under the scotoma, worked the best. [Nilsson et al., 1998] [Nilsson, 1991]. In recent years, efforts have been made to develop training of eccentric fixation for reading with computer programs. Fixation can be facilitated with the aid of support lines displayed on the screen, resulting in an increase of the number of words read per minute [Frennesson et al., 1995].

Interesting studies have been carried out with the SLO (Scanning Laser Ophthalmoscope) in mapping of the scotoma and in how subjects read with different types of visual reduction [Fletcher et al., 1991] [Guez et al, 1993].

In the early 1800s, scientist Thomas Young observed astigmatism in the human eye [Young, 1801]. And Herman von Helmholtz observed in the early 1900s that the optics of the eye contains so many optical faults that it would never be considered acceptable when compared to a system created by a lens designer [Bennet and Rabbets, 1998].

The work I have done on the peripheral optics of the eye and the possibilities of optically improving distant eccentric vision are summarized in this licentiate thesis. I will begin by introducing the three areas I have investigated:

1. Models, measurement methods and clinical measurements of eccentric imaging.
2. Correctional optics and its effects on peripheral visual function.
3. The knowledge gaps that exit between different professional groups.

1.1 Models, measurement methods and clinical measurements of peripheral optics.

Many *models* of the eye and its optical system have been published. In some cases, calculations of aberrations outside of the optical axis have also been carried out [Pomerantzeff et al., 1984] [Dunne et al., 1987] [Liou and Brennan, 1997] [Popiolek-Masajada and Kasprzak, 1999] [Kooijman, 1983] [Wang and Thibos, 1997]. A large number of models have been used that are based on the famous "Gullstrand's model eye" [Gullstrand, 1909].

Some of the calculations have dealt with how the aberrations change and increase with accommodation. The shape of the cornea has little or no significance for image quality in the oblique angle of the eye. Instead, it is mainly the lens and its placement that cause

Gullstrand's model eye.
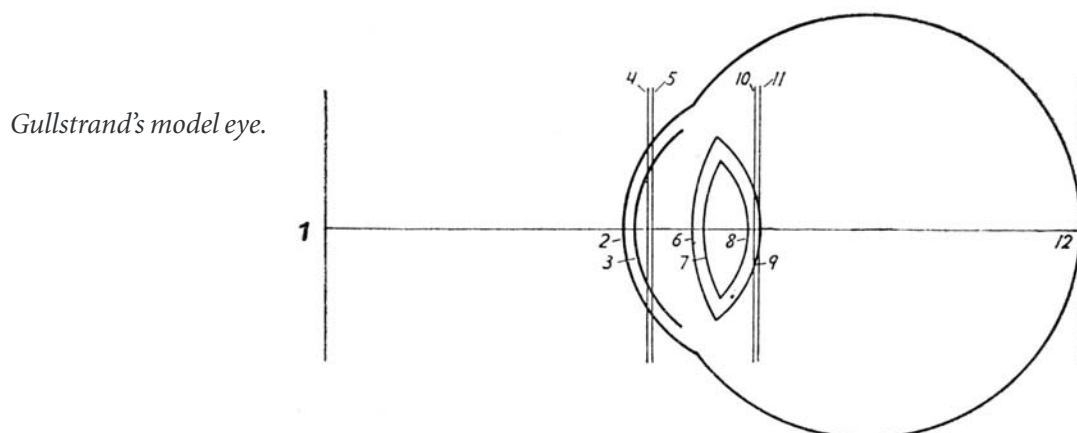
aberrations (primarily oblique astigmatism). The normal lens results in fewer aberrations than the intraocular (IOL) lens [Smith and Lu, 1991].

There are also in the world of eye models several calculations of peripheral optics, but methods for *measuring* peripheral eye optics are nearly non-existent. There is almost a total concentration on central optics. That is where one can obtain a high visual resolution and sharp focus, and even a mild nearsightedness should be corrected since it can have a great effect on central visual acuity. Recently, professionals have become interested in the possibilities of super vision: the use of correctional optics to increase central vision in normal eyes so that it is even shaper than what it can be naturally.

While scientists and researchers are making efforts to push the limits of central vision to new heights, the interest in peripheral optics has diminished. It has been assumed that the retina and its limited number of peripheral visual receptors cause the limitations, not the visual acuity. As a result of this assumption, practically all methods for measuring the optics of the eye have been developed for measuring the central area of the retina. Most of these are of no use in peripheral vision.

An article from 1975 is one of the few exceptions in the literature [Frisén and Glansholm, 1975]. The measurement results the authors present show that there are optical limitations in the periphery. In the same article they pursue an interesting line of reasoning as to why peripheral vision does not adjust itself to the eye's optical limitations but instead maintains a superior neural resolution ability. However, neither ophthalmologists nor optometrists have generally accepted these results and the line of reasoning, even though the article was published more that 25 years ago.

If one measurement of the field of vision, perimetry, indicates that the patient has a large central visual field loss, there has been no way of measuring the optical corrections needed to make better use of the remaining peripheral vision. People with this type of loss have been offered magnification devices.

Examination of the eye's optics in the area of eccentric visual function has not been a particular concern of research either. Those groups that have tried to make corrections in eccentric optics and who have measured the effects on vision consist almost exclusively of physicists in university departments of visual optics. Some work in optometry training programs and many cooperate with ophthalmologists from different institutions. Different traditions prevail in different countries.

Renowned research groups around the world have studied peripheral vision but not, to the best of our knowledge, in people with central scotoma.

In Spain, there is a long research tradition among physicist in the
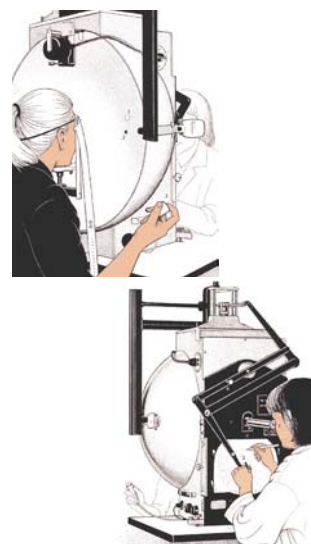
Visual field examination using Goldman perimetry as seen from the examiner's and patient's perspectives.

optics of the eye and its effect on vision. Currently, the most productive and well-known groups are Pablo Artal's in Murcia and Rafael Navarro's in Madrid [Navarro et al., 1993] [Artal, 1993]. In the USA, David William's group at the university of Rochester, New York, is best known for having been the first to photograph individual cone photoreceptors on the retina [Miller et al., 1996]. Larry Thibos and his group in Indiana have done considerable work on peripheral vision and the limitations of the retina [Thibos et al., 1987]. In Australia, George Smith in Melbourne and David Atchison in Brisbane have carried out theoretical calculations, among other things, and have written several books on the optics of the eye [Atchison and Smith, 2000].

1.1.1 SUBJECTIVE METHODS

The common subjective method used by optometrists is to ask the patient, "Better or worse?" when changing from lens to lens. This method is not accurate enough when dealing with peripheral visual function because the vision there is so poor that the participant seldom can subjectively detect small differences.

1.1.2 RETINOSCOPY

Streak retinoscopy is one of the optometrist's most common methods of measurement—referred to as retinoscopy or skiascopy. It is based on a divergent, moving light being directed into the eye. The optometrist interprets the movement of the reflex from the retina by using different lenses placed in front of the eye. The method works well out to about 5° from the optical axis of the eye [Bennet and Rabbets, 1989].

Further out in the eye, the method is more difficult to use because reflexes arise that are much more difficult to interpret. The only researchers who have asserted otherwise are Rempt et al. [Rempt et al., 1971], who 30 years ago said that it was possible to use what is called the "double sliding-door effect". In the 1970s they measured both eyes in 442 people with retinoscopy and made a "skiagram" of

Subjective examination of the eye's refractive errors with trial lenses in frames.

Retinoscopy being carried out at arm's length. Correctional lenses are mounted on a strip (pole with spherical lenses of increasing strengths).

In retinoscopy with divergent light (1) the reflex movement in the pupil is observed and evaluated at the red line (2). You see "with" movement in hyperopia and "against" movement in myopia. With different lenses in front of the eye, the optometrist can see how the reflex changes.

Hyperopia.

Myopia.
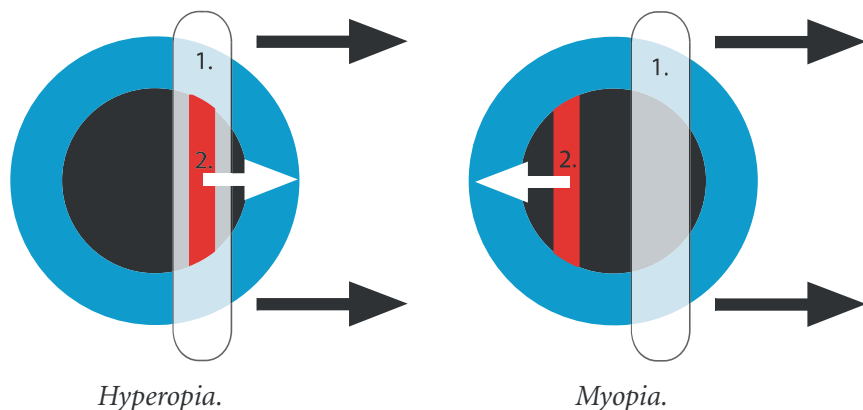
the results. This examination is often referred to in articles and books. We have not, however, been able to replicate the experiment, nor have we found anyone else who has done so or is able to do so. Since we now are able to measure with other, better methods, we have chosen not to pursue this line of research.

1.1.3 MEASURING WITH MANUAL OPTOMETERS

Before the development of modern autorefraction, manual optometers (refractometers) were used in which the optometrist was able to observe the image of the test marks on the retina through a telescope. The optometrist either studied acuity at the mark or used two test marks that would overlap. The instrument was used until the 1960s, and some work was carried out on oblique angles of the eye.

In the 1930s, measurements demonstrated that a strong astigmatism was common if the light did not fall centrally into the human eye. In "Refraction for the peripheral field of vision" [Ferree et al., 1931] a Zeiss parallax optometer was used to measure 21 eyes at 20°- 60° angles from the optical axis.

In the 1970s, several researchers used manual optometers and the largest study carried out was entitled "Effect of Ametropia on Peripheral Refraction" [Millodot, 1981]. They examined 62 eyes on the nasal and temporal sides out to a 60° angle. They measured farsighted, nearsighted and normal eyes. In the experiment, a Hartinger optometer was used with a periscope that reflected the fixation's mark. The refractor proved to be more reliable than the retinoscope with skiagram. Charman and Jennings later commented on the study, saying that it would be possible to predict the results with calculations from a model [Charman and Jennings, 1982].

Early on, we determined that manual optometers could be useful for our purposes. Unfortunately, they are very uncommon today.

Drawing of a retina with a nonfunctional macula.

1.1.4 MEASUREMENT WITH AUTOREFACTOMETERS

The very first automatic refractometers came out in the 1970s. They resulted in a significant and positive change for optometrists because they were able to directly, simply and quickly come up with measurement values of the eye's refraction. That all autorefractors are currently constructed so that they can only measure the central area is not seen as anything negative, since no one is interested in measuring the periphery anyway.

1.1.5 PHOTOGRAPHING WITH A FUNDUS CAMERA

The fundus camera is used by doctors to study pathological changes in the retina. Fundus cameras could, in principle, be used to study the differences between central and peripheral eye optics, but that has not happened before.

Photograph, taken with a fundus camera, shows a macula with changes seen in macular degeneration.

1.1.6 THE DOUBLE-PASS METHOD

This method is called "double-pass" because the light from a point source is imaged through the optic of the eye twice; first when the ray of light enters the eye and projects an image of the point source on the retina and then when it leaves the eye after reflecting off the retina. A light-sensitive measuring instrument registers how the image appears on the retina. Previously, photomultipliers were used and now CCD cameras. The method makes it possible to read the error of refraction directly on the dioptric scale [Santamaria et al., 1987] [Artal et al., 1995b]. See the description on page 24.

A number of measurements have been made at oblique angles but in small series with varying central refraction strength. In the 1980s, Jennings and Charman carried out the first calculations of the eye's optics outside the optical axis using the double-pass technique [Jennings and Charman, 1981]. They used an ordinary lamp as a source of light and photomultipliers as detectors. The measurements were carried out on one eye only and the conclusion was that they corresponded well with Rempt's. [Rempt, Hoogerheide and Hoogenboom, 1971]. They also make comments on Millodot's investigation [Millodot and Lamont, 1974], stating that the results could be predicted through calculations of models.

In the 1990s, many articles were published by groups of researchers who had carried out measurements using the double-pass method. The disadvantage with these studies it that they have only measured a few eyes with different refractions [Artal, Iglesias and López-Gil, 1995b] [Williams et al., 1996] [Navarro, Artal and Williams, 1993]. One can summarize their results for healthy eyes as follows: the natural optics of the eye is sufficient peripherally when the retina's limitations are taken into consideration. Another conclusion they reached was that the optics of the eye outside of the axis was better than expected, while the central optics did not manage particularly well when compared to commercial optical instruments. [Navarro, Artal and Williams, 1993].

In recent studies using the double-pass method, astigmatism,

An illuminated point on the retina causes a diverging spherical wave-front that spreads out of the eye. After passing through the eye's optics, the wave-front becomes deformed. Deviations from the ideal, level wave-front are called wave-front aberrations of the eye and provide a complete picture of the eye's aberrations.
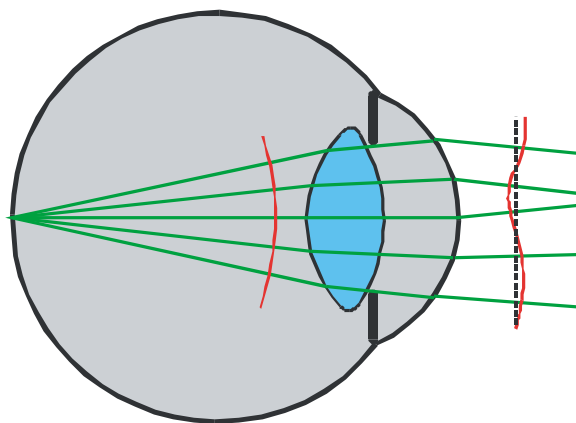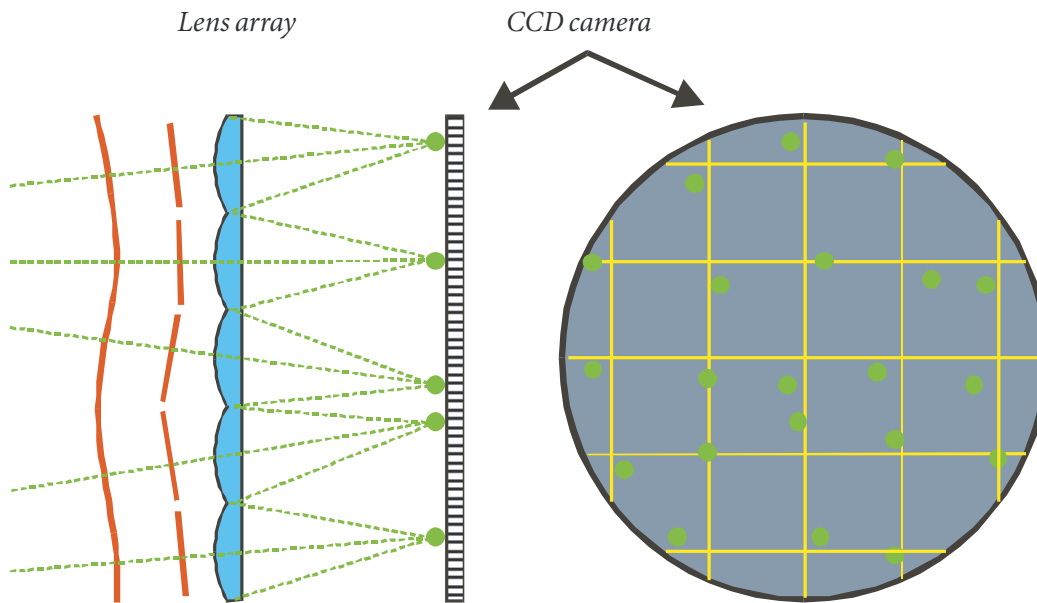
coma and defocusing of four eyes have been measured at angles up to 45° [Guirao and Artal, 1999]. At comparable angles, astigmatism and coma were quite similar while focusing varied. The incident angle of the light was the dominating cause of astigmatism.

1.1.7 WAVE-FRONT MEASUREMENT

A wave-front describes how far the light has come from a light source after a given time. The deviation from the ideal wave-front in an optical system is called the system's wave-front aberration. The technique for studying wave-front aberrations of the eye originated with the Hartmann-Shack sensor. It was first used in astronomy to reduce the atmosphere's disruptive influence when astronomers wanted sharp images from earthbound telescopes. It can be used to measure the shape of a perfect wave-front and the appearance of the actual wave-front. In this way, the aberrations are mapped. This technique was first used to measure the eye in 1994 [Liang et al., 1994] and has been further developed since than [Liang and Williams, 1997] [Liang et al., 1997].

The rapid development of laser treatment of the cornea with the excimer laser has resulted in there now being commercial instruments for wave-front measurement of the eye's central optics. The instrument cannot be used for oblique angles, though.

An alternative method to the Hartmann-Shack sensor is laser raytracing [Navarro and Moreno-Barriuso, 1999] or similar methods [Molebny et al., 1997]. These can be an alternative and offer the same possibilities but have not had the same impact as wave-front measurement with the Hartmann-Shack sensor [Navarro et al., 1998].

The deformed wave-front from the eye falls on the lens array of small micro lenses. Each lens focuses its portion of the wave-front at a point on a CCD camera. The position of the points of light can be converted to the wave-front's slop at a given micro lens and in that manner the shape of the wave-front can be calculated.

1.1.8 PHOTOREFRACTION

The PowerRefractor is a portable computer with a six-armed retinoscope that measures the refraction of both eyes simultaneously.

Photorefraction can simply be described as the light from a small light source near the camera's lens being reflected off the retina. It looks different in different refractive errors of the eye. The variation in how the pupil is illuminated can be interpreted by comparing photographs of different reflexes. Howland used the technology for the first time in 1974 [Howland and Howland, 1974]. The method is not widely used because it lacks adequate precision.

While doing this research, however, a new photorefractometer came onto the market, the PowerRefractor: www.multichannelsystems.com. Six segments with infrared, light-emitting diodes are mounted in a circle around the camera lens. They light up one after the other. The light enters the eye and the camera captures an image of the retinal reflex. The instrument's software analyzes the incoming image and measures the refractive error. The measurement takes place in real time and requires that the subject fixates on the camera at a distance of 1 meter (3.2 ft.). Both eyes are registered simultaneously and all the measurements are carried out very quickly. The equipment is also able to record a five-second-long video sequence of the measurement.

How the pupil is illuminated for measurements with photorefractioning, in this case using the PowerRefractor, for emmetropia, myopia and hyperopia.

The reflex from the retina is analyzed by the program, which can interpret the image of the illuminated pupil.
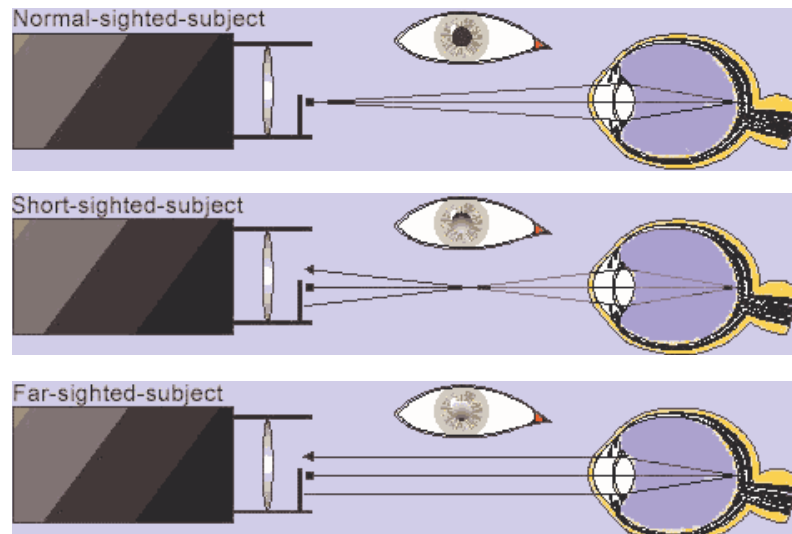
Unlike an ordinary refractometer, the PowerRefractor is able to carry out measurements even when the fixation is not central. Changes in astigmatism are clearly seen between different fixation points. What is particularly interesting is that it manages to measure eccentric angles from the optical axis and out to about 30°. The size of the pupil determines how far out one is able to measure. The reliability of the measurement values is documented and has proven to be particularly exact for astigmatism, diverging by only 0.4 diopters on the average in relation to the subjective correction [Choi et al., 2000].

1.2 Eccentric correction and its effects on vision

Few optical corrections of eccentric vision have being attempted due to the limited research that has been carried out on the *eccentric optics of the eye*. Consequently, studies of *eccentric vision* are not very common. Rempt and his group [Rempt et al., 1976] used values from skiagrams to correct eccentric refraction in angles between 10° and 60° in three people with normal vision. Rempt then tried to measure the subjects' visual acuity with Landolt's ring. The results indicated that no differences in their vision could be measured with or without correction. Rempt's results have been questioned and confirmed by different researchers [Lotmar and Lotmar, 1974].

Millodot and Lamont measured oblique astigmatism in one eye, with and without a spherical contact lens, in order to see if it would change the astigmatism. If so, the astigmatism could be explained by a flattening of the cornea against the limbus (the edge of the cornea). No changes in astigmatism could be measured with or without the contact lens [Millodot & Lamont, 1974 15/id].

A group of researchers has measured detection and refraction with lenses with spherical strengths from + 4 to – 7 diopters at 20°, 30° and 40° angles in three eyes. Computer-generated gratings, used as a subjective method for measuring refraction, were compared with retinoscopy and refractometer, Canon R1. In this experiment, the ability to see the gratings was sensitive to focusing errors at about 1 diopter (D) over a 20° angle [Wang et al., 1996]. One year later, they tested depth of focus for detection acuity with spherical lenses with grating at oblique angles. Measurements on only three eyes demonstrated that the subjects could vary an entire six diopters in the areas from 20° to 40°, that is, the subject's eyes appeared to be insensitive to focusing. The researchers pointed out, however, that great individual variations could be found and mentioned that the ideal would be to correct astigmatism, but they did not attempt this [Wang et al., 1997].

1.3 Publications and Conferences

The research I have carried out and that is reported in this thesis has previously been published or presented as follows:

Gustafsson, J., Terenius E., Buchheister, J., Unsbo, P. (2001).
Peripheral Astigmatism in Emmetropic Eyes,
Ophthalm. Physiol. Opt Vol 21, No. 5, pp 393–400.

Gustafsson, J., Unsbo, P. (2001).
Correcting peripheral refractive errors in low vision subjects with central scotomas, Proceedings from ARVO 2001 in Invest.
Opthalmol. Vis. Sci. 42, No. 4, p 853.

Included in "Developments in Low Vision: Abstracts of the Fourth European Conference on Low Vision".

Gustafsson, J. (2000).
"Widesight"—A Project Aimed at Improving Peripheral Vision.
De Blauwe Kamer Theofaan Groep, Visio, National Foundation for the Visually Impaired and Blind, ISBN 90-76898-01-4.
Presented at Eurosight 2000, 3-6 Sep., Veldhoven, Holland.

Unsbo, P., Biedermann, K., Buchheister, J., Gustafsson, J. Terenius, E. (2000)
Oblique Astigmatism and Curvature of Field in the Human Eye.
Poster presented at Northern Optics 2000, Uppsala, Sweden, Abstract Publication, ISBN 91-7170-589-9.

Gustafsson, J., Jönsson, B., Möller, B., Pettersson, S. (2000).
Raytracing in the Compensation of the Peripheral Optics of the Eye.
Poster presented at Northern Optics 2000, Uppsala, Sweden, Abstract Publication, ISBN 91-7170-589-9.

A popular science article in Swedish. *"Widesight"—Research on Using Residual Vision* (*"Widesight"—forskning om att utnyttja synrester*). Aktuell Optik och Optometri, 3/01, p 23–25, 2001, and in a revised format in SRF Perspektiv, 5/2001, p 26–27.

2. Measurement methods and tests

As I emphasized in the introduction, this research is pioneering. It has made my work both easy and difficult. Easy because it is relatively simple to come up with completely new ideas for methods and to carry out original measurements in the area of *peripheral optics* of the eye and *eccentric vision*. But it is difficult at the same time because there is so little material to refer to in the areas of theory and practice.

Several researchers have measured the optics of the eye at oblique angles from the optical axis without correcting the optical errors that were observed [Ferree, Rand and Hardy, 1931] [Ferree et al., 1932] [Ferree and Rand, 1933] [Guirao and Artal, 1999] [Jennings and Charman, 1981] [Millodot, 1981] [Rempt, Hoogerheide and Hoogenboom, 1971]. The goal of this research is for the methods and measurements to benefit people with reduced vision due to central scotoma so that their residual peripheral vision can be better used.

2.1 Models and calculations

Even though I am a clinician, it was natural for me to start with models. It is through the use of models of the optics of the eye that it becomes apparent what is known and what is not know about the eye as an optical system. The lack of reliable optical data is never as obvious as when a computer program requires it and one does not have access to it. One of the more striking observations is that despite a great number of refinements in recent years, there is still a dearth of knowledge about the optics of the eye outside of that for central vision.

Even though I now realize that individual variations in peripheral vision are so great that attempts to work with models may be entirely meaningless, the work with raytracing was still a fruitful place to begin. The greatest uncertainty concerning the optics of the eye at oblique angles is connected with the actual lens [Smith and Lu, 1991]. In the Smith study, the authors describe changes in aberrations when a new lens is surgically placed in the eye, an ILO (intraocular lens).

The largest commercially available raytracing programs that we considered using were:
– CODE V from Optical Research Associates
– OSLO from Sinclair Optics
– Sigma 2000 from Kidger optics
Long before I heard about these, I had the privilege of meeting
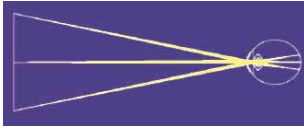
Associate Professor Sven-Göran Pettersson at the Physics Department, Lund Institute of Technology and cooperated with him in using a computer program he had developed using Gullstrand's schematic eye as the model. In Professor Pettersson's program, one could follow a ray of light and see the size on the image of a point-shaped object.

Next, I established contact with Wolfgang Fink, then in Tubingen, Germany and now at Caltech University in the U.S.A. His program meant that one could see not only how the points were deformed by the aberrations of the eye, but how the image of complex objects appeared on the retina as well [Fink et al., 1996].

Wolfgang Fink's raytracing program uses Gullstrand's model of the eye. One sees directly how the image will be represented by having the object projected back onto a screen in the shape it is reproduced on the retina.
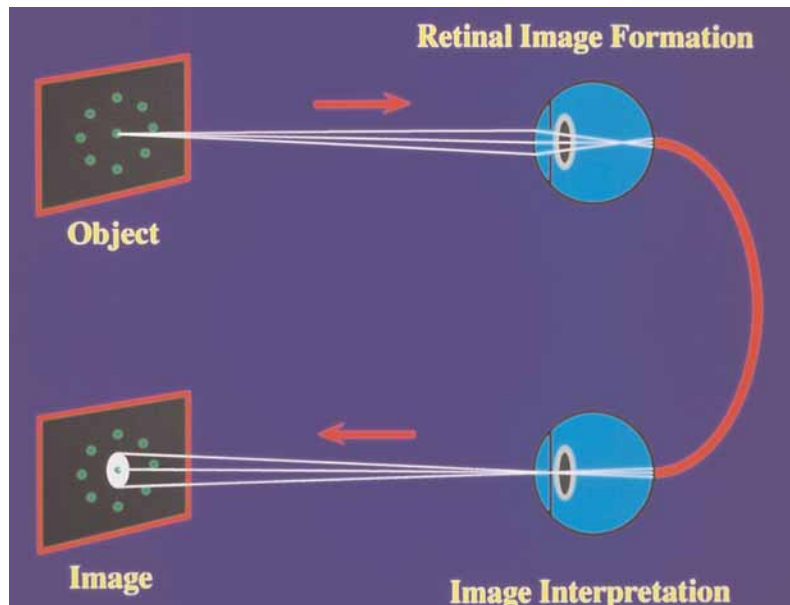
This was all very interesting. But my primary interest is not only in registering how it is, but in also contributing to optimizing the corrective optics that can improve the eye's imaging as much as possible. That is why I wanted to gain experience from programs that are developed to optimize optics, and that is what led me to the CODE V, OSLO and Sigma 2000. There were many reasons for me to choose OSLO, and probably the most important was the contact I established with an accommodating, qualified and experienced OSLO user, Bo Möller, who is a system and lens designer at the Zeiss Corporation.

A computer program as complex as the OSLO requires an expert user, and it was a great advantage to have Bo Möller's assistance in performing the calculations of the peripheral optics based on the most recent model of the eye [Liou and Brennan, 1997].

When we had the measurement values of the optical aberrations at different angles, we chose to construct the corrective lenses in collaboration with the MultiLens Company. We tested the lenses on ourselves but with little or no success.

Eye, Liou and Brennan Focal Length - 15,95 NA - 0,06271		Units: NN DES: Mir

5,6

Eye, Liou and Brennan Spot Diagram	FBY 1 FBX 0 Focus 0	REFHT 4,141 UV 1-3

Geometrical Spot Size
0.02646

Diffraction Limit
0.00504

0,1

Geometrical RMS Y Size
0.02405

Geometrical RMS X Size
0.01101

- 0,1
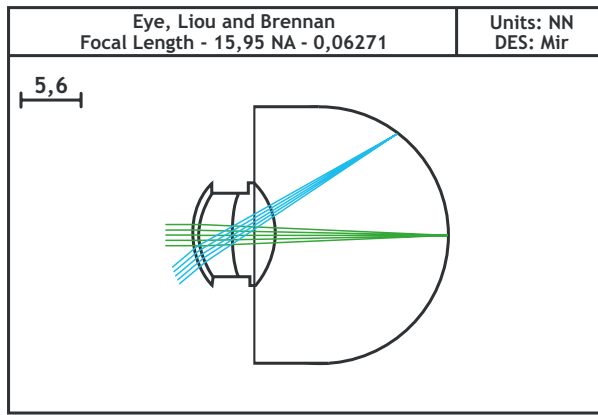
Calculations carried out by the OSLO raytracing program.
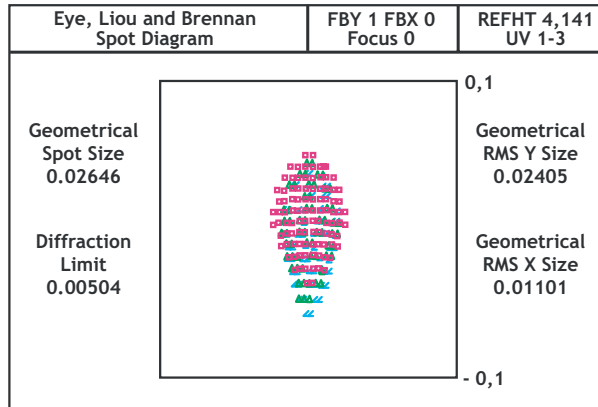
Liou and Brennan's eye model with central rays and eccentric incident rays at a 40° angle (above).

The spot diagram displays the image on the retina. One can see how poorly the light is focused in the spot diagram.

Eye, Liou and Brennan Optical System Layout		Units: NN DES: Mir

5,6

Eye, Liou and Brennan Spot Diagram	FBY 0 FBX 0 Focus 0	REFHT 4,141 UV 1-3

Geometrical Spot Size
0.005018

Diffraction Limit
0.005255

0,1

Geometrical RMS Y Size
0.005881

Geometrical RMS X Size
0.001278

- 0,1
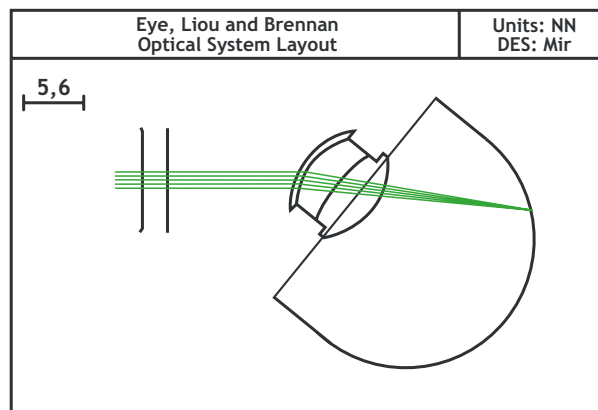
The optimizing function is calculated from the lens in spherical and cylindrical strengths that offer the best imaging. The example above: 40° angle, lens at 12 mm vertex distance.

The new spot diagram shows that the focusing is considerably better. Further improvement than this cannot be achieved with ordinary eyeglass correction.
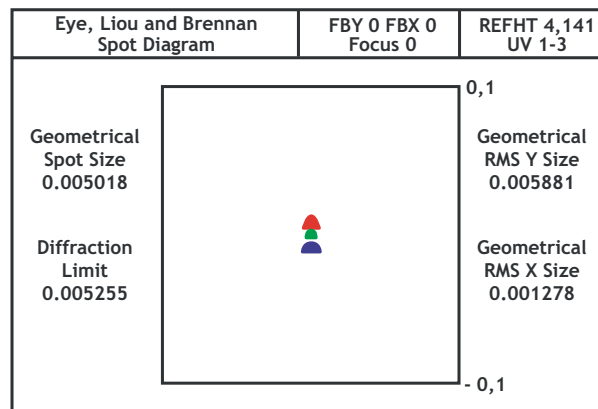
The glass was manufactured with combi-cylinder grinding (both surfaces have cylinder strength with effects in opposite directions to strengthen one another) in order to get as good imaging as possible. With them, trials were then carried out to measure the difference in vision by using a variety of visual field examinations. Unfortunately, these were difficult to interpret and exhibited neither improvement nor deterioration. On the other hand, an experiment was carried out with a digital fundus camera that took pictures with and without the compensating lenses at a 40° angle. It is possible to see a slight improvement in image quality with the calculated eccentric corrections.

Calculated compensatory lenses in acrylic (n = 1.492)				
Angle --	Radius in y-axis/mm	Diopters in y-axis	Radius in x-axis/mm	Diopters in x-axis
20°	462.9	−1.06	1720	+0.29
40°	118.6	−4.15	358	+1.37
60°	60.89	−8.07	157	+3.14

A lens with three astigmatic powers based on the raytracing calculations above was manufactured for these specially designed trial frames at the following angles:

20°:
sph. +0,25   cyl. −1,25   ax 90°

40°:
sph. +1,5   cyl. −5,5   ax 90°

60°:
sph. +3,25   cyl. −11,25 ax 90°

A lens was manufactured with these strengths in one and the same lens. It was placed in special test frames.

Trial measurements carried out on emmetropic eyes have demonstrated that there is little value in testing the corrections on normal eyes. Today it is easy to understand this negative outcome but it was not so then. We know now that the eccentric optics of the eye is exceedingly individual and angle dependent. The first optimizations and attempts with calculated corrections proved to be of no use. However, the results were important for our continued research because they contributed in giving us a common frame of reference, among other things.
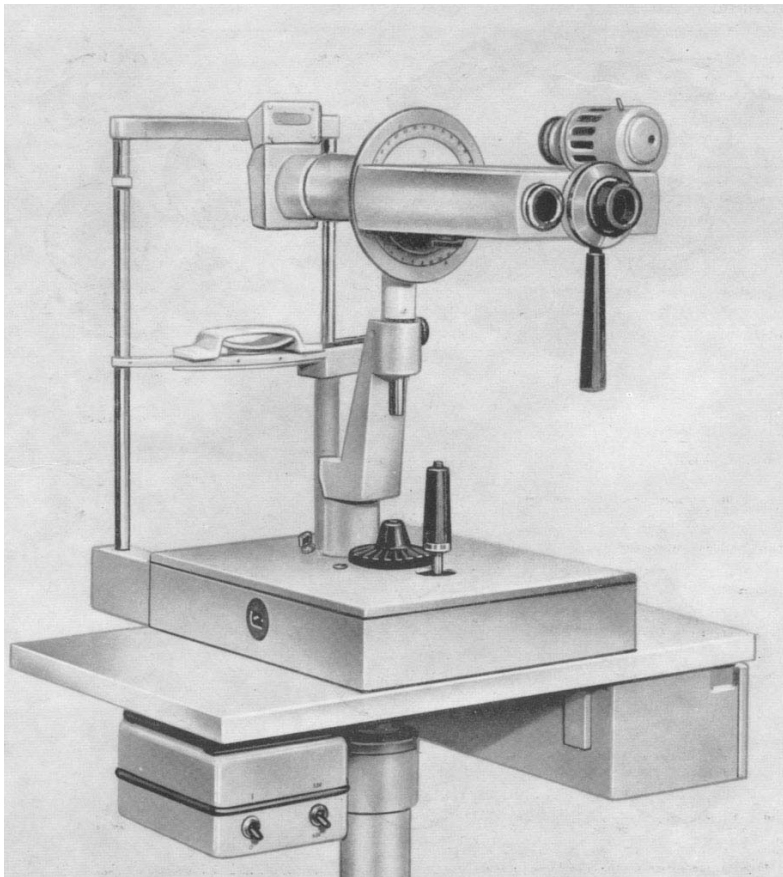
The first model of the Hartinger Optometer. It was used primarily in Germany but also to a limited extent in Sweden in the 1960s and 70s.

2.2 Measurement methods

Of the optical measurements and methods for central vision that were mentioned in the introduction, three of them cannot be used to measure oblique angles in the eye. This goes for subjective measurements with trial glasses as well as for retinoscopy and measurements with autorefractors. Others may contradict the assertion concerning retinoscopy, but I have not been able to make use of it as a method for precise or reproducible measurements outside of the optical axis in spite of extensive trials and consultations. I can see that the astigmatism increases further out and that it varies, but I am unable to obtain reliable measurements of it.

Of the other methods, the manual optometer (Hartinger Optometer) and fundus camera photography produced only marginal results. Measurements with the PowerRefractor and the double-pass method, on the other hand, were successful. We have further developed these methods and carried out measurements and have been able to demonstrate the effects of optical corrections on people who have participated in the study. It was by mere chance that I succeeded in finding a manual optometer (refractometer), the Hartinger Optometer. It is uncommon now since it was replaced by the modern autorefractor. I tried using it to measure the eye at an

oblique angle. It was possible to clearly see from the test pictures how the astigmatism varied at the eccentric angles. The measurements that were carried out, however, provided no reproducible results. The primary difficulty was in getting the subjects to maintain a stable fixation. Even though I modified the instrument so that the head support could be turned, that still did not provide reliable results.

2.2.1 MEASUREMENTS USING THE DOUBLE-PASS METHOD

The double-pass method was first developed by Santamaria and colleagues [Santamaria, Artal and Bescos, 1987]. Associate Professor Peter Unsbo and his colleagues built the equipment that was used in our research at The Royal Institute of Technology, Stockholm.
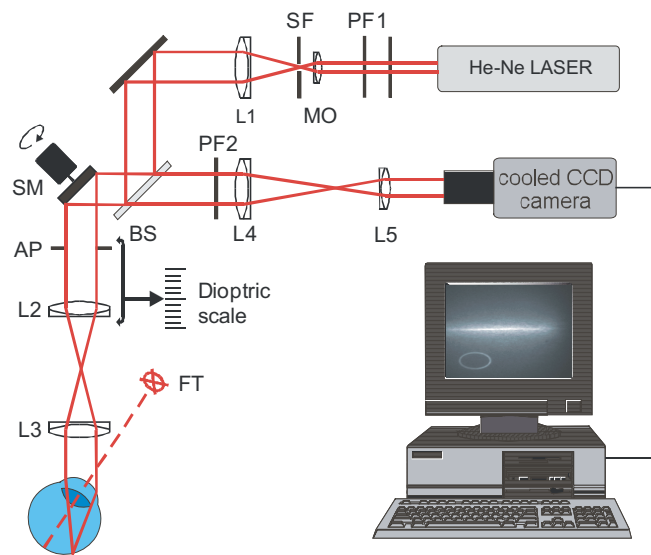
The light from a 10 mW He-Ne laser is first passed through a filter, PF1, to reduce it to a safe, approved intensity level. The laser light is then focused to a point source and is thereafter collimated (made parallel) by lens L1 into a broad parallel beam. Only 10% of the light is reflected by the beam splitter BS, and lenses L2 and L3 image the point source to the far point of the examined eye.

The image on the retina can be focused by moving the L2 lens so that the refractive error range from −10 D to +10 D can be measured. The optics of the eye and its imaging can be examined in this way by studying the image of the point source on the retina. The diffusely reflected light from the retina is imaged via a telescope (L4 and L5) onto a cooled, scientific-grade CCD camera. The two-line foci and the circle of least confusion are both registered in order to measure astigmatism of the eye.

To minimize the problem of speckles (interference that makes the camera image grainy) in the first set up, a spinning mirror, SM, is mounted to move the spot in a circle on the retina during the exposure of the CCD. A more detailed description can be found in the article [Gustafsson et al., 2001] in the Appendix.

Our contributions to method development are as follows: In order to carry out oblique measurements of the eye it was necessary to build a head support in which the person being examined could be rotated around the eye's entrance pupil (3 mm. [0.118 in.] behind the cornea). In order to achieve sufficient stability, an ordinary chin and forehead support used in ophthalmologic examinations was not adequate. We had to stabilize the head with a bite bar. A piece of metal was wrapped with dental paste in order to make an impression of each person's teeth. When the paste had hardened, the bite bar was screwed on to the holder and the head was held stably in a fixed position the next time the subject bit the bar.

In order to keep accommodation and fixation stable, we used a simple lens system that imaged an illuminated, green fixation cross to infinity. The pupil was visible on a monitor so that we could see that the direction of fixation was correct. We were aided in this endeavor by four holes in the aperture, AP that was imaged
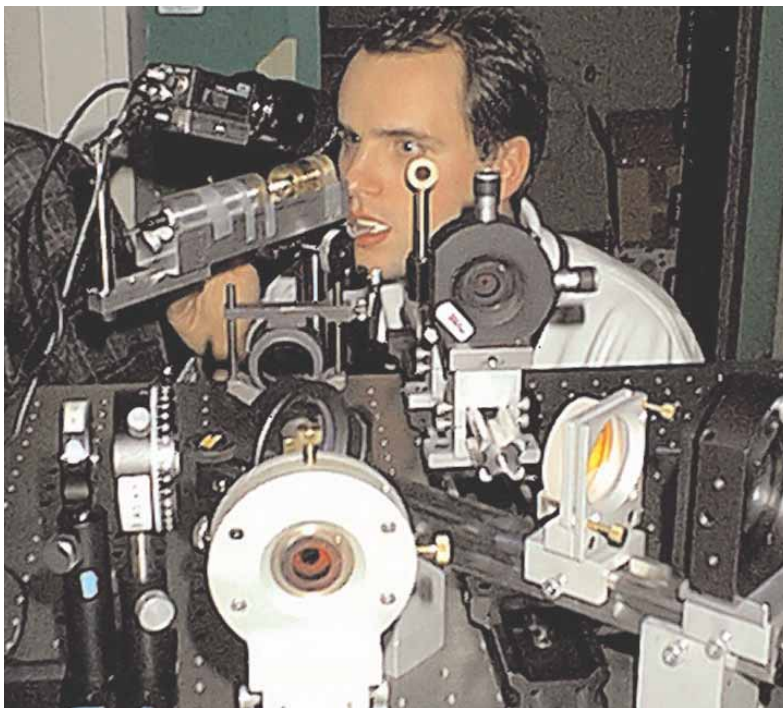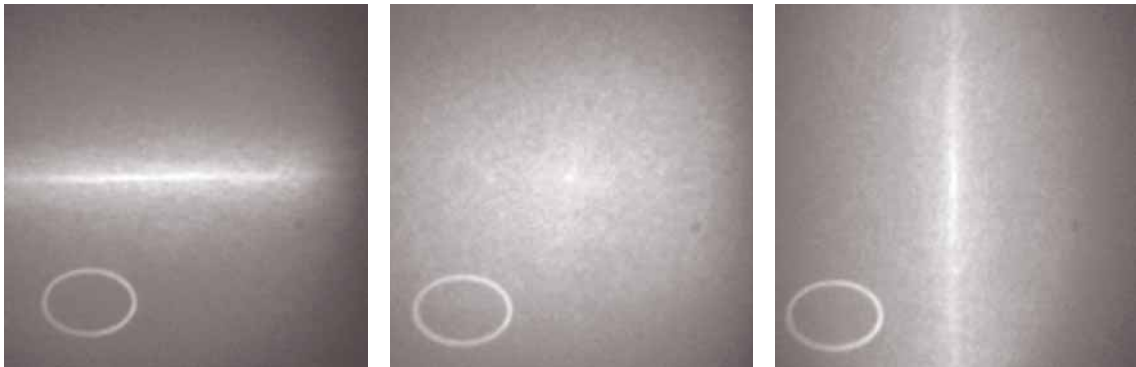
Horizontal and vertical line foci as well as the circle of least confusion from a double-pass measurement at an oblique angle.

Measurements using the double-pass method with equipment built on an optical table in the laboratory at The Royal Institute of Technology, Stockholm.

Notice that it was necessary to use a bite bar to achieve good centering of the eye and sufficient stability.

symmetrically on the iris around the pupil. A large number of measurements were carried out on each eye.

In the optical lab at The Royal Institute of Technology, measurements using the double-pass method were carried out during the spring of 2000. The measurements were performed on emmetropic eyes, which did not have greater spherical or cylindrical errors than 0.5 diopters. Most of the participants were young, between 20 and 45, and they were recruited from among the students. The average age was 28 years. They were sent printed information describing the process and asking for their written permission.

The measurements were performed temporally and nasally in the horizontal plane at the angles 10°, 20°, 30°, 40° and 60° from the optic axis.

We applied for and received approval to carry out these measurements from the Research Ethics Committee: LU 660-99 and KI 00-067.

The values from measurements using the double-pass method have only been used in one case to optically correct the eyes of a subject with central scotoma. The measurement values in that case were checked and compared with the measurements from the Power-Refractor (see the next section). The values corresponded well.

2.2.2 MEASUREMENTS WITH THE POWERREFRACTOR

For people who are unable to fixate directly on the PowerRefractor's camera without using eccentric fixation, other fixation marks need to be designed. We chose a pattern with large, concentric rings and support lines vertically and horizontally (see the picture below). Subjects with eccentric fixation assisted in designing the fixation-supporting pattern. The pattern, which became fluorescence in UV light (which does not interfere with the IR sensitive camera), is mounted on a transparent Plexiglas sheet with a hole in the middle for the camera. The rings cover 25° of the field of vision (the five

Measurement of eccentric refraction with the PowerRefractor, which measures with IR light. The yellow fluorescent fixation rings, which are illuminated with UV light, help to keep the subject's gaze stable.

Fixation direction is registered at the same time as the error of refraction.
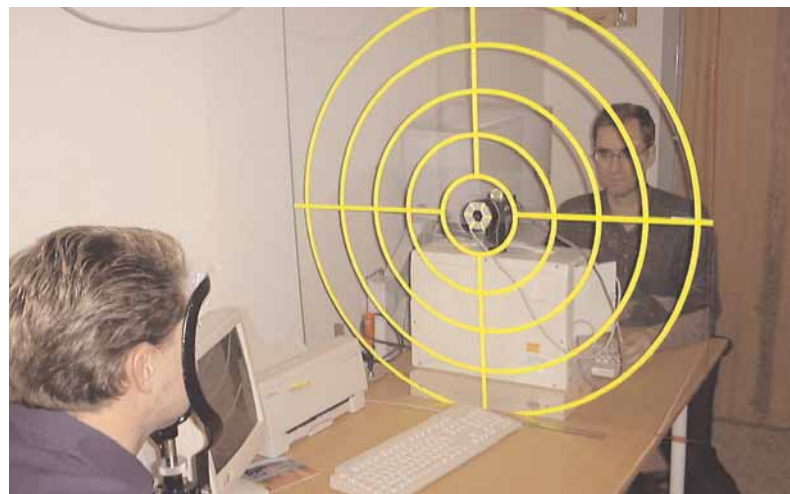
rings are placed at 5°, 10°, 15°, 20° and 25° and are mounted at a distance of 1 meter [3.2 ft.] from the subject).

After the initial trial measurements and development of fixation rings around the camera, 38 people with low vision were measured.

Several subjects have been 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 see better. In order to keep the eye in as stable an eccentric fixation direction as possible, the participants were encouraged to look sideways at the angle that they usually use to see straight ahead. 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° up-ward, for example. It is at this point that the fourth ring from the center meets the vertical line and when a subject redirects his gaze so as *not* to see where the fourth ring meets the vertical line. That the fixation point is correct can also be easily measured and checked from measurement to measurement in the Power-Refractor at the same time as the eccentric refraction is being measured.

Although the PowerRefractor is developed for rapid measurement of central refraction, it is useful for our purposes. Some examples:

– It measures the refraction obliquely (at eccentric angles) as quickly as it measures centrally.

– It registers the fixation point at the same time as it carries out optical measurements. This makes it possible to make sure that the subject actually is focusing on the agreed-upon fixation ring.

– It is portable to the extent that I am able to take all the equipment with me to perform measurements in other places.

– It requires no optical laboratory or access to more advanced optics.

Unlike the double-pass method and other methods that require an optical laboratory, subsequent versions of the PowerRefractor may be able to find their way to low vision centers, ophthalmologists and optometrists. This can happen within a few years, as the interest for peripheral vision increases and as eccentric corrections become more common.

Measurements of central correction.
R: sph.–0.25 cyl.–1.0 ax 106°
L: sph.+ –0 cyl.–0.75 ax 79°

Measurements of eccentric correction 19° up.
R: sph.–1.25 cyl.–1.75 ax 14°
L: sph.–1.0 cyl.–1.0 ax 173°
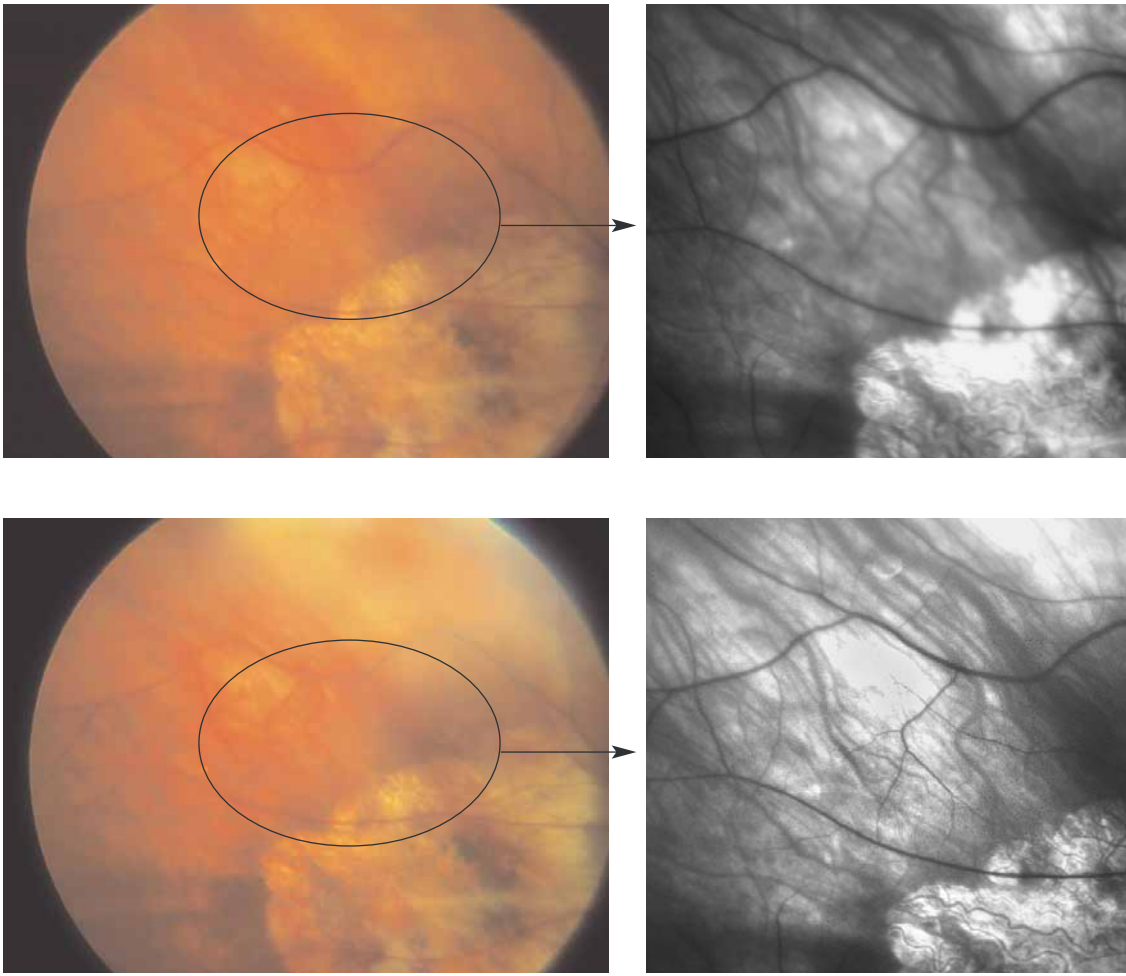
Photographed fundus of a subject. On the left, large portions of the retina and next to that an enlargement of a part of that. The scotoma is seen in the lower, right corner in the colored photo.
The upper pictures show the image of the retina without correction.
In the lower pictures, you can see that the image quality is better in the area that the person uses, that which is directly over the scotoma.

2.3 Photographing the difference in image quality

Attempts to see the difference in image quality on the retina by taking photographs with a fundus camera have been carried out on two occasions. When we started this research, we only had access to standard corrections that were calculated, as described previously, with raytracing of an eye model. By photographing with and without correction at a 40° angle, we succeeded in actually achieving a minimal improvement of acuity with correction. It is not possible to show this in print, but on the computer screen one can see a difference. The second attempt was carried out with and without eccentric correction on a subject who had developed a steady eccentric fixation point with the right eye, about 20° to the right and 8° up. Without the eccentric correction, the photographer found it much more difficult to find acuity than with correction. The photographs demonstrate that it is also possible to observe a difference from the outside, with and without correction.

3. Participants in the study

Even if the group that can potentially benefit from eccentric optical corrections is large, it was necessary in the beginning to follow strict selection criteria in the choice of subjects for initial measurements. The distinct criteria we had for choosing the first subjects were to find people with absolute central scotomas (preferably greater than 10°) in both eyes and with a conscious eccentric fixation.

This limited the group considerably, and we saw before us a laborious search for suitable participants when we received unexpected help from the media. On January 4, 2001 the local television news program, *Sydnytt*, and later that evening the national news program, *Rapport*, broadcasted a segment about the *Widesight* Research Project. This resulted in over 500 people who voluntarily and directly contacted us. Low vision centers and eye clinics were also inundated with requests from interested people.

The problem of finding suitable subjects was solved and we were able to direct our energies towards making the best selection. Not all of the 500–1000 persons who had reached us in different ways met the three criteria. It proved meaningful to examine 197 medical records, which I received directly from the people involved or from clinics, low vision centers and other places. Of these, I was able to pick 60 people who had sufficiently large and total scotomas in both eyes and a conscious eccentric fixation in one or more habitual directions. Of the 60, I have measured 38 persons and chosen 7 who were supplied with optical correction at an oblique angle. Three methods have been used to measure changes in their vision (see Chapter 4). In addition, I have collected their subjective descriptions.

The Research Ethics Committee granted approval for carrying out the measurements and corrections: LU 196-01.

The selected persons have been visually impaired for a long time, have a scotoma in both eyes and a conscious eccentric fixation.
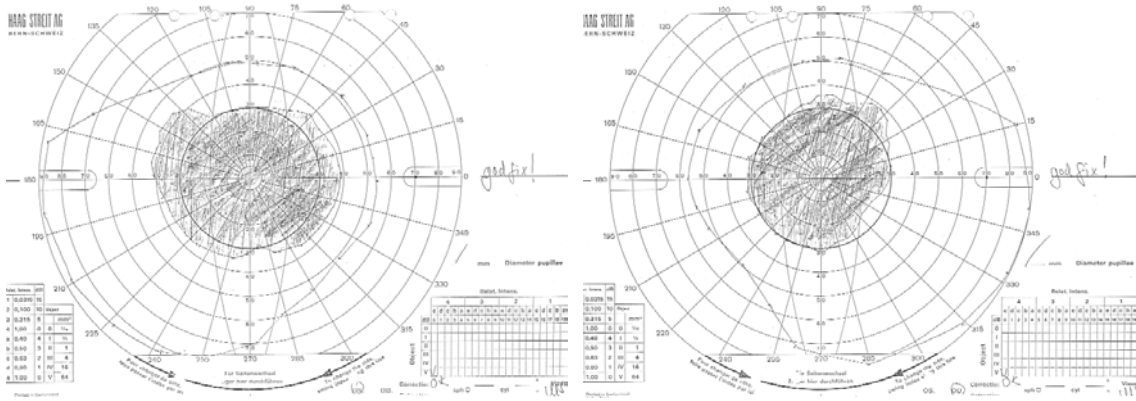
CASE 1

Male, born 1947. Diagnosis: Macula Degeneration.
Low vision since 1969.
Previous correction: R: sph.+2.0 cyl.–1.0 ax 25° L: sph.+2.0.
Visual acuity from medical records: R: 20/2000 L: 20/4000 eccentric fixation.
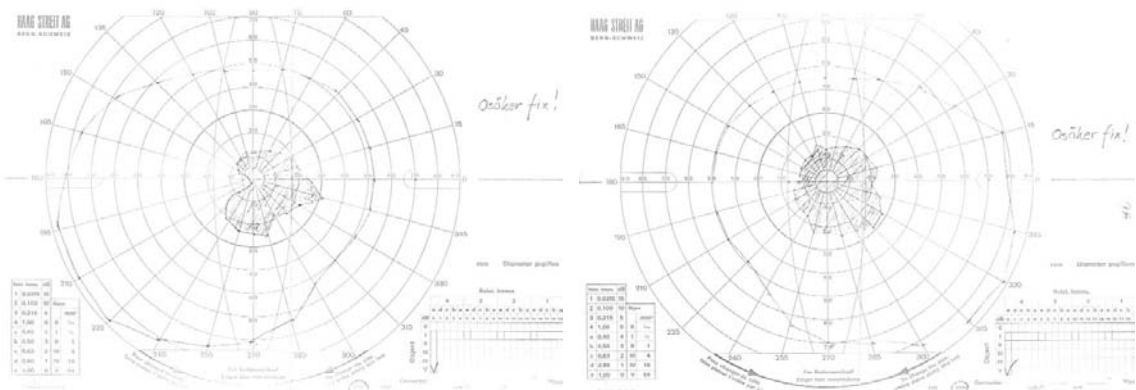
CASE 2

Female, born 1943. Diagnosis: Tapetoretinal Degeneration.
Low vision since 1980.
Previous correction: R/L: sph.–3.75.
Visual acuity from medical records: R: 20/700 L: 20/2000.
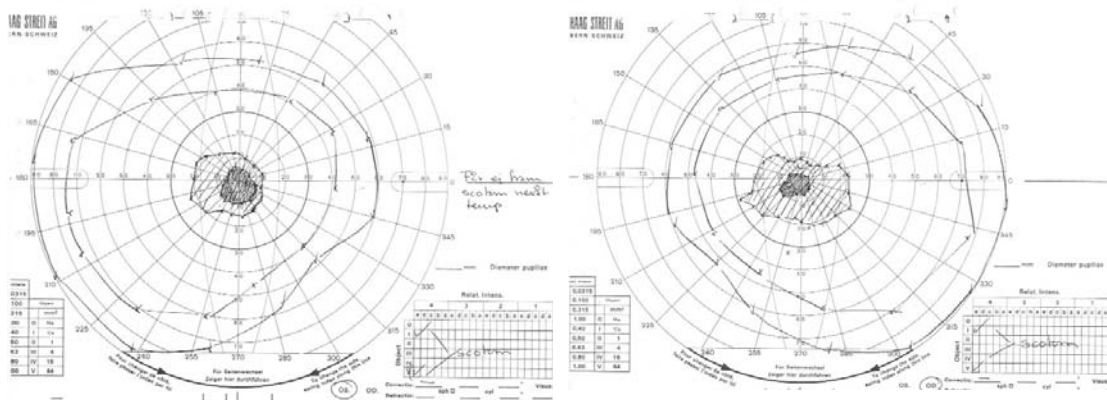
CASE 3

Male, born, 1971. Diagnosis: Leber's Opticusatrophy.

Low vision since 1992.

Previous correction: none

Visual acuity from medical records: R: 20/700 L: 20/2000

CASE 4

Female, born 1931. Diagnosis: Macular Degeneration.

Low vision since 1995.

Visual fields: CFL in the central 10°–15°.

Previous correction: R: sph.+2.0. L: sph.+2.0 cyl.–1.0 ax 20°.

Visual acuity from medical records: R: 20/400 R: under 20/2000.
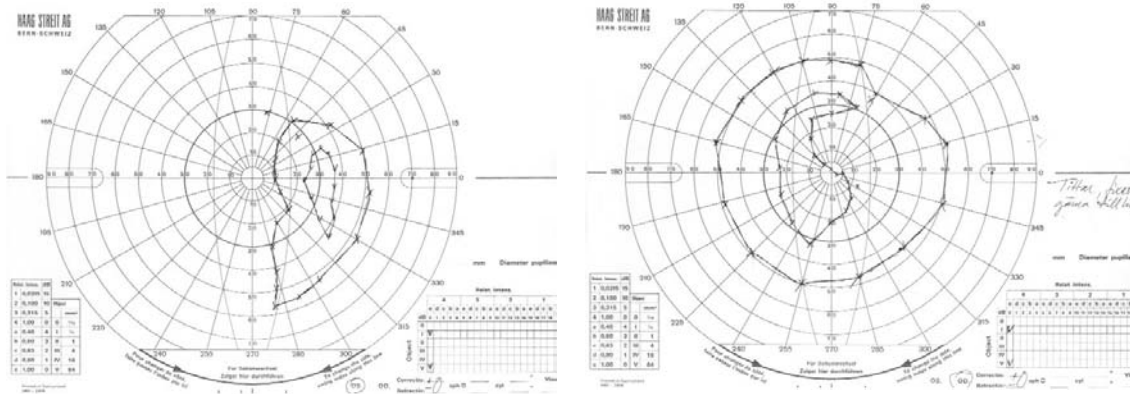
CASE 5

Male, born 1929. Diagnosis: Macular Degeneration

Low vision since 1996.

Previous correction: R: sph.–1.25 L: sph.+1.0 cyl.–2.0 ax 85°.

Visual acuity from medical records: R: 20/400 L: 20/2000.
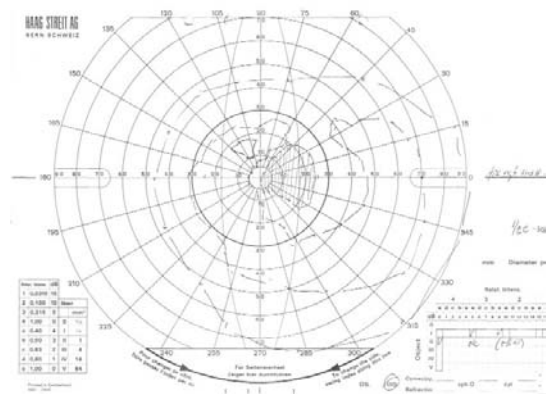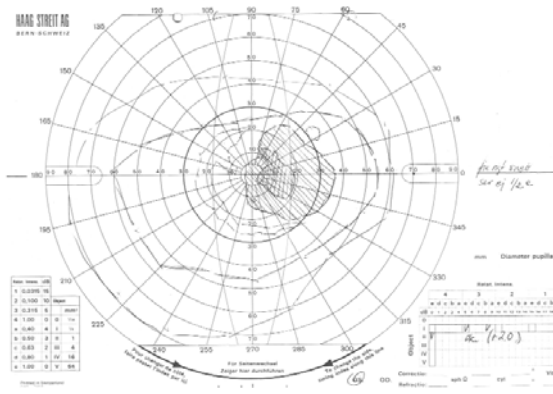
CASE 6

Male, born 1984. Diagnosis: Stargart's Syndrome from birth (fundus falvi maculatus).
Low vision since 1994.
Previous correction: none
Visual acuity from medical records: R/L or binocular 20/300.
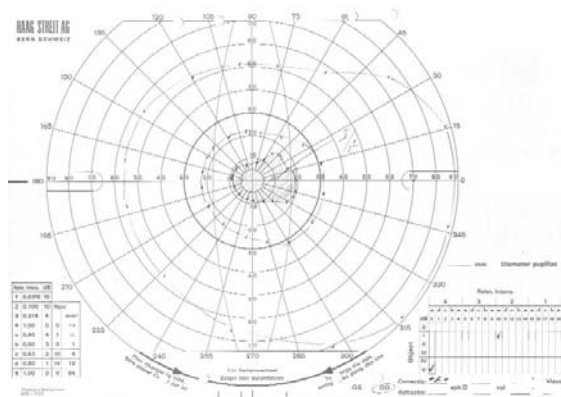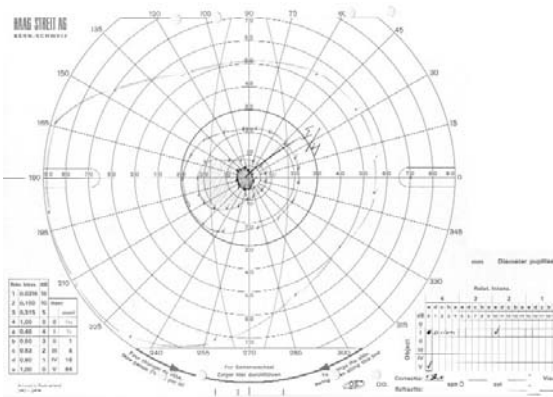
CASE 7

Male, born 1947. Diagnosis: Leber's Opticusatrophy.
Low vision since 1967.
Previous correction: R/L: sph.–1.5
Visual acuity from medical records: R: 20/400 L: 20/700.

4. Methods for measuring vision outside of the macula

Surprisingly little is documented about visual measurements outside of the macula. The exceptions are [Millodot et at., 1975] [Rempt, Hoogerheide and Hoogenboom, 1976] [Wang, Thibos and Bradley, 1997]. These researchers, who tried to correct eccentric optics, have all come to the conclusion that corrections are of little significance in peripheral vision. Exceptions have been improvement in motion detection and orientation that are thought to be limited by refractive errors [Leibowitz et al., 1972] [Artal et al., 1995a].

There are no obvious methods apart from perimetry for measuring visual function outside of the macula. Perimetry does not offer sufficient accuracy for the evaluation of eccentric correction; neither can traditional visual acuity tests with eye charts if you try to use them peripherally. Instead, the three methods that have been of use in my work are:

– Measuring of ring object from High Pass Resolution Perimetry (HPR) visual acuity
– Measuring of contrast sensitivity
– Measuring of picture identification ability

The measurements have in all three cases been carried out with and without optical correction of the eccentric astigmatism.

4.1 Measurements of ring target visual acuity (HPR)

Visual acuity of the 7 subjects falls in the following range: VA: 20/1000, 20/200 (0.02-0.1). With an ordinary visual acuity chart, your are not able to measure lower than VA 20/200 (0.1) at a standard distance of 5 meters (16.4 ft.) (this means that the person being examined can only read the top row). If visual acuity is worse than that, you can use shorter distances. A patient with a visual acuity of 20/500 (0.05) can, for example, see the top row of the chart at a distance of 2.5 meters (8.2 ft.).

For the seven subjects, visual acuity was to be measured with and without optical correction. There were two more reasons why the visual acuity chart (or a projected optotype test) was not adequate for our purposes: fixation cannot be controlled and measurements are too uncertain. The only method that we could find for lower visual acuity, with more relevant values than ordinary measure-

Behind the fixation rings is a computer screen for measuring ring visual acuity.

The fixation rings, which were described earlier, are used as support in gaze fixation.
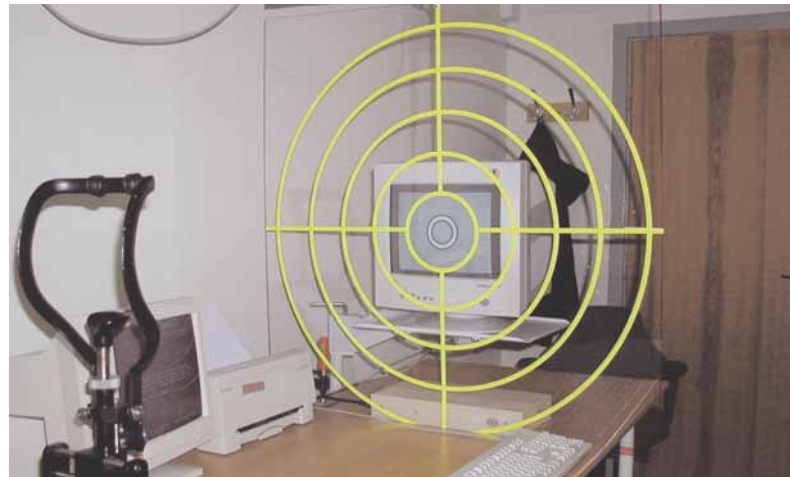
ments, were the optotypes in the ring perimetry that Lars Frisén developed [Frisén, 1992]. He had also made use of the same rings that are used in ring perimetry to measure acuity out to 50°, but only on two healthy eyes [Frisén, 1987]. He very kindly gave us access to his program and we used it to measure ring target visual acuity as described below.

A special computer screen was placed at the PowerRefractor's location. Previously used fixation rings were mounted around it and the subjects fixated on the same ring as when their eyes were measured for refractive error. The distance to the screen was the same as with the optical measurements, 1 meter (3.2 ft.). We chose to let the ring light flash only one time (the program offers a choice of one flash, constant flashing or a fixed ring glow). Of the two possible contrast levels, we chose the highest (90%) because the people who were measured saw too poorly to be able to detect lower contrasts. The examiner then let circles of successively decreasing size flash on the screen and the subjects had to say when they saw the ring. The examiner registered this.

Let's suppose that in one case the size was 15, which corresponds to VA 20/600 (0.033) The examiner enters "15" in the program and that in turn shows a random set of 50 rings with sizes close to the one chosen. The subject reports each time he/she sees a ring, the examiner presses the "plus" button, and the next ring appears. If the subject does not see the ring, the examiner presses the "minus" button until the next randomly chosen ring comes into view.

Appearance of the rings in the program we used for measuring ring visual acuity.
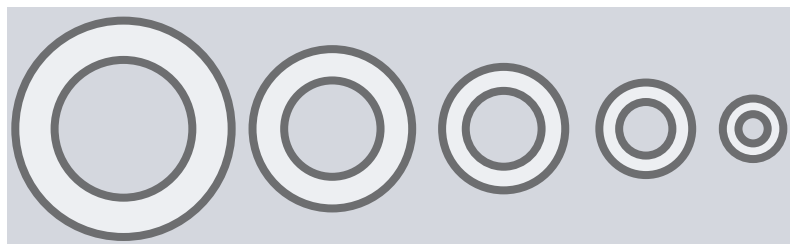
The rings can be displayed in 22 different sizes corresponding to VA from 20/90 (0.224) down to 20/1428 (0.014)

After the measurement is fed into the computer program, it produces a curve like the one below along with the values for visual acuity. If the 95% confidence interval was reasonably small (as below), the visual acuity value could be directly used.

```
    100 +                        *        Ring target acuity test
P
e                         *               Test distance 1.0 meters.
r    80 +
                                          Single blink enabled
c
e                                         Start estimate 16.65 min.
n    60 +          *                       (No. 10)
t

c
o    40 +                                 50% threshold: 15.894 min
r                                         95% confidence interval:
r              *                          14.938 - 16.844
e    20 +
c                                         Decimal acuity 0.06
t                                         Snellen acuity 20/317

     0  *                                 Date and time:
        +-----+-----+-----+-----+
      13.01 14.57 16.65 18.21 20.81

        Minutes of arc (log scale)


 4.16  5.20  6.24  7.80  8.85  10.41 11.45 13.01 14.57 16.65
18.21 20.81 23.41 26.02 29.14 32.78 36.94 41.62 46.31 52.03
58.27 65.56
```
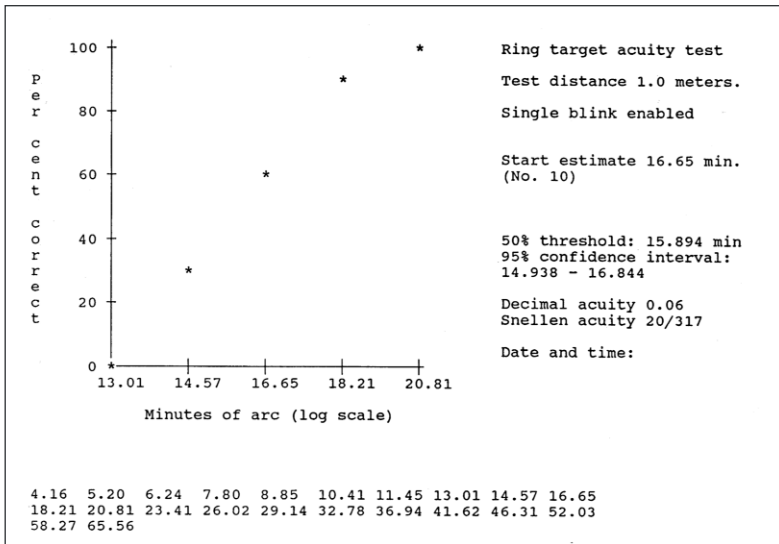
Reliable measurement results of ring target acuity.

If, on the other hand, the curve appeared as it does below, with a 95% confidence interval that is entirely too large, the measurement was retaken. It was often better because the subject had gotten used to the situation and was better able to concentrate. It varied between subjects as to how far down they could go and still have a satisfactory confidence interval.

```
    100 +                 *               Ring target acuity test
P
e                    *          *         Test distance 1.0 meters.
r    80 +
                                          Single blink enabled
c
e                                         Start estimate 31.22 min.
n    60 *                                  (No. 15)
t

c
o    40 +      *                          50% threshold: 25.188 min
r                                         95% confidence interval:
r                                         15.132 - 28.237
e    20 +
c                                         Decimal acuity 0.04
t                                         Snellen acuity 20/503

     0  +-----+-----+-----+-----+         Date and time:
      25.09 27.87 31.22 35.12 39.58

        Minutes of arc (log scale)


 4.46  5.57  6.69  8.36  9.48  11.15 12.26 13.94 15.61 17.84
19.51 22.30 25.09 27.87 31.22 35.12 39.58 44.60 49.62 55.75
62.44 70.24
```

Unreliable measurement results of ring target acuity.

For all of the subjects, it was possible to carry out measurements of ring target acuity with and without correction with reasonable precision on three different occasions.

PELLI-ROBSON CONTRAST SENSITIVITY TEST

0.00	H S Z		D S N		0.15
0.30	C K R		Z V R		0.45
0.60	N D C		O S K		0.75
0.90	O Z K		V H Z		1.05
1.20	N H O		N R D		1.35
1.50	V R C		O V H		1.65
1.80	C D S		N D C		1.95
2.10	K V Z		O H R		2.25

Right Eye

Log Contrast Sensitivity: _____

Measurement of contrast visual acuity (Log Contrast Sensitivity, LCS) with the Pelli-Robson test carried out at a distance of 1 meter (3.2 ft.).

On the right you see the formula with all of the contrast levels that can be measured.

4.2 Contrast sensitivity

The "Buser" test, containing Landholt's rings with full contrast on one side of the card and reduced contrast on the other, produced no results with the subjects. On the other hand, the "Pelli-Robson" test demonstrated useworthiness [Pelli et al., 1988]. It makes use of letters of the same size but with reduced contrast, which the subject attempts to read in the traditional manner. The test distance is 1 meter (3.2 ft.), but for some of the subjects it was necessary to use a shorter distance. The highest contrast for the letters has the designation 0.00 Log Contrast Sensitivity (LCS), which corresponds to 100% contrast. The weakest contrast, which is even difficult for a person with normal vision to see, was designated as 2.25 LCS, which corresponds to 0.6% contrast. The measurement was carried out with and without eccentric correction on the 7 subjects.

4.3 Measurements of picture identification ability

Because the reality we live in consists of environments with different contrasts, colors and sizes, the results of a standard vision test cannot be directly converted to tell how well or poorly a person with reduced vision manages with peripheral vision. To bridge the gap between objective vision tests and subjective experience, Björn Breidegard, Bodil Jönsson and I developed a test of the ability of subjects to identify pictures eccentrically. When this method is refined, it is possible that it can become a complement to other measurements of visual function.

A picture is displayed on a large computer screen at predetermined time intervals of between 0.1 and 5 seconds, i.e., a considerably longer exposure time than with a tachistoscope. In the initial tests, we have only displayed the pictures for one second. The subject tried to identify 50 pictures without correction and using eccentric fixation in the first series of pictures by telling what the pictures represented. After that, he or she repeated the task but with

The Widesight Wizard picture presentation program displays pictures with short exposure times and at the distance of 1 meter (3.2 ft.) for most subjects. They used their habitual eccentric fixation and the number of pictures correctly identified was measured with and without eccentric correction.

correction and with a second series of pictures of the same level of difficulty. The procedure was again repeated but this time without correction for series 2 and with correction for series 1.

The method is primitive and gives a rough idea. Systematic errors may occur in the first version in part because the series of pictures may not in reality have the same level of difficulty, and because learning of the series occurs. This program is in the developing stages and further work is needed on the idea.

It should be mentioned as background information that subjects with healthy eyes managed to identify 43–47 of the 50 pictures on the average at a 30° angle to the right.

5. Results

The most important result of this research is that the entire limitation of vision in peripheral visual function does not exist on the receptor level (retina). The optical correction that was tested on persons with CFL and the improvement in visual function that it produced shows that it is meaningful to correct their refractive errors at the angle they use in their trained eccentric fixation.

5.1 Double-pass measurement

The most important result of the double-pass measurements is that even in eyes with centrally perfect imaging (emmetropia), there are great individual variations in the peripheral optics of the eye. This is clearly seen in the measurement results presented in the figure below. The individual variations in eccentric astigmatism for one and the same angle can amount to 10D. Great differences can also be seen temporally and nasally in one and the same eye. On the average, the astigmatism is greater at an increased eccentric angle as would be expected, but even here, it differs considerably from individual to individual. See the Appendix.

All measurement values in astigmatism from double-pass measurements of centrally emmetropic eyes.
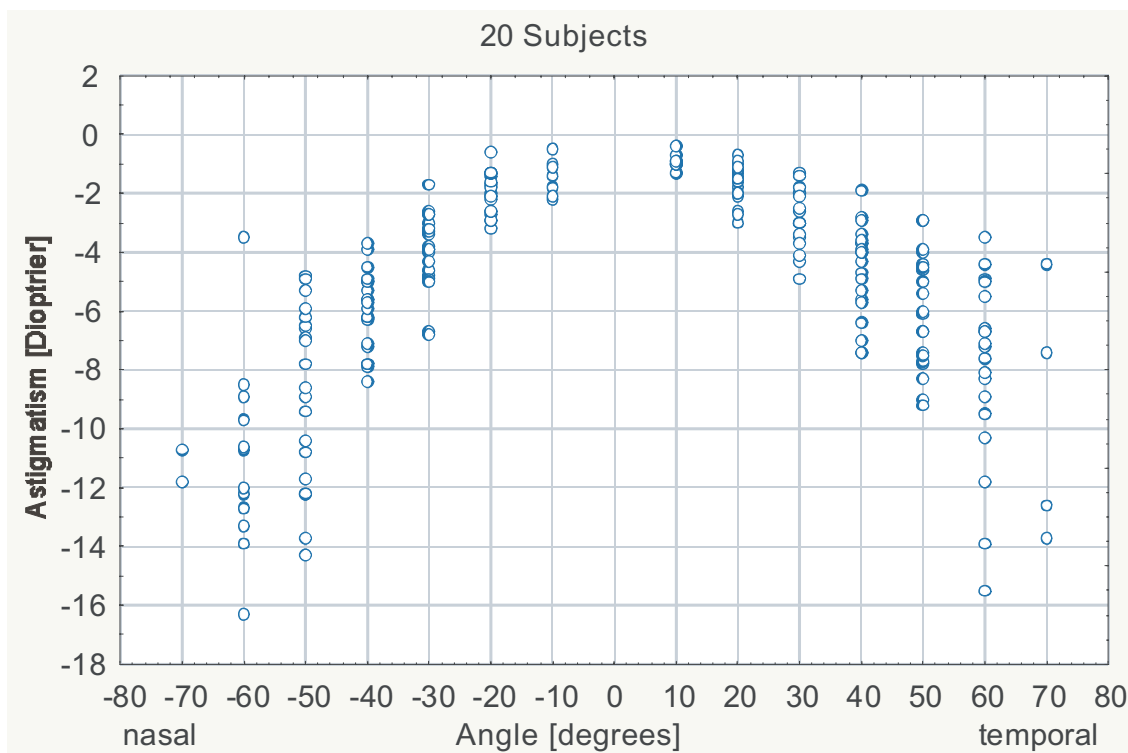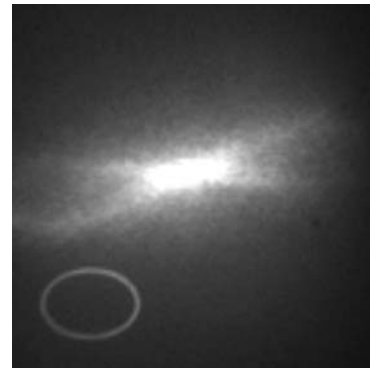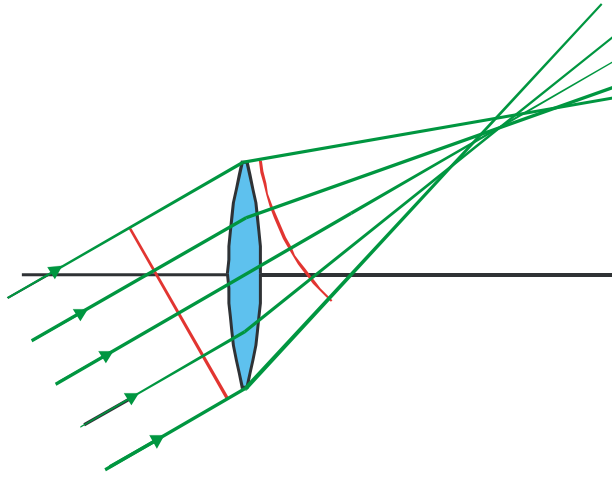
Astigmatism and defocus are not the only aberrations that arise in oblique incident in the optical system. The diagram on the left shows how the tangential beam appears in a person with considerable coma. The picture on the right shows an example of how it appears in a double-pass measurement in one eye with coma. The picture resembles two comets with tails that collide in the middle. The two comets are a result of the light passing through the optics of the eye twice when being measured.

In some of the eyes that were measured, it was demonstrated that there were other significant aberrations than astigmatism. The most obvious of these is coma.

5.2 The PowerRefractor

Measurements with the PowerRefractor show that it works well and makes it easy to measure oblique astigmatism in eccentric fixation. By making use of the fixation rings, sufficient reliability and stability can be achieved in gaze orientation. The instrument also gauges the direction in which the optical error is measured. The results of the case studies show that it is possible to arrive at sufficiently reliable values in order to make corrections. In some cases it was not possible to measure far enough out, i.e., angels greater than 25°–30°.

5.3 Changes in visual acuity

Of the seven people whose vision was corrected, we were able to demonstrate significant visual improvements in five of them with the ring target visual acuity test. The measurements were repeated three times to ensure the results.

The table on the next page provides evidence of the reproducibility of the measurements.

Subjects	Snellen acuity 1 (95% conf. interval)		Snellen acuity 2 (95% conf. interval)		Snellen acuity 3 (95% conf. interval)	
	Uncorr.	With corr.	Uncorr.	With corr.	Uncorr.	With corr.
1	20/800 (20/870-20/714)	20/526 (20/571-20/488)	20/870 (20/909-20/769)	20/606 (20/625-20/526)	20/909 (20/952-20/800)	20/645 (20/741-20/588)
2	20/377 (20/385-20/345)	20/323 (20/345-20/303)	20/392 (20/426-20/364)	20/290 (20/345-20/282)	20/400 (20/417-20/364)	20/282 (20/323-20/266)
3	20/714 (20/833-20/606)	20/476 (20/556-20/435)	20/606 (20/625-20/571)	20/417 (20/526-20/345)	20/667 (20/741-20/606)	20/455 (20/500-20/426)
4	20/357 (20/408-20/345)	20/364 (20/400-20/350)	20/392 (20/435-20/364)	20/417 (20/488-20/385)	20/385 (20/417-20/323)	20/370 (20/408-20/364)
5	20/645 (20/740-20/588)	20/426 (20/488-20/377)	20/606 (20/645-20/571)	20/455 (20/465-20/385)	20/645 (20/690-20/588)	20/392 (20/455-20/357)
6	20/323 (20/339-20/274)	20/253 (20/270-20/238)	20/312 (20/323-20/299)	20/256 (20/299-20/241)	20/263 (20/308-20/208)	20/215 (20/227-20/164)
7	20/351 (20/364-20/303)	20/339 (20/377-20/323)	20/476 (20/645-20/370)	20/417 (20/513-20/377)	20/400 (20/476-20/308)	20/357 (20/370-20/295)

How visual acuity changed with eccentric optical correction for the 7 subjects. The values in parentheses are for the 95% confidence interval's size, converted from minutes of arc to Snellen VA (visual acuity).

Uncorr.= uncorrected,
With corr.= with correction.

5.4 Changes in contrast sensitivity

Most of the subjects (five of seven) have exhibited improved contrast sensitivity with the Pelli-Robson Contrast Sensitivity Test.

Subject	Un-corr.	With corr.
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

How contrast sensitivity was changed with and without correction in Log Contrast Sensitivity, LCS.

5.5 Picture identification ability

We were able to demonstrate improvements in eccentric correction in three of the six people tested with the Widesight Wizard picture presentation program. Two had the same results with and without eccentric correction. In one case, the person's vision was so poor that the measurements could not be carried out, even at a shorter distance from the screen.

Number of pictures correctly identified				
Subject	Series 1 Uncorr.	Series 2 With corr.	Series 1 With corr.	Series 2 Uncorr.
1	6	8	uncertain	saw too few
2	not carried out			
3	25	34	39	30
4	30	34	35	39
5	22	35	35	24
6	42	48	40	39
7	30	41	42	35

Compare the comments on page 37 on how subjects with healthy eyes saw about 45 of the 50 pictures at a 30° angle.

5.6 Subjective experiences

The subjective experiences of the people involved in this study are encouraging in many cases. The most apparent is that guide vision ability has improved in two of the subjects to the point that others in their environment also report that the subjects have a more stable gait. Even if the improvement in visual acuity is only from VA 20/700 (0.028) to 20/500 (0.04), this has obviously influenced daily activities. Some have reported positive effects that we were unable to measure such as improved balance. Two of the subjects have reported improved stability when walking. All five, who have significantly improved vision according to our tests, subjectively describe how they can see better when watching television and, for some of them, even when using the computer. That eccentric correction has made it possible for our subjects to better recognize faces of people at 1 or 2 meters' (3.2 or 6.4 ft.) distance is for us an important indication that we are going in the right direction.

5.7 Summary table

All the objective and subjective improvements in the seven subjects are marked with an X in the following table.

	Better guide vision	Easier to see TV	Easier to see faces	Sees further	More stable gait	Better ring acuity	Better contrast LCS	Better picture vision
1	–	X	–	X	–	X	X	–
2	X	X	X	–	X	X	X	X
3	–	X	X	X	–	X	X	X
4	–	X	–	–	–	–	–	–
5	X	X	X	X	X	X	X	X
6	–	X	X	X	–	X	–	–
7	–	X	–	X	–	–	X	X

5.8 Method development

The results should also include the fact that we have adapted the double-pass method for eccentric measurement, provided PowerRefractor and ring target visual acuity tests with fixation rings as well as initiated measurements involving eccentric picture identification abilities.

5.9 Corrected subjects

CASE 1   Male, born 1947. Diagnosis: Macula Degeneration.
Field of vision with a central scotoma comprising 30° centrally.
Previous correction: R: sph.+2.0 cyl.–1.0 ax 25°   L: sph.+2.0.
Visual acuity from medical records: R: 20/2000 L: 20/4000 eccentric
fixation.

Measurements   Eccentric fixation angle: mostly downward, sees over the scotoma
when reading watching television and looking at faces. Has noticed
that he has better field of vision with upward fixation but has
difficulties using it.

When carrying out these measurements we realized that he sees
best at a fixation of about 25°–30° temporally with his right eye. Has
a fixation that lies further out than 30° is some directions!

Centrally	R: sph.+2.0	cyl.–0.75	ax 16°
(As close as possible)	L: sph.+6.25	cyl.–4.0	ax 95°

Eccentric measurement values according to the PowerRefractor (PR):

Fixed downward 22–24°	R: sph.+4.0	cyl.–2.5	ax 160°
	L: sph.+4.25	cyl.–1.5	ax 84°
Fixed upward 22°	R: sph.+4.25	cyl.–3.25	ax 21°
	L: sph.+4.75	cyl.–1.75	ax 163°
Fixed 25° to the right	R: sph.+4.0	cyl.–3.5	ax 96°
	L: sph.+7.75	cyl.–7.25	ax 89°
Fixed 25° to the left	R: sph.+6.25	cyl.–2.5	ax 66°
	L: sph.+4.75	cyl.–4.5	ax 98°

Ring target acuity without correction in this case.


```
         100 +
  P                              *        Ring target acuity test
  e                                        Test distance 1.0 meters.
  r   80 +                 *
                                           Single blink enabled
  c
  e   60 +            *                     Start estimate 44.60 min.
  n                                         (No. 18)
  t
  c   40 +                                  50% threshold: 42.585 min
  o                                         95% confidence interval:
  r         *                               38.324 – 46.387
  r   20 *                                  Decimal acuity 0.02
  e                                         Snellen acuity 20/851
  c
  t    0 +                                  Date and time:
         35.12  39.58  44.60  49.62  55.75

         Minutes of arc (log scale)
```
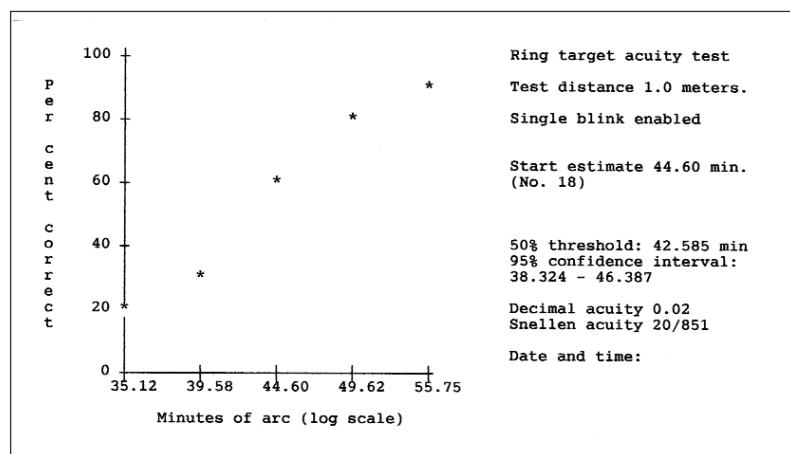
Vision according to HRP with or without own correction: VA 20/950
(0.02).

```
P
e
r    80
c
e
n    60
t

c    40
o
r
r    20
e
c
t     0
     27.87   31.22   35.12   39.58   44.60

        Minutes of arc (log scale)
```

Test distance 1.0 meters.

Single blink enabled

Start estimate 35.12 min.
(No. 16)

50% threshold: 32.506 min
95% confidence interval:
27.575 - 35.883

Decimal acuity 0.03
Snellen acuity 20/650

Date and time:
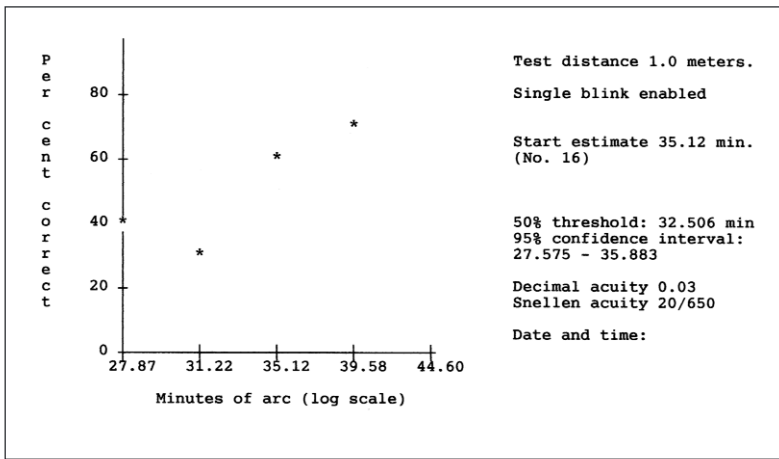
Result of measurement of ring target acuity. In this case with correction of the eccentric angle 30° to the right.

Ring target acuity according to HRP (High-pass Resolution Perimetry) at a fixation of 30° to the right with eccentric correction: VA 20/650 (0.03).

Contrast sensitivity

According to the Pelli-Robson test:
With or without own correction: Log Contrast Sensitivity 0.30.
With eccentric correction: Log Contrast Sensitivity 0.40.

Wizard picture test

Unreliable values because he saw too poorly even at a distance of only 25 cm. (9.8 in.). Saw only 5-8 pictures of 50.

Eccentric correction

R/L: sph.+4.0   cyl.–4.0 ax 90

Effects

Subjective experiences: Clearly better vision, primarily when watching television, which he can see at a distance of 50 cm. (19.7 in.). Is better able to follow. Is able to wear his glasses all the time but is bothered by reduced ability to judge distances and consequently feels uncertain. Vision is blurred when he looks downward. Experiences that the picture has become bigger at 3 to 5 meters (9.8 to16.4 ft.).

Comments: Found a point of fixation 30° to the right when measured by the PowerRefractor (PR) and had not used it before, not consciously anyway. Vision is best when he changes between different directions. Can shift between looking to the right and left side of the scotoma and has a similar refraction on both sides.

Fixates further out than the PowerRefractor is able to measure. The correction stated above is an estimate, but there is in all likelihood greater optical error. Has several fixation points and this explains why he finds it more difficult to determine distance when wearing the glasses all the time. For a long time has had the habit of fixating downward, over the scotoma, and in those positions the eccentric correction does not help.

Has tried having corrections only on the sides and experiences better guide vision ability.

An experiment in placing the correction on the side for this subject. It makes it easier for him to walk around and to use more than one point of fixation.

CASE 2 Female, born 1943. Diagnosis: Tapetoretinal Degeneration.
Field of vision with a central scotoma comprising 10-15°.
Previous correction: R/L: sph.–3.75.
Visual acuity from medical records: R: 20/700 L: 20/2000.

Measurements Eccentric fixation angle: 17–20° to the right, only that direction and stable.

Eccentric correction according to PR:
R: sph.–2.25   cyl.–3.25   ax 90°
L: sph.–1.75   cyl.–4.5   ax 90°

Vision according to HRP with own correction:
Binocular VA 20/400 (0.05).
Vision according to HRP:
Binocular with eccentric correction: VA 20/300 (0.07).

Contrast sensitivity According to the Pelli-Robson test:
With the previous correction: Log Contrast Sensitivity 0.90.
With eccentric correction: Log Contrast Sensitivity 1.05.

Wizard picture test Not carried out.

Eccentric correction R: sph.–2.0   cyl.–3.0 ax 90°
L: sph.–2.0   cyl.–3.0 ax 90°

Effects (subjective experiences) Has worn the correction all the time since the middle of July. Feels better and sees better. Experiences a more stable gait and does not misstep as much. Sees the television better but removes the eccentric correction at the computer and for other activities that are close up, but to a lesser extent than with the old glasses.

The actual eccentric correction in this case is for 17–20° to the right, which has been a habitual direction for many years. Also has a habitually fixed head position to the right due to her visual impairment.

Male, born, 1971. Diagnosis: Leber's Opticusatrophy.
Field of vision with a central scotoma comprising about 10° in height and 20° in width.
Previous correction: none
Visual acuity from medical records: R: 20/700 L: 20/2000

Vision according to HRP without correction:
Binocular VA 20/700 (0.03).
Central refraction according to PR:
R: sph.+3.0   cyl.–0.5   ax 120°
L: sph.+1.25   cyl.–0.5   ax 187°

Measurements

Eccentric fixation angle 13° upward.
Eccentric correction according to PR:
R: sph.+3.0   cyl.–1.0   ax 158°
L: sph.–0.25   cyl.–0.5   ax 140°
Vision according to HRP with eccentric correction:
VA 20/500 (0.04).

According to the Pelli-Robson test:
Without correction: Log Contrast Sensitivity 0.45.
With eccentric correction 13° upward: Log Contrast Sensitivity 0.75.

Contrast sensitivity

Without correction: 25 correct of 50.
With eccentric correction: 34 correct

Wizard picture test

Eccentric correction
R: sph.+3.0   cyl.–1.0 ax 160°
L: sph.+–0

Eccentric correction

The subject's spontaneous experience is that his vision is clearly better, but he had some problems getting used to the glasses. Uses the glasses primarily when watching television and inside and can definitely see an improvement in being able to more clearly distinguish faces.

   Is very positive to the glasses and thinks that this is the only positive thing that has happened since he became visually impaired. Wears them more and more. Has perhaps a bit more difficulty with judging distances but notes that it is easier for him to recognize road signs with the correction.

Effects (subjective experiences)

CASE 4	Female, born 1931. Diagnosis: Macular Degeneration.

CASE 4 Female, born 1931. Diagnosis: Macular Degeneration.
Field of vision: CFL but visual field assessment is lacking.
Previous correction:
R: sph.+2.0.
L: sph.+2.0   cyl.–1.0   ax 20°.
Visual acuity from medical records: R: 20/400 L: under 20/2000.

Measurements Vision according to HRP with own correction:
Binocular VA 20/400 (0.05).
Central refraction according to PR:
R: sph.+1.75   cyl.–1.75   ax 88°
L: sph.+1.25   cyl.–1.25   ax 22°

Eccentric fixation angle: 18-20° to the right.
Eccentric correction according to PR:
R: sph.+4.0   cyl.–5.0   ax 90°
L: sph.+2.0   cyl.–2.25   ax 90°

Vision according to HRP:
R: VA 20/400 (0.05) experiences subjective improvement and has
large eccentric astigmatism, is therefore corrected.

Contrast sensitivity According to the Pelli-Robson test:
With own correction: Log Contrast Sensitivity 1.05.
With eccentric correction 20° to the right:
Log Contrast Sensitivity 1.05.

Wizard picture test With own correction: 30 correct out of 50.
With eccentric correction: 34 correct.

Eccentric correction First pair of glasses
R: sph.+4.0   cyl.–5.0   ax 90°
L: +–0
Did not accept these because there was no correction for the left eye.

Second pair of glasses
R: same
L: sph.+3.0   cyl.–4.0   ax 90°
*The reason being that the person feels that she has to have correction
for the left eye too.*

Effects (subjective experiences) Generally no improvement. Sees just as well with her own glasses as
with the eccentric correction. Has noticed that the television picture
is slightly bigger and so has used them mostly with that activity. Can
walk around with them on without being bothered.

Male, born 1929. Diagnosis: Macular Degeneration
Field of vision according to the visual field assessment, which
unfortunately is not current.
Very clear central fixation.
Previous correction:
R: sph.–1.25
L: sph.+1.0   cyl.–2.0   ax 85°
Visual acuity from medical records: R: 20/400 L: 20/2000.

Vision according to HRP with own correction or without:
Binocular VA 20/700 (0.03).

Measurements

Eccentric fixation angle: 20° to the right and 8° upward, only that
direction.
Eccentric correction according to PR:
R: sph.–1.0   cyl.–4.5   ax 88°
L: sph.–0.25   cyl.–4.25   ax 84

Vision according to HRP with eccentric correction: Binocular VA
20/400 (0.05).

According to the Pelli-Robson test:
With correction or with previous correction:
Log Contrast Sensitivity 0.30.
With eccentric correction: Log Contrast Sensitivity 0.60.

Contrast sensitivity

Without correction: 22 correct out of 50.
With eccentric correction: 34 correct.

Wizard picture test

R: sph.–1.0   cyl.–4.0   ax 90°
L: sph.+–0   cyl.–3.0   ax 90°

Eccentric correction

The new glasses make it possible for him to see through 75% of the
"fog" that he wants to get rid of. We have 25% left to remove in his
opinion. Sees more than twice as far: 5–10 meters (26–32 ft.) without
correction, 20–25 meters (65–82 ft.) with correction. Could watch
television before at a distance of only a few decimeters (7–10 in.), but
can now watch from 0.5–1 meter's distance (1.6–3.2 ft.). "My walking
balance feels much, much better. The neighbors say that I walk more
stably and securely." Wears the eccentric correction all the time and
the only disadvantage is that the "fog" has become even more
obvious in the parts of the eye that he does not use for seeing.

*Effects (subjective
experiences)*

CASE 6	Male, born 1984. Diagnosis: Stargart's disease Syndrome from birth (fundus falvi maculatus).

Male, born 1984. Diagnosis: Stargart's disease Syndrome from birth (fundus falvi maculatus).
Field of vision with central scotoma comprising about 10–15° according to the field of vision pattern.
Previous correction: none
Visual acuity from medical records: R/L or Binocular VA 20/300.

Measurements

Central refraction according to PR:
R: sph.–1.0   cyl.–1.0   ax 178°
L: sph.–1.25   cyl.–1.25   ax 10°

Vision according to HRP without correction or with correction for central refraction: Binocular VA 20/350 (0.06).

Eccentric fixation angle: stable 20–24° to the right.
Eccentric correction according to PR:
R: sph.–1.0   cyl.–2.0   ax 80°
L: sph.–1.0   cyl.–2.75   ax 28°

Vision according to HRP with eccentric correction:
Binocular VA 20/250 (0.08).

Contrast sensitivity

According to the Pelli-Robson test:
Without correction: Log Contrast Sensitivity 1.05.
With eccentric correction: Log Contrast Sensitivity 1.05.

Wizard picture test

Without correction: 42 correct out of 50.
With eccentric correction to the right as stated above: 48 correct.
Reduced to 50% smaller picture size without correction: 39 correct.
Reduced to 50% smaller picture size with correction: 40 correct.

Eccentric correction

R: sph.–1.0   cyl.–2.0   ax 80°
L: sph.+0.5   cyl.–2.0   ax 30°

Effects (subjective experiences)

Sees the television better: 1.5 meter's distance (4.9 ft.) from a 32-inch screen. Sees faces and what is happening better. With a constant fixation to the right, he finds it easier with the correction to find the area for the best vision. This area is smaller without the glasses. Sees contours of details better in common environments. The board in school looks blank without the correction, but with glasses the drawings and descriptions stand out so that they can be understood. The glasses work best in situations when he is sitting still. When moving around in ordinary environments, the glasses disturb more than assist. Scans by gazing in different directions and then understands that they make the images in his surroundings worse.

Male, born 1947. Diagnosis: Leber's Opticusatrophy.
Field of vision: central absolute concentric scotoma about 8°.
Previous correction: R/L: sph.–1.5
Visual acuity from medical records: R: 20/700 L: 20/400.

Vision according to HRP with own correction: VA 20/400 (0.05). *Measurements*
Eccentric fixation angle: The most common eccentric fixation
direction is 7–10° upward, nearest the scotoma primarily when
reading. To improve field of vision and get a better overview, a
fixation of 20° upward is used, for example, when he cycles or goes to
the cinema. To watch television at 50 cm. (19.68 in.) distance, he
fixates at about 12–15° out to the left.

Eccentric correction according to PR:

	Centrally or nearest the scotoma:	L: sph.+–0	cyl.–0.5	ax 75°
Fixed upward to 20°:		L: sph.–1.0	cyl.–2.0	ax 175
Fixed to the left 12-15°:		L: sph.+–0	cyl.–1.5	ax 85°

Vision according to HRP:
In all the above fixations with eccentric correction: VA 20/400 (0.05).
In some measurements VA was almost 20/300 (0.06), but it was not a
significant improvement.

According to the Pelli-Robson test: *Contrast sensitivity*
Without correction: Log Contrast Sensitivity 0.90.
With eccentric correction 20° upward: Log Contrast Sensitivity 1.05.

Without correction: 30 correct out of 50. *Wizard picture test*
With eccentric correction 20° upward: 41 correct.

The first correction with only one strength, i.e., for an upward *Effects (subjective*
fixation of 20°: *experiences)*
R: sph.–1.0   cyl.–2.0   ax 10°
L: sph.–1.0   cyl.–2.0   ax 175°
Better vision when fixating upward 20° and makes good use of it at
the cinema and when he cycles. The eccentric correction is
bothersome in other directions.

The second correction with three cylinder strengths in the same lens
(see picture on p. 52): This experimental correction is difficult to use
and does not function at all satisfactorily when he cycles, cannot see
downward. It is also difficult to find the right place in the different
gaze directions.

Eccentric experimental correction with three strengths in the same glass made for distance vision in three eccentric directions.

Up 20° cyl.–2,0 ax 175°
sph: –1,0

Up 7°
sph.+–0
cyl.–0,5
ax 75°

Left 12°
sph. +–0
cyl.–1,5
ax 85°
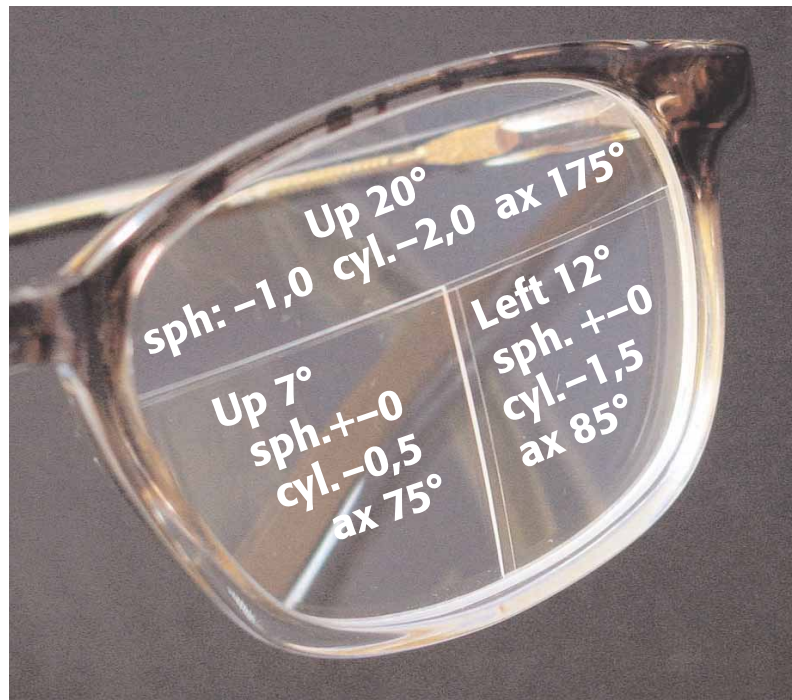
The third correction with two cylinder strengths (see pictures below): Functions optimally when he goes to the cinema or is a passenger in a car. Can identify and check out his surroundings easier and alternates between central and eccentric correction. After three weeks he has learned the technique better, easier to identify pictures on the film screen where he can shift between central and eccentric vision. Works best when he is sitting still. Uses eccentric vision with correction for identification in traffic when he is biking. Experiences difficulties in moving, checks head eye movements at the same time.

When fixating upward, the subject makes use of the lower part of the glasses, which have an eccentric correction for 20° upward.

R: sph. –1,0   cyl. –2,0   ax 10°
L: sph.–1,0   cyl. –2,0   ax 175°

The optics of the center of glasses are manufactured so that they meet at the seam between the segments.

In the upper part there is correction for central or near central sight.

R: sph. +–0   cyl. –1,0   ax 100°
L: sph.+–0   cyl. –1,0   ax 70°

6. Discussion and conclusions

This thesis has been written during ongoing development of methods and concepts, at the same time as several participants were waiting their turn. The work continues with unabated energy, but it is important now to extend the discussions to a wider circle in order to continue research under the best possible conditions.

That seven out of the seven subjects have all experienced at least some improvement in visual function when they utilize eccentric correction is impressive. The subject who has benefited the most exhibits improvements in all the areas of visual function that were examined. He also attests to a number of subjective improvements (see table on p. 43). The subject who benefited the least noticed an improvement in watching television only. Between these two extremes there are five others with more complex profiles: one has improved visual function in acuity but not in contrast sensitivity, another vice versa, etc.

The oldest of the subjects is the one who exhibited improvement in all the areas listed in the table on page 43. He is also one of the two who noticed improved balance and stability when walking. That an improvement in eccentric correction can result in better balance for many people is a possibility that looms on the horizon. Many older people have balance problems and macular degeneration, for example. We have not been able to find anyone who has studied a potential statistical correlation between these two conditions, but we plan to examine the extent to which balance can be improved through eccentric correction.

For the results to achieve widespread application means that we need to progress from having corrected in only one direction to being able to correct in many. It is entirely possible that this can happen in the future with a contact lens or a specially manufactured, surgically implanted lens (IOL).

Contrast sensitivity, which is important in daily living, improved for five of the seven subjects. It is also significant that four of the seven are better able to recognize faces and people, and that three of these have improved contrast sensitivity vision. The most significant improvement, measurements of which were repeated three times on each subject, is that five of the seven exhibited better vision when measured with ring visual acuity. Their experience of subjective improvement is also the strongest.

One reason for the improvements in watching television for all the subjects can be that they sit still while doing so. In that way, they only make use of the vision in the direction for which the eccentric correction is measured. This correction can, however, be entirely wrong in other directions (one person was lucky enough to require of the same eccentric correction in the two directions of fixation that he used). The experiment that is being carried out with several astigmatic corrections in the same eyeglass lens has not yet been entirely successful. The trials have only been run on one person and the most recently constructed bifocals for seeing at a distance with central and eccentric correction appear to work better, especially after a few weeks' conscious training.

The attempt has produced the very best results for the two subjects who only have a single direction of fixation. These two people wear their glasses with eccentric correction all the time and have also exhibited improved gait stability (according to their own testimony and observations by others).

Above and beyond the corrections, our work has also resulted in a number of other subjects becoming aware of how they should fixate to make better use of their remaining vision. The most striking example is a woman who has had reduced vision for 20 years and who also happens to work in eye care services. Yet no one had instructed her in how to train eccentric fixation. When measured with the PowerRefractor and the fixations rings, however, she became aware that the remaining vision in one direction was considerably better. Previously she had searched or scanned without in any way being aware of where her vision was the best. In her case, there was no optical error to correct, but by just making her aware of how she could fixated, she found it easier to manage visually. It is only reasonable that methods should be developed in low vision rehabilitation that enable as many as possible to discover their eccentric direction of fixation.

Wave-front measurements in low vision subjects with a Hartmann-Schack sensor is close at hand in this research project. With this method we figure that we will be able to procure measurement values at greater angles and with greater precision than what the PowerRefractor can offer.

Another interesting possibility is being able to use wave-front measurements to not only get at astigmatism but at coma too.

Let me conclude this look into the future by showing the results of the first, preliminary wave-front measurements (see the figure on p. 55) that we have carried out in the new optical laboratory that was built at the Visual Optics Section, Department of Physics, Royal Institute of Technology in Stockholm. The subjects do not belong to the group of people with low vision—it is a matter of purely
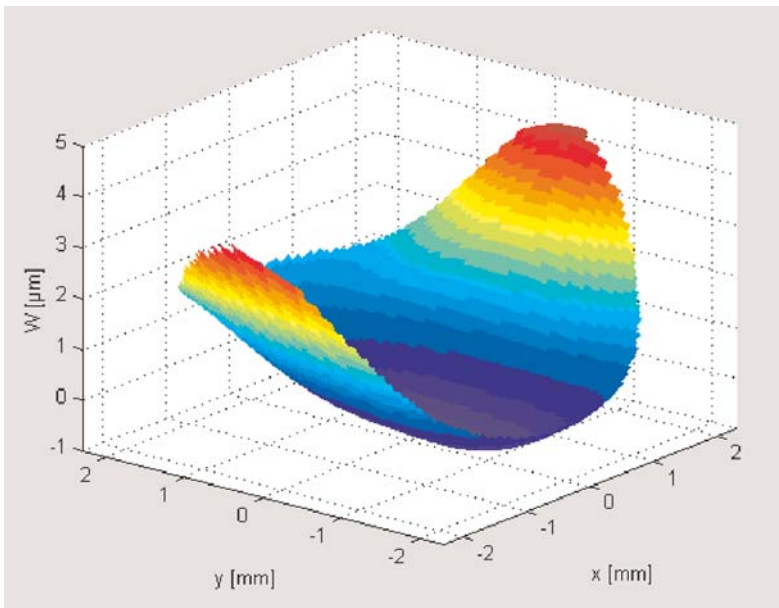
The results of an eccentric wave-front measurement with a Hartmann-Shack sensor, about 30° temporally in a centrally corrected eye. The picture shows a three dimensional image of a wave-front taken from within the eye. The dimension of the x-y plane is limited by the pupil. The height represents deviations from the plane expressed in micrometers.

The measured wave-front corresponds to a myopia of −0.5 D and a astigmatism of −3.5 D.

preparatory test measurements. Up to now, no one has measured and published the results for measurements of aberrations at eccentric angles with this technique.

I hope that more people will pursue research in the area of eccentric optics/eccentric vision, and that this area will receive better resources. If that happens, we can more quickly achieve results that will benefit the large group of people who have a central visual field loss. We can then broaden the scope to include other areas of interest, such as the effects of improved eccentric correction in traffic for people with normal vision.

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Peripheral astigmatism in emmetropic eyes

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Summary

The long-term aim of the work introduced here is to investigate the influence of off-axis aberrations on human vision, especially for subjects with a large central scotoma. The latter use their peripheral vision in spite of its poor off-axis optical quality, and a correction of the off-axis aberrations might be of great assistance. The eccentric fixation angles used by these subjects can be up to 20–30°. In this initial study we have measured oblique astigmatism, the major off-axis aberration, in 20 emmetropic eyes in 10° steps out to 60° nasally and temporally using a 'double pass' setup. The results show very large individual differences and the oblique astigmatism also varies from nasal to temporal side. In an off-axis measurement angle of 30° the astigmatism varied between subjects from 1 to 7-D, with a mean astigmatism of about 4-D on the nasal side and about 1.5-D lower on the temporal side. At 60° temporally, the mean astigmatism was 7-D. At 60° nasally, all subjects had astigmatism larger than 8-D and the mean astigmatism was 11-D. The results indicate that any attempt to correct the off axis astigmatism in an eye with central scotoma cannot be based on central refraction; instead, individual measurements are necessary. © 2001 Published by Elsevier Science Ltd on behalf of The College of Optometrists.

Introduction

The quality of the optical image in the human eye outside the area of central vision has, so far, been less studied than the central visual quality. The reason for the relatively low interest in the peripheral optics of the eye is that for healthy eyes peripheral vision is considered to be of less importance. The eye is by nature optimised for central vision. Most people use peripheral vision mainly for orientation and motion detection with fewer demands on image quality. However, if central vision is lost, i.e. there is a central scotoma, any improvement of the peripheral visual function is most valuable. The eccentric fixation angles used in these cases can be up to 20–30°. Age-related macular degeneration (ARMD) is the most common cause of central scotoma, and with the ageing population there is an increasing number of people with visual handicaps related to ARMD. In the age group of 70 and older, about 30% have some type of agerelated defect in central vision, which for some of them, results in a total central scotoma. About half of them are sufficiently visually impaired that they can be regarded as low vision patients (The Lighthouse, 1994). There are also a group of younger subjects with retinal problems, like Stargart's disease or opticusatrophy, that lead to central scotomas. The long-term goal of this project is to help patients with central scotoma to use their remaining vision in the best possible way. We want to investigate if it is possible to improve their visual function by correcting the off-axis aberrations.

Background

Many authors have investigated the optical limitations and aberrations of the human eye. Already in 1801, Thomas Young (Young, 1801) discovered that there is astigmatism in oblique angles in all-human eyes. It is now well known that the aberrations greatly increase for objects located off-axis, and that astigmatism and defocus are the most important aberrations. In the present work we have measured the off-axis refraction by using double-pass measurements in an optical laboratory on a group of emmetropic subjects. The future purpose for this study is to test if any improvement of
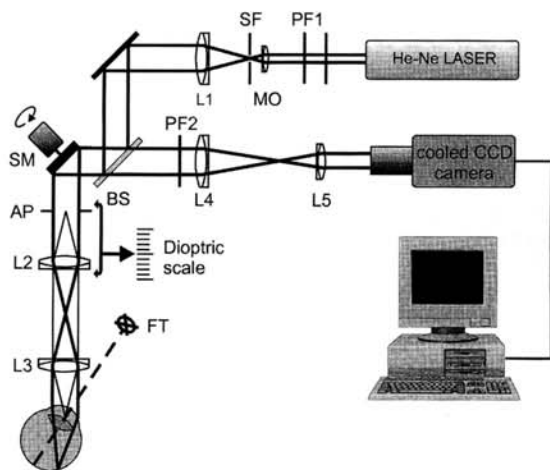
Figure 1. The experimental set-up for double-pass measurements of the off-axis astigmatism.

visual functions can be measured in subjects with central scotomas by correcting these aberrations.

Ferree and colleagues (Ferree *et al.*, 1931, 1932, 1933) studied oblique astigmatism using a Zeiss parallax optometer and Millodot (1981) used a Hartinger optometer. We have tried to use a Hartinger optometer to measure oblique astigmatism and found this to be most difficult because the results are not reproducible. Retinoscopy was used (Rempt *et al.*, 1971) to assess the off-axis astigmatism. They used a method called 'double sliding-door effect' to interpret the reflex. Technically, peripheral retinoscopy is complicated and we found it impossible to get reliable results with this method. A quite common situation is when the retinoscope reflex in the peripheral parts of the pupil moves 'against' while the central part of the reflex has a 'with' motion. In central retinoscopy this corresponds to spherical aberration but in the periphery it can be caused by a variety of aberrations. Because of this we have found this method to be unreliable and we question that the 'double sliding-door effect' can be used in clinical practice.

There are also many previous works that have used mathematical models of the eye for theoretical predictions (Lotmar and Lotamar, 1974; Pomerantzeff *et al.*, 1984; Dunne *et al.*, 1987a; Smith and Lu, 1991). We have also tried this by using commercial ray-tracing software, but there is a lack off sufficient information on the off-axis structure of the eye to create a good mathematical model for the peripheral vision. Many eye models have been developed for a restricted set of conditions (Wang *et al.*, 1983; Liou and Brennan, 1997; Wang and Thibos, 1997; Escudero-Sanz and Navarro, 1999). Work done in modelling by Dunne and colleagues show that the off-axis astigmatism is virtually unchanged in Gullstrand's model eye, when the lens is removed (Dunne *et al.*, 1987b). This is in conflict with experimental reports stating that aphakic eyes have less off-axis astigmatism than phakic eyes (Millodot, 1984), showing that the lens contributes to the oblique astigmatism. Models inevitably only reflect the behaviour of the 'average' eye, whereas individual differences and their influence on the visual ability in the peripheral visual field are of great interest.

More recently some researchers have measured refraction and optical performance in the peripheral field with modern techniques. The double-pass-method has been used for off-axis measurement in several works (Jennings and Charman, 1978, 1981, 1997; Navarro *et al.*, 1993; Guirao and Artal, 1999). However, in these references only 3–4 eyes have been measured with a variety of refractive (on-axis) errors. In some studies MTF measurements have been performed together with corrections of peripheral defocus and astigmatism (Artafl *et al.*, 1995a).

Methods

The major off-axis aberration in the eye for large field angles is astigmatism. Since macula degeneration is a disease in the retina, it is not obvious that it is connected to optical anomalies of the eye. As a background material for future studies on low vision patients we chose emmetropic, healthy eyes because they are easy to measure. We have measured astigmatism and curvature of field in 20 eyes with a double-pass method. The inclusion criterion for the selection of subjects was that the eye should not have a refractive error of more than ± 0.5 dioptres in either sphere or cylinder. This is within the range of the normal classification of emmetropia. We screened all the subjects to include only those with normal visual function and a visual acuity of at least 1.0 (20/20 or 6/6). The subjects ages range from 20 to 45 years and the mean age was 28 years.

Apparatus

We used a double-pass apparatus (Santamaría *et al.*, 1987) much similar to those used by others in peripheral measurements (Artal *et al.*, 1995a; Guirao and Artal, 1999). *Figure 1* shows a schematic layout of the experimental setup. The light from a 10 mW He–Ne laser is focused to a point source by a spatial filter, SF, and collimated by lens L1. The collimated light is reflected by beam splitter BS ($R = 10\%$) and the diameter is controlled by the artificial pupil AP (3 mm in diameter), conjugate to the entrance pupil of the eye. Lenses L2 and L3 image the point source to the far point of the examined eye. By moving lens L2 together with AP, the image of the point source can be adjusted within the range of -10 to D refractive errors. The optics of the eye then focuses the light to an aberrated image on the retina. The diffusely reflected light from the retina is imaged via a 4× telescope (L4 and L5) onto a
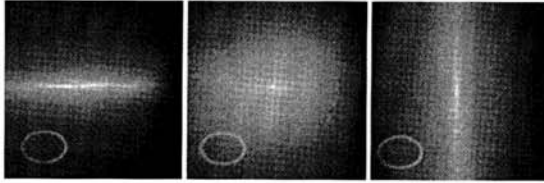
Figure 2. The two line foci and the circle of least confusion as recorded by the CCD-camera. The small elliptic shape is caused by a reflection from one of the lenses.

cooled scientific-grade CCD camera. *Figure 2* shows typical CCD-images of the two line-foci and the circle of least confusion. To minimise the problem of speckles, a spinning mirror SM (3000 rpm) is used to move the spot in a circle (0.2 arc–min in diameter) on the retina during the exposure (about 250 ms) of the CCD. PF2 and PF3 are crossed polarisation filters to remove specularly reflected light from, e.g., the cornea. Polarisation filter PF1 was rotated to adjust the power of the laser so that 3 μw entered the eye during the measurements. The subject was exposed to laser light for a maximum of 5 min for every measurement angle. This gives an exposure of about 1 mJ at each location of the retina, which is almost two orders of magnitude below safety standards.

No cycloplegic drugs were used. The subject's head was fixed by use of a well fitting bite bar permitting rotation of the head around a vertical axis through the centre of the pupil. This allowed a rapid change of measurement angle while maintaining the centration of the artificial pupil. The centration of the pupil was monitored by an external CCD-camera. During the measurements the subject looked straightforward at a diffusely illuminated fixation target that moved along with the rotation of the bite bar. The fixation target was imaged to infinity by a lens system to relax the accommodation. The position of the two line foci were subjectively defined by the operator as the two most narrow light distributions in the CCD image while manually moving lens L2. The actual measurement of the position of the two line foci and the circle of least confusion took about 1 min for every angle.

Spherical and plano-cylindrical lenses of known powers were used to test the system for systematic errors. The test lenses where placed at the pupil plane and the movable block (L2 and AP in *Figure 1*) was adjusted so that the laser beam was focused 2 m after the test lenses. This procedure was then repeated several times for spherical test lenses with focal powers up to ±10-D and plano-cylindrical test lenses with focal powers up to ±3-D. The repeatability and linearity was found to be within ±0.2-D over the full range. The position of the block and the distance that the block needed to be displaced in order to achieve a certain focal power at the corneal plane corresponded to theoretically calculated values.

It should be noticed that the refraction is measured at the pupil plane and not at the spectacle plane.

Measurements

We measured each patient at angles from 60° nasally to 60° temporally in steps of 10°. For each measurement angle we measured five different parameters. We measured the refraction for the circle of least confusion and for each one of the two line-foci we measured the refraction and the orientation of the line. Of these five measurements, three were used for further calculation; the refraction of the two line-foci and the angle of the most hyperopic line. The position of the circle of least confusion and the angle of the most myopic line were only used for comparison. In some subjects the angle between the two line foci was different from 90°. In other subjects, the circle of least confusion was significantly different from the midpoint of the two line foci. At large measurement angles, the circle of least confusion actually showed a systematic drift from the midpoint towards the most hyperopic line focus. These anomalies probably arise from significant contributions from other aberrations.

One particular subject was measured on eight different occasions and the standard deviation was calculated for each angle separately. We found the mean value, over all angles, of the standard deviation of the measured astigmatism to be 0.60-D. The difficulty in taking precise readings varied between test subjects; this subject was considered representative, being somewhere in the middle on the difficulty scale.

Results

The refraction of the focal lines as a function of the measurement angle varies greatly between different test subjects. For example, at a measurement angle of 60°, the standard deviation of the refraction of the more myopic line is close to 4 dioptres. For each individual eye, however, the measured refraction, as a function of measurement angle, normally shows a smooth curve with only small deviations from the general shape of the curve.

In *Figure 3* the refraction for the two line foci and the circle of least confusion is plotted as a function of the measurement angle for three different subjects. For the subject in *Figure 3a* the curve is growing astigmatism in higher eccentricities, almost symmetrical on nasal and temporal sides. The subject in *Figure 3b*, on the other hand, has a much lower peripheral astigmatism, but with a marked hyperopic shift in larger angles. *Figure 3c* shows an example of a subject with a large nasal-temporal asymmetry.

In order to analyse the results statistically we used astigmatic decomposition, mapping the refraction of the two line foci and the angle at the most hyperopic line to M, X and Y co-ordinates. M is the spherical equivalent,
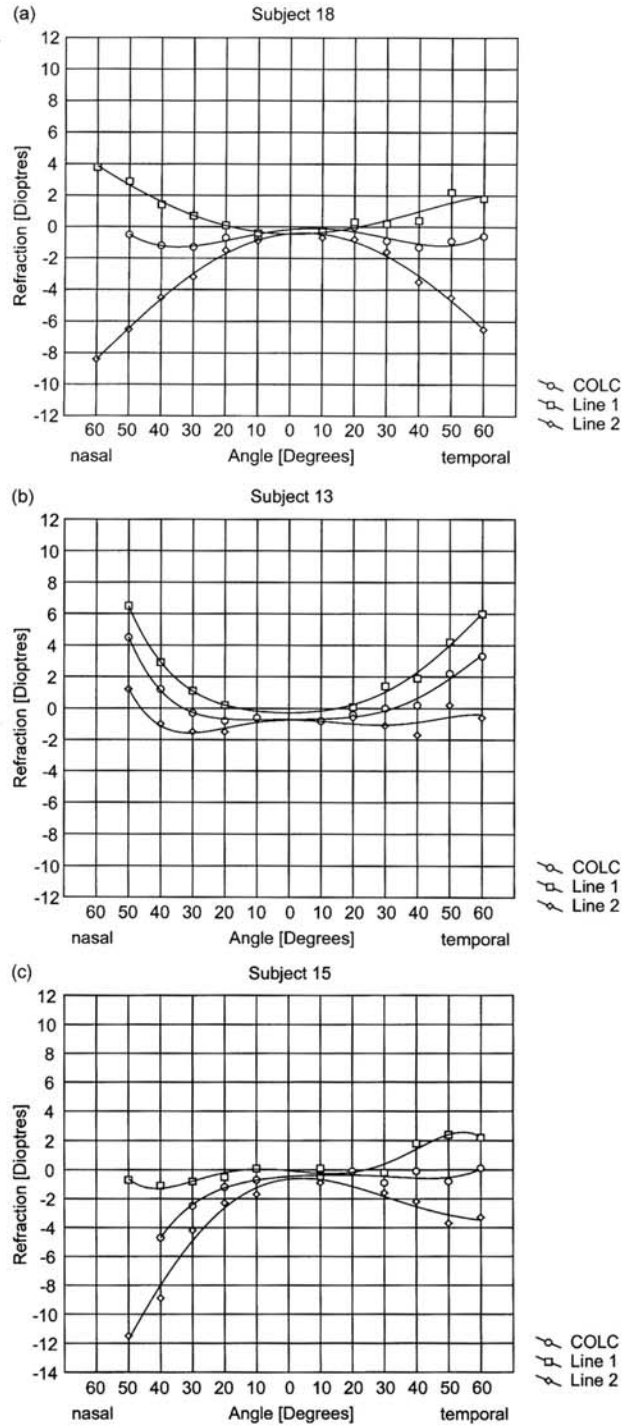
Figure 3. The refraction for the two line foci (line 1, line 2) and the circle of least confusion (COLC) plotted as a function of the measurement angle for three different subjects. The lines connecting the data points are only to guide the reader's eye.
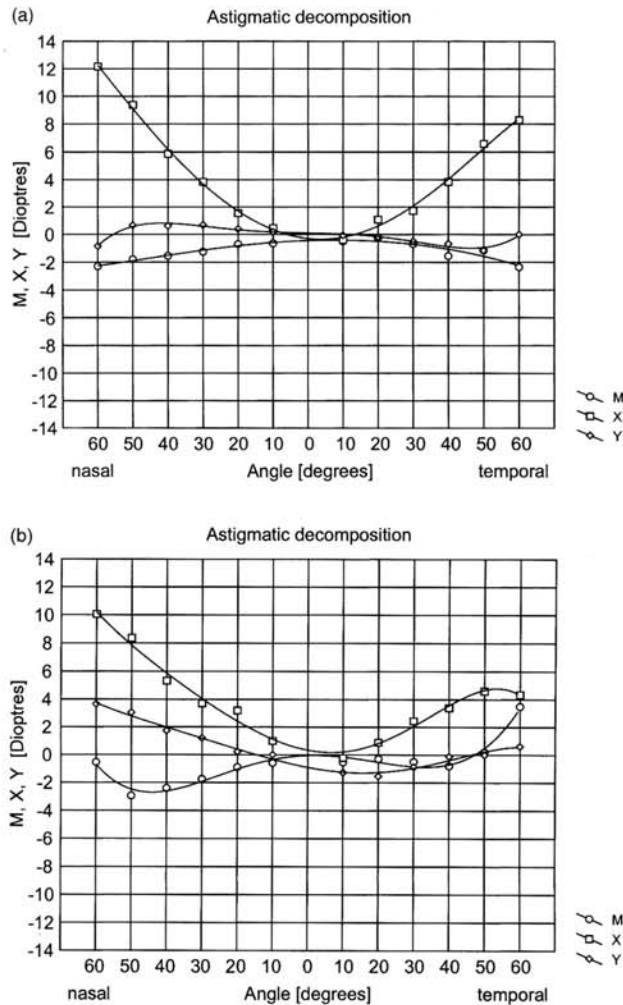
Figure 4. Astigmatic decomposition of the measured data for two subjects. (a) shows a normal situation with an induced astigmatism mainly in the vertical and horizontal direction ($X - D$). In (b) the astigmatism in 45° and 135° ($Y - D$) is as large as 4-D at 60° nasally. This corresponds to a rotation of the cylinder axis of about 10°.

which is the mean refraction of the two line foci. X is the with/against the rule component of the astigmatism (often written as $C00$) which is calculated from $C * \cos (2v)$, where C is the magnitude of the cylinder and v is the angle of the cylinder axis. Similarly, Y is the oblique component of the astigmatism (often written as $C45$), calculated from $C * \sin (2v)$. The new set of co-ordinates (M, X, Y) creates an additive vector space that is well suited for statistical purposes. More information on astigmatic decomposition can be found in textbooks on visual optics (Rabbetts, 1998).

Contrary to the case of a rotationally symmetric lens system, the astigmatism caused by off-axis fixation within the horizontal plane is not always aligned 'against

the rule'. For some subjects, the astigmatism induced along the 45 or 135-° meridians (the Y co-ordinate) was as large as four dioptres. *Figure 4b* shows such an example.

Mean astigmatism and spherical error for all test subjects

Figure 5a shows the mean and the spread of the 'against the rule astigmatism' (X-value) for all test-subjects. At a measurement angle of 30° nasally the mean astigmatism is about 4-D and about 1.5-D lower on the temporal side. At larger angles the astigmatism increases dramatically and significantly more so for measurements made on the nasal side of the fixation point. For example, at 60° temporally,

(a)
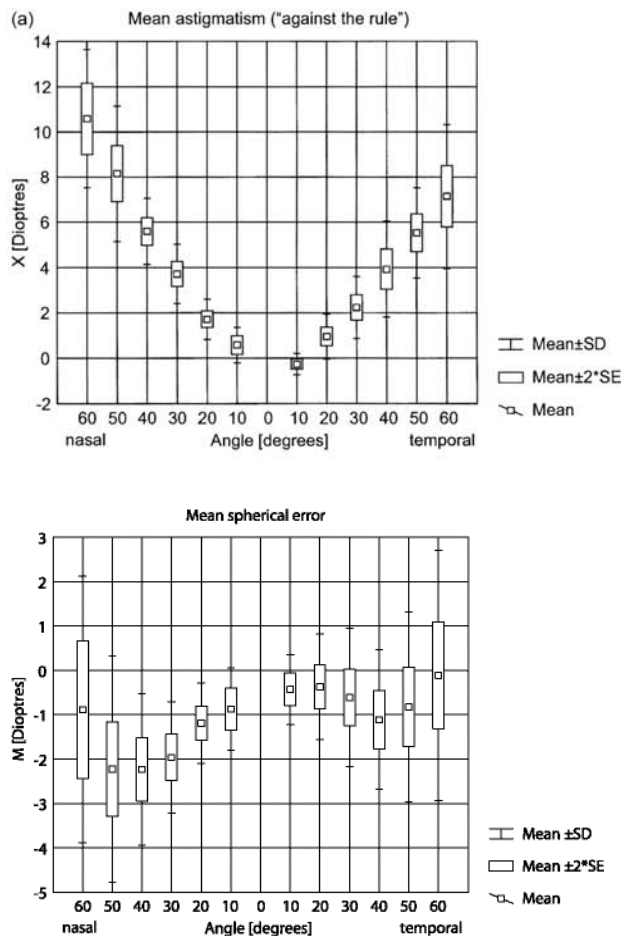
Figure 5. (a) the mean 'against the rule' astigmatism (*X*) for all test-subjects. (b) the mean value of the spherical equivalent (*M*) for all test-subjects. The small squares show the measured mean value as a function of the measurement angle. The larger rectangles show the confidence interval of the mean value at a 95% confidence level. The bars show the standard deviation (SD) of the individual data.

the mean astigmatism was 8-D. At 60° nasally, all subjects had astigmatism larger than 8-D and the mean astigmatism was 11-D. The angle for minimum astigmatism is shifted towards the temporal side due to the angle between the eye's optical axis and the visual axis (angle 'alpha'). Near the minimum we measure a slight 'with the rule' astigmatism.

The mean spherical refractive error of all subjects is shown in *Figure 5b*. For measurement angles up to about 40° there is a clear myopic shift towards the periphery. At larger angles there is an opposite effect leading to lower myopia or even hypermetropia in the far periphery. *Table 1* shows all the mean values of the measured peripheral refraction (*M*, *X* and *Y*) in a table format.

Discussion

As expected, the results show an increased astigmatism with increased fixation angle for most eyes. This is in agreement with other studies. From the present study it is not possible to distinguish groups of subjects with typical behaviour of astigmatism and defocus in the way described in the early papers about off-axis astigmatism (Ferree et al., 1933; Millodot, 1981; Rempt *et al.*, 1971; Lotmar and Lotmar 1974). We found large individual differences between all subjects and in some cases the differences were dramatic (*Figure 3*). This shows that there are the same or even larger individual differences in the 'off-axis' aberrations of the human eye as for

Table 1. Mean values of the astigmatic decomposition of the peripheral refraction. *M* is the spherical equivalent, which is the mean refraction in the two principal meridians. *X* and *Y* are the with/against the rule component and oblique component of the astigmatism, respectively

	Nasal					Angle				Temporal		
	60°	50°	40°	30°	20°	10°	10°	20°	30°	40°	50°	60°
X	10.6	8.2	5.6	3.7	1.7	0.6	− 0.3	1.0	2.2	3.9	5.5	7.1
Y	1.2	0.5	0.7	0.3	0.3	− 0.3	− 0.1	− 0.5	− 0.3	− 0.3	− 0.3	− 0.6
M	− 0.9	− 2.2	− 2.2	− 2.0	− 1.2	− 0.9	− 0.4	− 0.4	− 0.6	− 1.1	− 0.8	− 0.1

normal, on-axis, and refractive errors like myopia, hypermetropia and astigmatism.

In some cases, especially the older subjects (45 years) we have seen a marked influence of other aberrations like coma. The line-foci then looked more like a cross (Guirao and Artal, 1999; Williams *et al.*, 1997; Artal *et al.*, 1995b). The number of these cases is too small to say if this phenomenon is a function of age or if is just another individual difference.

It would seem reasonable to believe that the peripheral refraction of two, otherwise normal, emmetropic eyes would be similar. From the present study, however, we now know that the individual differences in the peripheral refraction are so large that we have to measure and correct each subject with central scotoma individually. The measured amount of astigmatism in the mid-range eccentricity is so large for several subjects that it can have an impact on the peripheral visual performance.

In mean values, the results we found in this study generally show a larger value for the peripheral astigmatism compared to a recent compilation of earlier measurements (Atchison and Smith, 2000). This difference is probably a result of the different measurement techniques used. Furthermore, our measurements show a significant nasal-temporal asymmetry in the oblique astigmatism with the point of minimum astigmatism shifted towards the temporal side. This is in good agreement with previous work and the shift in the minimum has been shown before (Dunne et al., 1993). We also see a relevant myopic shift of the spherical refractive error, especially in the mid-periphery, which has not been pointed out before.

Contrary to other published papers that have used the double-pass method to measure peripheral astigmatism we have included only emmetropic eyes. This makes our data useful also for wide-angle eye modelling with a correct description of the oblique astigmatism in the average emmetropic human eye.

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I t is not often that one is instantaneously able to apply the results of basic research. This work is an example of such an exception. A widely held conviction has been that human peripheral vision could not be improved through optical correction. It was assumed that all limitations in eccentric vision were due to the low density of visual receptors outside the retina's macula. Although rough estimates have demonstrated that peripheral images in this area are not the sharpest, it has still been considered meaningless to correct these optical errors.

This research, however, shows that optical corrections can significantly improve visual acuity as well as contrast sensitivity and balance for people with central scotoma and conscious eccentric fixation. The results have been achieved through the development of new methods for measuring eccentric optics as well as eccentric vision.

The results show great individual variation and that standard correction for off-axis aberrations is not a meaningful task. Instead accurate means of measuring eccentric eye optics and vision have to be created, perhaps initially in the area of low vision rehabilitation.

At Certec, the development of measurement methods continues. More case studies and more clinical measurements will be carried out. It is hoped that the research will expand to include a more in-depth study of the effects of optical correction on balance. There has, moreover, been a longstanding interest in investigating how eccentric correction affects people in traffic situations.

Jörgen Gustafsson

Eccentric Correction in Central Visual Field Loss