Optics for Low Vision Enabling

Jörgen Gustafsson

Division of Rehabilitation Engineering Research
Department of Design Sciences
Lund University
optics for low vision enabling
Preface

For the greater part of my career as an optometrist, I have worked clinically to help people with low vision make use of their residual vision as effectively as possible. I have had the same approach to research. First, I would like to thank all the visually impaired people who have taken part in the many evaluations and to the low vision centers and ophthalmologists who have recommended subjects.

I am still surprised over the fact that I, at this stage in my life, have been given the opportunity to work with research and development at the university level. It is a great asset to be able to introduce all my experience of low vision rehabilitation and optometry to the university world and more recently to the new Ingvar Kamprad Design Center where we have established the Low Vision Enabling Laboratory. Actually, it wasn’t all that long ago that I carried out the first evaluations in a small office in Certec’s previous location.

The person who without a doubt should receive the biggest and warmest thanks is my advisor, Professor Bodil Jönsson. There is much that could be said, but you know what I feel. None of this would have been possible without you. There is probably no one else who would have dared take on an optometrist, traditionally trained and with my background. Thank you for the many ideas (even though I didn’t see all of them through), for the patience, encouragement and especially for all you have taught me, not the least of which has been towards the end in the process of writing this thesis.

My assistant advisor, Associate Professor Peter Unsbo, along with his doctoral student, Linda Lundström, have been the ones who I have worked the closest with during many long planning sessions, series of measurements and analyses. Thank you, Peter, for your support and all your expertise about optics from physics and because you made sure that your laboratory was built to be able to measure my subjects’ needs. To Linda, I extend my thanks for all the patience and all the answers to those simple questions, the ones you physicists find so self-evident. Thanks for the enormous effort you have made so that the evaluations could be completed, particularly that time right after Easter, a day we will never forget!

A person who is and has been both a subject and a colleague is Krister Inde. He was the first person I tested everything on, and has participated in much of the method development with both good and bad suggestions. Thanking you isn’t a simple task because there is so much we have done together. But I would really like to let you know how much I appreciate your support and all the publicity you have given the program. As you know, I sometimes think it is exaggerated, but you have, to a great extent, contributed to the fact that we have come as far as we have.

I am grateful to Ivonne Fetchenheuer, recently graduated optometrist from Germany, for good collaboration.
her Bachelor of Science research at the LVE Lab. The same goes for Ingrid Svensson in Stockholm who did her Bachelor’s work at KTH.

My colleagues at Certec and other departments are fun loving, creative, competent, congenial – and unique. I thank you all for the support you have given me. This goes for my co-workers in the LVE laboratory and, in particular, Anna Blixt. Thank you for all you have accomplished, for all you have put right and for all the illustrations and other things you have cheerfully and willingly taken care of. A big thanks to Eileen Deane who has translated this thesis into English and to Karin Rehman for the excellent graphic design.

What is most important in life is to have family and friends who stand by you, believe in you and see you through the times of crisis, which is what the work that goes into getting a doctorate can generate. The support from my wife, Annelie, has been indispensable, who, like our sons, has put up with my long absences from home and provided those well-needed lifts to and from the train station.

Resources of different kinds have been necessary to carry out this work. I would like to thank all who have contributed financially and materially. The largest contributor has been the Berit and Carl-Johan Wettergren Foundation, to which I am deeply indebted. I would also like to thank Multilens AB which has custom made our corrective lenses; the Hellström family who have contributed with all kinds of optical corrections; Topcon Scandinavia who has supplied us with equipment; BBGR Svenska AB; Björn Sjöberg, Lidingö; the Crafoord Foundation; the Association of Low Vision Rehabilitation Workers (FFS); the Helfrid and Lorentz Nilsson Foundation; the Karl Simson Fund; the Knowledge Foundation’s IT and Health Program; the Swedish Optometry Association; Optoteam AB; Skåne Regional Council; the Sparbank Foundation, Skåne; the Foundation for Support to Research in Vision and Visual Impairment; the Synoptik Foundation; and the Swedish Road Administration’s Road Safety Fund.
Summary

For people with central visual field loss, eccentric vision is all that they have to rely on. Even for those who learn how to correctly utilize their eccentric vision, it will never be as good as the central for two entirely different reasons: the off-axis optics of the eye can result in large refractive errors, and the low function of the peripheral retina. This thesis deals with the first of these factors: how to study and correct the eccentric aberrations in people with low vision by measuring the optics of their eyes, correcting the aberrations, particularly astigmatism, and evaluating improvements in visual functions.

The individual variations are large for both astigmatism and higher order aberrations such as coma. The main results of this research show that visual improvements through eccentric corrections are possible in spite of the retina’s poor function outside of the macula.

Eccentric optical correction affects both resolution and detection capacities. A person’s visual ability can also be influenced by their awareness and training of eccentric viewing.

All in all, this thesis opens the door to a large area of research, one that is particularly important as the number of elderly people is growing and, as a result, increasing the number of people who are developing macular degeneration. The hope is that it will be possible to develop more and better evaluation methods as well as refractive corrections for eccentric vision and that it will be possible to study separate aspects of visual function in more detail. In so doing, we can increase understanding for how different diseases of the eye affect a variety of visual abilities. It is also essential that the examinations and improvements in the future involve more people than those with large central visual field loss and conscious eccentric viewing, as well as that the results find their application in clinical settings.

Keywords
Aberrations
Astigmatism
Central scotoma
Central visual field loss (CFL)
Contrast sensitivity
Detection
Eccentric correction
Eccentric viewing
Low vision optics
Low vision rehabilitation
People with low vision
Preferred retinal locus (PRL)
Resolution
Visual acuity
Purpose

The overall purpose of this research is to provide people with severe central visual field loss with better opportunities to utilize their residual vision through:

1. Measurements of optics of the eye in people using eccentric viewing who have severely reduced vision (worse than 1.0 logMAR; decimal acuity under 0.1).
2. Correction of measured optical aberrations.
3. Evaluation of the influence different corrections have on eccentric vision.
# Table of Contents

Preface 3  
Summary 5  
Purpose 6  

1. Introduction 9  
Studies included in the thesis: scope, nature and contribution to knowledge 9  
Visual functions 10  
Optics of the eye 13  
Publications 15  

2. Subjects 19  
Selection criteria and recruitment 19  
The large group: 78 subjects 20  
Group of seven 21  
MoviText Project: 9 subjects 23  
Visual field measurements: 17 subjects 23  
Normally sighted subjects: 20 + 50 people 24  
See More Project: 17 children 24  
Recruitment base 25  

3. Development of methods and technology to evaluate the optics of the eye when using eccentric viewing 27  
Raytracing 28  
The double pass method 28  
Photorefraction 29  
Eccentric wavefront measurements 31  
New subjective method – optimizing contrast sensitivity 36  

4. Development of methods for measurement and training of eccentric vision 37  
Computerized visual acuity charts – measurement of visual acuity 37  
Measurement of contrast sensitivity 38  
Vanishing optotypes 38  
PVE – Peripheral Visual Evaluation 39  
Perimetry in central visual field loss 42  
Training of eccentric visual field loss 43  

5. Results 45  
Off-axis optics of the eye 45  
Eccentric visual function, with and without correction 53  
Effects of training 63  

6. Discussion 65  
Evaluation of optical results 66  
Evaluation of visual functions results 66  

7. Conclusions 69  
References 70  
Appendices 75
1. Introduction

This thesis deals with visual functions and optics in people with low vision. It investigates how visual functions and optics can be measured and how both functions and measurement methods can be improved. The subjects involved have an absolute central visual field loss (CFL)/scotoma. Their visual acuity is worse than a logMAR of 1.0, i.e. with a decimal visual acuity under 0.1. They often make use of eccentric viewing and what they want to see is thus imaged on a portion of the retina that is outside of the scotoma. There in the periphery, however, retinal function is significantly reduced. Moreover, the image can be distorted as a result of substantial aberrations in the oblique optics of the eye. The question at issue is if an optical compensation for these aberrations improves vision, and how the oblique optics in this case can be measured.

In this investigation, we have limited ourselves to people who can utilize eccentric viewing, preferably in a conscious manner, but there is nothing to indicate that this limitation has to remain in the future. I hope that in the long run, the results of this thesis can be of help to many others.

Studies included in the thesis:
scope, nature and contribution to knowledge

In all, a total of 170 subjects have contributed to the results that are presented here. Of them, 100 belong to the group of people with low vision. I have, however, experience of considerably more people with low vision – I estimate that during the time I have practiced optometry, I have dealt with at least 5,000 patients in this category. To some extent, these people are also included in this thesis, because it is my experience with them and their problems that has been the motivation, source of inspiration and original bank of knowledge and understanding from which I began my research.

This thesis is unique in that it studies eccentric vision in people with reduced central vision – what the other isolated studies on the topic have in common is that they deal with eccentric vision in normally sighted people [Thibos et al. 1987; Wang et al. 1997b]. Even though several general series of measurements in this research have taken a long time, most of the breakthrough results are based
on individual case studies of a small group of subjects. There are a variety of reasons for this:

- The measurements have presupposed subjects with particularly distinctive characteristics: their degree of visual impairment, their ability to view eccentrically, and their ability to take part in repeated measurements of various types on several different occasions.
- Most of the measurement methods are, at present, both time-consuming and strenuous.
- The area still lacks well-validated instruments that enable categorization and the subsequent statistical series of measurements.

Among our subjects with large central visual field losses, a core group of 20 to 30 people gradually crystallized. They have been (and continue to be) of invaluable significance, not only as subjects to be measured, but also because they have reflected over the experiences of their vision problems and have been able to share these reflections with us. Since no established theoretical framework or set of concepts exists, it is especially important to concentrate on the most significant problems, and it is the subjects themselves who know best what is most important for them to be able to manage. The discussions with the subjects have in some cases resulted in “aha” experiences for them over and above anything we could have accomplished optically. To this category belongs the subject who was able to improve his vision through training from 1.2 logMAR to better than 1.0 (decimal visual acuity of 0.06 to over 0.1) – objectively verified – entirely without the aid of refractive correction. The only thing that was needed was for him to become consciously aware of a usable eccentric viewing location.

The contributions the research this thesis is based on makes to previous knowledge in the area of low vision are:

- Increased knowledge of the use of residual vision in people with large central scotomas.
- The significance of refractive corrections of aberrations in peripheral vision for the utilization of residual vision.
- Development of methods and technology for measuring the optics of the eye while viewing eccentrically.
- Development and evaluation of methods and tests for the measurement of visual function in eccentric viewing.
- How raising the person’s level of awareness and/or training of eccentric vision in cases of CFL can affect visual function.

**Visual functions**

Vision has many different functions (seeing images, resolution ability, contrast sensitivity, motion vision, face recognition) and affects
balance as well. An optically well functioning eye (with or without refractive correction) is a necessary prerequisite for good vision. Some problems can be remediated almost entirely through optical corrections, whereas others can only be marginally influenced.

Health care has its approach to vision (clinical examinations in departments of ophthalmology, low vision centers, compensatory devices, educational programs); cognitive research and experimental psychology have theirs. For the group I am particularly interested in, namely people whose visual acuity is worse than a logMAR of 1.0 (decimal visual acuity under 0.1), with an absolute central scotoma, there are remarkably few studies besides those that deal with training the use of eccentric viewing [Deruaz et al. 2002; Frennesson et al. 1995; Lei and Schuchard 1997; Nilsson et al. 2003]. In this regard, Sweden has been a pioneer [Bäckman and Inde 1979; Inde 1978].

Different methods are needed in order to measure the various visual functions. This is particularly the case for people with low vision. For them, traditional vision evaluation methods are inadequate because optical improvements seldom result in them being able to read in a normal manner. But refractive corrections can still positively affect both the ability to see images and resolution. Furthermore, they can affect motion vision, face recognition, balance, etc.

Vision is the sense that provides the normally sighted person with the most information. Visual acuity, the ability to identify something, is the most common measurement of visual function, but visual acuity tells us far from everything about visual function. There are several other additional measures:

<table>
<thead>
<tr>
<th>Visual function</th>
<th>Typical stimuli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection</td>
<td>Single black spot</td>
</tr>
<tr>
<td>Localization</td>
<td>Offset parallel lines</td>
</tr>
<tr>
<td>Resolution</td>
<td>Two black spots/lines/gratings</td>
</tr>
<tr>
<td>Identification</td>
<td>Letters or numbers</td>
</tr>
</tbody>
</table>

Detection is the most basic – you see something but do not know what it is. The smallest angle that a black spot at high contrast needs to occupy in order to be detected by a normally sighted eye is about 15 seconds of arc (corresponding to a 0.07 mm spot at 1 m distance).

Localization is the smallest spatial displacement that can be detected between two lines (Vernier visual acuity). It is easier to detect a displacement between two parallel lines than to detect a spot as described above. Depending on the length of the lines, a person can detect differences of 2-6 seconds of arc, that is to say, often less than 0.03 mm displacement between two lines at 1 m distance.

Resolution is often expressed as the distance between two black lines in the smallest letter a person can distinguish. On average, normal resolution capacity for a human eye is usually specified as 1
minute of arc (corresponding to a distance of 0.3 mm between the lines at 1 m distance) resulting in a logMAR of 0.0 (decimal visual acuity of 1.0).

Identification is what we normally refer to as visual acuity, the smallest possible letter, number, symbol or optotype that can be identified at a standard distance. In practice, an identification test is considered to be the same as a resolution test [Norton et al. 2002].

This thesis is entirely focused on examining and improving visual function in people with low vision. Consequently, the diagnosis of eye diseases falls outside of its scope. For vision as well as for other human abilities, function and diagnosis comprise two essentially different domains of an impairment. The World Health Organization (WHO) has consequently come up with one system for classifying functions, the International Classification of Functioning, Disability and Health (ICF) [WHO 2001], and one for classifying diagnoses, the International Classification of Diseases (ICD-10) [WHO 1992].

Functions always exist in a context. As Arne Svensk noted [Svensk 2003], Rosseau was hardly correct in his assertion: “In the land of the blind, the one-eyed man is king.” In the land blind people would build for their own purposes, there would be no cars, no traffic lights, no freeways, no houseplants, no lipstick, no paintings, nor other phenomena that require a person to see. In the land of the blind, people would orientate themselves through odors, touch and hearing and in such a society, the one-eyed person’s sight would be of little advantage, rather the opposite. But in reality, blind and partially sighted people live and interact with seeing people, often on seeing people’s terms. That is why it is important in the world of the seeing, to arrange things so that a reduction in visual function results in as little of a functional disability as possible.

Whether a functional reduction becomes a severe functional disability or not depends in part on the individual and her assistive devices, and in part on her surroundings. Two people with the same visual impairment can, in one and the same setting, experience quite different functional reductions. Some react as if they could see as before dashing up and down subway stairs, for example, while others find it quite difficult to at all manage on their own. Some of these differences are apparent as the result of direct measurements of visual function, while others manifest themselves primarily in complex everyday situations. When many different cognitive abilities interact, not least of all the different ones involved in vision, effects become apparent that are not revealed in the clinical tests that predominate. There are partially sighted people who are unable to recognize another person by appearance, are unable to read or do needlework, but who, on the other hand, can immediately see something lying on the floor that should not be there. Many visually impaired people with central scotoma (not to mention their relatives) witness as to
what good “detection vision” they have: they cannot read small text but can detect “litter on the floor and the airplane in the sky.”

More situated research is needed in this area as well as in others involving functional reduction. See Situated Research and Design for Everyday Life [Jönsson et al. 2004], research focused on what people actually do, “Where the action is” [Dourish 2001]. In anticipation of that, you need to listen extra carefully to how people themselves describe their view of everyday situations. How do they think their balance, for example, is influenced by refractive corrections?

During the more than 16 years I have worked at low vision centers, I have noticed the variation in how people with similar central vision reductions utilize their residual vision. This is most evident when you compare visual acuity with the size of the central scotoma. Some people can have quite a small reduction but very poor visual acuity, while others can have a large reduction but better visual acuity. The differences cannot always be explained by differences in eye disease or injury, different losses of receptors on the retina or different connections to the brain through the optic nerve.

When measuring refraction in people with low vision, you often come up with objective results that fluctuate and are difficult to judge, and which differ from subjective refraction measurements (“Better or worse?” in which the person himself determines which of two corrections provides the best improvement). There is no doubt that the subject himself knows best. At the same time, this thesis demonstrates how the interaction with research can offer new possibilities, sometimes directly and sometimes in the long run.

Optics of the eye

Studies of the optics of the eye can be carried out in part by using the concepts and methods of measurement to be found in physics, and in part by using analogous ones from the world of optometry. This research effort utilizes both. As an optometrist, I am already very familiar with the concepts and measuring methods used in optometry. I have encountered those of physics through close cooperation with the Visual Optics Group in the Division of Biomedical and X-Ray Physics, Department of Physics, Royal Institute of Technology (KTH), Stockholm.

Many models of the eye and the optical system have been published since the famous Gullstrand’s schematic eye [Gullstrand 1909]. In some cases, calculations of aberrations outside the optical axis have also been made [Dunne et al. 1987; Kooijman 1983; Liou and Brennan 1997; Pomerantzef et al. 1984; Popiolek-Masajada and Kasprzak 1999; Wang and Thibos 1997a]. It has been demonstrated that the shape of the cornea has less significance for the presence of oblique astigmatism in cases of oblique angle of incidence in the eye [Smith and Lu 1991]. Instead, it is primarily the lens and
its placement that cause aberrations (for the most part in oblique astigmatism) [Millodot 1984]. The normal lens of the eye produces fewer aberrations than an intraocular one [Aoshima et al. 2004; Vilarrodona et al. 2004].

The off-axis optics of the eye have been studied previously. It should be pointed out that physicists in Spain have had a long tradition of carrying out research on the optics of the eye and its effects on vision [Artal et al. 1995a; Navarro et al. 1993]. In the USA, the physicist Larry Thibos and his research group at Indiana University have done a considerable amount of work on peripheral optics and the limitations of the retina [Thibos et al. 1987; Thibos et al. 1996; Wang et al. 1996; Wang et al. 1997b]. In Australia, Atchison and Smith have studied the optics of the eye, both theoretically and experimentally [Atchison and Smith 2000; Atchison and Scott 2002; Smith and Lu 1991]. Another comparison has recently been published of measurements of the optics of the eye using different methods [Atchison 2003].

When it comes to measurement methods of the off-axis optics of the eye, most of the initial work was carried out using the first types of manual optometers [Charman and Jennings 1982; Ferree et al. 1931; Millodot 1981]. An extensive study was carried out in the 1970s of 442 subjects using retinoscopy, the results of which have frequently been cited in the literature [Rempt et al. 1971]. In the 1980s, Jennings and Charman performed the first assessment of the optics of the eye off-axis using a variation of the double pass method [Jennings and Charman 1981]. The method has since been improved with the addition of laser light [Santamaria et al. 1987]. Many articles were published during the 1990s by different groups of researchers who carried out measurements with the double pass method. The disadvantage with these is that they only measured a small number of healthy eyes with different refractions [Artal et al. 1995b; Navarro et al. 1993; Williams et al. 1996]. To summarize their results: In healthy eyes, the natural optics are sufficiently good peripherally, bearing in mind the limitations of the retina. In a more recent study using the double pass method, the astigmatism, coma and defocusing of four eyes were measured in angles out to 45° [Guirao and Artal 1999]. At comparable angles, astigmatism and coma (the largest of the higher order aberrations that produces a comet-like image) were quite similar, but focusing varied. The angle of incidence on the optical axis was the predominant cause of astigmatism. Researchers interested in myopia and emmetropization have used photorefraction and measured refractive errors in peripheral vision [Seidemann et al. 2002].
Publications

This thesis is based on studies of the eye’s optics and of visual function. These have resulted in seven articles as well as a number of papers presented at conferences. My licentiate dissertation from 2001 (listed in the references) is also part of the basis of this thesis.

Published Articles:

   The purpose of the study was to survey the optics of the eye outside of the optical axis in the eyes of central emmetropia subjects. By doing this, it was possible to illustrate whether defocusing and oblique astigmatism could be assessed by means of eye models or if entirely individual measurements were needed for each eye and each eccentric angle in question.

   The study describes the first case of eccentric correction in a patient that resulted in improved vision. With the large loss of central vision and the resulting large eccentric viewing angle, it was possible to improve the image quality on the retina.

   This study reported the results of the eccentric corrections of seven Subjects with large central visual field losses. The article describes the methods that were developed and discusses the problems involved in adequate measuring of the eye’s eccentric optics and vision.

   People with large central visual field losses can be in need of strong magnification devices for reading. This, in turn, requires good training methods. The article presents MoviText which is one such method and reports the results of the training program.

   The purpose was to investigate if visual field measurements can be improved through fixation assistance for people with large central field losses and, in that case, which types of fixation assistance is the best.

Describes the wavefront aberrometer built for eccentric measurements. It also provides an example of measuring the optics of a person with a large central scotoma.


The study reports the results of an investigation of similarities and differences of four measuring methods when they were applied to the optics of 50 centrally emmetropic eyes at eccentric angles of 20 and 30°.

**PAPERS PRESENTED AT CONFERENCES**

Portions of this research have been presented at several large conferences:


Gustafsson, J., Unsbo, P. (2001). *Correcting peripheral refractive errors in low vision subjects with central scotomas.* Poster 4581 ARVO, Fort Lauderdale, USA.


Lundström, L., Unsbo, P., Gustafsson, J. (2004). *Assessment of objective and subjective eccentric refraction*. Poster 2757, ARVO, Fort Lauderdale, USA.


In addition, a series of presentations were made for people with low vision (at 5 large meetings) and for rehabilitation personnel (at 6 large meetings). I have also published 4 popular science articles. Ongoing information about the project is presented on Certec's web site at [www.certec.lth.se/lve](http://www.certec.lth.se/lve) and [www.certec.lth.se/widesight](http://www.certec.lth.se/widesight).
2. Subjects

This chapter presents all the subjects, how they were recruited and how successive selections were made by means of different assessments and measurements. This constitutes a major portion of the work that has gone into the thesis. Lund University’s Research Ethics Committee approved the research proposal (LU 660-99 and LU 196-01) as did the Karolinska Institute Research Ethics Committee (DNR 02-205).

Selection criteria and recruitment

Even though disabled people often want to improve their situation, it is not always easy to get in contact with them. That over 700 people with low vision have expressed a desire to participate in this project is due, to a large extent, to the interest the mass media has shown from the start. We have obtained access to the medical records of over 400 patients from ophthalmologists and/or low vision centers. The original selection criteria required that the subjects had or were able to develop conscious eccentric viewing. After an initial trial, when the first photorefraction measurements were carried out, it became apparent that further specification was called for. The selection was made in cooperation with the 34 low vision centers in Sweden.

The final selection criteria statement was as follows:

*The subjects involved in this research will have had a stable visual impairment for several years with a central absolute scotoma in both eyes. It will cover at least 10° of the central visual field. The subjects will have found or have the ability to find one or more eccentric viewing locations, i.e. be able to place the image outside of the macula.*

Figure 1. Typical visual field diagram from Goldman perimetry of an absolute central scotoma in one of the low vision subjects selected for measurement.
All who had given permission to have their medical records sent to us from their ophthalmologist or low vision center received a written response with information about the initial assessment as to whether or not they were included. There have been many follow-up calls because the interest has been (and still is) great, not only in overall number but on the individual level as well.

The large group: 78 subjects
A total of 82 people were selected as appropriate candidates to come to a screening test at the laboratory. Of these, 78 came and were actually screened to determine their suitability for eccentric correction.

Most of the subjects were born between 1915 and 1925. The distribution, however, was skewed with the mean being the years 1937-1938. As a rule, their impairments had been stable, showing little or no change in visual acuity for 5 to 10 years. Even here the distribution was skewed and the average length of visual impairment was 13 years (Fig. 2a and b). In other words, several subjects had had a long time to grow accustomed to only seeing with their peripheral vision.

Among the 78 subjects, 40 were men and 38 were women, a notably even distribution considering the age group involved.

Of the 78 subjects, 67 clearly had a better eye. The right eye was best in 31 subjects and the left in 36. Eleven subjects had fairly similar visual function in both eyes. The dominant eye was not determined; only the eye that had the highest visual function. Of those who had similar vision in both eyes, most could consciously interchange using them.

The etiology of the visual reduction in the 78 people who were screened was as follows:

<table>
<thead>
<tr>
<th>Number</th>
<th>Etiology of visual reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>Age related macular degeneration (AMD)</td>
</tr>
<tr>
<td>23</td>
<td>Degeneration of the retina at an earlier age*</td>
</tr>
<tr>
<td>4</td>
<td>Leber’s Opticus Atrophy</td>
</tr>
<tr>
<td>9</td>
<td>Other **</td>
</tr>
<tr>
<td>Total 78</td>
<td></td>
</tr>
</tbody>
</table>

*Diseases such as Stargardt’s Syndrome or something similar. All of these subjects had acquired their visual impairment between the ages of 15 and 30 and had lived with it for many years. **Examples: postoperative condition after tumor removal or inflammation.

The approximate size of the absolute visual field loss in the entire group is presented in Fig. 3. There is a clear predominance of scotomas about 10° in size. We have been primarily interested in people with large absolute scotomas. Most of the subjects who
subsequently were given an eccentric correction had scotomas between 15–30°.

Surprisingly few were entirely aware of the ability they had for eccentric viewing. This indicates that there is a great potential for professionals in visual rehabilitation to initiate vision improvements just by making their patients conscious of eccentric viewing. A total of 48 subjects (59%) in our well-selected group were not even aware that they were using eccentric viewing. Only 30 (37%) had a somewhat clear understanding of how they could make use of another location on the retina to best utilize their residual vision. Even among these, there were some people who had not found their optimal eccentric viewing direction outside of their CFL but who did so during the measurement session.

Astigmatism was determined during the first session through photorefraction using the PowerRefractor. In order for the correction of oblique astigmatism to be meaningful, it was estimated that at least 1.0–1.5 diopters (D) of astigmatism were required.

From this group of subjects, 15 (19%) fulfilled our criteria and were selected for eccentric correction.

Group of seven

Seven of the visually impaired subjects are presented individually here. Many measurements have been carried out only on them and they turn up in several places in Chapter 5, Results. Originally, the group consisted of eight people, but the eighth chose not to complete the measurements.

The identification numbers of the subjects (SUB. 1, SUB. 2, etc.) are also used in Chapter 5. The visual field measurements that are presented are those from the best eye with the computer version of Auto-Plot CAPP [Fetchenheuer and Gustafsson 2004], which is described on page 42. What follows is a description of each of the subjects.

SUB. 1: MAN, 57 YEARS

Visual impairment unchanged for 20 years (low vision for 40 years), caused by degeneration of the retina.

Scotoma according to perimetry in Fig. 4, visual acuity 1.7 logMAR (decimal visual acuity 0.02) with the right, best eye. No correction used. Views eccentrically both upward and downward and has good mobility function in spite of his severe low vision. Works in telephone sales for a large furniture corporation.

SUB. 2: WOMAN, 61 YEARS

Visual impairment unchanged for 20 years (low vision for 30 years), caused by degeneration of the retina. Scotoma according to perimetry in Fig. 5, visual acuity 1.4 logMAR (decimal visual acuity 0.04) with
the left, best eye. Uses correction –3.75 DS. Has found a distinct and stable eccentric viewing location on her own with the left eye about 20° to the right in relation to the eye’s optical axis. Utilizes her residual vision well and is well supplied with devices. Works as a developer of large computer systems for an insurance company. Has previously also worked with computer programming.

Due to a well-trained eccentric viewing location, this person is a good candidate for evaluation of eccentric correction. That is why she appears as an example in several places.

**SUB. 7: KRISTER INDE, 57 YEARS**

Visual impairment unchanged for 30 years (low vision for 35 years), caused by Leber’s Opticus Atrophy.

Scotoma according to perimetry in Fig. 6, visual acuity 1.3 logMAR (decimal visual acuity 0.05) with the left, best eye. Sometimes uses correction –1.0 DS. He is trained in using eccentric viewing mostly upward and uses it for reading approximately 8° upward. For orientation, for example when bicycling, he views about 20° upward. Works as a low vision therapist and in business in a variety of positions, among them, as a copywriter at an advertising agency. In this thesis, Krister Inde was the first one to try all the different methods and programs. He has also assisted in the development of certain methods.

**SUB. 11: MAN, 79 YEARS**

Visual impairment unchanged for 4 years (low vision for 6 years), caused by macular degeneration.

Scotoma according to perimetry in Fig. 7, visual acuity 1.3 logMAR (decimal visual acuity 0.05) with the left, best eye. His cataract has been removed and an intraocular lens (IOL) implanted. He has some benefit from a correction for a weak astigmatism, +0.5 DS −0.75 DC x 165°. Has learned on his own to find his best eccentric viewing location with the left eye at approximately 10° upward. Is no longer professionally active, but still keeps up on his former area of research.

**SUB. 17: MAN, 42 YEARS**

Visual impairment unchanged for 5 years (low vision for 26 years), caused by a chronic inflammation of the eye (uveit/retinitis). Has a certain amount of opacity in the lens and vitreous body. Scotoma according to perimetry in Fig. 8, visual acuity 1.6 logMAR (decimal visual acuity 0.025) with the left, best eye. Uses correction −2.5 DS −1.0 DC x 50°. Mostly uses eccentric viewing to the right and a little upward. Has a Ph.D. in management and works with trademark strategies.
SUB. 21: WOMAN, 33 YEARS

Visual impairment unchanged for 10 years (low vision for 18 years) after surgery on a brain tumor in the optic nerve (chiasma). Scotoma according to perimetry in Fig. 9, visual acuity 1.4 logMAR (decimal visual acuity 0.04) with the right, best eye. No correction used. Uses only one eccentric viewing location about 17° out to the right for all conscious seeing. Utilizes residual vision well. Has a college degree in economics and is able to work as an accountant using a computer magnification program and a CCTV system.

SUB. 70: MAN, 44 YEARS

Visual impairment unchanged for 2–3 years (low vision for 4 years), caused by degeneration of the retina.

Scotoma according to perimetry in Fig. 10, visual acuity 1.5 logMAR (decimal visual acuity 0.032) with the right, best eye. No correction used. When he came to us as part of his rehabilitation, he was not aware of his eccentric viewing. Has been unemployed for many years.

MoviText Project: 9 subjects

MoviText aims to increase awareness and the systematic use of eccentric viewing when reading a text presented at variable speeds on a computer screen. Twelve people from the large group were asked to be included. Of these, 9 completed the entire training program.

Visual field measurements: 17 subjects

In another project associated with this thesis, different fixation devices for the visual field measuring instrument CAPP (Computerized Auto-Plot Perimeter) were tested [Fechenheuer and Gustafsson 2004]. In most visual field measurements, there is only a small fixation mark which requires the patient to have good central vision. Thus, if you lack central vision, visual field measurements in most cases are unreliable. Knowledge of the central scotoma’s position and appearance are important for low vision rehabilitation, particularly if you want to train eccentric viewing.

Seventeen people from the total group of 78 took part in these measurements, 7 women and 10 men between 30 and 80 years of age. The average age was 56 and the visual impairments had been stable for between 3 and 43 years with an average of 14 years. In most of the subjects, the visual field measurements could be carried out on both eyes in spite of the large CFL.
Normally sighted subjects: 20 + 50 people

Two studies were carried out to measure refractive errors and aberrations of the eye in a normal population. The subjects consisted of students, work colleagues and acquaintances. Only refractive measurements were involved here; no measurements of visual function were performed. Twenty central emmetropic (not more than \(\pm 0.5\) DS or DC) eyes were screened in order to estimate the distribution of individual aberrations in the form of oblique astigmatism at angles greater than 10° off-axis [Gustafsson et al. 2001].

Normally sighted subjects with equally good vision in both eyes and without binocular vision problems (but with different central refractive errors) were also used to compare four different methods for measuring refraction at two eccentric angles. Several of the 50 people involved were selected from a university environment, which is why a certain predominance of myopia was not surprising [Feldkamper and Schaeffel 2003].

See More Project: 17 children

This project is on the fringe of my thesis research, but I am including it here – in spite of certain doubts – both for the differences and similarities it has with my main focus. Among the differences are that the See More Project deals with young children who have visual impairments that are not the result of scotomas but have entirely different etiologies (see following table). Among the similarities are: that the See More Project also deals with considerable visual impairments; that I have carried out the visual examinations and refractive corrections; that we have also been successful in recruiting participants; and that the expressed aim, as for the principle group, is to increase both visual capabilities and the desire to see. For young children with low vision who have been given the opportunity at an early age to improve the use of the vision they have with the help of optical magnifying devices, the positive effects can be even greater than what they are for adults.

The children were recruited through good contacts with the four low vision centers in Skåne, the southernmost province of Sweden. The project was inspired by and is being run in conjunction with the PAVE Project (Providing Access to Visual Environment) at Peabody College, Vanderbilt University, USA.

Forty-three children from 2 to 9 years of age were invited to participate. Twenty-three children and their parents came to the first meeting. I examined refraction, visual acuity (high and low contrast), need for magnification, and other functions that it was possible to evaluate. After these examinations, it proved to be the case that the visual function of 5 of the children was too good to be included according to the criteria we had set. Of the remaining 18 children, we
are now in the process of training 17 with telescopes. The youngest is 2½ years old. Several have been given microscopic lenses for short reading distances and other have started to use magnifiers.

The following table presents the children who are participating in the See More Project:

<table>
<thead>
<tr>
<th>Sex</th>
<th>Year of birth</th>
<th>Decimal visual acuity</th>
<th>logMAR</th>
<th>Diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girl</td>
<td>2002</td>
<td>0.2</td>
<td>0.7</td>
<td>Nystagmus</td>
</tr>
<tr>
<td>Girl</td>
<td>2002</td>
<td>0.025</td>
<td>1.6</td>
<td>Uvea/iris coloboma, microphthalamus, nystagmus</td>
</tr>
<tr>
<td>Girl</td>
<td>2001</td>
<td>0.25</td>
<td>0.6</td>
<td>Achromatopsia, nystagmus</td>
</tr>
<tr>
<td>Boy</td>
<td>2000</td>
<td>0.03</td>
<td>1.5</td>
<td>Congenital glaucoma</td>
</tr>
<tr>
<td>Boy</td>
<td>2000</td>
<td>0.1</td>
<td>1.0</td>
<td>Albinism</td>
</tr>
<tr>
<td>Boy</td>
<td>1999</td>
<td>0.2</td>
<td>0.7</td>
<td>Optic nerve hypoplasia</td>
</tr>
<tr>
<td>Boy</td>
<td>1998</td>
<td>0.16</td>
<td>0.8</td>
<td>Achromatopsia, nystagmus</td>
</tr>
<tr>
<td>Boy</td>
<td>1997</td>
<td>0.12</td>
<td>0.9</td>
<td>Albinism, nystagmus</td>
</tr>
<tr>
<td>Boy</td>
<td>1997</td>
<td>0.13</td>
<td>0.9</td>
<td>Congenital cataract, secondary glaucoma</td>
</tr>
<tr>
<td>Boy</td>
<td>1996</td>
<td>0.2</td>
<td>0.7</td>
<td>Nystagmus</td>
</tr>
<tr>
<td>Girl</td>
<td>1996</td>
<td>0.06</td>
<td>1.2</td>
<td>Nystagmus, sclerocornea</td>
</tr>
<tr>
<td>Boy</td>
<td>1996</td>
<td>0.16</td>
<td>0.8</td>
<td>Nystagmus</td>
</tr>
<tr>
<td>Boy</td>
<td>1996</td>
<td>0.06</td>
<td>1.2</td>
<td>Optic nerve hypoplasia, nystagmus</td>
</tr>
<tr>
<td>Boy</td>
<td>1996</td>
<td>0.2–0.5</td>
<td>0.7–0.3</td>
<td>Subluxed lens</td>
</tr>
<tr>
<td>Girl</td>
<td>1995</td>
<td>0.25</td>
<td>0.6</td>
<td>Congenital cataract, secondary glaucoma</td>
</tr>
<tr>
<td>Boy</td>
<td>1995</td>
<td>0.25</td>
<td>0.6</td>
<td>Achromatopsia</td>
</tr>
<tr>
<td>Boy</td>
<td>1995</td>
<td>0.05</td>
<td>1.3</td>
<td>Optic atrophy, nystagmus</td>
</tr>
<tr>
<td>Girl</td>
<td>1995</td>
<td>0.16</td>
<td>0.8</td>
<td>Nystagmus</td>
</tr>
</tbody>
</table>

**Recruitment base**

We have essentially limited our research to a well-defined group of people with central scotoma, but all of the measurement methods and efforts that we have undertaken can be of relevance for other groups with considerably reduced vision. With this in mind, a summary of the available statistics on the number of people with low vision is presented here.

The information varies substantially from country to country (see the European Blind Union web site, [www.euroblind.org](http://www.euroblind.org)), most likely the result of how well established the different registers and rehabilitation programs are. A general estimate is that between 1 and 2% of the population in the West has such a reduction in visual function that it constitutes an obstacle in daily living. In Sweden, 100,000 were considered to be visually impaired in 2001. 80% of them were considered to be elderly, i.e. over 65 years of age.
The group that is of the greatest relevance for this thesis is composed of those people with central visual field loss. This group is dominated by those who have age related macular degeneration (AMD).

According to WHO, approximately 8 million people worldwide are severely visually impaired as the result of AMD. Approximately 2 million of them have significantly reduced vision [Ferris and Tielsch 2004]. In the USA, 1 in 10 over the age of 80 are considered to have pronounced visual losses due to macular degeneration [Bressler et al. 2003]. In Sweden, this would correspond to approximately 50,000 people. This figure will increase as our longevity increases. To this can be added other eye diseases that result in absolute central scotomas.

The most common are injuries to the optic nerve or other kinds of macular degeneration, most often encountered in the younger years, which can result in visual impairments.

If you look into the availability of optical devices for these large groups, you will see that there are many companies that manufacture them, but not especially many that can come up with optical solutions that are entirely tailored to individual needs. These include corrective lenses with multiple segments that have unusual powers and higher additions with good optical image quality. The Multilens Company has been our main partner because they develop optical devices that are relevant to our area of research. We have also had good contacts with manufacturers and testers of computerized devices for partially sighted people as well as manufacturers of ophthalmic wavefront sensing instruments.

<table>
<thead>
<tr>
<th></th>
<th>Children</th>
<th>Working age</th>
<th>Elderly</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>1,500</td>
<td>10,300</td>
<td>29,000</td>
<td>40,800</td>
</tr>
<tr>
<td>Female</td>
<td>1,500</td>
<td>10,300</td>
<td>50,000</td>
<td>61,800</td>
</tr>
<tr>
<td>Total</td>
<td>3,000</td>
<td>20,600</td>
<td>79,000</td>
<td>102,600</td>
</tr>
</tbody>
</table>
3. Development of methods and technology to evaluate the optics of the eye when using eccentric viewing

The results of ordinary clinical refraction in people with CFL are often unreliable which, among other things, can be due to variations in eccentric viewing (see Fig. 11). Because of this, even greater refractive errors can be overlooked. The objective measurement does not always correspond to the subjective refraction. Since subjective measurements lack precision at low visual acuity, it is not obvious which results should be considered optimal. Subjective refraction is particularly difficult if the eye has large higher order aberrations. The risk in this case is that you will arrive at a false, best correction which in reality only constitutes a local minimum for the aberrations (in the language of optical design).

For people with central visual field loss, one really needs to measure eccentrically, since it is the peripheral optics of the eye that these people use. But every examiner who tries to make use of retinoscopy at an oblique angle of incidence in the eye notices how the reflex is distinctly different from the one that arises along the optical axis. It is the aberrations that make the reflex difficult to interpret. In previous research by Rempt et al., among others, they have, nevertheless, utilized retinoscopy off-axis in a large number of healthy eyes [Rempt et al. 1971]. It is not clear how they interpreted the reflex from the retina. Nor have their studies been replicated by others or proven useful in clinical practice. I asked an experienced optometrist, who has worked many years in visual rehabilitation, to carry out central and eccentric refraction on a small number of people with conscious eccentric viewing. He also carried out
subjective refraction using the most stable and most utilized eccentric viewing direction the person had. This was difficult to perform, however (see page 52).

With most modern autorefractors, it is not possible to measure eccentrically – error messages pop up as soon as you try to perform measurements off-axis. It may be possible, however, to perform these measurements with the first generation of autorefractors. Atchison used one of these as well as an entirely new autorefractometer with an open visual field [Atchison 2003]. We were able to locate an old manual instrument, a Hartinger optometer from 1960 that we used to carry out measurements; unfortunately, intra-subject reproducibility was poor. Measurements of the off-axis refraction of the eye were published many years ago, but the replicability has not been clarified [Ferree et al. 1932].

Raytracing

Computer models of the eye were our first undertaking. Following the path of a ray of light into the eye, raytracing, is just as easy for peripheral rays as it is for central ones – on the condition that you have sufficiently good information about the optics of the eye, particularly the lens. In my licentiate dissertation [Gustafsson 2001], I demonstrated what the image quality was like at 20°, 40° and 60° angles off-axis and which corrections (sphere and cylinder) were needed for the best possible image. In one experiment, specially segmented lenses were produced for all three angles.

The double pass method

The work with raytracing resulted in a better understanding of the optics of the eye, but for corrections of individual eyes, individual measurements are necessary. This became particularly evident in our initial attempts to measure the right eyes of 20 healthy, normally sighted people with the well-known double pass method [Santamaria et al. 1987]. The Visual Optics Group at KTH developed the measurement set up. The subjects fixated straight ahead on a distant image of a fixation cross in order to avoid stimulating accommodation. The measurements were made at angles of 10°, 20°, 30°, 40° and 60° off-axis. The criterion for subjects to participate was that the central refractive error did not exceed 0.5 D, i.e. that the eye was centrally emmetropic. The individual differences off-axis were large [Gustafsson et al. 2001].

It became evident as a result of this investigation that individual measurements are just as important in the periphery as they are centrally. The double pass method, however, was entirely too difficult, demanding and time consuming to be used on subjects with visual impairments.
Photorefraction

Photorefraction is based on an analysis of the reflex from the retina. A light source is placed as close as possible to the measuring camera’s aperture. In the PowerRefractor, infrared light is used that is emitted from a “six-armed retinoscope” – six segments with light diodes that are mounted around the aperture [Choi et al. 2000]. The individual segments light up one after the other. The moving reflex is then analyzed by the software and the results are presented in the form of a refractive correction in spherical and cylindrical power as well as in axis direction. At the same time, pupil size and viewing gaze in relation to the eye’s optical axis are measured.

If the subject views eccentrically, the surface of the pupil appears smaller and elliptical. This is because the instrument can only register the pupil’s projection perpendicular to the measurement axis. Straight ahead, the projection is identical with the pupil, but the more obliquely the subject gazes, the smaller and more elliptical the projected pupil becomes. For some subjects who have small pupils, the oblique angle of incidence thus can mean that it is not possible to utilize the instrument’s entire measurement area (maximum of 30°).

When the first pre-trials were carried out, it quickly became evident that the biggest difficulty was in establishing a sufficiently stable eccentric viewing. People who have lost their central vision are unable to gaze normally. Those who do not have a consciously preferred eccentric viewing location, referred to as preferred retinal locus (PRL), have considerably greater difficulties than others in keeping a steady gaze.

As a solution to this difficulty, a fixation screen was developed (see Fig. 12). In the first set up, UV light was used to illuminate the yellow fluorescent rings that were mounted on a Plexiglas sheet around the PowerRefractor camera. In the current set up, light wires (linear light sources) are used, mounted in the same way in rings of
5°, 10°, 15°, 20° and 25° from the center of the camera lens. In the dimly illuminated room, the subjects can see their own scotoma in the “fixation rings” and in that way use the scotoma as a marker for holding their gaze in a given direction. If the eccentric viewing direction that is mostly used is 20° to the right, the person will place her absolute scotoma where the horizontal line and the ring for 20° meet (see Fig. 13). This method has proven to work well for most subjects and is used now in other situations in which a stable eccentric viewing is required. For SUB. 2 and SUB. 21, who only use one eccentric viewing direction, this fixation support is unnecessary.

The PowerRefractor with the “fixation rings” proved to be an excellent instrument for finding and selecting suitable subjects. In the measurement process, it is quite noticeable how aware or unaware the person is of his or her eccentric viewing and if there is one or more eccentric viewing directions. On some occasions, subjects have become aware of a new PRL and with that, have better been able to use their residual vision. All low vision subjects in the large group were measured with the PowerRefractor and of these, 20 to 30 were judged to be appropriate candidates for eccentric correction in order to evaluate possible effects on visual function.

Initially, we selected seven people after photorefraction, all of whom had a large, oblique astigmatism that had not been previously corrected. Several methods have then been used to study the eye’s optics and visual function of these seven people. Three of them had, for a long time, been using only one well-trained, oblique angle and because of that, they were particularly suitable candidates on which to test eccentric correction. Some of them have been of great assistance in the development of the methods that are presented in this research. They have been helpful in both the pre-trials and in the test trials.

Figure 13. The fixation rings on a sheet of Plexiglas are mounted at angles of 5° intervals out to 25° around the camera of the PowerRefractor. The person with CFL sees his scotoma, simulated here by the grey area, at an angle of 20° to the right.
Eccentric wavefront measurements

The Visual Optics Group at KTH in Stockholm has built/adapted a wavefront analyzer, based on the Hartmann-Shack (HS) principle [Liang et al. 1994] for off-axis measurements of the eye’s optics (see Fig. 14). With this instrument, all aberrations of the eye can be analyzed, both ordinary refractive errors (lower order) and higher order aberrations (ones that cannot be corrected with spectacle lenses). Special software has been developed to deal with the eccentric aberrations [Lundström and Unsbo 2004b], which are considerably greater than the central ones. The software is also able to calculate the image quality on the retina, and take into account that the pupil is not circular but elliptical when eccentric viewing is used [Lundström et al. 2004c].

Commercial instruments based on the Hartmann-Shack principle have also begun to show up on the market. We have tested the WASCA analyzer from Zeiss and consider it suitable for eccentric use because it has an open field around the measuring head.

The fundamental parts of a Hartmann-Shack sensor are the light source, the lenslet array and the CCD camera. A brief description of the method: A narrow laser beam is sent into the eye and forms a spot on the retina. Part of the light from the spot is reflected and imaged through the optics of the eye, as if it came from a point source on the retina and forms what is referred to as the “wavefront”. If the eye were a perfect optical system with the far point in infinity, the rays coming out of the eye would be parallel with one another. The wavefront, which is perpendicular to the rays would be plane (entirely straight), but this is not the case in a real eye (see Fig. 15).

The shape of the wavefront, which emerges from the pupil, contains all information about both the refractive errors and higher order aberrations. A myopic eye gives, for example, a spherically
curved wavefront that converges towards the far point, while the aberrations produce a more irregular wavefront. The wavefront from the eye falls on the lenslet array where several hundred small lenses focus their part of the wavefront to a small spot on the CCD camera. If the optics of the eye were perfect and the wavefront plane, the points would end up on the CCD camera directly behind each micro lens. But since the eye has aberrations, the light falls in towards every micro lens from different directions. The displacement of the spots from every lens provides an opportunity to calculate the
tilt of the wavefront at each point (see Fig. 15–17). The wavefront’s local tilts can then (mathematically) be summarized in order to give the wavefront’s shape, which describes the optical system’s total aberrations.

The aberrometer with the Hartmann-Shack sensor built for eccentric measurements for people with CFL is described in the article, *Measuring Peripheral Wavefront Aberrations in Subjects with Large Central Visual Loss* [Lundström et al. 2004c]. To facilitate viewing for the subjects, we have also utilized “fixation rings”, similar to those in previous experiments. In order to save space, we have had to place them close to the eye; a dark plastic film with multicolored light wire rings corresponding to every 5th degree of eccentric angle has been used. The rings themselves shine and the space in between is black (see Fig. 18). In these, a person with CFL who is being measured can see his or her scotoma and use it as a marker for holding a stable gaze. Another fixation device is a shining green light diode, sufficiently large to be seen, which is reflected by a mirror in the direction of measurement. The idea is that a person with a well-developed PRL should be able to fixate on the diode with his or her eccentric viewing direction outside of the scotoma. In order to know the direction in which the measurement should be carried out and to be able to do several measurements at the same angle, an eyetracker has also been installed (Tobii Technology Inc.®). This specially manufactured eyetracker is equipped with software that can measure eccentrically and follow an oval pupil in real time.

**CALCULATIONS**

The results in the form of the optimal refractive correction with sphere and cylinder can be calculated from the shape of the wavefront with several different methods [Guirao et al. 2003]. In this research, two calculation methods have primarily been used. The first is a pupil plane calculation that minimizes the wavefront error, the root mean square (RMS) in the same plane as the pupil. The second is an image plane calculation that optimizes the quality of the retinal image, subsequently referred to as the Strehl method.

The most common approach is to calculate refractive corrections with the RMS method, which directly calculates the wavefront’s aberrations. This is used by the first wavefront instruments, which are now commercially available, and is quite adequate if there are no significant higher order aberrations. The RMS correction adjusts sphere and cylinder, as well as it possibly can, over the entire wavefront in the measurement direction. If there are larger deviations in a portion of the wavefront, it can have a large influence on the RMS correction even though it does not have particular importance for the image quality on the retina.

The more advanced Strehl method includes all of the aberrations’ effects on image quality. Thus, it can find a different correction in
cases of greater higher order aberrations. The image plane method, in this case, uses the retinal image of a point-like object, referred to as the point-spread function, PSF, in order to describe image quality (see Fig. 19). The ratio of the highest intensity in PSF to the corresponding intensity if the eye is aberration free is called the Strehl ratio and it is optimized with this method in order to achieve as good image quality as possible.

Thus, the difference, when compared with the RMS method, is that the Strehl method optimizes image quality and does not minimize the wavefront errors. If certain portions of the wavefront are strongly aberrated, the refractive correction will only be adjusted to those portions of the optics that can produce an image of good quality. The poorer portions will have residual errors, resulting in a diffuse background on the retina that lowers the contrast (see Fig. 20 on Strehl and RMS). Optimization is accomplished through

![Figure 19. The point-spread function for a corrected eye, centrally (broken line) and eccentrically 20° horizontally in the nasal visual field (solid line). The considerable difference is due to greater higher order aberrations in the periphery. The height of the PSF is described by the Strehl ratio, see scale on the left.](image1)

![Figure 20. The difference between RMS correction (left) and Strehl correction (right). The figure shows the residual wavefront aberrations (above) and the corresponding point-spread functions (PSF) (below) with the two corrections. Note that the RMS correction produces a flatter wavefront, but worse image quality, whereas the Strehl correction has optimized the PSF. The figures are simulations from 20° off-axis measurements in a subject with CFL; the pupil diameter is 4 mm.](image2)
computerized calculations that test large numbers of spherical and cylindrical lenses. This is carried out in the area ±10 D with 0.1 D steps around the RMS correction in order to find the combination that gives the highest Strehl ration, i.e. the best image. This method can also be used to optimize corrections of higher order aberrations, when this is possible.

In the two pictures in Fig. 21, you can see the difference in improved optics simulated for a visual acuity chart through one of our subject’s eye optics. This subject has only one eccentric viewing location with the left eye, 20° to the right, which he uses for all visual tasks. The picture on top shows the image quality with central correction; on the bottom, the image quality with the eccentric correction in which the astigmatism is corrected. Those that are left are other aberrations and the largest of these, after the oblique astigmatism has been corrected, is often coma.

Figure 21. Difference in improved image between central and eccentric correction when astigmatism is corrected.
New subjective method – optimizing contrast sensitivity

In addition to photorefraction, retinoscopy (in spite of all its problems) and wavefront sensing, we added a fourth subjective refraction method: optimization of contrast sensitivity. These four methods were later compared with one another [see Lundström et al. 2004a]. The new subjective method was developed in cooperation with the Visual Optics Group. It was the outcome of a Bachelor of Science thesis in optometry [Svensson 2003]. The subjects view horizontal, vertical and oblique moving sinusoidal gratings with constant spatial frequencies of 2 cycles/degrees on a computer screen through different spherical and cylindrical corrective lenses (see Fig. 22). The lenses are varied to find the one that provides the highest contrast sensitivity in each of the three meridians. In this way, the subjective power in sphere and cylinder can be calculated. From a low level, the contrast is increased until the person sees the gratings. The method is, unfortunately, time demanding and strenuous for the subject.

Other researchers have used a similar method but have varied the spatial frequency [Anderson et al. 1996; Wang et al. 1996]. The new aspect that has been added here is that the contrast is varied.
4. Development of methods for measurement and training of eccentric vision

To understand how vision functions outside of the macula, especially in people who only have useable vision there, good and reliable measurement methods are needed. It is an area that has been neglected and I hope to contribute to its development.

Measurements of visual function outside of the macula are primarily carried out in ordinary clinical practice with large optotypes and shorter test distances. Evaluations of visual acuity or contrast sensitivity are mostly performed without observing the viewing direction. The patient is left to find the best viewing angle herself. Perimetry, which determines the extent of the visual field, only maps where the patient sees or is unable to see with stimuli of different intensities.

Computerized visual acuity charts – measurement of visual acuity

Measuring visual acuity with ordinary visual acuity charts works rather poorly when dealing with patients whose vision is substantially reduced. This is because the person has often learned the existing individual optotypes, which in turn influences the results. Computerized visual acuity charts have been around for a few years, primarily as complete systems. One such system developed by David Thomson, at City University in London, is the Test Chart 2000 Pro (www.thomson-software-solutions.com). It can be used on an ordinary flat screen computer monitor (see Fig. 23). The advantage over the ordinary visual acuity charts is the great variation in optotypes. They can also be displayed at different contrast levels and the program can be adjusted to test low levels of vision. Letters (or other optotypes) of the same size can be displayed randomly to clearly and more reliably establish the exact threshold value. This is one way to eliminate the test-learning factor. It is also possible to display optotypes such as Landolt C, numbers or symbols. They...
can be shown in a row or one by one. One disadvantage is that the program lacks a built-in registration function.

Measurement of contrast sensitivity

Since the world in which we live does not only consist of well illuminated, high contrast objects, it is important to also evaluate visual function using low contrast optotypes. The contrast sensitivity test that we have utilized is Peli-Robson’s [Pelli et al. 1988]. It is also suitable for measurement in people with CFL since the letters are large and presented at a distance of 1 meter, which suits our group of subjects with low visual function. The test is included in Test Chart 2000 Pro. In this program it is easy to reduce the contrast of all optotypes and in that way measure in one or more low contrast areas (see Fig. 24). If after measuring in full contrast you also measure at 10% contrast, for example, you can clearly detect if the contrast sensitivity function is good or poor.

Vanishing optotypes

We have tested several special methods for measuring peripheral vision. The first was High Pass Resolution Perimetry (HRP) with optotypes (see Fig. 25) from ring perimetry developed by Professor Lars Frisén [Frisén 1987; Frisén and Nikolajeff 1993]. What was studied was the ability of a subject to see the rings in the form of high pass filtered objects, with or without eccentric correction. These optotypes are not sensitive to astigmatism in the same way that other test objects are. The rings are easy to recognize even with peripheral vision, and the distinct form of a ring makes it possible to differentiate it from the shapeless light phenomena that sometime appear in the visual field due to disturbances in the visual system. Fifty ring objects of different sizes around a previously estimated threshold value were randomly presented. Since the subjects had a logMAR worse than 1.0 (decimal visual acuity 0.1), only the highest contrast of 90% could be used. The area of measurement for the program we used consisted of logMAR of 0.7–1.9 (decimal visual acuity 0.2–0.015).

According to the inventor and the research he has presented, HRP is a method in which the thresholds for resolution and detection are nearly the same [Frisén 1987]. Others maintain that HRP only measures detection [Anderson and Ennis 1999; Ennis and Johnson 1999].
In our case, with relative measurements, it was important to evaluate whether the refractive correction had any positive influence on vision: our interest was not primarily in evaluating the difference between resolution and detection. More on the method used can be found in the article *Eccentric Correction for Off-Axis Vision in Central Visual Field Loss* [Gustafsson and Unsbo 2003].

**PVE – Peripheral Visual Evaluation**

It became increasingly apparent that the visual evaluation tests we wanted to perform were not available. Thibos, Wang and Anderson’s studies of visual function in peripheral vision in healthy eyes show that there is a significant difference between resolution and detection thresholds in peripheral vision [Anderson and Ennis 1999; Thibos et al. 1987; Wang et al. 1997b]. That is why we wanted to develop specific tests for these functions as well as to measure in both the high and low contrast areas.

We have developed a program, Peripheral Visual Evaluation (PVE), which consists of two parts: a number identification test for visual acuity measurement (resolution synonymous with identification) and a grating test for detection. In the development of the program, we used the beta version of WinVis, a plugin for MatLab ([www.neurometrics.com/winvis/index.jsp](http://www.neurometrics.com/winvis/index.jsp)), developed for psychophysical visual evaluation and stimuli presentations.

The measurements were carried out on a computer screen (Eizo Flex Scan T 765 with 85 Hz and a resolution of 1024 x 768) using WinVis’s calibration function to achieve the right contrast levels. The screen’s background luminance (gray) was set at 50 cd/m², test distance was 1 meter and the refractive correction used compensated for that distance. Around the computer screen there were black fixation rings painted on a white background at 15°, 20° and 25° for the subjects who needed support in finding a more stable gaze during the measurements. The same eccentric viewing direction was used in the measurements that had previously been used to determine the optical aberrations of the eye.

**Resolution**

The visual acuity measurements involved numbers exclusively, which had a similar degree of difficulty. In order to be able to compare with other measurement methods, we chose the numbers 5, 6, 8 and 9 (see Fig. 26), which are also to be found in Test Chart 2000 and in the Lea Vision Test ([www.ea-test.fi](http://www.ea-test.fi)). Using numbers is also more common in low vision optometry than it is in usual clinical practice.

![Figure 26. The numbers that were used for measuring resolution at high and low contrast are presented here in a line at 10% contrast. During the measurements, a single number was displayed.](http://www.ea-test.fi)
The numbers can be displayed at both high and low contrast and in varying sizes. It is possible to measure down to a logMAR of 2.0 (decimal visual acuity 0.01) at 1 meter’s test distance. Bearing in mind the low vision of the subjects, 1 meter is a suitable distance and it is also used in other tests [Gustafsson 2002; Gustafsson and Unsbo 2003; Pelli et al. 1988].

The subject’s task is to identify the numbers. A sound signal precedes each new display. The numbers are presented one at a time and a mistake or “I don’t know” are registered as errors. The subjects are always encouraged to guess, even if they are uncertain. A staircase method (predefined in WinVis) is used in which the numbers are displayed in decreasing size down to the point that they can no longer be identified (see Fig. 27). When an error is registered, the program reverses and displays a number that is one step bigger. The subject is required to see the stimulus on two successive trials (one-up-two-down) in order for the program to reverse directions again and display a smaller number. The number of reversals around the threshold value is at least 8. The staircase method begins with two-step intervals up to the second reversal. Thus, only the last 6 reversals are used to calculate the threshold value. In order to achieve sufficient sensitivity, intervals of 0.05 logMAR were used. The measurements were carried out in 100% contrast and in 10% when possible, otherwise in 25% contrast. The changes between high and low contrast occurred randomly. We would have preferred to measure at even lower contrast levels, but the pre-trials demonstrated that the subjects’ contrast sensitivity was too poor for this.

**DETECTION**

The detection test displays gratings predefined in WinVis with different spatial frequencies in a circle in the middle of the screen, what is called a Gabor grid, with a diameter of 5° visual angle. Since we wanted to measure in a defined angle that would optimally utilize the residual vision (the person’s PRL), the area that is displayed cannot be too large. The choice of the diameter stated is based on previous studies [Anderson et al. 1996], but is adjusted to the subjects we have.

At lower levels, we had to increase the diameter in order to get...
enough cycles. It was scaled so that there always were at least 6 cycles in the area that was displayed. Two separate staircase methods (same as above) were run simultaneously, one for the horizontal and one for the vertical (see Fig. 28). We started with wide gratings and went towards the narrower ones. They were displayed randomly, alternating both horizontally and vertically at both high and low contrast.

Here, the subject’s task is to tell in which of two sequentially presented stimuli he/she can see the gratings. A voice announces, “First” and “Second” before the object is displayed. The test administrator enters 1 or 2 for the choice of intervals the person has identified as containing the gratings. The subjects are only asked to report the interval in which the gratings are seen, not to try and determine their direction. The subjects are encouraged to guess but can also answer that they do not see anything in the two sequences presented. In that case, it is registered as an error.

In both of the tests, numbers or gratings were displayed under 2 seconds in steps around 0.05 logMAR (see Fig. 29). Attempts were made with shorter display times, but proved to be too difficult. Before the actual tests began, trials were carried out to find suitable test areas and to acquaint the subjects with the measurement techniques.
The same measurement area could be used in the resolution and detection tests and the measurements were carried out with the same low contrast levels in both of the measurement series. Background lighting in the room was dim orientation light, about 2 lux at the subject’s eye.

It took 10–15 minutes to carry out the resolution test at two contrast levels. The detection test took much longer, between 30 and 45 minutes. When measurements required considerable concentration, they were carried out in intervals of 2–3 minutes followed by a pause of at least 1 minute. The subject was encouraged to rest more often when he or she found it hard to concentrate.

**Perimetry in central visual field loss**

Normally, Goldman perimetry is used in the examination of a person with large CFL (see Fig. 30). In this method, the entire visual field is enclosed by a dome in which the object (a light stimulus) is presented. Consequently, a person with a large CFL does not have anything on which to hold her gaze since she cannot see the central fixation mark, a black spot. Thus, it is not unusual that the results of the examination are difficult to interpret. Notations of poor or uncertain viewing are common.

It is of considerable value to be able to graphically see where a person’s vision functions and where it does not. That is why perimetry that is accurately and quickly administered is of great value for rehabilitation personnel as well as for the individual with low vision. Ivonne Fetchenheuer from the School of Optometry at the Technische Fachhochschule Berlin (University of Applied Sciences), based her Bachelor of Science thesis on research carried out at the Low Vision Enabling (LVE) Lab at Certec. She tested a computerized, manual version of the American Auto-Plot method supplemented with three different fixation objects. The design was based on the beta version of software developed at the Vision Rehabilitation Laboratory at Shepens Eye Institute in Boston, [www.eri.harvard.edu/faculty/peli](http://www.eri.harvard.edu/faculty/peli). It goes under the name Computerized Auto-Plot Perimeter (CAPP).

Stimuli and fixation objects were displayed by means of back projection on a screen, 1 x 0.75 m, see Figure 31. We evaluated the commonly used, small fixation cross (which, as expected, was impossible for subjects with CFL to see), a large fixation ring in the periphery of the screen and a large, centrally projected cross.

The size and contrast of the stimuli and fixation objects can be regulated according to need and make it possible to find a favorable eccentric viewing direction. That is not the case for the ring in the periphery, which is placed outside the screen.

Enlarging the central fixation cross so much that subjects who entirely lack function in the macula can see it offers an alternative possibility for carrying out perimetry. In that case, though, the
optics for low vision enabling

Scotoma is no longer centered and the results cannot be compared to how visual field examinations are normally carried out. Movement of the blind spot can be used as an indicator and control of direction and angle in those cases it is not imbedded in a large scotoma.

Fig. 32 shows a case in which the subject views upward and directs his gaze close to the edge of the CFL. This examination was carried out with a large central fixation cross.

It should be possible to develop this program into a useworthy method in all low vision rehabilitation which aims to assist the patient in utilizing peripheral vision as effectively as possible [Fetchenheuer and Gustafsson 2004].

Training of eccentric vision

In several of the methods just described, eccentric viewing has been trained at the same time as we have measured visual functions at a distance. People with large central scotomas can certainly use CCTV systems for reading, but there are obvious disadvantages with only this solution, such as that it is most often a stationary device that needs electricity. With a spectacle-mounted microscopic lens system, you can read anywhere, but this requires that you can manage eccentric viewing and are able to move the text by hand in front of the lens. This involves the user holding the text very close to his face. Few partially sighted people with absolute central scotomas are aware of how to use eccentric viewing to gain the best visual function in a variety of everyday situations.

That is why we have developed the MoviText methodology in order to make subjects aware of and to train their eccentric viewing so that they can effectively learn to read at a very short distance [Gustafsson and Inde 2004]. Low vision therapist Krister Inde developed the method. My contribution has primarily involved selecting suitable subjects as well as performing the low vision assessment examinations, prescribing and fitting the microscopic lenses that were used.

By making use of ZoomText (version 7.1 in our case), a screen magnifying program in general use in low vision rehabilitation, participants practice reading with eccentric viewing even before

Figure 31. The picture on the left shows the back projection screen with a sheet of Plexiglas mounted over it on which a large ring is displayed. The vertical and horizontal lines assist the subject in gazing straight ahead. These can be moved further out so as to not interfere with the measuring procedure. Centrally, you can see the small fixation cross which is invisible for subjects with CFL. The picture on the right shows the centrally projected magnified cross, which the subject used in viewing with his or her PRL.

Figure 32. Graphic results from a measurement in which the person fixates on the magnified central cross with his PRL. If the fixation was central, the blind spot would be found on the ring to the left at 15°. Here the subject is viewing upward and you can see that the blind spot is decentered at the same angle. The scotoma was evaluated with two sizes of the stimulus.
they begin training with their microscopic reading devices. After the optometrist has fitted the participant with microscopic lenses, the low vision therapist is able to provide training in how to read moving text on the computer screen. The computer simulates the manual moving text effect by displaying it from right to left at the upper edge of the screen (Ticker Mode in the DocReader function). Text size and display speed can be adjusted. By initially viewing in eight alternative directions around the moving text, the subject finds his or her best eccentric viewing direction for reading. The display speed is individually adjusted and the subject then practices the art of reading, first with easier and then more difficult texts without having to go back in the text to re-read (see Fig. 33).

This method can easily be used in low vision rehabilitation. The ZoomText software can be found at every low vision center and in the computers of many visually impaired people in Sweden. By instructing more people in the MoviText method, training of eccentric viewing will become more widespread [Gustafsson and Inde 2004]. As a result, people with CFL will also be able to increase their reading rate. A prerequisite for good results is that sufficiently powerful magnification in microscopic lenses are tried out in connection with the training in a close cooperation between the low vision therapist and the optometrist. The concept of pre-optical training described here has proven to be very fruitful in many situations since the behavioral training required is already in place before the optical devices are even introduced.

The image quality of the optics greatly influences the results [Gustafsson 1997]. If the optical lens, with power between +30 and +50 D, produces aberrations (that reduce the usable visual field) and causes distortions when the text is moved, it is more difficult to profit from moving text training. It makes it hard to read for longer periods and the distortions in the text cause dizziness and, at times, even nausea.
5. Results

This research had its inception in 1996 when the first ideas were put forth. But the actual work has been carried out for the most part from September of 1999 through May of 2004.

Optics of the eye
The optics of the eye have been studied by means of *raytracing* (1999); *photorefraction* with the PowerRefractor (1999 forward), primarily in Lund but also in Stockholm, Sundsvall and Örebro; measurements with the *double pass method* (2000); and *wavefront measurements* (2002–2004) at KTH in Stockholm. In August and September of 2003, the measurements of 50 healthy eyes were carried out in order to compare the different measurement methods, including subjective refraction with optimization of contrast sensitivity.

Visual function evaluation
Aberration measurements and refractive corrections are necessary, but the primary aim of this research from the very beginning and all the way through has been to evaluate and improve visual function. The first measurements of how eccentric correction influences vision were performed in 2000–2001 with the HRP test. The Peli-Robson contrast sensitivity chart was used at the same time to evaluate the lower contrast visual function with and without eccentric correction. The computerized visual acuity chart, Test Chart 2000, has been used since 2001. During the last months of 2002 and the first months of 2003, the MoviText training project was implemented. In 2003, a Bachelor of Science thesis on Computerized Auto-Plot Perimeter was developed into a scientific study [Fetchenheuer and Gustafsson 2004]. The measurements of resolution (visual acuity, identification) and detection from the Peripheral Visual Evaluation (PVE) program were performed during April and May of 2004.

Off-axis optics of the eye
Since the greater part of this thesis deals with people who have to rely on their peripheral vision, it is primarily the optics outside of the optical axis that are of interest.
Raytracing, to follow rays of light in a computer model of an eye, was for me an excellent gateway to a better understanding of the off-axis optics of the human eye (www.certec.lth.se/doc/raytracing). We used the OSLO raytracing program and the Liou and Brennan eye model to study optical image quality (see Fig. 34) [Liou and Brennan 1997].

Raytracing in the model demonstrated quite clearly that eccentric image quality was poor at off-axis large angles, and that oblique astigmatism increased with increased eccentricity. Thus, it is not unreasonable to assume that correction can affect the use of peripheral vision.

THE DOUBLE PASS METHOD

Most of the results in this thesis are based on measurements on people with low vision, but we started on people with healthy eyes with no central refractive errors. Results demonstrated that the individual differences in eccentric refraction were large, both between individuals and between different directions in one and the same eye (see Fig. 35). Measurements from some individual subjects showed that there was a distinct difference between the nasal and temporal portions of the visual field. The difference in astigmatism between two individuals could be as high as 10 D at certain angles. Most had
a shift towards myopia, but some individual eyes had, instead, a shift
towards hypermetropia. Coma also differed between individual eyes.

**Conclusion:** When we study the aberrations that result from
eccentric viewing in people with low vision, it is crucial that we
measure individually in every viewing direction that can be of interest
[Gustafsson et al. 2001] and that we find a better method. The double
pass method proved to be entirely too difficult and time consuming
for the subjects.

**Photorefraction with the powerrefractor**

Due to the ease and speed of administration, the photorefraction
method could be used on a large number of subjects. A compilation
of the measurement results from 74 subjects with CFL is presented
here (although the table appears to have 81 subjects, the numbers

<table>
<thead>
<tr>
<th>SUB</th>
<th>Eye</th>
<th>Central correction</th>
<th>X</th>
<th>Eccentric viewing direction</th>
<th>Angle (°)</th>
<th>Eccentric correction</th>
<th>X</th>
<th>Pupil size (mm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R</td>
<td>+2.00</td>
<td>-1.00</td>
<td>25</td>
<td>R</td>
<td>30</td>
<td>+4.00</td>
<td>-4.00</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>L</td>
<td>-4.00</td>
<td>-0.50</td>
<td>12</td>
<td>R</td>
<td>24</td>
<td>-2.00</td>
<td>-3.00</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>R</td>
<td>+3.00</td>
<td>-0.50</td>
<td>120</td>
<td>Up</td>
<td>15</td>
<td>+3.00</td>
<td>-1.00</td>
<td>160</td>
</tr>
<tr>
<td>4</td>
<td>R</td>
<td>+2.00</td>
<td>-1.00</td>
<td>90</td>
<td>R</td>
<td>20</td>
<td>+4.00</td>
<td>-5.00</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>R</td>
<td>-3.75</td>
<td>-1.00</td>
<td>80</td>
<td>R/up</td>
<td>20</td>
<td>-1.00</td>
<td>-4.00</td>
<td>85</td>
</tr>
<tr>
<td>6</td>
<td>R</td>
<td>-1.25</td>
<td>-1.00</td>
<td>180</td>
<td>R</td>
<td>22</td>
<td>-1.00</td>
<td>-2.00</td>
<td>80</td>
</tr>
<tr>
<td>7</td>
<td>L</td>
<td>±0.00</td>
<td>-1.00</td>
<td>80</td>
<td>Up</td>
<td>20</td>
<td>±0.00</td>
<td>-1.50</td>
<td>170</td>
</tr>
<tr>
<td>8</td>
<td>L</td>
<td>-8.00</td>
<td>-3.50</td>
<td>5</td>
<td>R</td>
<td>30–40</td>
<td>Unable</td>
<td>3.5</td>
<td>Small pupil</td>
</tr>
<tr>
<td>9</td>
<td>L</td>
<td>+11.25</td>
<td>-5.50</td>
<td>20</td>
<td>Down</td>
<td>25</td>
<td>+10.00</td>
<td>-12.50</td>
<td>150</td>
</tr>
<tr>
<td>10</td>
<td>R</td>
<td>+0.25</td>
<td></td>
<td></td>
<td>Up</td>
<td>18</td>
<td>+0.25</td>
<td>-3.25</td>
<td>170</td>
</tr>
<tr>
<td>11</td>
<td>L</td>
<td>+0.50</td>
<td>-0.75</td>
<td>165</td>
<td>Up</td>
<td>10</td>
<td>+1.00</td>
<td>-3.50</td>
<td>170</td>
</tr>
<tr>
<td>12</td>
<td>R</td>
<td>+1.00</td>
<td>-4.00</td>
<td>90</td>
<td>R</td>
<td>15</td>
<td>+2.25</td>
<td>-9.00</td>
<td>80</td>
</tr>
<tr>
<td>13</td>
<td>R</td>
<td>Unable</td>
<td></td>
<td></td>
<td>R</td>
<td>10</td>
<td>Unable</td>
<td>3.0</td>
<td>Small pupil</td>
</tr>
<tr>
<td>14</td>
<td>L</td>
<td>+1.00</td>
<td>-0.50</td>
<td>70</td>
<td>L</td>
<td>22</td>
<td>+2.75</td>
<td>-2.00</td>
<td>105</td>
</tr>
<tr>
<td>15</td>
<td>R</td>
<td>+4.25</td>
<td>-1.25</td>
<td>95</td>
<td>R</td>
<td>16</td>
<td>+5.25</td>
<td>-3.25</td>
<td>95</td>
</tr>
<tr>
<td>16</td>
<td>L</td>
<td>+0.50</td>
<td>-1.50</td>
<td>175</td>
<td>Up</td>
<td>16</td>
<td>+1.50</td>
<td>-4.50</td>
<td>155</td>
</tr>
<tr>
<td>17</td>
<td>R</td>
<td>-3.00</td>
<td>-1.75</td>
<td>95</td>
<td>R/up</td>
<td>16</td>
<td>-3.00</td>
<td>-2.50</td>
<td>65</td>
</tr>
<tr>
<td>18</td>
<td>R</td>
<td>±0.00</td>
<td>-2.00</td>
<td>90</td>
<td>Up</td>
<td>14</td>
<td>-1.00</td>
<td>-3.50</td>
<td>95</td>
</tr>
<tr>
<td>19</td>
<td>L</td>
<td>Unable</td>
<td></td>
<td></td>
<td>Up</td>
<td>15</td>
<td>+1.25</td>
<td>-0.25</td>
<td>80</td>
</tr>
<tr>
<td>20</td>
<td>L</td>
<td>-4.50</td>
<td>-2.00</td>
<td>10</td>
<td>L</td>
<td>10</td>
<td>-4.75</td>
<td>-3.25</td>
<td>25</td>
</tr>
<tr>
<td>21</td>
<td>R</td>
<td>-0.25</td>
<td>-0.50</td>
<td>95</td>
<td>R</td>
<td>17</td>
<td>-0.75</td>
<td>-2.00</td>
<td>90</td>
</tr>
<tr>
<td>22</td>
<td>L</td>
<td>+0.75</td>
<td>-1.00</td>
<td>110</td>
<td>R</td>
<td>15</td>
<td>+3.00</td>
<td>-3.00</td>
<td>100</td>
</tr>
<tr>
<td>26</td>
<td>L</td>
<td>+1.75</td>
<td>-3.00</td>
<td>90</td>
<td>R</td>
<td>10</td>
<td>+2.25</td>
<td>-5.00</td>
<td>90</td>
</tr>
<tr>
<td>27</td>
<td>R</td>
<td>Unable</td>
<td></td>
<td></td>
<td>R</td>
<td>–</td>
<td>Unable</td>
<td>2.5</td>
<td>Small pupil</td>
</tr>
<tr>
<td>28</td>
<td>R</td>
<td>+0.50</td>
<td>-0.50</td>
<td>95</td>
<td>Down</td>
<td>13</td>
<td>+0.50</td>
<td>-1.25</td>
<td>125</td>
</tr>
<tr>
<td>30</td>
<td>R</td>
<td>+0.75</td>
<td>-0.50</td>
<td>135</td>
<td>R</td>
<td>10</td>
<td>+2.50</td>
<td>-1.00</td>
<td>80</td>
</tr>
<tr>
<td>32</td>
<td>L</td>
<td>Unable</td>
<td></td>
<td></td>
<td>R</td>
<td>17</td>
<td>Unable</td>
<td>4.5</td>
<td>IOL</td>
</tr>
<tr>
<td>34</td>
<td>R</td>
<td>±0.00</td>
<td>-1.00</td>
<td>100</td>
<td>R</td>
<td>18</td>
<td>+2.00</td>
<td>-2.50</td>
<td>105</td>
</tr>
<tr>
<td>35</td>
<td>R</td>
<td>+0.25</td>
<td>-1.25</td>
<td>180</td>
<td>R</td>
<td>15</td>
<td>-0.50</td>
<td>-0.50</td>
<td>115</td>
</tr>
<tr>
<td>36</td>
<td>L</td>
<td>-0.25</td>
<td>-2.75</td>
<td>85</td>
<td>R</td>
<td>17</td>
<td>Unable</td>
<td>3.5</td>
<td>Cataract</td>
</tr>
<tr>
<td>SUB</td>
<td>Eye</td>
<td>Central correction</td>
<td>Eccentric viewing direction</td>
<td>Angle (°)</td>
<td>Eccentric correction</td>
<td>Pupil size (mm)</td>
<td>Comments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
<td>---------------------</td>
<td>-----------------------------</td>
<td>---------</td>
<td>---------------------</td>
<td>----------------</td>
<td>----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sph. (DS)</td>
<td>Cyl. (DC)</td>
<td>X (°)</td>
<td>Sph. (DS)</td>
<td>Cyl. (DC)</td>
<td>X (°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>L</td>
<td>+3.75</td>
<td>-2.25</td>
<td>90</td>
<td>R</td>
<td>+3.00</td>
<td>-3.00</td>
<td>100</td>
<td>4.5</td>
</tr>
<tr>
<td>38</td>
<td>L</td>
<td>+0.50</td>
<td>-2.50</td>
<td>88</td>
<td>L</td>
<td>+1.25</td>
<td>-3.25</td>
<td>85</td>
<td>4.0</td>
</tr>
<tr>
<td>39</td>
<td>L</td>
<td>-2.00</td>
<td>-0.50</td>
<td>150</td>
<td>L</td>
<td>-0.75</td>
<td>-0.75</td>
<td>15</td>
<td>5.5</td>
</tr>
<tr>
<td>40</td>
<td>L</td>
<td>-3.50</td>
<td>-4.50</td>
<td>175</td>
<td>L/down</td>
<td>-3.50</td>
<td>-1.25</td>
<td>140</td>
<td>4.0</td>
</tr>
<tr>
<td>41</td>
<td>L</td>
<td>Unable</td>
<td>Centr.</td>
<td>–</td>
<td>Unable</td>
<td>–</td>
<td>–</td>
<td>3.5</td>
<td>Central fix.</td>
</tr>
<tr>
<td>42</td>
<td>Both</td>
<td>Unable</td>
<td>Altern.</td>
<td>–</td>
<td>Unable</td>
<td>–</td>
<td>–</td>
<td>4.0</td>
<td>Cataract</td>
</tr>
<tr>
<td>43</td>
<td>R</td>
<td>+0.25</td>
<td>-2.25</td>
<td>95</td>
<td>R</td>
<td>+0.00</td>
<td>-3.25</td>
<td>75</td>
<td>4.0</td>
</tr>
<tr>
<td>44</td>
<td>L</td>
<td>+1.75</td>
<td>-3.25</td>
<td>85</td>
<td>L</td>
<td>+1.00</td>
<td>-6.50</td>
<td>80</td>
<td>4.0</td>
</tr>
<tr>
<td>45</td>
<td>L</td>
<td>-1.25</td>
<td>-1.25</td>
<td>70</td>
<td>L/down</td>
<td>-0.50</td>
<td>-0.50</td>
<td>180</td>
<td>4.5</td>
</tr>
<tr>
<td>46</td>
<td>R</td>
<td>-2.00</td>
<td>-0.75</td>
<td>130</td>
<td>R</td>
<td>-0.75</td>
<td>-0.75</td>
<td>85</td>
<td>4.5</td>
</tr>
<tr>
<td>47</td>
<td>R</td>
<td>-1.75</td>
<td>-3.75</td>
<td>170</td>
<td>R</td>
<td>28</td>
<td>Unable</td>
<td>3.5</td>
<td>Small pupil</td>
</tr>
<tr>
<td>48</td>
<td>R</td>
<td>-1.25</td>
<td>-0.75</td>
<td>170</td>
<td>R</td>
<td>-0.25</td>
<td>-0.75</td>
<td>85</td>
<td>4.0</td>
</tr>
<tr>
<td>49</td>
<td>L</td>
<td>-0.75</td>
<td>-0.75</td>
<td>115</td>
<td>L</td>
<td>+0.75</td>
<td>-1.75</td>
<td>95</td>
<td>4.0</td>
</tr>
<tr>
<td>50</td>
<td>R</td>
<td>+0.25</td>
<td>-0.75</td>
<td>180</td>
<td>R</td>
<td>+2.25</td>
<td>-2.00</td>
<td>85</td>
<td>4.5</td>
</tr>
<tr>
<td>51</td>
<td>L</td>
<td>-2.25</td>
<td>-0.50</td>
<td>140</td>
<td>R</td>
<td>-1.25</td>
<td>-3.50</td>
<td>85</td>
<td>5.0</td>
</tr>
<tr>
<td>52</td>
<td>L</td>
<td>+1.00</td>
<td>-0.50</td>
<td>35</td>
<td>L</td>
<td>-0.50</td>
<td>-0.50</td>
<td>60</td>
<td>4.0</td>
</tr>
<tr>
<td>53</td>
<td>R</td>
<td>-0.50</td>
<td>-0.50</td>
<td>135</td>
<td>Up</td>
<td>-0.50</td>
<td>-0.50</td>
<td>10</td>
<td>5.5</td>
</tr>
<tr>
<td>54</td>
<td>R</td>
<td>-1.75</td>
<td>-4.75</td>
<td>105</td>
<td>R</td>
<td>-1.00</td>
<td>-6.00</td>
<td>90</td>
<td>4.5</td>
</tr>
<tr>
<td>55</td>
<td>L</td>
<td>+1.25</td>
<td>-2.25</td>
<td>85</td>
<td>L</td>
<td>+2.50</td>
<td>-3.00</td>
<td>90</td>
<td>4.5</td>
</tr>
<tr>
<td>56</td>
<td>L</td>
<td>-5.25</td>
<td>-0.50</td>
<td>125</td>
<td>R/up</td>
<td>-4.75</td>
<td>-1.25</td>
<td>175</td>
<td>5.0</td>
</tr>
<tr>
<td>57</td>
<td>Both</td>
<td>Unable</td>
<td>R</td>
<td>–</td>
<td>Unable</td>
<td>–</td>
<td>–</td>
<td>3.5</td>
<td>Cataract</td>
</tr>
<tr>
<td>58</td>
<td>L</td>
<td>±0.00</td>
<td>-0.50</td>
<td>15</td>
<td>Up</td>
<td>±0.00</td>
<td>-1.00</td>
<td>175</td>
<td>4.0</td>
</tr>
<tr>
<td>59</td>
<td>L</td>
<td>±0.00</td>
<td>-2.00</td>
<td>165</td>
<td>Up</td>
<td>±0.50</td>
<td>-2.00</td>
<td>155</td>
<td>5.0</td>
</tr>
<tr>
<td>60</td>
<td>R</td>
<td>+6.25</td>
<td>-1.00</td>
<td>95</td>
<td>R</td>
<td>+6.00</td>
<td>-2.75</td>
<td>85</td>
<td>4.0</td>
</tr>
<tr>
<td>61</td>
<td>L</td>
<td>+0.50</td>
<td>-1.25</td>
<td>95</td>
<td>L</td>
<td>+1.50</td>
<td>-2.75</td>
<td>85</td>
<td>4.0</td>
</tr>
<tr>
<td>62</td>
<td>R</td>
<td>-0.75</td>
<td>–</td>
<td>15</td>
<td>R</td>
<td>-1.25</td>
<td>-1.00</td>
<td>100</td>
<td>5.0</td>
</tr>
<tr>
<td>63</td>
<td>R</td>
<td>-0.25</td>
<td>-0.50</td>
<td>140</td>
<td>R</td>
<td>+0.50</td>
<td>-1.00</td>
<td>105</td>
<td>3.5</td>
</tr>
<tr>
<td>64</td>
<td>L</td>
<td>±0.00</td>
<td>-0.50</td>
<td>95</td>
<td>R</td>
<td>+0.75</td>
<td>-0.50</td>
<td>25</td>
<td>4.5</td>
</tr>
<tr>
<td>65</td>
<td>L</td>
<td>±0.00</td>
<td>-2.50</td>
<td>170</td>
<td>R</td>
<td>±0.00</td>
<td>-2.25</td>
<td>75</td>
<td>4.0</td>
</tr>
<tr>
<td>66</td>
<td>Both</td>
<td>±0.00</td>
<td>-1.50</td>
<td>25</td>
<td>Up</td>
<td>±0.00</td>
<td>-2.75</td>
<td>30</td>
<td>5.0</td>
</tr>
<tr>
<td>67</td>
<td>L</td>
<td>±0.50</td>
<td>–</td>
<td>5</td>
<td>R</td>
<td>±0.50</td>
<td>–</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>68</td>
<td>L</td>
<td>±3.00</td>
<td>-1.50</td>
<td>20</td>
<td>Up</td>
<td>±2.75</td>
<td>-2.00</td>
<td>25</td>
<td>4.5</td>
</tr>
<tr>
<td>69</td>
<td>L</td>
<td>±1.25</td>
<td>-0.50</td>
<td>40</td>
<td>Up/L</td>
<td>±0.25</td>
<td>-3.75</td>
<td>65</td>
<td>5.0</td>
</tr>
<tr>
<td>70</td>
<td>L</td>
<td>±0.25</td>
<td>-0.50</td>
<td>75</td>
<td>R</td>
<td>±0.25</td>
<td>-3.00</td>
<td>90</td>
<td>5.0</td>
</tr>
<tr>
<td>71</td>
<td>L</td>
<td>±0.50</td>
<td>-0.75</td>
<td>115</td>
<td>L</td>
<td>±1.00</td>
<td>-1.25</td>
<td>130</td>
<td>3.5</td>
</tr>
<tr>
<td>72</td>
<td>L</td>
<td>±0.75</td>
<td>-0.75</td>
<td>15</td>
<td>Up</td>
<td>±1.25</td>
<td>-1.50</td>
<td>175</td>
<td>4.0</td>
</tr>
<tr>
<td>73</td>
<td>L</td>
<td>±1.00</td>
<td>-0.75</td>
<td>115</td>
<td>L</td>
<td>±1.00</td>
<td>-3.75</td>
<td>100</td>
<td>4.5</td>
</tr>
<tr>
<td>74</td>
<td>L</td>
<td>±2.75</td>
<td>-0.50</td>
<td>70</td>
<td>L</td>
<td>±1.25</td>
<td>-1.75</td>
<td>85</td>
<td>4.0</td>
</tr>
<tr>
<td>75</td>
<td>L</td>
<td>±1.25</td>
<td>-1.50</td>
<td>160</td>
<td>R</td>
<td>±0.75</td>
<td>-2.00</td>
<td>90</td>
<td>4.0</td>
</tr>
<tr>
<td>76</td>
<td>L</td>
<td>±2.50</td>
<td>-0.25</td>
<td>125</td>
<td>R</td>
<td>±3.75</td>
<td>-3.75</td>
<td>90</td>
<td>4.5</td>
</tr>
<tr>
<td>77</td>
<td>L</td>
<td>±5.50</td>
<td>-1.75</td>
<td>95</td>
<td>R</td>
<td>±3.00</td>
<td>-3.00</td>
<td>100</td>
<td>3.5</td>
</tr>
<tr>
<td>78</td>
<td>R</td>
<td>±1.25</td>
<td>-0.75</td>
<td>85</td>
<td>R</td>
<td>±0.00</td>
<td>-2.00</td>
<td>90</td>
<td>4.5</td>
</tr>
<tr>
<td>79</td>
<td>L</td>
<td>±6.00</td>
<td>-0.75</td>
<td>5</td>
<td>R</td>
<td>±7.00</td>
<td>-1.25</td>
<td>175</td>
<td>5.5</td>
</tr>
<tr>
<td>80</td>
<td>L</td>
<td>±0.75</td>
<td>-0.25</td>
<td>10</td>
<td>L</td>
<td>±0.25</td>
<td>-1.25</td>
<td>130</td>
<td>4.0</td>
</tr>
</tbody>
</table>

48 • OPTICS FOR LOW VISION ENABLING
for the 7 who were not evaluated have been removed). Individual measurement values of central and eccentric correction are presented in the table. Astigmatism is greater eccentrically than centrally. There was a mean difference of 1.3 DC between the central and eccentric viewing direction, which on average was 15° off-axis. The individual differences are still the most interesting ones.

The results show the same degree of individual variations as we previously found in healthy eyes [Gustafsson et al. 2001]. In most cases, astigmatism increased with increased angle to the optical axis. But there are also examples of a central astigmatism decreasing or almost disappearing at larger angles, see SUB. 35, 40 and 61. Astigmatism can also change directions. In SUB. 7, 44, 48, 63 and 76, the direction changes almost 90°. The spherical values between central and eccentric correction can increase and decrease. If you calculate the spherical equivalent of cylinder and sphere, however, there is on average little difference. Although even here there are, in individual cases, examples of a shift towards more or less hypermetropia or myopia.

For three of the subjects, 43, 47 and 52, results from both eyes are presented. They have similar visual function in both eyes and alternate between using the left and right eye. One subject had no astigmatism at all and we were unable to find values for eccentric viewing direction in four subjects.

There are several reasons as to why it was not possible to measure all the eyes. In some cases, it was due to opacity in the ocular media, primarily incipient cataract. In others, it was not possible to use this method in eyes that had an intraocular lens implanted after cataract surgery. An intraocular lens in itself does not prevent one from carrying out the measurements, but in lenses with a high refractive index, photorefraction did not seem to work. Furthermore, small pupil size can make it impossible to carry out the measurements, especially at oblique angles.

WAVEFRONT MEASUREMENTS

Wavefront measurements have been carried out on six of the low vision subjects using an aberrometer built for this purpose with a Hartmann-Shack sensor. In some cases, a Zeiss WASCA instrument was also used (a commercially available wavefront sensor). The refraction has been calculated in two ways based on the wavefront measurements. Minimization of the wavefront error (RMS correction) and optimization of image quality (Strehl correction), were both calculated at 4 mm pupil size. For purposes of comparison, corrections were also measured with photorefraction using the PowerRefractor. All values are rounded off to 0.25 D and to the nearest 5° in axis direction.
SUB. 1: Right eye eccentric viewing, approximately 35° to the right

<table>
<thead>
<tr>
<th>Method</th>
<th>Angle</th>
<th>Sph. (DS)</th>
<th>Cyl. (DC)</th>
<th>X (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>33°</td>
<td>+2.25</td>
<td>–4.25</td>
<td>95</td>
</tr>
<tr>
<td>Strehl</td>
<td>33°</td>
<td>+2.50</td>
<td>–2.75</td>
<td>95</td>
</tr>
<tr>
<td>RMS</td>
<td>36°</td>
<td>+2.75</td>
<td>–6.00</td>
<td>100</td>
</tr>
<tr>
<td>Strehl</td>
<td>36°</td>
<td>+3.50</td>
<td>–1.50</td>
<td>110</td>
</tr>
<tr>
<td>RMS</td>
<td>40°</td>
<td>+3.25</td>
<td>–7.25</td>
<td>95</td>
</tr>
<tr>
<td>Strehl</td>
<td>40°</td>
<td>+4.50</td>
<td>–2.00</td>
<td>105</td>
</tr>
<tr>
<td>PowerRefractor *</td>
<td></td>
<td>+4.00</td>
<td>–4.00</td>
<td>90</td>
</tr>
</tbody>
</table>

* The PowerRefractor was unable to measure at 30–35° off-axis. This value is measured at 25°, i.e. slightly into the scotoma.

SUB. 2: Right eye eccentric viewing, approximately 20° to the right

<table>
<thead>
<tr>
<th>Method</th>
<th>Sph. (DS)</th>
<th>Cyl. (DC)</th>
<th>X (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>–2.75</td>
<td>–1.00</td>
<td>90</td>
</tr>
<tr>
<td>Strehl</td>
<td>–3.25</td>
<td>–1.75</td>
<td>80</td>
</tr>
<tr>
<td>WASCA</td>
<td>–2.75</td>
<td>–1.25</td>
<td>90</td>
</tr>
<tr>
<td>PowerRefractor</td>
<td></td>
<td>–2.00</td>
<td>–3.00</td>
</tr>
</tbody>
</table>

SUB. 11: Left eye eccentric viewing approximately 10° upward

<table>
<thead>
<tr>
<th>Method</th>
<th>Sph. (DS)</th>
<th>Cyl. (DC)</th>
<th>X (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>±0.00</td>
<td>–2.75</td>
<td>10</td>
</tr>
<tr>
<td>Strehl</td>
<td>+0.50</td>
<td>–2.50</td>
<td>5</td>
</tr>
<tr>
<td>WASCA</td>
<td>+0.75</td>
<td>–3.00</td>
<td>165</td>
</tr>
<tr>
<td>PowerRefractor</td>
<td></td>
<td>+1.25</td>
<td>–3.75</td>
</tr>
</tbody>
</table>

SUB. 17: Right eye eccentric viewing approximately 16° to the right and slightly upward

<table>
<thead>
<tr>
<th>Method</th>
<th>Sph. (DS)</th>
<th>Cyl. (DC)</th>
<th>X (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>–4.25</td>
<td>–5.25</td>
<td>75</td>
</tr>
<tr>
<td>Strehl</td>
<td>+1.75</td>
<td>–9.00</td>
<td>50</td>
</tr>
<tr>
<td>PowerRefractor *</td>
<td></td>
<td>–3.00</td>
<td>–2.50</td>
</tr>
</tbody>
</table>

* varying values

SUB. 21: Right eye eccentric viewing, approximately 17° to the right

<table>
<thead>
<tr>
<th>Method</th>
<th>Sph. (DS)</th>
<th>Cyl. (DC)</th>
<th>X (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>–3.00</td>
<td>–1.50</td>
<td>90</td>
</tr>
<tr>
<td>Strehl</td>
<td>–3.25</td>
<td>–1.50</td>
<td>80</td>
</tr>
<tr>
<td>WASCA</td>
<td>–2.50</td>
<td>–1.75</td>
<td>90</td>
</tr>
<tr>
<td>PowerRefractor</td>
<td></td>
<td>–0.75</td>
<td>–2.00</td>
</tr>
</tbody>
</table>

SUB. 70: Right eye eccentric viewing, approximately 20° to the right

<table>
<thead>
<tr>
<th>Method</th>
<th>Sph. (DS)</th>
<th>Cyl. (DC)</th>
<th>X (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS</td>
<td>+0.25</td>
<td>–2.25</td>
<td>85</td>
</tr>
<tr>
<td>Strehl</td>
<td>+0.50</td>
<td>–2.00</td>
<td>90</td>
</tr>
<tr>
<td>PowerRefractor</td>
<td></td>
<td>+1.50</td>
<td>–3.00</td>
</tr>
</tbody>
</table>
Comments:
For SUB. 1, the difference between the Strehl correction and RMS correction shows that astigmatism is less with Strehl, while the direct opposite is the case for SUB. 17: astigmatism is greater with the Strehl correction. If this is due to higher order aberrations such as coma or if the difference is the result of, for example, different pupil shapes is not clear. For SUB. 17, the PowerRefractor has given variable values the entire time. None of them resemble the Strehl corrections.

The remaining subjects do not have as large higher order aberrations and thus the measurement values vary less between the two calculation methods. The few measurements that were carried out with the WASCA commercial instrument agree well, as they should, with the RMS calculations.

VALIDATION OF THE REFRACTION METHODS
It is difficult to achieve any proper validation of methods for measuring refraction in people with low vision, i.e. to make sure the methods actually measure what they intend to. For validation to be possible, improved visual measurement methods for off-axis vision are needed (see the next section). The results of these will perhaps make it possible to understand which refraction method leads to the refractive correction that provides the best improvement in visual function.

We have compared four methods. For the sake of comparison, partially sighted subjects are not required, so we have used 50 normally sighted people and measured their right eye fixated to the right at 20 and 30° off-axis. The measurements have been carried out with the PowerRefractor, ordinary streak retinoscopy, wavefront sensing with the Hartmann-Shack sensor and subjective refraction with optimizing of contrast sensitivity. Agreement among all four methods is quite good [see Lundström et al. 2004a].

Wavefront measurements (HS) in general produce values that shift too much towards negative correction. In retinoscopy, it is difficult to find the right axis position, which is why this method appears to be the most unreliable. The subjective method is clearly more uncertain, resulting in a large distribution of the results. The primary reason for this is that the measurements are so strenuous and time-consuming. The one that proved to be the best is the Hartmann-Shack sensor, not the least because you are able to separate out the higher order aberrations. Perhaps the most important result of the comparison of the methods is that the fast PowerRefractor appears to give reasonably good results. But it most often cannot manage to measure at angles of 25–30° and larger because the projected size of the pupil is too small.
**Retinoscopy Without Prior Knowledge**  
*Measurements of 4 Eyes*

Retinoscopy was carried out by a colleague, an experienced low vision optometrist without any previous information about the subjects’ refractive errors. His tasks were: to carry out subjective refraction while the subject viewed eccentrically as best as he or she could to see the optotypes; to implement retinoscopy (without cycloplegia) when trying to use central fixation (viewing straight ahead without seeing the object); and then to carry out the same measurements but with eccentric viewing in the most used PRL.

<table>
<thead>
<tr>
<th>Person and eye</th>
<th>Pupil size in subjective refraction (mm)</th>
<th>Subjective refraction in low illumination</th>
<th>Sph. (DS)</th>
<th>Cyl. (DS)</th>
<th>X °</th>
<th>Pupil size in retinoscopy (mm)</th>
<th>Retinoscopy centrally</th>
<th>Sph. (DS)</th>
<th>Cyl. (DS)</th>
<th>X °</th>
<th>Eccentric viewing</th>
<th>Retinoscopy eccentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUB. 1 Right eye</td>
<td>4.5</td>
<td>+1.50</td>
<td>5.0</td>
<td>+1.50</td>
<td>–0.75</td>
<td>15</td>
<td>35° to the right</td>
<td>1.25</td>
<td>–0.50</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB. 11 Left eye</td>
<td>3.5</td>
<td>+1.00 –2.00 150</td>
<td>3.5</td>
<td>+0.50</td>
<td>–1.50</td>
<td>160</td>
<td>10° up</td>
<td>0.50</td>
<td>–1.75</td>
<td>170</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB. 21 Right eye</td>
<td>5.0</td>
<td>–1.00 –1.00 90</td>
<td>6.0</td>
<td>–0.25</td>
<td>–1.00</td>
<td>90</td>
<td>17° to the right</td>
<td>1.00</td>
<td>–1.00</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB. 70 Right eye</td>
<td>3.5</td>
<td>+1.25 –1.25 180</td>
<td>4.0</td>
<td>–0.75</td>
<td>–0.50</td>
<td>45</td>
<td>20° to the right</td>
<td>–0.75</td>
<td>–0.50</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Refraction values from subjective refraction with subject using his or her PRL, and retinoscopy centrally and eccentrically. Pupil size and angle of eccentric viewing.**

**Comments:**

SUB. 1: In a comparison of the results from the photorefraction and wavefront measurements which resulted in +3.0 DS –2.0 DC x 100°, you can clearly see that none of these clinical methods found the astigmatism.

SUB. 11: The ordinary clinical methods provide a relatively good indication but tend to undervalue astigmatism. The axis direction is also slightly different than with the other methods in which the Strehl correction resulted in +0.5 DS –2.5 DC x 5°.

SUB. 21: If you compare these values with the photorefraction and wavefront measurements, you can see that astigmatism is found but slightly undervalued. The PowerRefractor resulted in –0.75 DS –2.0 DC x 90°.

SUB. 70: None of these clinical methods have found the astigmatism that is shown in the photorefraction and wavefront measurements. The Strehl correction is +0.5 DS –2.0 DC x 90°.

The comment from the optometrist who carried out the examinations was that he felt the values were uncertain when performing retinoscopy off-axis. He thought objective measurement with retinoscopy was a rough estimation. In SUB. 1 and 70, the oblique astigmatism was not detected.
Eccentric visual function, with and without correction

In my licentiate dissertation [Gustafsson 2001] and in a study [Gustafsson and Unsbo 2003], measurements of visual functions with and without eccentric correction were presented for SUB. 1–7. Eccentric corrections were measured with the PowerRefractor, described previously, and the visual function was evaluated with the HRP ring objects. All the measurements were performed three times on each subject and the results showed that the measured improvements agreed well with the subjects’ subjective experiences.

Contrast sensitivity was evaluated using the Peli-Robson charts. This test is not equipped with any fixation assistance, which means that the eccentric viewing may have varied more than in the other tests. Likewise, there is a risk that subjects will remember the letters since there are just two charts. Only a slight improvement in contrast sensitivity could be measured in the above-mentioned subjects with eccentric correction.

PERIPHERAL VISUAL EVALUATION, PVE

The repeatability of the PVE measurements was studied on a healthy right eye by taking 10 measurements at an angle of 30° horizontally to the right. The subject sat with her head straight ahead and gazed at a fixation mark to the right, 3 m away. This results in the subject looking with the nasal visual field, that is to say, using the temporal portion of the retina. In order to see the fixation mark, the central correction of −3.0 DS −0.5 DC x 50° was used and the left eye was covered. Resolution with numbers and detection with grating were evaluated at both high and low contrast. Fig. 36 shows the mean value and standard deviation for the 6 different tests, resolution at two contrast levels as well as detection vertically (vertical gratings) and horizontally (horizontal gratings) at two contrast levels. The results found are valid only for this subject in the direction evaluated.

The standard deviation is substantially less in the detection tests (approx. 0.03 logMAR) than in the resolution tests (approx. 0.09 logMAR).

Figure 36. The graph shows the mean value and standard deviation for the threshold values, in logMAR, from the 10 repeated measurements at 30° off-axis. DV = detection vertically, DH = detection horizontally and R = resolution, at contrasts of 100% and 10% each.
This is because the detection test is a less complicated task than the resolution test and thus not as dependent on the subject’s attention. In addition, a two alternative forced choice (2AFC) method was used in the detection test to keep the level of guessing at 50%. In the resolution test, this level was uncontrolled.

**Changes in Visual Function in the Group of Seven**

What follows is a description of the visual function measurements and refractive correction effects on the 7 main subjects in the investigation. All corrections have been adjusted to a measurement distance of 1 meter, that is to say, +1.0 DS has been added to the values listed below. The visual acuity values have been rounded off to the nearest 0.05 logMAR.

**SUB 1: The first correction.**

*Man, 57 years, right eye, eccentric viewing 30–35° to the right.*

In previous low vision rehabilitation, he received correction for central hypermetropia and astigmatism but has not experienced any improvement. The most common eccentric viewing direction has been about 30° down, possibly upward at times. When he was measured with the PowerRefractor, he became aware that a viewing about 30° to the right resulted in improved vision. He had previously used this viewing direction now and again, but not consciously.

To exclude the fact that the difference in improved vision was only a matter of finding a better PRL, many measurements have been carried out with and without eccentric correction.

**HRP: In the first assessments with the HRP ring, values were used from estimates made with photorefraction. With the central correction of +2.0 DS –1.0 DC x 25°, the result was 1.70 logMAR (decimal visual acuity 0.02). The eccentric correction used was +4.0 DS –4.0 DC x 90°. The result was 1.55 logMAR (decimal visual acuity 0.03).**

This example shows that improved optical quality outside of a large scotoma can make a difference and that a small amount of residual vision is sufficient, if the image can just be improved and magnified.
To watch TV, this subject uses his new eccentric correction at a viewing distance of 0.5 meter from the screen. He can utilize the new viewing direction because the eccentric correction improves the image.

PVE: Measurements with the PVE program that are presented in Fig. 37 were carried out with a central correction of +2.0 DS –1.0 DC x 25°. This eccentric correction is from the wavefront measurements and has been calculated using the Strehl method to +3.0 DS –2.0 DC x 100°.

Because of the subject’s limited residual vision, it was impossible to measure detection at 25% low contrast. Several attempts were made without success. This is a bit surprising because we were able to measure resolution at 25% contrast. At a resolution of 100% contrast, visual acuity improved from 1.70 to 1.45 logMAR (decimal visual acuity approx. 0.02 to 0.035). The measurement at 25% contrast resulted in a smaller difference and less accuracy. A difference can also be found in detection horizontally from 1.20 to 1.05 logMAR (decimal visual acuity approx. 0.063 to 0.09).

We also evaluated corrections calculated with the RMS method, which resulted in higher cylinder values but poorer visual function, which the subject found unacceptable.

This is the subject who received the first correction based on estimated values from photorefraction. The visual function was then assessed with the HRP rings and a slight improvement was noted. The difference was small, in a positive direction in the first eccentric correction. The correction based on the Hartmann-Shack measurement and calculation according to the Strehl method was the best. The subject’s subjective judgment confirms that the eccentric correction from the wavefront measurements calculated according the Strehl method resulted in the best visual function. He uses the correction primarily when watching TV.

**SUB. 2: Woman, 61 years, left eye, eccentric viewing 20° to the right.**

Has for a long time used just one stable viewing with the left eye, approximately 20° to the right. Correction for myopia –3.75 DS has been used for many years.
HRP: At the time of the first evaluation with HRP, values from photorefraction were used. With the central correction of −3.75 DS, the result was 1.30 logMAR (decimal visual acuity 0.05). The eccentric correction that was used was −2.0 DS −3.0 DC x 90° resulting in a visual acuity of 1.20 logMAR (decimal visual acuity 0.063).

PVE: The central correction is −4.0 DS −0.5 DC x 12°. The eccentric correction that was used in the measurement presented in Fig. 38 was −3.25 DS −1.75 DC x 80°, calculated according to the Strehl method from the Hartmann-Shack sensor.

The detection tests show almost no differences between the two corrections. A slight improvement can be seen with the resolution test at a low contrast of 10%, from 1.55 to 1.35 logMAR (decimal visual acuity approx. 0.03 to 0.045) but no appreciable difference at high contrast.

Since there was an improvement with the first eccentric correction from photorefraction, it is a bit surprising that we did not find any difference with the PVE measurements. If you compare the two corrections, photorefraction and wavefront measurement, the latter resulted in the best visual function. The subjective experience of both eccentric corrections has been positive. However when asked, the subject described the second and newest eccentric correction as more comfortable in comparison with the first which was more “disturbing”.

SUB. 11: Man, 79 years, left eye, eccentric viewing 10° upward. Uses a mild astigmatic correction corresponding to a central correction.

HRP: At the first assessment with HRP, the values from photorefraction were used. The central correction of +0.5 DS −0.75 DC x 165° resulted in 1.25 logMAR (decimal visual acuity approx. 0.06). The eccentric correction from the PowerRefractor was +1.0 DS −3.5 DC x 170°, and resulted in a visual acuity of approximately 1.15 logMAR (decimal visual acuity 0.07).

Figure 39. The graph shows visual acuity in logMAR and the standard deviation of the reversals in the staircase method, with central and eccentric correction for SUB. 11. DV = detection vertically, DH = detection horizontally, R = resolution, at contrasts of 100% and 10% each.
PVE: The central correction used in these measurements is +0.5 DS –0.75 DC x 165°, and the eccentric correction is +0.5 DS –2.5 DC x 5°, calculated with the Strehl method from the Hartmann-Shack sensor (Fig. 39).

A considerable improvement can be seen in the detection threshold horizontally at high contrast, otherwise no significant improvement in detection with eccentric correction was noted. A slight improvement can be seen in resolution at high contrast, from 1.15 to approximately 1.0 logMAR (decimal visual acuity of approx. 0.07 to 0.1) which is a high value for a 10° off-axis angle. Likewise, the values for detection measurements are considerably better than in the other subjects with retinal degeneration.

For this subject, the objectively measured change is not particularly great, but he still experiences enough of a positive subjective difference so that he is very willing to use his eccentric correction. Even if he does not view 10° upward all the time, he feels this correction does not have any negative side effects in the remaining visual field. He now wears this eccentric correction all the time. In the future, the correction will be included in the magnifying devices for reading with microscopic lenses at very short distances.

**SUB. 17: Man, 42 years, right eye, eccentric viewing approximately 20° to the right and slightly upward.**

Wears corrective lenses that correspond to the centrally measured values.

HRP: Measurements not performed.

PVE: Examinations with photorefraction and attempts at retinoscopy produced unstable values and eccentric correction was not tested before the wavefront measurements were completed. In the measurements presented in Fig. 40, the central correction was –2.5 DS –1.0 DC x 25° and the eccentric was +1.75 DS –9.0 DC x 50°, calculated according to the Strehl method from the Hartmann-Shack sensor.

**Figure 40.** The graph shows visual acuity in logMAR and the standard deviation of the reversals in the staircase method, with central and eccentric correction for SUB. 17. DV = detection vertically, DH = detection horizontally, R = resolution, at contrasts of 100% and 25% each.
Figure 41. All measurements for SUB. 17, carried out three times, one staircase line for each measurement. The broken lines represent the central correction and the solid ones the eccentric correction for each step when measuring at DV 100% = detection 100% contrast vertically, DH 100% = detection 100% contrast horizontally, DV 25% = detection 25% contrast vertically, DH 25% = detection 25% contrast horizontally, R 100% = resolution 100% contrast and R 25% = resolution 25% contrast. The horizontal lines represent the measured threshold values for each measurement.
In the PVE evaluations from three measurements that were carried out on three different days separated by approximately 2 weeks each, we see a more general improvement of all the values. The smallest improvement is in detection horizontally at high contrast. Vertically, the detection threshold improved from 1.50 to 1.15 logMAR (decimal visual acuity of approx. 0.03 to 0.075) at 100% contrast. At 25% contrast, the detection threshold changed vertically from 1.60 to 1.30 logMAR (decimal visual acuity of approx. 0.025 to 0.05) and horizontally, the improvement was almost the same, 0.3 logMAR. The threshold value in the resolution test at 100% contrast improved from 1.55 to 1.3 logMAR (decimal visual acuity approx. 0.03 to 0.05) and at the lower contrast level of 25%, from 1.70 to 1.5 logMAR (decimal visual acuity approx. 0.02 to 0.035).

Subjectively, this subject is able to clearly confirm the improved vision that was objectively reported. He can use his glasses with the large astigmatic correction primarily when sitting still and watching TV or using his computer. When he moves around, he finds it difficult to wear them.

The measurement data for SUB. 17 from all three PVE measurement sessions, plotted with a broken line for central correction and a solid line for eccentric correction are displayed graphically in Fig. 41.

SUB. 21: Woman, 33 years, right eye, eccentric viewing 17° to the right. Has received refractive correction in spectacles on a few occasions without any effect.

HRP: At the time of the first evaluation with HRP, values from photorefraction were used. The results were 1.4 logMAR (decimal visual acuity approx. 0.04) entirely without correction. Correction of the minimal myopia and astigmatism centrally resulted in no measurable difference. The eccentric correction used was –0.75 DS –2.0 DC x 90°, and it resulted in a visual acuity of 1.10 logMAR (decimal visual acuity approx. 0.08).
PVE: In the following measurements (see Fig. 42), the insignificant central correction of $-0.25 \, \text{DS} - 0.5 \, \text{DC} \times 95^\circ$ was used. The eccentric correction used was $-0.75 \, \text{DS} - 2.0 \, \text{DC} \times 90^\circ$ from the measurements carried out with the PowerRefractor, since they produced better visual function. The improvement was about 0.1 logMAR, both at high and low contrast, compared with the correction from the wavefront measurements $-3.25 \, \text{DS} - 1.5 \, \text{DC} \times 80^\circ$.

Here we can see a clear improvement, particularly in detection, as an effect of the eccentric correction. For vertical gratings at 100% contrast, the improvement is 0.95 to 0.65 logMAR (decimal visual acuity approx. 0.1 to 0.3) and at 25%, 1.30 to 0.90 logMAR (decimal visual acuity approx. 0.05 to 0.13). The clearly greatest improvement, 0.4 logMAR, is shown here by detection vertically at 25% contrast. The threshold value for detection is near the levels that a healthy eye reaches. In this case, it is not the retinal receptors that are injured but the optic nerve.

Resolution improved from 1.35 to 1.20 logMAR (decimal visual acuity approx. 0.045 to 0.065) at 100% contrast and from 1.45 to 1.30 logMAR (decimal visual acuity approx. 0.035 to 0.05) at the lower level of 25% contrast.

The subject experienced improved vision from the correction and uses it all the time for viewing distances longer than an arm’s length. Previously, the subject had received a central correction with a weak minus power that was never used.

SUB. 70: Man, 44 years, right eye, eccentric viewing 20° to the right.
Was not aware of his use of eccentric viewing; has trained a lot and has found his best PRL when viewing to the right. Has never used refractive correction.

HRP: At the time of the first evaluation with HRP, values from photorefraction were used. The results, entirely without correction, were 1.30 logMAR (decimal visual acuity 0.05). Correction of the minimal myopia and astigmatism centrally made no difference. The eccentric correction used was $+1.5 \, \text{DS} - 3.0 \, \text{DC} \times 90^\circ$, and resulted in a visual acuity of 1.20 logMAR (decimal visual acuity approx. 0.06).

Figure 43. The graph shows visual acuity in logMAR and the standard deviation of the reversals in the staircase method, with central and eccentric correction for SUB. 70. DV = detection vertically, DH = detection horizontally, R = resolution, at contrasts of 100% and 25% each.
PVE: In the measurements presented in Fig. 43, the central correction used is –0.25 DS –0.5 DC x 75°. The eccentric correction has a power of +0.5 DS –2.0 DC x 90°, and is calculated with the Strehl method from the wavefront measurements.

There is no direct difference between the two corrections. A slightly larger difference exists for detection of the horizontal grating at both high and low contrast.

On the subjective level, though, the subject experienced a certain improvement and uses the eccentric correction primarily for watching TV at a distance less than a meter. He can use the correction without problem when moving but does not experience any improvement.

**PVE MEASUREMENT ON KRISTER INDE**

This section describes some of the experiments and measurements that were carried out on Krister Inde.

**SUB. 7: Man 57 years, left eye. Has three different eccentric viewing directions (functional PRLs).**

He was previously aware of two: approximately 8° upward for reading and approximately 20° upward for the best orientation. To watch TV at home, he utilizes eccentric viewing at approximately 12° to the left, which he had not observed on his own previously. He has different eccentric refractions in these three directions.

**HRP:** The many measurements that have been carried out have not shown any significant improvement with eccentric correction [Gustafsson and Unsbo 2003]. Still, the measurements have been valuable for the method development.

**PVE:** The left eye is the best and has a central correction of ±0 DS –1.0 DC x 80°. In the largest eccentric viewing direction, 20° upward, the eccentric correction is –1.0 DS –1.5 DC x 170°.

We were not able to demonstrate any direct effect of the eccentric correction based on the PVE measurements.
Comparison of two PRLs: The measurements were carried out in the two PRLs mostly used: upward approximately 8° uncorrected and to the left at approximately 12° with a correction of ±0 DS –1.5 DC x 80°. In the direction upward at approximately 8°, most measurements have shown that there is almost no astigmatism.

A large difference was noted between high and low contrast, particularly in the detection measurements (see Fig. 44). That there was a clear reduction in contrast sensitivity in this subject was already well known, but not that the difference in detection function could be so great between high and low contrast. If we look at the horizontal detection thresholds, we see that they differ from 1.45 to 0.55 logMAR (decimal visual acuity approx. 0.045 to 0.35) between low and high contrast, quite similar in both PRLs. The threshold values here for high contrast detection are entirely on the same level as what healthy eyes can achieve.

The most important clarification that came out of the measurements on Krister Inde was that his resolution is noticeably better when viewing to the left than when viewing upward. The difference in resolution between upward and left viewing at 100% contrast is almost 0.3 logMAR, 1.50 (upward) to 1.20 logMAR (left) (decimal visual acuity approx. 0.03 to 0.065) in these measurements. Reading is clearly best when viewing upward because the visual field is wider, but it requires a higher magnification than when viewing to the left. These results explain why he chooses to view to the left when watching TV and in a number of other situations.

We also carried out several eccentric experimental corrections on Krister Inde, who was one of the most trained and aware subjects. The first was done only at the most extreme angle, 20° upward. He could see a difference at this angle, even though the measurements that were performed did not show a significant improvement. This first eccentric correction was difficult to use because it only worked in one direction and resulted in poorer visual function in other directions. A pair of demonstration spectacles with corrections for
the left eye, with three segments, shows the powers for the eccentric correction from previous measurements with photorefraction when his three PRLs were used (see Fig. 45). It shows how eccentric correction can vary and that it is possible to manufacture glass with segments that have different, multifocal astigmatic corrections for distance vision. They do not function in practice but have been used for demonstration. The corrections in the segment for 20° upward proved later to be overvalued in cylinder correction.

The eccentric correction that works best according to Krister Inde are the bifocals that have both central and eccentric correction (see Fig. 46).

**Effects of training**

What is presented in this section are some of the results we have seen when the subjects involved in our research become aware of their eccentric viewing capacities and participate in the subsequent training.

**Reading with high magnification and moving text**

In a mini project, 9 (originally 12) subjects with CFL were trained with the MoviText method, which is based on the training of viewing direction in order to read moving text in the best manner possible. The subjects were supplied with microscopic lenses with good optical quality. Each subject’s reading rate was measured on four occasions during three visits. See the table in Fig. 47 for the results.

The results are encouraging when it comes to improvement of reading ability. Subjects with large scotomas were also able to read with high power microscopic lenses [see Gustafsson and Inde 2004]. Some individuals show only a slight improvement, but for the group on the whole, the improvement is clearly significant. This methodology can be included in the concept “pre-optical training,” which means that you learn a new behavior before optical devices are introduced.

**Finding one’s best viewing direction through visual field measurement**

One side effect of several of the measurements presented and the evaluations of eccentric correction was that the subjects increased their awareness of where and how they were to view in order to see better. It was particularly obvious in the visual field measurements with CAPP, see pages 42–43. During the measurements, several of the subjects were able to find their best locations (PRLs) outside of the scotoma and graphically they could observe what part of the retina they could use and what part was not working.

In the project, three fixation support devices were tested: a small cross in the middle of the visual field, a large cross in the middle of...
the visual field that could clearly be seen (see Fig. 48), and a fixation ring on the edge of the screen (see Fig. 31). Over half preferred the large fixation cross and to view it using their PRL, which results in the scotoma being decentered when compared with ordinary perimetry (see Fig. 49) [Fetchenhauer and Gustafsson 2004].

Keeping in mind just how difficult it can be to perform good visual field measurements for the group affected, it is encouraging that this method not only enables subjects to manage visual field measurements quickly but also allows them to discover and train their viewing directions at the same time.

SEE MORE PROJECT — TRAINING OF CHILDREN WITH LOW VISION

As of yet, the See More Project has not been going on long enough to present any definitive results, but it seems that the “desire to see” has increased for most of the 17 children who are participating. For some, it is the higher addition at a short distance (microscopic lens) which is the most important (that they can manage to a great extent without magnifiers or CCTV). For others, it is using the handheld telescope (a little monocular one) and the opportunity to discover exciting new things at a distance that is the most important.
6. Discussion

People with severely reduced central vision should be entitled to receive the best possible refractive correction, treatment and training to improve their peripheral vision. There are many reasons as to why this has not been the case. The three primary ones are:

*The use of eccentric corrections to improve the vision of people with CFL has been considered pointless.* It has been assumed that the visual limitations are entirely due to the characteristics of the retina outside of the macula, i.e. refractive corrections beyond those of large central refractive errors have been seen as having no effect. *The research presented in this thesis has demonstrated that this assumption is erroneous. Eccentric corrections can influence vision in people with CFL.*

*It has been difficult to measure off-axis optics and evaluate eccentric vision.* Even if optometrists with extensive low vision experience attempt eccentric corrections, they are bound to fail if they do not have the very best of conditions. I have had these, thanks to good collaboration. I have made use of all the knowledge and experience I have acquired over the years working with people who have reduced visual function due to CFL; I have been able to develop ideas never before considered in excellent, state-of-the-art laboratory settings; and I have been allowed to learn from trial and error. The entire time I have maintained that measurements, refractive corrections and visual function measurements have to be carried out on an individualized basis for people with CFL. *This is the first published research effort that shows the results of eccentric correction in people with CFL.*

*The economic incentive for developing improved optics for these groups has not been strong enough.* Most of those affected are elderly people with macular degeneration. They are no longer in the workforce. Thus their visual impairments do not impinge upon working life and they have been left to manage as well as they can with magnification devices or nothing at all. The group of elderly people is sharply increasing. Most of them are healthy, are accustomed to living an active life; many are relatively well situated financially and are used to taking the initiative. *Consequently, the economic incentives are now in place for a rapid development of low vision optics.*
Evaluation of optical results

These are our most important findings:

1. The individual variations in off-axis optics are so large that general statements based on models of the eye are meaningless when it comes to aberrations and refractive correction. What is needed, instead, are measurements that are as reliable as possible of each separately used PRL.

2. It is possible to perform approximate measurements of the eye’s off-axis optics in regular clinical settings in a certain, given angle. The measurements lack precision, but provide reasonable indications. In this context, retinoscopy is the most uncertain, particularly when it comes to determining axis position in astigmatism.

3. Photorefraction with the PowerRefractor is considerably easier, faster and provides better results. The PowerRefractor also has a gaze direction registration function. But this instrument has its limitations: it is unable to measure further out than 25–30°; unable to measure projected pupil sizes less than 3 mm; has problems with some IOLs that have a high refractive index; and is unable to differentiate higher order aberrations.

4. Wavefront measurements with Hartmann-Shack sensors make it possible to measure eccentrically and to differentiate not only astigmatism but other aberrations as well. This type of instrument has started to appear commercially, one example is the WASCA from Zeiss. No doubt other more inexpensive ones will turn up. Software needs to be developed specifically for the purpose of measuring off-axis in order for this equipment to function optimally.

5. Higher order aberrations such as coma were noticeably bigger in some of the subjects. Correcting as much of this as possible with contact lenses or in other ways in a laboratory setting is important for evaluating how higher order aberrations affect the visual function.

6. Awareness and training of PRL are prerequisites, primarily for using visual function (see below), but also so that the measurement of the off-axis optics can be carried out in the right direction. In this regard, fixation rings and CAPP have been of great help.

Evaluation of visual functions results

These are our most important findings:

1. Our PVE (Peripheral Visual Evaluation) program has produced results that are reproducible for both CFL and normally sighted subjects.
2. The greatest visual improvements from eccentric correction for most of the CFL subjects are in *resolution*, not *detection capabilities*. For others who have studied healthy eyes, though, the greatest improvement was in detection [Wang et al. 1997b]. The improvements in resolution (identification, visual acuity) for our subjects were, at best, a little better than 0.2 logMAR, which for them is a significant improvement considering that they have such limited vision. Those who had the greatest objective improvements also had the most positive subjective experiences of the corrections.

3. The results of the detection measurements were exciting, even though the differences with and without eccentric correction were not as large as what others have found [Wang et al. 1997b]. The effect in our measurements is at most 0.3 logMAR at high contrast and 0.4 logMAR at low contrast in the direction where the refractive correction has the most effect. It was obvious that some subjects experienced greater improvements from their corrections than others. In the future it will be important to ascertain why this is so: is it due to the limitations of the retina; to the limits of a subject’s level of attention; or to something else entirely, related to the etiology of the visual impairment? In summary: For subjects with an optic nerve injury, detection thresholds were closer to those of healthy eyes; for subjects with macular degeneration, far under. This latter conclusion is surprising because so many subjects with CFL as the result of retinal degeneration describe how well they manage to detect things. But this can be because visual detection often takes place when the person or the object is in motion. That is why the next important step is to evaluate motion vision and the possible effect of eccentric correction on this function.

4. A well-focused eye detects horizontal gratings better than vertical ones in the periphery [Rovamo et al. 1982; Thibos et al. 1996]. This could not be clearly confirmed in our subjects with CFL – no significant difference was found between the ability to see vertical versus horizontal gratings.

5. Awareness and training of PRL are prerequisites for achieving the best possible visual function. In addition to the fixation rings and CAPP already mentioned, we have also seen the positive effects of the MoviText method for training reading.

6. Visual function measurements and training methods should be supplemented with an eyetracker so that we more reliably can determine that the visual stimuli we measure are coming from exactly the same part of the retina all the time.
The development of objective refraction and aberration equipment that can also be used in low vision rehabilitation would be helpful. In the first place, it is in the eccentric angles larger than 10° that there is reason to look for an astigmatism that has not previously been corrected. Eccentric correction is easiest for those who only utilize one PRL, in which case ordinary corrective lenses for astigmatism can be used. If the person with CFL uses different PRLs for different visual tasks, which many do, [Fletcher and Schuchard 1997; Guez et al. 1993; Lei and Schuchard 1997], the eccentric correction can vary considerably (see Chapter 5, Results). The refractive correction in those cases is more complicated. Nevertheless, a person such as SUB. 1 can clearly benefit from a single eccentric correction when sitting still, such as when watching television.

How many who can benefit substantially from eccentric correction is uncertain. Larger series of measurements are needed with considerably more CFL subjects and, in addition, with better methods to evaluate visual function than we have today. At least four of the subjects in the group of seven found their eccentric correction to be beneficial. This has been confirmed by better resolution function in PVE evaluations, at least in SUB. 1, 11, 17 and 21.

In several subjects, there is a pronounced difference between the detection values and the resolution values, but it is the latter that most resemble the results from the HRP optotype. Thus, it appears as if the HRP rings do not only measure detection, contrary to what others maintain [Anderson et al. 1999].

The thesis’s concentration on evaluation of aberrations and visual function should not discount the fact that the most important aspect of visual ability is the person’s own experience of it in his or her lived reality. Before and during this research, I have listened to the patients’ descriptions of how they experience their vision and have taken them seriously, which I plan to continue doing. I know from my work with clinical subjective refraction that many people with macula degeneration would like to have a different correction than the one that is objectively measured for central vision. In the table on pages 47–48 there are examples of astigmatism increasing with visual angles but also of changes towards both a more plus and minus in spherical equivalent values. The individual variations, in other words, are large. That subjective and objective refractive measurements should differ when they, in reality, measure different phenomena is not surprising. There are also areas in which the subjective measurements are the only ones we can rely on. This goes for the many people with macular degeneration who have a surprisingly good ability to detect an airplane in the sky or a puzzle piece on the floor in spite of vision that is otherwise severely reduced. Objective measurement methods for this need to be developed. Other important areas for measurement method development are motion vision – only thorough good evaluations of motion can we study how it is affected by refractive corrections.
7. Conclusions

This thesis demonstrates that visual improvements through eccentric corrections in people with CFL are possible. This has opened the door to larger areas of research with the hope that it will be possible to:

1. Develop more and better methods to evaluate visual function when using eccentric vision.
2. Go further in studying motion vision as well as the effects of refractive corrections and visual impairments on balance. One way to do this would be to make use of VR (virtual reality) environments.
3. Carry out trials with specially manufactured contact lenses shaped according to the wavefronts measured with the Hartmann-Shack sensor so that all important aberrations will be corrected eccentrically.
4. Better understand the influence different visual impairments have on what the refractive and aberration corrections can achieve.
5. Better understand why many people with CFL detect things so well in spite of their reduced visual function. This requires a combination of situated research and clinical research.
6. Contribute to research results and methods being put into practice in clinical settings.
7. Expand the group examined to include more people with CFL than those with large central scotomas and conscious eccentric viewing.
References


Fetchenheuer, I., Gustafsson, J. 2004, *Visual field testing in patients with central field loss and low vision rehabilitation implications*, manuscript.


Appendices


Theory and method at Certec

Situated Research and Design for Everyday Life, 2004,  
www.certec.lth.se/doc/situatedresearch

Doctoral and licentiate theses at Certec:
Calle Sjöström, Non-visual Haptic Interaction Design, 2002,  
http://www.certec.lth.se/doc/hapticinteraction/

Eve Mandre, From Medication to Education, 2002,  
http://www.certec.lth.se/doc/frommedicationto/

Arne Svensk, Design for Cognitive Assistance, 2001,  
http://www.certec.lth.se/doc/designforcognitive/

Jörgen Gustafsson, Eccentric Correction in Central Visual Field Loss, 2001,  
http://www.certec.lth.se/doc/eccentric/

Björn Breidegard, En datorexekverbar modell för lärande  
(Executable Computer Models of Learning), 2000,  
http://www.certec.lth.se/dok/datorexekverbamodell/

Håkan Eftring, The Useworthiness of Robots for People with Physical Disabilities, 1999,  
http://www.certec.lth.se/doc/useworthiness/

Eve Mandre, Designing Remedial Education, 1999,  
http://www.certec.lth.se/doc/designingremedial/

Peter Anderberg, Internet Learning for All, 1999,  
http://www.certec.lth.se/doc/internetlearningforall/

Calle Sjöström, The IT Potential of Haptics, 1999,  
http://www.certec.lth.se/doc/touchaccess/

Håkan Neveryd, Sensor-based Navigating Mobile Robots for People with Disabilities, 1998,  
http://www.certec.lth.se/doc/sensorbased/index.html
The age in which we live celebrates all that is innovative. From the point of view of methodology, this results in different forms of cross-fertilization of ideas by means of interdisciplinary studies, networks and close contacts between universities and the communities they are a part of. The contact can never be so close and so cross-fertilizing as when it exists within a single human being. If a person with extensive practical professional expertise continues in the same direction but at the research level, he has unique opportunities to benefit from his experiences at the same time as he can challenge established and ingrained assumptions. This has been the case for Jörgen Gustafsson. After many years at the Low Vision Center in Jönköping, Sweden, he came to Certec, a well-established cross-disciplinary division in the Department of Design Sciences at Lund University’s Institute of Technology. From there, he established strong external research networks while maintaining the clinical contacts he already had and developing new ones.

Above all, he worked diligently and persistently. The majority of all research is exactly that: hard, everyday work. Each idea has to be proven or rejected – in a scientifically sustainable manner. In this case, there was an additional stipulation: the ideas, methods and instruments had to also be sustainable when interacting with those who they are primarily intended for: people with low vision due to large central scotomas.

The double challenge from the people directly affected on the one hand, and science on the other, has been like walking on a knife’s edge and has resulted in this thesis. The edge has been sharp and threatening, but has also offered guidance: It has helped us to maintain focus and to keep on raising questions. The thesis is based on a large number of scientifically published articles and conference contributions. They are compiled here for the first time. The thesis presents to all an opportunity to gain insight into the entire research process and how it interacts with Jörgen Gustafsson’s underlying conceptual world. The research presented here takes us right up to today’s date, October 15, 2004, and also points out possible future directions.

Jörgen Gustafsson
Optics for Low Vision Enabling