Optimal Use of Peripheral Vision
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Cover image: The three-dimensional wavefront aberrations (colour image) measured at 25° nasal visual field in the left eye of a subject, for a pupil diameter of 5 mm, and the corresponding point spread function (PSF) is illustrated. Aberrations were measured by COAS-HD VR aberrometer and the image was obtained with WavefrontLab© (KTH, Stockholm).

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To my parents
Abstract


People who lose their central vision have to rely on their peripheral vision for all visual tasks. The ability to resolve fine details in the periphery is reduced due to retinal limitations and the optical aberrations arising from the use of off-axis vision. The aim of this work is to improve vision by enhancing the image quality at the preferred retinal locus by means of correcting the optical errors. The focus of this thesis has been to measure and correct peripheral optical errors, as well as to evaluate their impact on resolution acuity in both normal and central visual field loss subjects.

In order to measure peripheral optics we employed a COAS HD VR open view aberrometer which is based on the Hartmann-Shack principle. Psychophysical methods were used to evaluate peripheral grating resolution acuity. We assessed the repeatability of the wavefront sensor in measuring the peripheral ocular aberrations. The symmetry of peripheral ocular aberrations between the left and right eyes was examined. The influence of age on peripheral ocular aberrations was also investigated. We evaluated peripheral vision with sphero-cylindrical correction in healthy eyes and performed the first adaptive optics aberration correction at the preferred retinal locus of a single central visual field loss subject.

We found that the aberrometer was repeatable and reliable in measuring peripheral ocular aberrations. There was mirror symmetry between the two eyes for most of the peripheral aberration coefficients. Age had a significant influence on peripheral ocular aberrations; there were larger amounts of higher-order aberrations in old eyes than in young eyes. Peripheral low contrast resolution acuity improved with peripheral refractive correction in subjects who had higher amounts of off-axis astigmatism. Finally, adaptive optics aberration correction improved both high and low contrast resolution acuity measured at the preferred retinal locus of the single low vision subject.

Because of their versatility, open view aberrometers will hopefully be a standard clinical instrument at low vision clinics as they allow for measurements to be rapidly performed at any location in the visual field. The existence of off-axis astigmatism should be better communicated within the low-vision rehabilitation community. Currently, the off-axis refractive errors can be corrected with conventional methods and we hope that the higher-order aberrations can also be corrected in a more realistic way in the future.

In conclusion, this thesis has shown that peripheral visual function can be improved by optical correction. The findings of this thesis have broadened the knowledge of peripheral optical errors and their influence on vision.

Keywords: off-axis refractive errors, peripheral aberrations, aberrometers, central visual field loss, preferred retinal locus, eccentric viewing, absolute central scotoma, adaptive optics, eccentric correction.
POPULÄRVETENSKAPLIG SAMMANFATTNING

Vid sjukdomar i ögats gula fläck, makula, finns risk att förlora all syn i det centrala seendet. Dessa personer blir hänvisade till att använda det kvarvarande perifera seendet för att klara sig så bra som möjligt. Det perifera seendet begränsas av den lägre upplösningsförmågan i näthinnan, men även av de optiska fel som uppstår i ögat vid excentrisk fixation, det vill säga när man måste använda seendet utanför makula. Syftet med detta arbete är att försöka förbättra avbildningen i det perifera seendet med hjälp av optiska korrektioner, särskilt hos synskadade med ett absolut centralt bortfall i synfältet och en invand bästa näthinneplats utanför makula. För att förstå de optiska felens inverkan på det perifera seendet, har mätningar av dessa optiska felteckningar även genomförts på normalseende ögon.

För att mäta ögats optik i det perifera seendet, har en avancerad aberrometer använts som bygger på vågfrontsteknik. Vilket innebär att flera hundra olika punkter kan värderas samtidigt. För att utvärdera synfunktionen användes en metod som bygger på att personen får se gitter (rändor med olika kontrast) på en datorskärm. Aberrometerns repeterbarhet i det perifera seendet värderades genom mätningar på ett antal höga ögon och i ett annat delarbete kontrollerades båda ögonen för att de inte skulle ha olika mängder av aberrationer. Det genomfördes även en studie om hur aberrationerna påverkas av äldern, genom att mäta ögats optik hos yngre och äldre personer. I ett delarbete värderades även effekten av korrektion i det perifera seendet med hjälp av lågkontrastobjekt. slutligen genomfördes en studie om hur aberrationerna påverkas genom att korrigera alla aberationer i ögat med hjälp av adaptiv optik, en deformerbar spegel.

I de olika delarbetena som genomförts har det visats att den aberrometer som användes ger repeterbara värden i det perifera seendet, samt att det fanns en symetri mellan ögonens aberrationer. Det visade sig även att ögats aberrationer i det perifera seendet är högre i äldre ögon jämfört med yngre och att korrektion av astigmatismen som uppstår i det perifera seendet ger bättre syn när man mäter med lågkontrast objekt. Slutligen visades att synen kunde förbättras hos en synskadad med en sedan länge invand bästa näthinneplats, på grund av centrat synbortfall, genom att korrigera alla optiska aberrationer.

Den aberrometer som används i dessa arbeten har ett öppet synfält, vilket gör det möjligt att mäta i stora delar av synfältet. Eftersom aberrometern visade sig vara så användbar, hoppas vi att den i en mer klinisk version kan komma att användas på syncentraler och andra kliniker. Medvetenheten om den astigmatism som uppstår i det perifera seendet, kan tydligare kommuniceras inom synrehabiliteringen och på så sätt kan förhoppningsvis bättre patienter få så bra korrektion som möjligt. I framtiden borde det även vara möjligt att korrigera de mer avancerade optiska fel samt hjälp av individuellt tillverkade kontaktlinser eller intraokulära linser.

Detta arbete har visat att det går att förbättra synen i det perifera seendet med hjälp av optiska korrektioner. Avhandlingen har även bidragit till att öka kunskapen om de optiska synfelen i det perifera seendet och dess inverkan på synen.
LIST OF PUBLICATIONS

This thesis is based on the following papers, which will be referred to by their Roman numerals in the text:


*Authors contributed equally

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1 INTRODUCTION

It is well known that the vision at the fovea has the maximum resolution capacity. In comparison, resolution in the peripheral retina is limited by optical and retinal factors to varying degrees. The limitation of peripheral resolution is not perceptible in healthy eyes because of saccadic eye movements. These eye movements shift the objects detected by the peripheral retina onto the fovea for further resolution. Resolving objects in the periphery, however, becomes much more important for people who have lost their foveal vision. Damage to the fovea due to end-stage macular diseases, such as age-related macular degenerations, lead to reduced central vision or central visual field loss (CFL). Patients who have lost their central vision must adopt an eccentric viewing strategy to realign the object of interest on an area of the peripheral retina, known as the preferred retinal locus (PRL). Given that the peripheral retina has poorer resolution capabilities, the question is whether peripheral resolution could be improved by correcting off-axis optical errors at the PRL (see Fig 1).

Figure 1: The figure shows that the foveal rays (dashed line) are focused on the retina; the peripheral rays (solid line) have aberrations/deviations at the preferred retinal locus (PRL) due to off-axis optical errors.
In order to measure off-axis optical errors at the PRL previous studies have used techniques such as the double-pass method, photorefraction, and laboratory-based wavefront sensors (Gustafsson 2004; Lundström 2007). Moreover, studies have also corrected the off-axis refractive errors and showed improvements in resolution acuity at the PRL (Gustafsson & Unsbo 2003; Lundström et al. 2007a). In addition to off-axis refractive errors, they found that off-axis higher-order aberrations (like coma) were also responsible in degrading image quality at the PRL (Lundström et al. 2009). With the recent advancement of wavefront sensors as well as adaptive optics deformable mirrors, it became feasible not only to evaluate, but also to correct both lower- and higher-order off-axis optical errors in CFL subjects.

The focus of this thesis is to understand the importance of off-axis optical errors and their influence on peripheral resolution acuity in both normal and CFL subjects. Therefore, we have evaluated repeatability in measuring off-axis aberrations with a wavefront sensor, compared off-axis aberrations between healthy young and old eyes, and evaluated the importance of eccentric correction on low contrast resolution acuity in healthy eyes. Finally, with the understanding and knowledge obtained from the healthy eyes, we evaluated visual function after correcting both off-axis refractive errors and higher-order aberrations at the PRL of a subject with central visual field loss.
2 COMPONENTS OF VISION

Vision is the most important of all our senses. The human eye is a complex organ that acts both as an optical instrument and as a photosensor relaying images of the outside world to the brain. Even very small imperfections to this process would lower the quality of vision. Optical imperfections, such as refractive errors and aberrations, are the main cause of reduced image quality on the retina. The development of refractive errors and their impact on foveal vision (on-axis) has been extensively researched. There has however been considerably less interest regarding the effect of optical errors in the periphery (off-axis). This lack of interest is partly because peripheral vision is less distinct than central vision. In addition, there are several properties of the human visual system that vary with eccentricity, including optical quality, cone density, rod density, and ganglion cell density which leads to difficulties in evaluating peripheral vision. This chapter will present a brief overview of the anatomy of the eye and explain the optical and retinal differences that exist between central and peripheral vision.

2.1 Anatomy of the Eye

The structures of the human eye are shown in figure 2. The human eye is approximately spherical with a mean diameter of 24 mm. The eyeball consists of three coats with each having a distinct structure. The outer coat is made up of two parts, the cornea and the sclera. The transparent cornea form the anterior one-sixth of the circumference of the globe and the remaining five-sixths forms the opaque fibrous sclera. The sclera has a thickness that varies from 0.3 mm at extraocular muscle insertions to 1 mm at the posterior pole. Beneath the sclera lies the choroid, a vascular layer with a thickness of 0.1–0.2 mm (Forrester 2002). The main function of choroid is to provide oxygen and nourishment to the outer layers of the retina. Along with the iris and ciliary body, the choroid forms the uveal tract. The light sensitive layer of
the eye known as the retina lies on the choroid; the retina is sensitive to wavelengths between 390 nm to 780 nm.

The retina is a thin transparent membrane that extends over the posterior two thirds of the eye. Photoreceptors called rods and cones convert incident light energy into neural impulses, which are carried to the brain through the optic nerve. Two areas of the retina are of special interest, namely the macula and the optic disc. The anatomical macula is 5-6 mm in diameter and corresponds to approximately 15°–20° in the visual field. In the centre of the macula lies the fovea which is approximately 1.5 mm in diameter (Forrester 2002). The optic disc is the region where the optic nerve leaves the eye. The optic disc has a diameter of 1.7 mm and lies about 13° to the nasal side of the macula. It is lighter in colour and because of the absence of photoreceptors, it is known as the blind spot.

There are approximately 6.5 million cones and 115 million rods spread disproportionately across the retina (Forrester 2002). The density of rods and cones varies in different regions of the retina; the periphery being rod dominated whereas the central retina is cone dominated (See Fig. 3). The centre of the fovea, the foveola (0.35 mm diameter) contains only cones, with a density of 199 000 cells per mm² (Curcio et al. 1990). It is with the foveola that the eye normally fixates during so-called foveal fixation. The fovea has
long been recognized as the site of maximal visual acuity (Helmholtz 1924). The cones are used for high-resolution photopic (daylight) vision or central vision. In addition, they are colour sensitive and are classified into three types: long (L, red), medium (M, green) and short (S, blue) wavelengths. Outside the fovea the cones give way to rods which are insensitive to colour and are mainly used for motion detection and scotopic (low light and night) vision. The photoreceptors synapse to bipolar cells that in turn synapse to the ganglion cell layer, which carries information to the optic nerve through two different pathways. The parvo-cellular pathway is specialised for resolution of fine details and colour, while the magno-cellular pathway is sensitive to contrast and motion.

Figure 3: The linear density of rods, cones and ganglion cells in the human retina as a function of eccentricity in the horizontal meridian. Conversion from cells/mm$^2$ to cells/deg$^2$ was computed assuming a posterior nodal point of 16.68 mm from the retina, and a retinal radius of curvature of 12.1 mm. Conversion to cells/deg was obtained by taking the square root of areal density. The fovea is at 0° and the optic disc is at 10°-16° in nasal retina. Adapted from Giesler & Banks (1997).

Curcio et al. (1990) and Curcio and Allen (1990) found that there are one million ganglion cells spread unevenly across the total retinal area of 1000 mm$^2$. Although the fovea only occupies a mere 0.02% of the total retinal area and contains 0.3% of the total number of cones, it contains 25% of the ganglion cells, illustrating its importance in vision (see Fig. 3). A large portion of the higher centres in the brain is devoted to processing foveal information. For example, 40% of the primary visual cortex processes the central 5° of the visual field; this corresponds to an area approximately to that of the fovea (Curcio & Allen 1990; Tootell et al. 1988). In the central fovea, the peak
density of ganglion cells is 35 000 cells per mm², with at least two ganglion
cells connected to every cone. As one proceeds further into the periphery, the
ganglion cell receptive fields enlarge, and greater numbers of photoreceptors
must share each ganglion cell (Curcio & Allen 1990). The reduction in the
density of ganglion cells from fovea to far periphery is in the order of 1000: 1.
In addition, ganglion cell densities are 60% higher in the inferior visual field
than in the superior visual field at eccentricities beyond 15°. Similarly,
ganglion cell densities are 300% higher in the temporal visual field than in the
nasal visual field at eccentricities beyond 15°.

The optical structures, including the cornea, aqueous humour, crystalline
lens, and the vitreous body are enclosed within the three coats of the eye.
Of these structures, the cornea and lens refract incident light to form an image
on the retina. The total refractive power of the eye is approximately 60 dioptre
(D). The cornea has an anterior radius of curvature of about 7.8 mm with a
horizontal and vertical diameter of 12 mm and 11 mm respectively (Guillon et
al. 1986; Kiely et al. 1984). The cornea accounts for two-thirds of the
refractive power, ~43 D. The anterior chamber lies behind the cornea with a
depth of 3.5 mm. It is filled with aqueous humor, a clear transparent liquid
that supplies nutrition to the cornea and lens, as well as regulating the
intraocular pressure of the eye. The anterior chamber is separated from the
vitreous body by the iris and the lens. The iris is a 2 mm thick annular disc
with a diameter of 12 mm immediately anterior to the lens (Forrester 2002).
The central aperture in the iris is known as the pupil. The size of the pupil
regulates the amount of light entering the eye and is dependent on the
contraction of the pupillary muscles, the sphincter and dilator pupillae. The
average pupil size is between 2.5 to 4 mm in diameter during daylight and can
increase up to 8 mm in darkness (Forrester 2002).

The crystalline lens is biconvex with a diameter of 10 mm and an
unaccommodated refractive power of ~20 D (Liou & Brennan 1997). The lens
consists of three layers: innermost are the lens fibres, which can be divided
into cortical and nuclear fibres; the lens epithelium constitutes the second
layer, which is surrounded by the outermost lens capsule. Like the cornea, the
lens has an aspheric form and flattens towards the periphery. The lens has also
a gradient refractive index, varying from approximately 1.38 in the centre to
1.42 in the periphery (Liou & Brennan 1997). The elastic lens capsule is
attached to the ciliary body by the zonular fibres. The lens is in a relaxed state
when the zonular fibres and the lens capsule are stretched following the
relaxation of the ciliary muscle. When the ciliary muscle contracts, the zonular
fibres slacken and the lens capsule compresses the lens to a more convex,
accommodated state. The range of accommodation decreases with age. The
posterior chamber is the space between the lens and the vitreous body that is
filled with aqueous humour. The vitreous body consists of a colourless
transparent gel composed mainly of water and loose network of collagen fibres. Together, all the optical structures transmit light in the wavelength of 390 nm to 1400 nm. Nevertheless, wavelengths above 780 nm cannot be detected by the retina.

### 2.2 Refractive Errors

Emmetropia is defined as the ideal optical condition where parallel rays from a distance object come to sharp focus on the retina in a relaxed eye. As the eye grows, it must maintain a coordinated relationship between the optical structures such that the focal point of the optics falls on the retina (Sorsby & Leary 1969). This process is known as emmetropization and failure to emmetropize leads to ametropia (refractive errors), which results in myopia or hyperopia. Myopia occurs when the image falls in front of the retina and hyperopia occurs when the image falls behind the retina. Astigmatism occurs when the power of the eye is different in two perpendicular meridians. Refractive errors are the main cause of degraded retinal image quality leading to reduced central vision. Fortunately, central refractive errors can be easily corrected by appropriate spherical or cylindrical spectacle lenses.

Even in a centrally emmetropic eye, there are considerable refractive errors away from the optical axis. Off-axis astigmatism is always present to some degrees in the periphery (Atchison & Smith 2000; Gustafsson et al. 2001) whereas relative myopia or hyperopia is present only when there is a mismatch between the optical image shell and the retina (Atchison et al. 2006; Rempt et al. 1971). In healthy eyes, off-axis refractive errors are not given much importance due to the low resolution of the peripheral retina. Despite this, recent findings show that off-axis refractive errors may influence the emmetropization process, particularly regarding the progression of myopia (Smith III et al. 2009). Furthermore, correction of off-axis refractive errors appears to improve vision in CFL subjects (Gustafsson & Unsbo 2003; Lundström et al. 2007a). The refractive errors are also known as second-order or lower-order aberrations. In addition to refractive errors, there are also higher-order aberrations in the eye; these are discussed briefly in the following section.

### 2.3 Aberrations

An aberration is defined as the failure of light rays from a point source to form a perfect image after traversing an optical system. Aberrations are generally classified into monochromatic aberrations and chromatic aberrations. As the
name suggests, chromatic aberrations are present when using more than one wavelength of light whereas monochromatic aberrations are present even with a single wavelength of light. Chromatic aberrations occur due to dispersion, i.e. variation of the eye’s refractive index with the wavelength. The total refractive index of the eye is about 1.3404 for blue light (410 nm) and 1.3302 for red light (700 nm); this change in refractive index means that the eye is approximately 1.5 D more myopic in blue light than in red light (Thibos et al. 1992). The aberrations discussed in this thesis are, however, limited to monochromatic aberrations unless otherwise specified.

2.3.1 Representation of Monochromatic Aberrations

When discussing aberrations it is useful to understand the concept of wavefronts and wavefront aberrations. A wavefront is a surface perpendicular to the light rays with a uniform phase. Parallel light originating from a distant object has a plane wavefront. On the other hand, light emerging from or converging to a point will have a spherical wavefront with the centre of curvature at that point.

The wavefront aberration is the departure of the real wavefront from the ideal spherical or flat wavefront measured at the exit pupil of the optical system. The wavefront aberration of an optical system is often quantified using polynomial functions. The standard method for representing ocular aberrations is by use of Zernike polynomials, which describe the shape of the wavefront (American National Standards Institute. 2010). The Zernike polynomials, $Z_n^m$, constitute a complete, orthogonal set of functions, defined over a unit circle. The Zernike polynomial expansion of a wavefront aberration can be written as

$$W(\rho, \theta) = \sum_{n=\theta}^{k} \sum_{m=-n}^{n} c_{n}^{m} Z_{n}^{m}(\rho, \theta)$$

where $W(\rho, \theta)$ is a polar representation of the wavefront aberration, $Z_n^m$ a particular Zernike polynomial, and $c_{n}^{m}$, the coefficient of that particular Zernike polynomial. $\rho$ is the normalised distance from the centre of the pupil and ranges from zero to one. $\theta$ is the meridian measured in radians, which ranges from zero to $2\pi$. $k$ is the maximum radial order of the polynomial expansion. The Zernike polynomials are defined as

$$Z_n^m(\rho, \theta) = \begin{cases} N_n^m R_n^m(\rho) \cos m\theta, & \text{for } m \geq 0 \\ -N_n^m R_n^m(\rho) \sin m\theta, & \text{for } m < 0 \end{cases}$$
where $R_n^m$ is a radial polynomial and $N_n^m$ is a normalisation factor. The radial function $R_n^m$ is given by

$$R_n^m(\rho) = \sum_{s=0}^{\left\lfloor \frac{n-|m|}{2} \right\rfloor} \frac{(-1)^s(n-s)!}{s!(0.5(n+|m|)-s)!(0.5(n-|m|)-s)!} \rho^{n-2s}$$

(2.3)

where the index $n$ is the order of the radial polynomial and the index $m$ describes the meridional frequency of the sinusoidal component of the Zernike polynomial. The normalisation factor $N_n^m$ is defined as

$$N_n^m = \sqrt{n+1} \text{ for } m = 0, \quad N_n^m = \sqrt{2n+1} \text{ for } m \neq 0$$

(2.4)

The Zernike coefficients represent the contribution of individual Zernike terms to the total wavefront error given in micrometers ($\mu$m). Figure 4 shows the first twenty-one of the Zernike polynomials (up to fifth-order). The zeroth and first radial order are usually ignored because they do not have any impact on image quality. The second-order terms (lower-order aberrations) correspond to the well-known refractive errors, myopia, hyperopia and astigmatism. The third- and fourth-order terms, coma ($C_{-1}^3$, $C_1^3$) and spherical aberration ($C_4^0$) are similar to aberrations found in ordinary lens systems (Seidel aberrations). However, there are many other terms, which do not have Seidel counterparts because the eye is not rotationally symmetric.

Figure 4: The representation of Zernike polynomials up to fifth-order.
The total amount of aberrations of the eye is often described using the RMS (root-mean-square) value, which is essentially the square root of the sum of squared individual Zernike coefficients in micrometers and is defined as

\[ \text{RMS} = \sqrt{\sum (c_n^m)^2} \]  \hspace{1cm} (2.5)

When the second-order terms are included, then the resulting RMS is called ‘total RMS’; when these are excluded, leaving only higher-order terms (third-order and above), then it is called ‘HO RMS’.

One advantage of using Zernike polynomials are their orthogonality, i.e. the lower-order coefficients are not affected by the inclusion or exclusion of higher-order terms. Moreover, Zernike polynomials are normalized over the pupil area and individual terms correspond to the known Seidel aberrations. Even though the polynomials are normalized over the entire pupil, the coefficients remain highly dependent on the pupil radius, which should always be stated together with the Zernike coefficients. This is important when Zernike coefficients are used to compare wavefront aberrations of different eyes. One more thing to remember when comparing aberrations from different studies is that pupil size must be identical because the coefficients vary strongly with pupil size.

Another advantage of using Zernike polynomials is that they can be used to obtain the traditional refractive errors. The \( C_2^2 \) term corresponds to oblique astigmatism \( J_{45} \) with axes at 45° and 135°, \( C_0^0 \) (defocus) corresponds to spherical equivalent \( M \) and \( C_2^2 \) corresponds to with/against the rule astigmatism \( J_{180} \). The relationship between second-order Zernike coefficients and sphero-cylindrical components (\( M, J_{180}, \text{and } J_{45} \)) are given by the following equations. (Thibos et al. 2004)

\[
J_{45} = \frac{-2\sqrt{6}}{r^2} c_2^2, \quad M = \frac{-4\sqrt{3}}{r^2} c_0^0, \quad J_{180} = \frac{-2\sqrt{6}}{r^2} c_2^2 \]  \hspace{1cm} (2.6)

where \( r \) is pupil radius. If the Zernike coefficients are given in micrometers and \( r \) is in millimetres then the corresponding refractive errors will be in dioptres. The following equation can be used to convert the components \( J_{45}, M, \) and \( J_{180} \) to the conventional clinical negative-cylinder form (Thibos et al. 1997).

\[
S = M + \sqrt{J_{180}^2 + J_{45}^2}, \quad C = -2\sqrt{J_{180}^2 + J_{45}^2}, \quad \theta = \frac{1}{2} \arctan \left( \frac{J_{45}}{J_{180}} \right) \]  \hspace{1cm} (2.7)

where \( S \) represents the sphere, \( C \) represents the cylinder and \( \theta \) represents the cylindrical axis.
2.3.2 Measurement of Ocular Aberrations

The first basic principle for measurement of spherical refraction of the eye was discovered by Scheiner in 1619. Light from a distant object reduces to two small bundles after passing through the two pinholes of a Scheiner disc placed in front of the eye. A single focus image will be formed if the eye is emmetropic whereas double images will be seen in case of myopia or hyperopia. The refractive error can be determined by adjusting the position of the object until only one image is seen (Scheiner 1619). Most modern aberrometers and refractometers are based on Scheiner’s disc principle (Thibos et al. 2003).

Into-the-eye aberrometry works by having an image formed on the retina and re-imaged out of the eye for measuring aberrations. Laser ray tracing and Tscherning aberrometer are based on the into-the-eye principle. On the other hand, an aberrometer that projects a narrow beam of light into the eye and analyses the wavefront emerging from the eye is known as out-of-the-eye system. In an optically perfect eye, the wavefront emerging from the eye is plane, whereas in an aberrated eye the emerging wavefront is distorted. The Hartmann-Shack wavefront sensor works on the out-of-the-eye principle. Furthermore, aberrometers measure aberration either sequentially or simultaneously (Atchison 2005). Sequential aberrometers (such as laser ray tracing) measure aberrations in one location at a time and then move on to another pupil location. Simultaneous aberrometers (such as the Hartmann-Shack wavefront sensor) measure aberrations at multiple pupil locations at the same time.

The first subjective simultaneous aberrometer was an aberroscope developed by Tscherning (Tscherning 1894). This was later modified into the Cross-cylinder aberroscope by Howland and Howland in 1977. They were the first to report the aberrations up to the fourth-order for 55 eyes using their aberroscope (Howland & Howland 1977). Since subjective measurements of aberrations are difficult and prolonged, objective aberrometers were developed. Currently, most commercially available objective aberrometers are based on the Hartmann-Shack wavefront sensor, described in section 3.7.

2.3.3 Magnitude of On-axis Ocular Aberrations

There have been numerous studies describing the magnitude of aberrations in normal eyes (Castejón-Mochón et al. 2002; Porter et al. 2001; Thibos et al. 2002; Wang & Koch 2003). The general conclusion is that aberrations of the eye exhibit considerable variability in the population and that lower-order aberrations (refractive errors) dominate over higher-order aberrations. The
higher-order aberrations are a relatively small component, comprising about 10% of the eye’s total aberrations. The most important higher-order aberrations in the human eyes are vertical coma ($C^{-3}_3$), horizontal coma ($C^3_3$) and spherical aberration ($C^4_0$) as they are present in higher amounts than the other higher-order terms (Porter et al. 2001). On-axis higher-order aberrations increase with age and show mirror symmetry between eyes (Charman 2005).

The influence of higher-order aberrations on the retinal image quality is related to the size of the pupil. When the pupil is large, peripheral light rays are refracted at larger angles than paraxial rays resulting in increased aberrations. Consequently, the higher-order aberrations are smaller in photopic than in scotopic conditions. Generally, after lower-order aberration correction (sphero-cylindrical correction) most eyes are influenced by diffraction rather than aberrations at pupil diameters of less than 2 mm (Howland & Howland 1977; Walsh et al. 1984). The optimum image quality of the eye can be found for pupil sizes between 2 to 3 mm (Atchison & Smith 2000; Campbell & Green 1965). At larger pupil diameters, the influence of diffraction on image quality decreases and that of higher-order aberrations increases. Figure 5 shows the effect of pupil diameter on visual acuity.

Figure 5: Relationship between the visual acuity or resolving power of the eye (solid line) and the pupil size. The theoretical diffraction-limit is shown as a dashed line. Adapted from Rabbetts (1998).
As with refractive errors, the higher-order aberrations increase with off-axis angle in the periphery. A detailed description of aberrations in the periphery is given at the end of chapter 3.

2.4 Visual Functions

Human vision is very diverse and can perceive objects of different sizes, shapes, contrasts and colours. The most common measurement of visual function is visual acuity. Visual acuity is specified in terms of the visual angle subtended by the finest spatial detail that can be discerned by the subject. There are three types of visual acuity measurement: detection acuity, resolution acuity and the identification acuity. Detection acuity refers to the smallest stimulus object or pattern that can be distinguished from a uniform field (minimum angle of detection). The minimum angle that a black spot needs to subtend in order to be detected is about 15 seconds of arc. Resolution acuity is defined as the smallest spatial separation between two points or lines that can be discriminated. Identification acuity is the smallest spatial detail that can be resolved in order to recognize objects (letters, numbers). Both resolution acuity and identification acuity are denoted in terms of the Minimum Angle of Resolution (MAR). Visual acuity is commonly measured with high-contrast letter acuity charts and is inversely related to MAR. This gives the formula for visual acuity as

\[ V = \frac{1}{A} \quad (2.8) \]

where \( V \) is visual acuity, \( A \) is the line width of the strokes of the letter expressed in minutes of arc. When expressed in logMAR

\[ \log \text{MAR} = \log_{10}(A) = \log_{10} \left( \frac{1}{V} \right) \quad (2.9) \]

Visual acuity is commonly denoted with Snellen fractions or in decimal notation. Decimal acuity of 1.0 corresponds to logMAR acuity of 0.0.

As discussed earlier, visual acuity is best in the fovea and declines towards the periphery. This decline is due to the imperfection of the optical image and insensitivity of the peripheral retina (Anderson et al. 1991). The first study to determine grating visual acuity outside the fovea was conducted by Wertheim (1894). He showed that grating resolution decreased rapidly within 5° from the centre of the fovea and then continued to decrease at a slower rate out to the far periphery. Since then several studies have evaluated peripheral acuity using variety of test objects under different lighting levels (Kerr 1971; Low 1943; Low 1946; Low 1951; Mandelbaum & Sloan 1947; Randall et al.
The decline in peripheral visual acuity is also dependent on the task performed (for e.g., detection or resolution) and the location in the visual field. In foveal vision, both resolution acuity and detection acuity are the same as it is limited by the optics of the eye. In the periphery, detection acuity is however, far better than resolution acuity. While resolution is limited by retinal sampling, detection can still occur through the aliasing phenomenon. Figure 6 illustrates aliasing in terms of the contrast sensitivity function (CSF) for both detection and resolution. The CSF is a plot of contrast sensitivity (the inverse of the minimum contrast to detect/resolve a pattern) against different spatial frequencies. Aliasing means that spatial frequencies above the resolution limit are interpreted as lower, distorted frequencies. The distorted frequencies contain insufficient information to allow the object to be resolved, but show that an object is present in the visual system (Artal et al. 1995; Thibos et al. 1987a; Thibos et al. 1987b).

Apart from peripheral detection and resolution, there are other important visual functions such as colour discrimination and motion perception in the periphery, which are not included in, and are beyond the scope of this thesis.

Figure 6: Contrast sensitivity functions for detection and resolution tasks for the foveal and peripheral locations. Aliasing occurs between the two peripheral vision curves. Adapted from Atchison & Smith (2000).
2.5 Vision in the Periphery

Peripheral vision is important because it allows us to gather information regarding our surroundings; it is used to detect objects outside the very centre of gaze. Therefore, the main function of peripheral vision is to detect an object of interest in the peripheral retina (Atchison 1987; Fankhauser & Enoch 1962; Wang et al. 1996). Once an object is detected, then involuntary eye movements (saccades and fixational movements) place the image of the object in the fovea to allow for greater resolution and easier identification. Besides detection, peripheral vision is important for many visual tasks such as motion perception (Johnson & Leibowitz 1974), mobility and postural balance (Black & Wood 2005), and driving (Wood et al. 2009). The extent of peripheral vision (visual field) when the eye is stationary can be evaluated using perimetry. The normal visual field extends approximately 50° superiorly, 60° nasally, 70° inferiorly and 90° temporally. Mobility and orientation are heavily dependent on peripheral vision and the loss of peripheral visual field in diseases such as glaucoma and retinitis pigmentosa leads ultimately to tunnel vision, which can considerably affect quality of life (Goldberg et al. 2009; Hahm et al. 2008). In contrast, people with CFL due to macular degeneration have to rely on peripheral vision for all their visual tasks.

The resolution capability is the main limitation to peripheral vision; under normal circumstances, this limit is overcome by eye movements. Resolution acuity is fundamentally limited by retinal sampling in the periphery (Thibos et al. 1996). The retinal factors that limit peripheral resolution are, cone density (Curcio et al. 1990; Østerberg 1935), ganglion cell density (Perry et al. 1984) and the spatial frequency transfer characteristics of ganglion cells (Crook et al. 1988); all these factors decrease with increasing eccentricity. Furthermore, optical quality also decreases with increasing retinal eccentricity. The optical limitations of peripheral resolution are refractive errors, and aberrations such as oblique astigmatism, and coma, both of which tend to increase with increasing eccentricity.

In CFL subjects, it has been shown that correction of peripheral refractive errors improves peripheral resolution as well as detection acuity (Gustafsson & Unsbo 2003; Lundström et al. 2007a). In healthy eyes, detection acuity is influenced by the peripheral optics whereas high contrast resolution is limited by retinal sampling (Anderson 1996; Lundström et al. 2007a; Thibos et al. 1996; Wang et al. 1997).
3 PERIPHERAL REFRACTION TECHNIQUES

In the early 19th century, Thomas Young (1801) indicated that visual performance decreased as visual field angle increased. He was the first to recognize peripheral astigmatism in the human eye. Since then several studies have measured peripheral refractive errors using a variety of techniques. Ames and Proctor (1921) in their paper gave a summary of methods used to measure peripheral refractive errors in human eyes between 1801 and 1909. Unfortunately, the methods described were cumbersome and their results not expressed in a form that were practical to use. Ferree et al. (1931) were the first to measure peripheral refraction using an objective technique and recognize different patterns of peripheral refraction.

From 1931 to the present, there have been numerous studies, which have used various techniques to measure refraction and aberrations in the periphery. Peripheral refractive errors have usually been measured in steps of 5° or 10°, with techniques such as subjective refraction, retinoscopy, manual optometers, double-pass techniques, and objective instruments, such as autorefractors, photorefractometers, and aberrometers (Fedtke et al. 2009). The subjects turned either the eye or their head during peripheral measurements. The measurements were reported in “visual field angle” in most instances but some authors report their findings in relation to the angular distance at the retinal plane. The usage of peripheral or off-axis or eccentric angles in the following sections are interchangeable. This chapter continues with a literature review of the techniques available to measure peripheral errors. In the latter section of this chapter, the technique that has been used in this thesis is summarised.
3.1 Subjective Peripheral Refraction

Subjective refraction is a procedure in which the patient is asked to report on a lens combination that provides clearest vision. It is the gold standard for determining the final refractive error correction in central vision. In general, peripheral refractive errors can be determined subjectively by introducing trial lenses at a given eccentricity. A “bracketing” technique can be used to estimate both the spherical and cylindrical errors in the periphery. The bracketing technique for spherical errors involve systematically changing the power of the trial lenses in larger steps (for e.g., ±6 D) until the midpoint of the bracketing range is found. Once the range is found, it then involves adjusting the step size (in for e.g., ±1.00 or ±0.50 D steps) to fine-tune the refraction based on subject response (Bailey 1991). Similarly, for cylindrical errors Jackson cross cylinders with higher powers (±1.00 D) can be used to determine both the axis and power of the cylinder. Another alternative is to rotate a cylinder of substantial power (for e.g., −5 D) through 180° to find the preferred axis location, after which the bracketing technique can be employed to determine the cylindrical power (Bailey 1991). The cylindrical power prescribed in an optometric practice is always in a negative cylinder format based on the Tabo scheme.

Ronchi (1971) was the first to correct peripheral astigmatism in order to determine absolute luminance thresholds with increasing retinal eccentricity. She found that luminance thresholds were better after correction of peripheral astigmatism. Millodot and Lamont (1974) compared subjective peripheral refraction with two objective refraction techniques namely retinoscopy and Zeiss coincidence refractometry in three subjects out to 60° in the temporal visual field. The results obtained by these three techniques were qualitatively in good agreement. However, they also noted that it is difficult to assess refractive errors using retinoscopy beyond 50° eccentricity and that the refractometer overestimated peripheral refractive errors, possibly due to poor accommodation control. Wang et al. (1996) also compared subjective peripheral refraction with objective techniques, namely retinoscopy and with a Canon Autoref R-1 refractometer in four subjects up to an eccentricity of 40° in the nasal visual field. They concluded that objective retinoscopy and auto-refractometry agreed with subjective measurements. Lundström et al. (2005a) compared subjective peripheral refraction with three other techniques, namely retinoscopy, photorefraction and with Hartmann-Shack (HS) wavefront aberrometry. The findings showed that there was a larger spread in results of subjective refraction compared with other three techniques. They concluded that HS sensor is a useful objective tool to assess eccentric refraction.
It is difficult to compare results between the above studies because of the difference in the peripheral visual targets used in each study. Millodot and Lamont (1974) used a Landolt C for the subjective refraction whereas Wang et al. (1996) and Lundstom et al. (2005a) used a grating detection task. Even though peripheral subjective refraction can provide refractive error correction, it is a difficult and exhausting procedure, especially if multiple eccentricities need to be tested. The difficulties are mainly associated with a decrease in the optical quality, poor image quality, as well as neural factors that are stimuli dependent. Therefore, it would be advisable to determine the peripheral refractive error using an objective technique and then optimise it further by performing a peripheral subjective refraction.

3.2 Retinoscopy

Retinoscopy is an objective technique used to determine refractive errors of the eye. In a clinical setting, an examiner uses a retinoscope to direct a streak of light into the subject’s eye and observes the reflex off the subject’s retina. The examiner moves the streak of light across the subject’s pupil and observes the relative movement of the reflex. The examiner then uses trial lenses to “neutralize” the reflex. It is considered as an objective technique because no input is needed from the subject, the examiner needs however to make a subjective decision in determining the end-point by means of neutralizing the retinoscopic reflex.

Numerous studies have used off-axis retinoscopy either to measure refractive errors in the periphery (Anderson & Thibos 1999; Jackson et al. 2004; Johnson & Leibowitz 1974; Leibowitz et al. 1972; Rempt et al. 1971; Rempt et al. 1976; Rovamo et al. 1982; Scialfa et al. 1989) or to compare the findings with other techniques (Lundstrom et al. 2005a; Millodot & Lamont 1974; Wang et al. 1996). Rempt et al. (1971) were the first to measure refractive errors in the periphery using streak retinoscopy, in both eyes of 442 subjects. They commented that the objective technique (Zeiss parallax refractometry) used by Ferree et al. (1931) was accurate but too cumbersome to collect a large number of measurements. They developed a “Skiagram” based on their result for categorizing different peripheral refractive errors along the horizontal meridian up to 60°. Furthermore, they reported that peripheral retinoscopy is complicated by the “double-sliding door reflex”. Millodot and Lamont (1974) observed that it was difficult to obtain reliable measurements beyond 50°. Most studies (Jackson et al. 2004; Millodot & Lamont 1974; Scialfa et al. 1989) have also encountered difficulties in performing off-axis retinoscopy at larger angles due to elliptical pupil and increased aberrations in the periphery. As a result, the retinal reflex may be
split in central and peripheral parts of the pupil, making it difficult to
determine the axis of astigmatism (Gustafsson 2004; Jackson et al. 2004;
Lundström et al. 2005a; Millodot & Lamont 1974; Scialfa et al. 1989). In
conclusion, off-axis retinoscopy can be difficult, time consuming and less
reliable than other objective techniques.

3.3 Manual Optometer

Objective optometers are a class of instruments used to determine the
refractive error of the eye; they can be either manual or automated. Manual
optometers use visible radiation and project the image of an illuminated target
on to the subject’s retina. As an examiner needs to determine refractive error
manually by adjusting the focus of the target on the subject’s retina, it is
known as manual objective optometer. Most studies have either used the Zeiss
parallax refractometer, the Hartinger coincidence optometer (Zeiss, Jena,
Germany) or the Topcon model III refractometer (based on the Hartinger
coincidence refractometer) to determine peripheral refractive error.

The Zeiss parallax refractometer has a test target that is arranged in the
form of an upright cross (broken lines) with a small dot in the centre to
transmit light. The Hartinger coincidence optometer has two sets of three
vertical bars and two sets of two horizontal bars as a test target. The examiner
observes the retinal image and aligns the test targets to be in coincidence
thereby determining the refractive error. Ferree et al. (1931) and Ferree and
Rand (1933) used a Zeiss parallax refractometer to evaluate peripheral
refractive errors up to 60° eccentricity in the horizontal visual field. Even
though they stated that this method was reasonably feasible and accurate, it
was difficult to measure refractive errors beyond 60° because the illuminated
image was too dim. Rempt et al. (1971) stated that the above technique would
be difficult and cumbersome for performing large sample studies.

Millodot and Lamont (1974) used a Zeiss Hartinger coincidence
optometer and compared the findings with subjective refraction and
retinoscopy. They found that the optometer was reliable and that the results
agreed with the other two techniques. Millodot also used the Topcon model
III refractometer in his other studies because the measurements were faster
and more reliable compared to retinoscopy and subjective refraction (Millodot
1981; Millodot 1984). Dunne and Barnes (1990) also used the Zeiss
Hartinger coincidence optometer to measure peripheral astigmatism up to 40°
in 34 young subjects. They reported that measurements for eccentricities
greater than 40° could not always be obtained and that those could be obtained
were inconsistent. Gustafsson (2001) also tried to use a Zeiss Hartinger
coincidence optometer to measure peripheral refractive error but found the intra-subject reproducibility to be poor. Since the examiner has to align the targets, similar difficulties occur as mentioned for retinoscopy. Oblique astigmatism, higher-order aberrations and elliptical pupil have a profound effect on the adjustment of targets in the periphery (Smith et al. 1988).

### 3.4 Double-Pass Technique

Since its first introduction by Flamant (1955), the double-pass technique has been used extensively in physiological optics. The technique is based on recording aerial images of a point or line source projected on the retina (first pass) which, after retinal reflection, passes (second pass) through the optical media (Campbell & Gubisch 1966; Santamaria et al. 1987). Refractive errors can be measured by placing corrective lenses in front of the eye and observing the shift in focus of the tangential and sagittal line spread image. In addition to refractive errors, the double pass technique can also be used to measure higher-order aberrations. However, the system requires further modification in order to measure paraxial asymmetric aberrations like coma and distortion, which are important aberrations in the periphery (Artal 2000).

Only few studies have used the double-pass technique to measure refraction and optical performance in the peripheral field. Jennings and Charman (1978; 1981) used a line source to assess the image quality across the horizontal meridian. They measured the line spread function (LSF) of a single subject in 5° steps up to 45° along the horizontal meridian. They reported that the optical quality in the periphery degrades much slower than the visual acuity. Navarro et al. (1993) measured monochromatic image quality in a wider field (120°) for four subjects and concluded that off-axis optical quality of the eye is much better than the findings reported by Jennings and Charman (1978; 1981). Guirao and Artal (1999) modified the double-pass technique to measure higher-order aberrations, in particular coma, in the periphery of four normal subjects. Gustafsson et al. (2001) measured off-axis astigmatism in 10° steps up to 60° in a larger group (20 eyes) of emmetropic eyes using double-pass technique. They reported that off-axis astigmatism increased with increasing eccentricity and that subjects showed large individual variations. In addition, they also observed aberrations like coma had a negative effect on the recorded image especially for older subjects. A study by Seidemann et al. (2002) used both a double-pass technique and photorefraction (PowerRefractor) to compare peripheral refractive errors in a group of myopes, emmetropes and hyperopes. One aim of their study was to compare the results of photorefraction with the double-pass technique. They found significant correlation between the two techniques in measuring peripheral refractive
error on six participants. The above studies show that double-pass technique can be used reliably to measure peripheral refractive errors but this method is mainly restricted to research labs.

### 3.5 Autorefractors

Autorefractors are a class of automated instruments, which employ electronic detectors to determine refractive errors. Conventional autorefractors measure lower-order aberrations in the form of sphere, cylinder, and axis (defocus and astigmatism) represented in dioptres. They are fast and easy to use and do not require subjective judgements from the examiner or subject. They have been used successfully for on-axis refractive error measurements for more than four decades. Most of the instruments are “closed view” type i.e. they need fogging mechanisms to avoid instrument myopia. Moreover, it is difficult to evaluate peripheral refractive errors with a closed view refractometer.

In order to avoid instrument myopia, Canon introduced in 1981, the first “open-view” refractometer called the Canon Autoref R-1. Shin-Nippon introduced its open view refractometer, the Shin-Nippon SRW-5000 (Shin-Nippon, Rexxam Industrial Co., Ltd, Japan) nearly 20 years after the introduction of the Canon Autoref R-1. Both instruments have shown to be reliable and accurate in measuring on-axis refractive errors and have a similar mode of operation (Mallen et al. 2001; McBrien & Millodot 1985). The Shin-Nippon uses a near infrared ring target (850 nm) which is projected on to the retina and the light reflected containing the refractive error information travels the same path back towards a focusing lens on a motorized track. The focusing lens move back and forth until a sharp image is captured on an image detector. It requires a minimum pupil diameter of 2.9 mm and the images are analyzed in numerous meridians for calculating astigmatism. Atchison et al. (2003) compared peripheral refraction obtained by the Canon Autoref R-1 with the Shin-Nippon SRW 5000 and a Hartmann-Shack wavefront sensor. They concluded that the Canon Autoref R-1 was the least comparable instrument having the poorest agreement among all three instruments.

Dunne et al. (1993) were the first to use the Canon Autoref R-1 refractometer along with Hartinger coincidence optometer to measure peripheral astigmatism. They evaluated the association between peripheral astigmatic asymmetry and angle alpha; which was found to be poor. Mutti et al. (2000) used the Canon Autoref R-1 to measure peripheral refractive errors in a group of 822 children along with ocular biometry in order to determine ocular shape. Since the turn of the millennium, several studies have used the Shin-Nippon SRW 5000 autorefractometer for measuring peripheral
refractive error (Atchison 2003; Atchison et al. 2005; Atchison et al. 2006; Calver et al. 2007; Charman et al. 2006; Charman & Jennings 2006; Ma et al. 2005). All the studies that used Shin-Nippon SRW 5000 evaluated peripheral refraction by having the subjects turn the eye along the horizontal meridian in steps of 5° up to between 30° to 35°. A study by Atchison et al. (2006) also evaluated peripheral refraction along the vertical meridian in myopes using this instrument. Radhakrishnan and Charman (2008) also evaluated the effect of the head turning as opposed to the eye turning on peripheral refraction using this instrument. They found no significant difference in peripheral refractive errors between the two methods.

The successor to the Shin-Nippon SRW 5000 is the Shin-Nippon NVision K5001, which uses a better target (three arcs of infrared light) and requires a minimum pupil diameter of 2.3 mm to measure refraction. It has been shown to give accurate on-axis refraction as compared with subjective refraction (Davies et al. 2003). Berntsen et al. (2008) compared peripheral refraction obtained by the Shin-Nippon NVision K5001 with the Complete Ophthalmic Analysis System (COAS) aberrometer. They concluded that there were no significant differences between Shin-Nippon NVision K5001 and COAS in measuring peripheral refractive error. They reported that the COAS is more valuable than the Shin-Nippon NVision K5001 because it could be used simultaneously to collect both peripheral refraction and aberration data. In general, commercially available open view autorefractometers are reliable and fast in obtaining peripheral refractive errors. However, they cannot measure higher-order aberrations that play a role in peripheral image degradation.

3.6 Photorefractors

In photorefraction, as the name suggests, the eye is illuminated by a point light source and the retinal reflex in the pupil plane is photographed. This method has not been used clinically prior to the availability of the PowerRefractor instrument (previously manufactured by Multichannel Systems now by PlusOptix, Germany).

The PowerRefractor measures refractive errors by means of photorefraction and has been commercially available for more than 10 years. Six infrared LEDs segments are mounted in a circle around a camera objective, which is placed 1 m from the eye. The video camera captures the light reflected from the retina in real time; the brightness characteristics at the pupil are directly related to the extent of the refractive error. The instrument’s software algorithm analyses the illumination of the pupil by comparing it to the typical
illumination and subsequently calculates the refractive error. The advantage of the PowerRefractor over other autorefractors is its ability to obtain faster measurements from both eyes simultaneously in an open field of view. The range of the instrument is between $-6$ D to $+4$ D and in addition, it gives information about the pupil size, interpupillary distance, and the alignment of the eyes (Choi et al. 2000). The PowerRefractor is shown to be useful for central refractive error measurements in infants and children. This technique has been modified in a few studies to enable measurement of off-axis refractive errors.

Seidemann et al. (2002) were one of the first to use the PowerRefractor to investigate the relationship between foveal and peripheral refractive errors. They investigated peripheral refractive errors along the horizontal visual field in a group of young emmetropic, myopic, and hyperopic subjects. They found that the instrument was fast and convenient to measure peripheral refractive errors up to $25^\circ$ eccentricity. They also compared peripheral refraction up to $25^\circ$ eccentricity obtained by a double-pass technique with the PowerRefractor for six subjects. They found that both techniques agreed favourably in measuring peripheral refractive errors. On the contrary, Lundström et al. (2005a), comparing four different techniques found that the PowerRefractor could not measure at large eccentric angles and had difficulties when measuring high myopia. They concluded that a Hartmann-Shack sensor gave more reliable results than PowerRefractor measurements, retinoscopy, and subjective refraction.

Gustafsson et al. (2002) and Gustafsson and Unsbo (2003) were the first to use a PowerRefractor at the PRL of eight CFL subjects to measure refractive errors. The CFL subjects oriented their PRL with the help of five concentric rings (separated by 5° up to 25°) surrounding the PowerRefractor camera. The aim of their study was to determine and correct refractive errors at the subject’s PRL. They found the PowerRefractor to be useful and repeatable for obtaining peripheral refractive errors in CFL subjects. They also commented that large amounts of peripheral coma could make the PowerRefractor readings less reliable. In their later studies, they employed a Hartmann-Shack sensor as it as an advantage of giving information about both lower-order and higher-order aberrations simultaneously. Even though the PowerRefractor can obtain reliable results in the periphery, there are certain limitations with large eccentric angles and elliptical pupils.

All the above techniques with their own pros and cons can be employed to measure peripheral refractive errors. In general, most studies have reported high amounts of peripheral refractive errors even when the eye is centrally emmetropic. An eye with a small central astigmatism can exhibit several dioptres of astigmatism by $40^\circ$ eccentricity. Moreover, peripheral refractive
errors show large inter-individual variation and asymmetry about fixation, with higher astigmatism in the nasal field than temporal field (Atchison et al. 2006; Dunne et al. 1993; Gustafsson et al. 2001; Millodot 1981; Mutti et al. 2000; Rempt et al. 1971; Seidemann et al. 2002). However, none of the above techniques can be employed without prior modification to measure peripheral higher-order aberrations. In order to measure both refractive errors and higher-order aberrations simultaneously the use of an aberrometer is warranted.

3.7 Aberrometers

3.7.1 The Hartmann-Shack Wavefront Sensor

The Hartmann-Shack principle can be traced back to the early 20th century, when Hartmann used a screen to determine the aberrations of a large telescope (Hartmann 1900). In the so-called Hartmann test, a screen with an array of small perforations is placed at the entrance pupil of an optical system. This isolates the light into small ray bundles, making it possible to study the variation in refraction across the system. In 1971, the Hartmann test was modified by Shack and Platt (2001) in which they replaced the perforated screen with an array of small lenses (lenslets) – the Hartmann-Shack wavefront sensor. This technique was originally developed for astronomy to improve the resulting image quality of stars and satellites and Liang et al. (1994) adapted it to measure the aberrations of the human eye.

The essential components of a Hartmann-Shack wavefront sensor are a monochromatic light source, a lenslet array, and a light detector (see Fig. 7).

Figure 7: The principle of the Hartmann-Shack sensor. For the sake of clarity, the aberrations are exaggerated and the telescope that images the wavefront from the exit pupil to the lenslet array is omitted. Courtesy of Lundström (2007)
The light source is usually a near infrared laser or diode, because a narrow beam of parallel light is needed to project a spot on the retina. Some part of the light is reflected back from the retina as if coming from a point source on the retina. The wavefront exiting the eye then falls on the lenslet array. Each lenslet focuses its part of the wavefront to a spot on the detector (usually a charge-coupled device). The position of the spot depends on the local slope of the wavefront and thus information can be derived about the aberrations of the eye. The wavefront from a perfect eye will be a flat wavefront, which will produce a regular pattern of spots on the detector. An aberrated wavefront will produce a distorted pattern on the detector due to different wavefront slopes for different lenslets. Mathematically integrating the slope information enables construction of a wavefront aberration (Atchison 2005; Thibos 2000).

The aberrations measured from the emerging light are not identical to those present in the light that is incident on the retina. The incoming and the outgoing wavefronts follow different paths in the optical system and therefore the outgoing wavefront may not theoretically represent the image quality of the eye. Nonetheless, Moreno-Barriuso and Navarro (2000) investigated this effect of difference in path on an artificial eye, and found a close match between wavefront aberrations for the incoming and outgoing wavefront. The point spread function (PSF) of the artificial eye and the stimulated PSF from the outgoing wavefront aberrations of the artificial eye compared well. Another difficulty is that the exact longitudinal location of the light reflected from the retinal plane is not known. It is usually assumed to be at the plane of the photoreceptor layer and a number of studies have shown that this is the case for visible and near infrared light (Llorente et al. 2003; Lopez-Gil & Artal 1997; Williams et al. 1994). Infrared light with a longer wavelength is reflected from deeper layers of the retina than visible light, resulting in a myopic shift. This myopic shift is however, partly compensated by the chromatic aberration of the eye. Using infrared radiation for aberration measurement is better than visible light because it does not influence pupil size or stimulate accommodation. It also gives a higher retinal reflectance than visible light. As infrared light is used, a correction of the Zernike coefficients must be made, so that results are representative of the image quality in the visible spectrum. Most Zernike coefficients, other than defocus, are only marginally affected by the difference in infrared and visible wavelengths. This change can be calculated by using the formula below (Salmon et al. 2003)

\[ \epsilon_{n_\lambda}^{m} = \epsilon_{n_\lambda}^{m} \left( \frac{n_{\lambda} - 1}{n_{\lambda} - 1} \right) \]  (3.1)

where the refractive index value for infrared \((n_\lambda)\) and visible light \((n_\lambda)\) can in turn be obtained using the dispersion formula below (Salmon et al. 2003; Thibos et al. 1992).
The Hartmann-Shack based aberrometers are popular for measuring on-axis ocular aberrations as they are faster, more sensitive and are less affected by light scattering compared to most other aberrometers (Dai 2008). They are reliable and accurate for the measurement of lower- and higher-order aberrations for both clinical and research purposes (Cheng et al. 2003; Cheng et al. 2004; Thibos & Hong 1999).

### 3.7.2 Peripheral Ocular Aberrations

While most previous studies have concentrated on on-axis ocular aberrations, investigations of peripheral optical errors have increased dramatically in recent years. During the last ten years, many studies have measured peripheral ocular aberrations using Hartmann-Shack sensors.

Navarro et al. (1998) were the first to measure off-axis aberrations in detail and quantify them in terms of Zernike polynomials. They used a laser ray tracing technique and measured aberrations in four observers at four different positions in the nasal visual field. Atchison and Scott (2002) were the first to report off-axis aberrations with a laboratory-built Hartmann-Shack aberrometer along the horizontal visual field up to an eccentricity of 40°. Both studies concluded that the third-order aberrations increased with eccentricity. In addition, Atchison and Scott reported substantial asymmetry in aberrations between the temporal and nasal visual fields. Lundström et al. (2005a; 2005b) and Mathur et al. (2008) were able to measure higher-order aberrations using the Hartmann-Shack principle at different locations in the visual field. Mathur and co-workers modified a commercial COAS-HD aberrometer to measure peripheral aberrations in various groups of healthy subjects (Mathur et al. 2009; Mathur et al. 2010). In contrast, Lundström and co-workers used a lab-based wavefront sensor to measure peripheral aberrations in CFL subjects as well as normal subjects (Lundström et al. 2007a; Lundström et al. 2009). More recently, new scanning Hartmann-Shack sensors have been developed, which can measure peripheral aberrations in higher angular resolution and acquire data more rapidly along the horizontal visual field (Jaeken et al. 2011). The common conclusion of all the studies is that higher-order aberrations increase with increasing eccentricity.

One particular problem faced by the above studies was the perceived elliptical shape of the pupil in large eccentricities. Since Zernike polynomials, are defined over a unit circle, allowances have to be made for the correct estimation of coefficients for elliptical pupils. There are three ways in which to
quantify the aberrations with Zernike coefficients for elliptical pupils: across a small circular aperture within the elliptical pupil; over a large circular aperture encircling the elliptical pupil; or by stretching the elliptical pupil into a circle. Lundström et al. (2009) compared all three representations and concluded all the three showed similar trends in determining the Zernike coefficients. More recently, Charman et al. (2012) suggested that all three representations can be employed within 30° eccentricity. In this thesis, we have opted for the small circular aperture within the elliptical pupil for determining Zernike coefficients. The advantage of this method is that the coefficients can be treated in the same manner as for foveal measurements. An additional advantage is that they can be directly used to compare the coefficients between different viewing angles (Lundström et al. 2009).

3.7.3 Aberrometer used in this Work

Peripheral ocular aberrations have been mostly measured either with a laboratory built aberrometer or by modifying a commercially available aberrometer. There were several commercial aberrometers available that are based on Hartmann-Shack principle to measure on-axis aberrations but none are suited for measuring off-axis aberrations without modification. With the introduction of the COAS High Definition Vision Research open-view aberrometer (AMO Wavefront Sciences, Albuquerque, NM) it was possible to measure off-axis aberrations without any further modifications to the instrument (see Fig. 8).

![Figure 8: The COAS-HD VR aberrometer with its visually transparent hot mirror/beamsplitter and the vision research open-view optical relay system in combination with COAS-HD.](image)

We used this aberrometer to measure off-axis refraction and aberrations in Papers I, II, III and IV. We measured monochromatic aberrations in 10°
steps in both the horizontal (±40°) and inferior visual field (−20°) using the COAS-HD VR. The aberrometer integrates a COAS-HD with a Vision Research (VR) open-view optical relay. The light source used is a superluminescent diode, which emits 840 nm infrared light. The wavefront sensor uses an 83 × 62 array of lenslets each being 108 μm in diameter. The pupil magnification factor is 0.68, and this samples the exiting wavefront in steps of 158 μm at the pupil plane. There are approximately 766 sample points for a pupil diameter of 5 mm. The aberrometer provides a map of the wavefront error, and this map is subjected to Zernike analysis. The aberrometer can calculate aberration coefficients up to 10th order. The VR consists of a large 10 × 20 cm hot mirror, which transmits 95% of visible light but reflects 95% of infrared light from the superluminescent diode. The optical relay consists of two infrared achromat lenses and forms a unity magnification system. The advantage of the VR system is that the subject can fixate at any distance target either binocularly or monocularly.
4 VISION EVALUATION IN THE PERIPHERY

In order to correct off-axis refractive errors, conventional sphero-cylindrical lenses are adequate, but to correct higher-order aberrations an adaptive optics system is essential. Previous studies have shown that the correction of off-axis refractive errors improves some of the peripheral visual functions, such as differential light sensitivity, motion thresholds and absolute luminance thresholds (Fankhauser & Enoch 1962; Leibowitz et al. 1972; Ronchi 1971). This thesis focuses upon the effect of off-axis optical correction on peripheral resolution acuity. The means of correcting peripheral optical errors and the psychophysical procedures to evaluate peripheral resolution after correction are summarized in this chapter. In addition, the concepts of central scotoma and preferred retinal locus are also presented.

4.1 Optical Correction

The most common way to correct central refractive errors is by prescribing sphero-cylindrical lenses, in the form of either spectacles or contact lenses. Similarly, peripheral refractive errors can also be corrected using sphero-cylindrical lenses at a given eccentricity. However, in healthy eyes, correction of peripheral refractive errors across the entire visual field is an exceedingly difficult task. In addition, in normal eyes, peripheral refractive correction is of limited visual impact. In light of recent findings, that the peripheral retina is of importance for emmetropization, novel spectacle and contact lens designs that reduce peripheral hyperopia in myopes have been trialled (Sankaridurg et al. 2010; Sankaridurg et al. 2011). Adaptive optics visual stimulators, such as crx1™ (Imagine Eyes, France), and aberration controlled contact lenses are commercially available for correcting foveal higher-order aberrations. Currently there are no such devices for correcting peripheral higher-order
aberrations and a lab based adaptive optics system is the only available solution.

There are relatively few studies, which have evaluated the influence of defocus on peripheral detection and resolution acuity. Millodot et al. (1975) and Rempt et al. (1976) evaluated resolution acuity before and after peripheral refractive error correction. Rempt et al. (1976) used Landolt rings whereas Millodot et al. (1975) used both Landolt rings and sinusoidal gratings to evaluate resolution acuity. They both concluded that the correction of refractive errors had no influence on peripheral high-contrast resolution acuity. Artal et al. (1995) evaluated detection and discrimination of motion in the periphery with high-contrast drifting sinusoidal gratings after refractive error correction. They reported that direction discrimination was less dependent on refractive correction while the detection task depended critically on correction. Anderson (1996) and Wang et al. (1997) evaluated effect of defocus on high-contrast grating acuity for detection and resolution in the peripheral visual field. Both studies reported that high-contrast detection acuity is strongly influenced by optical defocus and is optically limited. On the other hand, peripheral high-contrast resolution acuity is relatively insensitive to optical defocus and requires several dioptres of defocus before it decreases (Anderson 1996; Wang et al. 1996; Wang et al. 1997). While the aforementioned studies induced defocus in the periphery, Lundström et al. (2007b) corrected both peripheral refractive errors and high-order aberrations using adaptive optics and found negligible improvement in high-contrast resolution in normal subjects. In contrast, studies have shown that in CFL subjects high-contrast resolution acuity improves following the correction of peripheral refractive errors (Gustafsson & Unsbo 2003; Lundström et al. 2007a). Moreover, a recent study by Rosén et al. (2011) showed that even in healthy subjects, peripheral low-contrast resolution, (but not the high-contrast resolution), is influenced by optical defocus. In a later study using adaptive optics, Rosén et al. (2012) found that low-contrast resolution acuity improved with peripheral aberration correction compared to solely refractive error correction at 20’ nasal visual field. However, they did not report the unaided peripheral low-contrast resolution thus making it difficult to know the true effect of refractive error correction on low-contrast resolution.

4.1.1 Adaptive Optics

The concept of adaptive optics was first proposed by Horace Babcock in 1953 for use in astronomy (Babcock 1953). However, it took almost two decades before the first system was implemented in the ground-based telescopes used by the military, followed by the astronomical community. Dreher et al. (1989) were the first to apply adaptive optics correction in the human eye. They employed a deformable mirror to give a static correction of astigmatism in a
scanning laser ophthalmoscope. Liang et al. (1994) were the first to use a Hartmann-Shack wavefront sensor to measure wavefront aberrations of the human eye. They later used the Hartmann-Shack wavefront sensor in conjugation with a deformable mirror to correct higher-order aberrations and also imaged human cone photoreceptors in vivo (Liang et al. 1997). Since then, adaptive optics has been successfully implemented for several ocular applications. These applications can relate either to retinal imaging or to vision correction. A discussion of adaptive optics used in retinal imaging is beyond the scope of this thesis.

The adaptive optics system performs two consecutive tasks: measurement of the ocular aberrations with a wavefront sensor and correction of these aberrations with a wavefront corrector through the control computer (see Fig. 9). Most adaptive optics systems operate in closed–loop, which means the remaining wavefront error after correction is continually measured and corrected.

![Figure 9: The components and the principal of adaptive optics system. Adapted from Lundström (2007).](image)

The wavefront sensor employed in most vision science adaptive optics systems is a Hartmann-Shack wavefront sensor. The wavefront correctors are typically deformable mirrors, even though studies have used liquid crystal spatial light modulators (Thibos & Bradley 1997; Vargas-Martín et al. 1998). There are different kinds of deformable mirrors, such as segmented mirrors, piezoelectric mirrors, bimorph mirrors, electromagnetic mirrors (Fernandez et al. 2006) and microelectromechanical systems (Fernandez et al. 2001). Since the study by Liang et al. (1997) a large number of subsequent studies have confirmed that the correction of higher-order aberrations improves on-axis...
visual functions, these including visual acuity, contrast sensitivity and face recognition (Li et al. 2009; Marcos et al. 2008; Sabesan & Yoon 2009; Sawides et al. 2010; Yoon & Williams 2002). Conversely, only two studies have used adaptive optics on peripheral vision; this has been discussed in the earlier section (Lundström et al. 2007b; Rosén et al. 2012).

The adaptive optics system in paper V uses Hartmann-Shack wavefront sensor and an electromagnetic deformable mirror. Figure 10 shows the adaptive optics system in combination with the visual psychophysics system. It was developed by the Visual Optics group at KTH, the Royal Institute of Technology in Stockholm.

![Figure 10: Schematic representation of the adaptive optics system used in this thesis. L1 – Achromat f' = 120 mm, L2 – Achromat f' = 200 mm forms a telescope with L1, L3 – Achromat f' = 200 mm forms a telescope with L2, L4 – Achromat f' = 120 mm forms a telescope with L3, L5 – Achromat f' = 50 mm forms a telescope with L3, LD – Laser diode tower 4-μW intensity at 830 nm that is sent to the eye through a pellicle beamsplitter, BS1–Hot mirror reflects infrared and transmit visible light, BS2 – Pellicle beamsplitter, DM – Deformable mirror, CCD – Pupil camera, A – 5 mm aperture, HASO – Wavefront sensor, C – Visual stimulus computer screen, TL/S – Trial lenses/Spectacle, O – Occulder.](image-url)
The main components of the system are the HASO™ wavefront sensor, the mirao™ 52-d deformable mirror from Imagine Eyes™ and a CRT screen for visual stimulus presentation. The pupil plane was made conjugate with the deformable mirror and wavefront sensor using telescopes. The stimulus on the CRT screen, 2.6 meter away, was imaged through the system by the telescopes formed by the lens L4, L3, L2 and L1, with a total magnification of one. The refractive errors were corrected using trial lenses and the remaining aberrations were corrected by the adaptive optics system in a continuous closed loop.

4.2 Psychophysics

Psychophysical methods quantitatively determine the relationship between a physical stimulus and a perceptual response (Corliss & Norton 2002). Vision evaluation with a visual acuity chart is a form of psychophysical test. The patient reads (the perceptual response) from a chart of varying letter sizes (physical stimuli) and the clinician records the smallest letter size that the patient can recognize. Visual acuity thresholds will fluctuate with the attention and response bias of the subject. A psychophysical method helps to control the response bias and considers the random fluctuations of the subject.

Psychophysical methods and procedures are useful in determining the threshold. For a perfect observer, the threshold refers to a boundary that separates stimulus strengths that elicit a response from the stimulus strengths that do not elicit a response, or elicit a different response. Humans are not perfect observers, and as such, thresholds are often defined in probabilistic terms. Therefore, a threshold can be considered as the point where 50% of stimuli are detected as shown in the frequency-of-seeing curve (see Fig. 11). The task required of a subject during threshold measurements varies in complexity; there are generally three types of task, ranging from simple to complex (Corliss & Norton 2002). The simplest task is the detection task in which the subject has to report whether he or she does or does not see something. A second type and a more complex task is the discrimination task. This measures the threshold by comparing the given stimulus with a reference stimulus. A third and more complex threshold task is the recognition task in which, the subject is asked to name an already visible object. Visual acuity tasks fall into this category and are performed routinely in optometric clinics.

There are three main classical psychophysical techniques used to measure thresholds. They are the method of adjustment, the method of limits (staircase) and the method of constant stimuli (Corliss & Norton 2002). The simplest way to measure a threshold, is by using the method of adjustment. This method involves asking the subject to increase the stimulus strength...
(such as luminance) from not visible to just noticeable, or to decrease the stimulus level until the stimulus has just vanished. One can measure the mean threshold and variance after a certain number of trials. Since the subject has control over the stimulus, they may have a subjective bias in determining the threshold in the successive trials.

A better technique would entail the examiner controlling the stimulus levels instead of the subject. The method of limits involves the examiner presenting the stimulus above the visible threshold limit and slowly decreasing the stimulus intensity in small steps until the subject can no longer detect the stimulus (descending limits) or vice versa (ascending limits). A possible disadvantage of both these methods is that subject may become accustomed in perceiving the stimulus and may report seeing it even beyond threshold (habituation error). Conversely, the subject may also anticipate that the stimulus is about to be detected and make a premature judgement (anticipation error) (Corliss & Norton 2002). In order to overcome these errors, a slight variation of the method of limits known as the staircase method was proposed. The staircase method involves both ascending and descending limits within a trial. The stimulus is increased until the subject reports seeing it and then reduced until the subject reports not seeing it. Threshold is calculated as the average of several of these reversal points.

The third and the better technique is the method of constant stimuli. This method involves repeated presentation of a stimulus levels randomly around the threshold. The subject has to report whether they see the stimulus or not.
with a simple yes or no answer. The percentage of correct responses is determined as a function of stimulus intensity. The threshold value is the value where 50% of the stimuli are seen. Psychophysical procedures like yes-no and forced choice could be used to reduce the variability in obtaining the threshold. The yes-no procedure involves the subject responding to the presence or absence of the stimulus. The forced choice procedure involves the subject to choose from two alternatives, one that contains the stimulus. A two-alternative forced choice (2AFC) requires the subject to choose between two alternatives and it is the most frequently used procedure (Corliss & Norton 2002). In a 2AFC, there is already a 50% chance of giving a correct response just by guessing; therefore, the threshold is commonly considered the level when the subject answers correctly 75% of the time. The main disadvantage with the method of constant stimuli is that it is a time consuming and tedious procedure. Therefore, adaptive strategies are used to arrive quickly at the thresholds.

Adaptive methods are easier for both the subject and the examiner as they reduce the duration of the test and increase the efficiency of the psychophysical procedure. Adaptive methods increase efficiency by presenting stimuli at levels where most information can be gained. They are known as adaptive methods because they adjust the stimulus level to be used on each trial based on the responses obtained from the preceding trials. There are many specific adaptive methods available but in this work, we have used the “psi method” (Kontsevich & Tyler 1999). The psi method uses a Bayesian adaptive estimation in determining both the threshold and the slope parameters of a psychometric function. Moreover, of all the adaptive methods, the psi method is arguably the most sophisticated method in use (Kingdom & Prins 2010). The accuracy of this method in obtaining the peripheral resolution threshold is described in detail by Rosén et al. (2011). We have used this psychophysical method in papers IV and V to estimate peripheral grating resolution acuity in both normal and CFL subjects.

4.3 Central Visual Field Loss

End stage macular diseases often result in vision loss in the central 15°–20° of the visual field (i.e. central scotoma). The loss of central vision is the characteristic of diseases such as age-related macular degeneration, diabetic retinopathy, optic neuropathy, hereditary macular disorders and other conditions. Macular diseases can affect younger people, in the form of juvenile macular dystrophies (Stargardt disease), and older people in the form of age-related macular degeneration (AMD). Stargardt disease (also known as fundus flavimaculatas) is a severe form of macular disease that begins in late
childhood, leading to legal blindness. It is symptomatically similar to AMD and affects one in 10,000 children (Mäntyjärvi & Tuppurainen 1992). On the other hand, AMD affects approximately 12% of the population aged 80 years and older in the United States (Friedman et al. 2004). The European prevalence shows a similar pattern with 11% of the population aged 80 years and older affected by AMD (Augood et al. 2006).

Macular diseases often affect both eyes, leading to severe visual impairment and low vision. Low vision is defined as having a visual acuity of less than 0.5 logMAR in the best eye with best possible correction. Schuchard et al. (1999) found that 92% of 255 AMD patients had bilateral central scotoma. Measurements of the boundary of a central scotoma can be performed by conventional perimetry. However, conventional perimetry assumes foveal fixation whereas CFL subjects use an eccentric fixation, which results in limited accuracy of macular scotometry. To overcome this problem, scanning laser ophthalmoscope (SLO) has been alternatively used to determine the boundary of the central scotoma more accurately. The SLO scans a low energy laser (or superluminescent diode) across the retina and reconstructs two-dimensional images from the reflected light. The raster scan technology also provides a platform for manual and automated perimetry (Mainster et al. 1982). A few studies have used SLO to determine the boundaries of central scotomata and found that scotomata have a variety of shapes (Guez et al. 1993; Schuchard et al. 1999). Guez et al. (1993) found the mean diameter of central scotoma to be 10.3° in 40 eyes of 24 subjects. Schuchard et al. (1999) evaluated the median width and height of the scotoma in 255 AMD subjects. They found that the scotoma width (21.8°) is usually larger than the scotoma height (17.9°) and concluded that the scotoma normally looks like a horizontally oriented ellipse.

Patients with bilateral central vision loss have difficulties in performing day-to-day visual tasks such as reading, driving and recognizing faces. Rovner and Casten (2002) found that out of 51 AMD patients, 87.5% gave up reading and 33.3% gave up driving due to vision loss. The adverse impact of a central scotoma on reading has been extensively researched (Fletcher et al. 1999; Legge et al. 1985; Legge et al. 1992). These studies concluded that patients with central scotoma read half as fast than the patients with other forms of low vision who did not have a central scotoma. In addition, patients with AMD read relatively slower than the patients with juvenile macular degeneration (Legge et al. 1992). Another ability that is severely affected because of central vision loss is driving. A study by Decarlo et al. (2003) found that out of 126 AMD patients, only 24% continued driving, and of those who did drive, most had reduced the number of miles driven.
In order to compensate for the loss of central vision, patients often use an eccentric viewing strategy. They adopt a peripheral retinal location for fixation and other visual functions without any specific instructions or training. Fuchs (1938) was the first to document the term “pseudo-fovea” to denote a peripheral retinal location that was used for fixation. Since then researchers have adopted a new term known as the “preferred retinal locus” (PRL) to describe the shift of fixation from the dysfunctional fovea to a new peripheral retinal location. The explanation as to what determines the location of the PRL is beyond the scope of this thesis and an excellent review on this subject has been published by Cheung and Legge (2005).

In Sweden, the first person to describe rehabilitation in low vision population including CFL subjects was Krister Inde (1978). Later this work resulted in a book called “Low Vision Training” by Bäckman and Inde (1979). Following the establishments of low vision centres in Sweden, several studies were performed to improve quality of life in the low vision population. These studies showed that the remaining vision of the CFL subjects could be effectively used if they are systematically trained or made aware of their “best retinal area” (Frennesson et al. 1995; Nilsson et al. 1998; Nilsson et al. 2003; Nilsson & Nilsson 1986).

Crossland et al. (2011) defines a PRL as “one or more circumscribed regions of functioning retina, repeatedly aligned with a visual target for a specified task that may also be used for attentional deployment and as oculomotor reference.” An extensive study by Fletcher and Schuchard (1997) reported that 84.4% eyes with central scotomas demonstrated a PRL. They also found that 88.7% of the PRL were located in proximity (2.5°) to the border of the scotoma. Of these 39.7% of the PRL had at least one dense scotoma border and the central field defect was located superior to fixation in 39.0% of eyes, right of fixation in 33.7%, left of fixation in 19.9%, and inferior to fixation in 7.5%. Sunness et al. (1996) also found that the PRL was located within 2° of the scotoma border in 27 AMD patients. Moreover, the location of the PRL in the peripheral retina also depends on the size of the central scotoma.

There has been considerable interest on the fixation stability at the PRL. Schuchard et al. (1999) reported the fixation stability ranged from 1° to 8° with a median of 3° diameter in a group of 255 AMD patients. In addition, Whittaker et al. (1988) found that the fixation stability decreased with an increase in the scotoma size, and that patients had multiple PRLs when the scotoma size was greater than 20°. Crossland and Rubin (2002) reported that in six normal subjects, the foveal fixation stability obtained by both SLO and an infrared eye tracker ranged from 100 to 650 arc min squared (equivalent to circular areas of 0.2° to 0.5° in diameter). When compared to fixation stability
of normal subjects, CFL subjects have a substantially less stable fixation and a larger fixation area at the PRL (Culham et al. 1993). However, according to Déruaz et al. (2004) poor fixation could be a functional advantage as it overcomes the perceptual fading of peripheral targets during stable fixation also known as Troxler’s phenomenon.

In paper V, we evaluated the fixation stability at the PRL of a subject with a central scotoma using the Spectral OCT/SLO scanning laser ophthalmoscope (OPKO Health, Miami, FL). The subject had a single PRL located 25° nasally from the dysfunctional fovea. We projected a cross (1 cm in width and height) on the PRL and asked the subject to fixate the cross for a duration of 20 seconds. The subject had a fixation stability of approximately 2°-3° diameter at the PRL, which is in agreement with the findings of Schuchard et al. (1999).
5 AIM OF THE THESIS

The overall aim of this work is to improve vision for people with central visual field loss. This far-reaching aim requires building up a knowledge base regarding peripheral optics and its influence on vision. The focus of this work has been to measure and correct peripheral optical errors, as well as to evaluate its impact on resolution acuity in both normal and central visual field loss subjects. Therefore, the specific aim was divided into two parts: the first part deals with quantifying peripheral optics (Papers I-III) and the second part evaluates resolution acuity after the correction of peripheral optical errors in normal subjects and in a central visual field loss subject (Papers IV & V). In order to fulfil this, the following objectives were evaluated:

Paper I: The aim of this paper was to assess the intrasession repeatability of peripheral ocular aberration measurements with a commercially available Hartmann-Shack aberrometer and to quantify the amount of higher-order off-axis aberrations in young healthy emmetropic eyes.

Paper II: The aim of this paper was to determine the amount of symmetry in peripheral ocular aberrations between right and left eye.

Paper III: The aim of this paper was to compare peripheral lower- and higher-order aberrations in a group of healthy young and old emmetropes.

Paper IV: The aim of this paper was to evaluate low contrast (10%) resolution acuity with and without peripheral refractive error correction in normal young healthy emmetropes.

Paper V: The aim of this paper was to investigate the effect of eccentric refractive correction and full aberration correction on both high- and low contrast grating resolution at the PRL of a single low vision subject with a longstanding central scotoma.
6 SUMMARY OF PAPERS

The results of this thesis add more knowledge to the field of peripheral optics and peripheral vision. In all papers, informed consent was obtained from every participant after the nature and the intent of the study had been explained both verbally and in written format. The research was approved by the local ethics committee, etikprövningskommitten Sydost, in Växjö. The research protocol was designed in adherence with the tenets of Declaration of Helsinki.

6.1 Repeatability of Peripheral Aberrations in Young Emmetropes (Paper I)

The purpose of this study was to evaluate the intrasession repeatability of off-axis aberration measurement using the COAS-HD VR. In addition, higher-order off-axis aberrations of young emmetropes were reported. Five repeated measures of aberrations were obtained in steps of 10° in the horizontal (±40°) and inferior visual field (−20°) of 18 young healthy emmetropes. The subjects viewed the target (red light emitting diodes), which were placed 3 meters from the eye. Aberration measurements were obtained in the right eyes of the subjects while the left eye was occluded. The results showed that there was no statistically significant difference in the variance of HO RMS between on- and off-axis measurements. The repeatability of third- and fourth-order aberrations was better than fifth- and sixth-order aberrations in all eccentric angles. In addition, horizontal coma changed linearly and the HO RMS changed quadratically with increasing eccentric angle while spherical aberration was slightly lower at large off-axis angles. This study concluded that the aberrometer provided fast, repeatable and valid peripheral aberration measurements. The instrument’s open field of view would allow a researcher to present stimuli at various distances and field angles in the visual space. The author was responsible for subject recruitment, data collection, data analysis and writing the manuscript.
6.2 Symmetries in Peripheral Ocular Aberrations (Paper II)

Peripheral optical quality is often evaluated in only one eye because it is time efficient and the findings are generalized to the other eye. It is well known that the on-axis aberrations show mirror symmetry between the right and left eyes and a similar symmetry for the peripheral aberrations is more likely, but has not been investigated. Therefore, this study was done to justify whether the results obtained from one eye can be generalized to the other eye as well.

We measured peripheral ocular aberrations in both eyes of 22 subjects out to ±40° in the horizontal visual field, using two Hartmann-Shack sensors located at Kalmar (Sweden) and Murcia (Spain). The findings showed that the largest aberrations (defocus, astigmatism and coma) were significantly correlated between the left and right eyes when comparing the same temporal or nasal angle. This study showed that peripheral ocular aberrations had mirror symmetry between the right and left eyes over the horizontal visual field. The fact that there is off-axis mirror symmetry means that one eye of a subject could be used for measurements and the results could be generalized for the other eye. However, this finding applies to a population of subjects and there can be individual differences. The author was responsible for recruitment of subjects and data collection in Kalmar.

6.3 Influence of Age on Peripheral Ocular Aberrations (Paper III)

In general, it is difficult to obtain normative data of off-axis aberrations from CFL subjects because their PRL can be located anywhere in the periphery. Therefore, it would be ideal to have normative data of off-axis aberrations of healthy younger and older subjects. It is well known that the axial higher-order aberrations increase with age. This study was done to investigate the influence of age on peripheral ocular aberrations in normal healthy eyes. We measured off-axis aberrations in two groups of 30 younger and 30 older emmetropic subjects. The aberrations in the right eye were measured using the COAS-HD VR aberrometer in steps of 10° to ±40° horizontally and −20° inferiorly in the visual field. We found that off-axis refractive errors were similar for both age groups. Among the higher-order aberrations, horizontal coma and spherical aberration showed greatest variation between the groups. Off-axis coma increased linearly with eccentricity at a more rapid rate in the older group than in the younger group. Spherical aberration was larger in the older group than the younger group. The peripheral higher-order aberrations increased with age, particularly coma and spherical aberration. The author was
responsible for design of the study, subject recruitment, data collection, data analysis and writing the manuscript.

6.4 Clinical Impact of Objectively Determined Peripheral Refractive Error Correction on Low-Contrast Resolution Acuity (Paper IV)

High contrast resolution acuity is not much influenced by optical defocus in the periphery, whereas defocus has detrimental effect on peripheral low contrast resolution acuity. This study was done to examine the effect of off-axis refractive error correction on peripheral low contrast resolution acuity in young healthy emmetropic subjects. We measured low contrast resolution acuity after correcting off-axis refractive errors at 20° nasal visual field of 10 emmetropic subjects. Our findings showed that subjects who were emmetropic centrally had an off-axis astigmatism ranging from −1.00 DC to −2.00 DC in the 20° nasal visual field. The average uncorrected off-axis low contrast resolution acuity was 0.92 logMAR, which improved to 0.86 logMAR after off-axis refractive error correction. This suggests that optical factors do influence peripheral visual tasks involving low contrast and that there are definite benefits in correcting even moderate amounts of off-axis refractive errors. The author was responsible for design of the study and data collection.

6.5 Benefit of Adaptive Optics Aberration Correction at Preferred Retinal Locus (Paper V)

In this case report, we investigated the effect of off-axis refractive correction and aberration correction on resolution acuity at the PRL of a CFL subject. The CFL subject was a 68-year-old woman with bilateral absolute central scotoma due to Stargardt disease. She had a PRL located 25° nasally from the dysfunctional fovea in her left eye. We evaluated high and low contrast grating resolution acuity using four different correction conditions. The first two corrections were solely refractive error corrections (habitual spectacle correction and full spherocylindrical correction) and the latter two were two versions of adaptive optics corrections of all aberrations. The results show that the high and low contrast resolution acuities improved by 0.06 and 0.16 logMAR respectively with full spherocylindrical correction as compared with the habitual correction. With adaptive optics, there was further improvement of 0.10 logMAR in both high and low contrast resolution acuity. The author was responsible for collecting data regarding the fixation stability, mapping the PRL, fundus photography and writing the manuscript. He was also partly involved in taking aberration data and evaluating vision.
7 DISCUSSION & OUTLOOK

This thesis presents new findings regarding the improvement of peripheral visual functions with optical correction. We have also documented the magnitude of peripheral ocular aberrations in young and old subjects.

Since the commencement of this thesis, there has been a huge increase in research regarding peripheral optics due to findings that suggests peripheral refractive state can also influence myopia progression (Smith III et al. 2009). This encouraged the research community to develop better instruments for measuring peripheral optics. The instruments available at that time, including the COAS-HD VR aberrometer, were only able to measure peripheral optics at one eccentricity at a time. The newly developed lab-based instruments use scanning technology allowing for quicker measurement of optical errors across the peripheral retina; with both high angular resolution and minimal discomfort to the subject (Jaeken et al. 2011; Tabernero & Schaeffel 2009). Alternative instruments were also developed to measure the optical errors across the retina, instantaneously at multiple eccentric locations (Fedtke 2011). These instruments were based on either Hartmann-Shack wavefront sensors or photorefraction techniques. Even though the technology behind these instruments has improved, an open view aberrometer is sufficient in order to measure optical errors at the PRL of CFL subjects. Therefore, the best clinical device for measuring aberrations in low vision patients would be an open view aberrometer that can measure at any location in the visual field. The open view also permits the possibility of showing fixation targets of any size at any position in the visual space. We hope that in the future, open-view aberrometers can be used routinely in assessing both axial and peripheral optical errors in a clinical setting.

In the absence of reliable objective peripheral refraction, it is still possible to estimate the axis orientation of off-axis astigmatism from the results presented in this thesis. In a centrally emmetropic eye, the off-axis astigmatism beyond 10° eccentricity in the horizontal plane (denoted in a
negative cylinder format) would always have an axis orientation of approximately 90°; in the vertical plane, the axis orientation is approximately 180°. In line with this, patients using a PRL located in the horizontal plane will have off-axis astigmatism with axis orientation of 90°; axis orientation for PRLs located in the vertical plane will tend towards 180°. If there are higher degrees of on-axis astigmatism, this will of course influence peripheral off-axis astigmatism, making it more difficult to estimate the orientation of the cylinder axis. With knowledge of the orientation of the off-axis astigmatic axis, it is easier to perform subjective refraction at the PRL of low vision patients in the clinic.

It is well known that there are other aberrations in the peripheral visual field besides off-axis astigmatism. As the focus of this thesis was ultimately on helping CFL subjects, where the majority of patients are elderly, we investigated the effect of age on peripheral ocular aberrations. Due to the lack of normative aberration data on healthy elderly subjects, we also investigated difference between young and old eyes. During the period following our data collection, a similar study was published by Mathur et al. (2010). Nevertheless, our study included a larger number of subjects and covered a larger area of the visual field. We found that coma, spherical aberration and HO RMS increased with age. We also found that coma is the predominant higher-order aberration, constituting 70% to 90% of HO RMS at eccentricities >10° in the periphery. The finding of this study was in agreement with Mathur et al. (2010). We also found that even after removing coma and spherical aberration from HO RMS calculation, the old group had, higher amounts of aberrations than the young group (see unpublished figure 12).

Figure 12: The unpublished figure from paper III shows that older eyes have significantly higher amounts of aberrations even after removing the dominant aberrations (coma and spherical aberration) from HO RMS calculation.
This showed that peripheral ocular aberrations are significantly influenced by age. We also speculated that this increase was due to the loss of balance between corneal and lenticular aberrations with aging in the periphery. This was later confirmed in the study by Mathur et al. (2012). We would like to emphasize that coma is the most significant aberration in the periphery. The important optical errors that need to be considered for off-axis correction in CFL subjects are defocus, astigmatism and coma.

Recently, Rosén et al. (2011) showed that optical defocus has a detrimental effect on low-contrast resolution acuity in the periphery. To investigate this further, we corrected objectively determined off-axis refractive errors in healthy eyes and examined the effect on low contrast resolution acuity. We found that correcting subjects with higher amounts of off-axis refractive errors resulted in significantly improved low contrast resolution acuity. This result suggests that some peripheral visual functions are optically limited even in healthy eyes and can be improved by appropriate optical correction; which argues in favor of correcting peripheral optical errors, especially for those with absolute central visual field loss.

This was confirmed in the final experiment, whereby correcting both refractive errors and remaining higher-order aberrations at the PRL improved both high and low contrast resolution acuity in a single CFL subject. To our knowledge, this is the first study to correct both lower- and higher-order aberrations and to show improvement in visual functions at the PRL. In order to understand the full potential of this finding, similar experiments need to be performed on a larger group of CFL patients in the future. The subject in this experiment was exceptional, as she had a long-standing central scotoma (more than 40 years of eccentric viewing) and stable fixation at her PRL. Patients who have a newly developed PRL require stable fixation before an advanced optical correction can be of any advantage. Unsteady fixation will result in unpredictable changes in the aberrations thus making any correction unusable. On the other hand, one can speculate that giving an optimal optical correction may actually assist in a more rapid development of a stable PRL.

Patients with multiple PRLs would require different corrections for each PRL making use of a single correction somewhat more difficult. Nevertheless, if the subject uses one of the multiple PRLs for a specific visual task (for e.g. reading) then that specific PRL can be targeted for correction. Despite the limitations imposed by unstable fixation and multiple PRLs, it can still be beneficial to give optical corrections along with other low vision devices. One advantage of such a correction is that it can possibly reduce the magnification required for certain visual tasks.
The aberration correction implemented for the subject in paper V was a lab-based system, and we hope that in future that new practical ways to correct higher-order aberrations will be developed. As we know from this study, the predominant peripheral higher-order aberration is coma and we anticipate that customised correction of coma with contact lenses or intraocular lenses will be possible in the future. When such correction modalities do exist, further studies will be required to determine the degree of improvement in peripheral visual function, preferably on patients with central visual field loss. Optimally one should examine not only visual function, but also functional vision.

This thesis has shown that peripheral visual functions can be improved by optical correction, thus allowing for optimal use of peripheral vision, in particular for a CFL patient.
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Repeatability of Peripheral Aberrations in Young Emmetropes

Karthikeyan Baskaran*, Baskar Theagarayan*, Staffan Carius†, and Jörgen Gustafsson‡

ABSTRACT

Purpose. The purpose of this study is to assess the intrasession repeatability of ocular aberration measurements in the peripheral visual field with a commercially available Shack-Hartmann aberrometer (complete ophthalmic analysis system-high definition-vision research). The higher-order off-axis aberrations data in young healthy emmetropic eyes are also reported.

Methods. The aberrations of the right eye of 18 emmetropes were measured using an aberrometer with an open field of view that allows peripheral measurements. Five repeated measures of ocular aberrations were obtained and assessed in steps of 10° out to 40° in the horizontal visual field (nasal and temporal) and 20° in the inferior visual field. The coefficient of repeatability, coefficient of variation, and the intraclass correlation coefficient were calculated as a measure of intrasession repeatability.

Results. In all eccentric angles, the repeatability of the third- and fourth-order aberrations was better than the fifth and sixth order aberrations. The coefficient of variation was 30% and the intraclass correlation coefficient was 0.90 for the third and fourth order but reduced gradually for higher orders. There was no statistical significant difference in variance of total higher-order root mean square between on- and off-axis measurements (p > 0.05). The aberration data in this group of young emmetropes showed that the horizontal coma (C31) was most positive at 40° in the temporal field, decreasing linearly toward negative values with increasing off-axis angle into the nasal field, whereas all other higher-order aberrations showed little or no change.

Conclusions. The complete ophthalmic analysis system-high definition-vision research provides fast, repeatable, and valid peripheral aberration measurements and can be used efficiently to measure off-axis aberrations in the peripheral visual field.

Key Words: repeatability, off-axis wavefront aberrations, COAS-HD VR aberrometer, peripheral aberrations, visual field

The human eye suffers from a variety of aberrations (lower and higher orders), both foveal (on-axis) and peripheral (off-axis). In the past, there have been numerous studies, which used different techniques (e.g., Shack-Hartmann, laser ray tracing, and Tscherning) to measure the ocular aberrations objectively. The Shack-Hartmann is the most commonly used technique for measuring both on-axis and off-axis aberrations. Measurements of off-axis aberrations have gained interest in the last decade. The main reason for this is the discovery of a possible link between myopia development and peripheral optics. Such measurements are also of interest in the field of low vision and in other aspects of research (e.g., optical, psychophysical, and visual benefits). The lower-order refractive errors defocus (C02) and astigmatism (C24) in the periphery have been studied using commercially available open-field autorefractors and modified commercial aberrometers. These studies found a quadratic increase in astigmatism and relative ametropia in the periphery.

Recently, several groups have undertaken studies to determine the eye’s higher-order aberrations in the peripheral visual field. Navarro et al. was the first to measure off-axis aberrations in detail and quantify them in terms of Zernike polynomials. They used a laser ray-tracing technique and measured aberrations at four different positions in the nasal visual field. The first report on off-axis aberrations with a Shack-Hartmann aberrometer along the horizontal visual field was published by Atchison and Scott in

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2002, Lundström et al.6 and Mathur et al.14 were able to measure higher-order aberrations using Shack-Hartmann principle at different locations (nasal, temporal, superior, and inferior) in the visual field. The above studies found that the higher-order root mean square (HO RMS) increased quadratically in the periphery.

So far, off-axis aberrations were mostly measured with a laboratory-built Shack-Hartmann aberrometer or by modifying the commercially available Shack-Hartmann aberrometer [complete ophthalmic analysis system (COAS)].2 All the studies mentioned above have used slightly different techniques to measure the off-axis aberrations; the repeatability when measuring the aberrations in the periphery is yet to be evaluated. There are several commercial aberrometers available that are based on the Shack-Hartmann principle for measuring on-axis aberrations (e.g., Wavefront sciences [Albuquerque, NM], Bausch & Lomb [Rochester, NY], Alcon [Fort Worth, TX], Topcon [Oakland, NJ], etc.), but none available to measure off-axis aberrations. With the recent introduction of the first commercial COAS-high definition-vision research (COAS-HD VR)

FIGURE 1.
Schematics and picture of the measuring setup with the open-view COAS-HD VR aberrometer. The schematic drawing shows the positioning of fixation targets relative to the measuring direction for off-axis measurements. The picture shows a test person fixating at a target seen through the visually transparent hot mirror/beam splitter.
open-view aberrometer, we were interested in its ability to perform fast, repeatable, and valid peripheral aberration measurements.

There have been number of studies published describing the repeatability of on-axis aberration measurements with different aberrometers.\textsuperscript{15–22} However, to our knowledge, there are no studies relating repeatability of off-axis higher-order aberration measurements done with a commercially available aberrometer. Therefore, the purpose of this study was to evaluate the intrasession repeatability of peripheral aberration measurement using the first commercially available open-view Shack-Hartmann aberrometer. The distribution of higher-order off-axis aberrations in a small group of young healthy emmetropic eyes is also reported.

**METHODS**

**Subjects**

A prospective study was done on the right eye of healthy subjects chosen among students from the Linnaeus University in Kalmar. The subjects had no history of ocular surgery or pathology. All the subjects gave their informed consent after the nature and the intent of the study had been explained. Eighteen subjects were enrolled in the study (11 females and seven males). The mean age was 23.9 ± 3.1 years. An Early Treatment Diabetic Retinopathy Study logMAR visual acuity chart at 4 m was used to record visual acuity of the subject. Uncorrected visual acuity ranged from 0.0 to −0.1 logMAR and the subjective refraction was <±0.5 DS and −0.5 DC. The research was approved by the local ethics committee, and the study protocol was designed in accordance with the tenets of the Declaration of Helsinki.

**Description of Apparatus**

Monochromatic aberrations were measured with a Complete Ophthalmic Analysis System Model 2800 High Definition aberrometer; AMO Wavefront Sciences, Albuquerque, NM). The COAS-HD VR integrates a COAS-HD aberrometer with VR (VR aberrometer; AMO Wavefront Sciences, Albuquerque, NM). The Ophthalmic Analysis System Model 2800 High Definition aberrometer; AMO Wavefront Sciences, Albuquerque, NM) was used for the measurements. The subjects positioned their head in a chin rest in front of the instrument. Wavefront errors were measured under monocular conditions on the right eye while the left eye was occluded. The subjects remained stationary and were asked to fixate at the distant target through a glass slide hot mirror. The target was a nonaccommodative red light emitting diodes (LED) with a wavelength of 635 nm. The LED was 3 mm in diameter placed 3 m from the subject’s eye. The target construction consisted of 11 LEDs placed in a radial geometry subtending a ±40° horizontally and +20° superiorty. The measurements were performed at 11 different retinal locations: fovea (on-axis), out to ±40° horizontally and +20° superiorty, in steps of 10° (Fig. 1). When interpreted to visual field, the measurements were made ±40° horizontal visual field (nasal + and temporal −) and −20° in the inferior visual field.

Before each measurement, the observer aligned the visual axis of the subject with the instrument axis using the iris camera. Subjects

**Experimental Procedures**

A model eye provided by the manufacturer of the COAS-HD VR was used to test the on-axis instrument accuracy. Five repeated readings were taken and analyzed for in vitro repeatability. A similar procedure was done in a single human eye and the in vivo repeatability analyzed.

The monochromatic aberrations were measured with a natural pupil in a dim room illumination. A single observer performed all the measurements. The subjects positioned their head in a chin rest in front of the instrument. Wavefront errors were measured under monocular conditions on the right eye while the left eye was occluded. The subjects remained stationary and were asked to fixate at the distant target through a glass slide hot mirror. The target was a nonaccommodative red light emitting diodes (LED) with a wavelength of 635 nm. The LED was 3 mm in diameter placed 3 m from the subject’s eye. The target construction consisted of 11 LEDs placed in a radial geometry subtending a ±40° horizontally and +20° superiorty. The measurements were performed at 11 different retinal locations: fovea (on-axis), out to ±40° horizontally and +20° superiorty, in steps of 10° (Fig. 1). When interpreted to visual field, the measurements were made ±40° horizontal visual field (nasal + and temporal −) and −20° in the inferior visual field.

Before each measurement, the observer aligned the visual axis of the subject with the instrument axis using the iris camera. Subjects

**TABLE 1.**

The results of the repeatability analysis for on-axis measurements

<table>
<thead>
<tr>
<th>Zernike coefficient</th>
<th>Mean ± S_{sw} (μm)</th>
<th>CV (%)</th>
<th>CR (μm)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{1})</td>
<td>0.081 ± 0.014</td>
<td>17</td>
<td>0.028</td>
<td>0.970</td>
</tr>
<tr>
<td>(C_{2})</td>
<td>0.076 ± 0.018</td>
<td>24</td>
<td>0.035</td>
<td>0.931</td>
</tr>
<tr>
<td>(C_{3})</td>
<td>0.064 ± 0.014</td>
<td>22</td>
<td>0.027</td>
<td>0.931</td>
</tr>
<tr>
<td>(C_{4})</td>
<td>0.051 ± 0.011</td>
<td>21</td>
<td>0.022</td>
<td>0.976</td>
</tr>
<tr>
<td>(C_{5})</td>
<td>0.020 ± 0.008</td>
<td>40</td>
<td>0.015</td>
<td>0.895</td>
</tr>
<tr>
<td>(C_{6})</td>
<td>0.012 ± 0.007</td>
<td>56</td>
<td>0.015</td>
<td>0.832</td>
</tr>
<tr>
<td>(C_{7})</td>
<td>0.058 ± 0.011</td>
<td>19</td>
<td>0.022</td>
<td>0.965</td>
</tr>
<tr>
<td>(C_{8})</td>
<td>0.023 ± 0.012</td>
<td>52</td>
<td>0.024</td>
<td>0.836</td>
</tr>
<tr>
<td>(C_{9})</td>
<td>0.022 ± 0.009</td>
<td>41</td>
<td>0.018</td>
<td>0.885</td>
</tr>
<tr>
<td>(C_{10})</td>
<td>0.014 ± 0.009</td>
<td>66</td>
<td>0.018</td>
<td>0.767</td>
</tr>
<tr>
<td>(C_{11})</td>
<td>0.014 ± 0.008</td>
<td>57</td>
<td>0.016</td>
<td>0.704</td>
</tr>
<tr>
<td>(C_{12})</td>
<td>0.012 ± 0.011</td>
<td>94</td>
<td>0.021</td>
<td>0.352</td>
</tr>
<tr>
<td>(C_{13})</td>
<td>0.012 ± 0.010</td>
<td>83</td>
<td>0.020</td>
<td>0.438</td>
</tr>
<tr>
<td>(C_{14})</td>
<td>0.013 ± 0.007</td>
<td>56</td>
<td>0.013</td>
<td>0.833</td>
</tr>
<tr>
<td>(C_{15})</td>
<td>0.013 ± 0.007</td>
<td>53</td>
<td>0.014</td>
<td>0.826</td>
</tr>
<tr>
<td>(C_{16})</td>
<td>0.013 ± 0.006</td>
<td>69</td>
<td>0.011</td>
<td>0.778</td>
</tr>
<tr>
<td>(C_{17})</td>
<td>0.007 ± 0.005</td>
<td>69</td>
<td>0.010</td>
<td>0.676</td>
</tr>
<tr>
<td>(C_{18})</td>
<td>0.007 ± 0.006</td>
<td>90</td>
<td>0.012</td>
<td>0.480</td>
</tr>
<tr>
<td>(C_{19})</td>
<td>0.010 ± 0.006</td>
<td>83</td>
<td>0.016</td>
<td>0.613</td>
</tr>
<tr>
<td>(C_{20})</td>
<td>0.008 ± 0.007</td>
<td>100</td>
<td>0.016</td>
<td>0.489</td>
</tr>
<tr>
<td>(C_{21})</td>
<td>0.008 ± 0.006</td>
<td>74</td>
<td>0.012</td>
<td>0.686</td>
</tr>
<tr>
<td>(C_{22})</td>
<td>0.008 ± 0.007</td>
<td>83</td>
<td>0.014</td>
<td>0.639</td>
</tr>
<tr>
<td>(HO RMS)</td>
<td>0.141 ± 0.015</td>
<td>11</td>
<td>0.029</td>
<td>0.929</td>
</tr>
</tbody>
</table>

The mean and within \(S_{sw}\), CV, and ICC for on-axis measurements are shown. The bold numbers are the most repeatable measurements for on-axis with CV <25% and ICC >0.90. The RMS value of each coefficient was used to calculate the mean.
FIGURE 2.
The CV of third-order (A) and fourth-order (B) aberrations across horizontal visual field. The CV of the third-order and the spherical aberrations ($C_4^0$) is <25%.

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were asked to blink once and hold their eyes wide open before each measurement. The subjects turned their eye to view the off-axis fixation target during the measurement. Five readings were taken at each angle. Each such measurement took approximately 5 s to perform. It took approximately 30 s to perform a set of five repeated measurements. Fifty-five measurements in total were recorded for each subject. With the increase in eccentricity, the view of the pupil transforms from a circle to ellipse. The Zernike analysis was restricted to the 5-mm central part of the wave front, i.e., a circle of 5 mm diameter entirely enclosed by the pupil. In this study, all the subjects had equal horizontal pupil diameter in all eccentric angles. This enabled COAS-HD VR to calculate the Zernike polynomials for the eccentric wavefront data. This was done to facilitate the comparison between the different off-axis angles. The above procedure for calculating Zernike coefficients has been described in detail elsewhere. All the analyses were reported according to Optical Society of America recommended standards.

Data Analysis

The aberration data were exported from COAS-HD as individual Zernike coefficients with its inbuilt software into Microsoft Excel (Microsoft, Redmond, WA). All the statistical analysis was done with the SPSS software package version 17.0.0.235 for Windows (SPSS, Chicago, IL).

The aberrations from third- to sixth-order and HO RMS were analyzed. The variance ($S^2_w$) of the five repeated measurements was determined for each subject. The average of all the 18 subjects’ variances was calculated. The square root of the average variance is defined as within-subject SD ($S_w$). The measurement error was expressed in terms of 95% range according to Bland and Altman. This is also defined as coefficient of repeatability ($CR = 1.96 \times S_w$). A low absolute value of CR indicates that the method of obtaining a measurement is more repeatable, i.e., a large number of repeated measurements show little spread. The intraclass correlation coefficient (ICC) was calculated for each parameter. The ICC indicates the proportion of total variability within a data set that is “between subject” and the rest being “within-subject” variability. An ICC value $>0.90$ is considered acceptable for clinical work. We also calculated the coefficient of variation ($CV = 100 \times (S_w / \text{mean})$) for each parameter. Repeated-measures analysis of variance (ANOVA) was done to find whether there was a statistical significant difference between the on- and off-axis variance ($S^2_o$). The change in horizontal coma ($C^3_1$), spherical aberration ($C^4_0$), and HO RMS with off-axis angle along the horizontal visual field was analyzed using repeated-measures ANOVA with Bonferroni correction. A p value of $<0.05$ was considered statistically significant.

RESULTS

In Vitro and In Vivo Repeatability

The SD of five repeated measurements for on-axis total HO RMS in the model eye was 0.001 μm, whereas the SD for a single human eye was measured to be 0.006 μm. This showed that the contribution of the instrument noise is negligible.

On-Axis Repeatability

The Zernike coefficients that showed more accurately reproducible values were the third-order coefficients, spherical aberration ($C^4_0$), and the HO RMS, with $CR \leq 0.035 \mu m$, $CV < 25\%$, and $ICC \geq 0.93$. The coefficients showing the least reproducible values were those of fourth order (except $C^4_0$), fifth order, and sixth order, with $CV > 30\%$ and ICC $\leq 0.89$. The results of the repeatability analysis for on-axis measurements are presented in Table 1.

Off-Axis Repeatability

In the peripheral visual field (horizontal and inferior), the most repeatable coefficients were those of third order, spherical aberration ($C^4_0$), and the HO RMS, with $CR \leq 0.04 \mu m$, $CV \leq 30\%$ (Figs. 2 and 3), and $ICC \geq 0.90$. The least repeatable coefficients were those of fourth order (except $C^4_0$), fifth order, and sixth order.
The off-axis repeatability was found to be similar to the on-axis repeatability.

**On-Axis Variance Compared with Off-Axis Variance**

The HO RMS variances ($S^2$) for all the eccentric angles were compared with the on-axis variance. The results from the repeated-measures ANOVA showed that there was no statistically significant difference in variance across the visual field ($p > 0.05$). The CV for HO RMS for all the eccentric angles is shown in Fig. 4.

**Distribution of Peripheral Aberration in Young Emmetropes**

The horizontal coma ($C^3_1$) decreased linearly across the horizontal visual field with a slope of $-0.013 \mu m/deg$. The spherical aberration ($C^4_0$) showed a moderate quadratic dependence ($R^2 = 0.99$) across the visual field with a slight decrease at $\pm 40^\circ$ eccentricity. The total HO RMS also showed a quadratic dependence ($R^2 = 0.99$) with a 2.2 times increase from center to periphery (Fig. 5).

The vertical coma ($C^3_{-1}$) also had a similar linearity (slope $0.007 \mu m/deg$) in the inferior visual field. There were no significant changes in the spherical aberration ($C^4_0$) or the HO RMS at off-axis angle in the inferior visual field (Fig. 6).

The results showed that there was a statistically significant difference in the horizontal coma, spherical aberration, and HO RMS with off-axis angle ($p < 0.05$) along the horizontal visual field. A post hoc Bonferroni multiple comparison test indicated that horizontal coma changed significantly at each off-axis angle. The spherical aberration and HO RMS showed statistically significant changes only at $\pm 30^\circ$ and $\pm 40^\circ$ eccentricities.

**DISCUSSION**

Our results show that there is no significant difference between on- and off-axis repeatability using this method. The aberrometer is able to measure aberrations consistently at the off-axis angles. The repeatability and the magnitude of aberrations reduced as the radial order increased for both on and off-axis aberrations. The reduction in repeatability can be attributed to the insignificant amount of higher-order (fifth and sixth) aberrations. In addition, the variability caused by biological changes (microfluctuations in accommodation, tear film instability, and small fixational eye movements) and the measurement noise (mainly operator misalignment and fixation errors) also limits the repeatability. We found that the main cause of variation is because of biological changes in the eye compared with the variability caused by measurement noise.

The variability found with a model eye was 0.001 $\mu m$, whereas it was measured to be 0.006 $\mu m$ with a human eye. This showed that the variability observed with the human eye is dominated by the measuring conditions. Cheng et al. and Efron et al. also found that the variability in the human eye was nine times greater...
than that of a model eye with the COAS and the irx3 aberrometers, respectively. This comparison shows that there was negligible instrument noise contributing to the variability observed in the human eye.

Cheng et al.\textsuperscript{15} also have shown that the COAS was minimally affected by lateral and axial operator misalignments. In our study, we used a COAS-HD VR iris camera and subjectively cross-checked that there was no major operator misalignment during measurements. The fixation errors were also controlled during measurements by reinforcing subjects to fixate at the illuminated target, so variations because of measurement noise could be kept minimal in the study. We could deduce that the majority of variation was biological: mainly microfluctuation of accommodation and instability of tear film. It should be emphasized that these variations affected the repeatability of the fifth and sixth order, whereas the repeatability of third- and fourth-order aberrations were almost unaffected.

**On-Axis Repeatability**

We found that the repeatability of third-order aberrations, spherical aberration ($C_4^0$), and HO RMS to be better than the fourth-, fifth-, and sixth-order aberrations. This finding was consistent with most of other repeatability studies.\textsuperscript{17,19,20} We compared the results of our on-axis repeatability with that of other published repeatability studies. The above comparison is presented in Table 2. From the table, we can note that COAS-HD VR had a better repeatability in measuring higher-order aberrations compared with other commercially available aberrometers.
The reason for high repeatability when using the COAS-HD VR can be attributed to a high-resolution Shack-Hartmann sensor, which uses 1546 sample points compared with 1024 sample points used in the irx3, 80 sample points in the Zywave, 1440 sample points in the Optical Path Difference-scan, and 872 sample points in earlier version of COAS.

**Off-Axis Repeatability**

Up to now, there has been no published work for off-axis repeatability using either laboratory-built or commercial aberrometers. Our study is the first to report off-axis repeatability with a commercially available open-view aberrometer. Because there was no previous literature available, we compared the off-axis repeatability with our on-axis repeatability. The comparison of variance between on- and off-axis showed no significant difference. In all the eccentric angles, HO RMS was highly repeatable with CR ranging from 0.019 to 0.032 μm, CV ranging from 5 to 10% (Fig. 4), and ICC >0.90. This result was similar to that of on-axis HO RMS with a CR of 0.029 μm, CV of 11%, and ICC >0.90. At the eccentric angles, the third-order aberration and spherical aberration (C3) were highly repeatable, whereas for the fifth- and sixth-order aberrations, the repeatability reduced. Again this was a similar finding compared with the on-axis repeatability. The above findings indicate that the COAS-HD VR can be used efficiently to measure both on- and off-axis aberrations.

**Distribution of Peripheral Aberrations in Young Emmetropes**

Our findings of a linear dependence of the horizontal coma along the horizontal visual field and the vertical coma along the inferior visual field are consistent with Seidel theory and other studies.12–14,24,32,33 In addition, we found a slight decrease in spherical aberration (C3) with angle, and this finding was similar to other studies.12–14,24,32,33 We also found a quadratic increase in HO RMS from center to periphery along the horizontal field by a factor of 2.2. This finding is similar to that of Lundström et al.24 who reported a 2.7-times increase in the HO RMS from center to periphery. The above findings are similar to other studies that used either a laboratory-built aberrometer or a modified commercial aberrometer. Our conclusion is that the COAS-HD VR can be used to obtain reliable and repeatable peripheral aberation data. The other studies have used either samples with few subjects having varying amounts of ametropia or measured only one part of the visual field. Our study adds to the existing literature of peripheral aberation measurements in 18 emmetropic subjects along the horizontal (±40°) and inferior (−20°) visual field.

**Advantages of the Instrument**

This instrument has an open field of view that allows a researcher to present any stimuli at any distance and gaze angle. Simultaneous presentation of binocular stimuli is also possible. Any changes in aberrations with accommodation can also be measured for both central and peripheral vision. In conclusion, the COAS-HD VR provides fast, repeatable, and valid peripheral aberration measurements and can be used efficiently to measure off-axis aberrations in the peripheral visual field.

**ACKNOWLEDGMENTS**

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The authors thank Sebastian Carlström for being the test person in Figure 1.

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**REFERENCES**


**TABLE 2.**

Comparison of this study on-axis repeatability with other published on-axis repeatability

<table>
<thead>
<tr>
<th>Authors</th>
<th>Instrument</th>
<th>Subjects (eyes)</th>
<th>Analysis diameter (mm)</th>
<th>No. repeated measurements</th>
<th>CR (μm)</th>
<th>CV (%)</th>
<th>ICC</th>
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<td>Miranda et al.21</td>
<td>irx3</td>
<td>23 (23)</td>
<td>4</td>
<td>3</td>
<td>0.045</td>
<td>27.8</td>
<td>—</td>
</tr>
<tr>
<td>Efron et al.17</td>
<td>irx3</td>
<td>13 (13)</td>
<td>4</td>
<td>3</td>
<td>0.076</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
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<td>OPD scan</td>
<td>36 (61)</td>
<td>6</td>
<td>3</td>
<td>—</td>
<td>—</td>
<td>0.448</td>
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<tr>
<td>Mirshahi et al.19</td>
<td>Zywave</td>
<td>20 (40)</td>
<td>7</td>
<td>6</td>
<td>—</td>
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<td>—</td>
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<tr>
<td>This study</td>
<td>COAS HD VR</td>
<td>18 (18)</td>
<td>5</td>
<td>5</td>
<td>0.029</td>
<td>11</td>
<td>0.929</td>
</tr>
</tbody>
</table>

The CR, CV, and ICC are compared.


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Optometry and Vision Science, Vol. 87, No. 10, October 2010
Repeatability of Peripheral Aberrations in Young Emmetropes: Erratum

In the October 2010 issue of Optometry and Vision Science, Figure 5 on page 757 of “Repeatability of Peripheral Aberrations in Young Emmetropes” is incorrect. The corrected Figure 5 and legend appear below.

**Figure 5.**
Aberration data plotted across the horizontal visual field for horizontal coma ($C_3^1$), spherical aberration ($C_4^0$) and HO RMS. The horizontal coma decreases linearly with significant difference between each off-axis angle, there is a slight decrease of spherical aberration in the periphery ($±40°$) and the total HO RMS shows a 4.2 times increase in the aberrations from center to periphery. The spherical aberration and HO RMS show a significant difference only at the $±30°$ and $±40°$ eccentricity. The error bars represent the standard error of the mean (SEM).

**REFERENCE**
Symmetries in peripheral ocular aberrations


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A mirror symmetry in the aberrations between the left and right eyes has previously been found foveally, but while a similar symmetry for the peripheral visual field is likely, it has not been investigated. Nevertheless, the peripheral optical quality is often evaluated in only one eye, because it is more time efficient than analyzing the whole visual field of both eyes. This study investigates the correctness of such an approach by measuring the peripheral wavefront aberrations in both eyes of 22 subjects out to \(C_6\) horizontally. The largest aberrations (defocus, astigmatism, and coma) were found to be significantly correlated between the left and right eyes when comparing the same temporal or nasal angle. The slope of the regression line was close to \(1\) (within 0.05) for these aberrations, with a negative slope for the horizontally odd aberrations, i.e. the left and right eyes are mirror symmetric. These findings justify that the average result, sampled in one of the two eyes of many subjects, can be generalized to the other eye as well.

Keywords: peripheral visual field; off-axis wavefront aberrations; left and right eyes; mirror symmetry

1. Introduction

The image on the peripheral retina is often degraded compared with the foveal image, primarily by oblique astigmatism and coma [1–7]. Information on these peripheral aberrations is of interest for research on, for example, the effect of optical errors on peripheral vision [8–11], improving vision for people with central vision field loss [12,13], and eye modeling with individual data retrieved from ocular wavefront tomography [14,15]. Furthermore, the interest in measurements of peripheral refractive errors has increased, due to their possible link to myopia [16–18]. One potential problem in peripheral refraction is that the determination of the far-point is not unambiguous. For example, Charman and Atchison have discussed the influence of oblique astigmatism and higher-order aberrations on the best focus value [19]. Therefore, a full wavefront measurement is desired even when only the peripheral refractive state is of interest.

Ideally, data from the whole peripheral visual field of both eyes should be evaluated. However, for reasons of time efficiency, it is common that only a few angles in one of the eyes are sampled. A previous study on foveal aberrations [20] found significant correlations between the left and right eyes for most subjects, with a mean correlation coefficient of 0.517. The aim of this study is to investigate the correlation of peripheral aberrations over the horizontal meridian between the left and right eyes for different states of accommodation in myopic and emmetropic subjects. The results can give an insight into the overall symmetries that exist between the left and right eyes and justify the prevalent modus operandi of measuring one eye.

2. Methods

Peripheral wavefront measurements were performed using two Hartmann–Shack wavefront sensors. These were one laboratory Hartmann–Shack sensor in Murcia, Spain, which has been previously used for peripheral measurements [21,22], and one commercial Hartmann–Shack (COAS-HD-VR) sensor in Kalmar, Sweden, which has been shown to provide repeatable measurements of peripheral aberrations [23]. In total, there were 22 subjects. Informed consent was obtained beforehand, and the study followed the tenets of the Helsinki declaration. The subjects were measured without any refractive correction and with natural pupil size and accommodation (no cycloplegia). With both systems, three measurements per angle were performed and the resulting Zernike coefficients were averaged.

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2.1. Laboratory Hartmann–Shack wavefront sensor

The peripheral aberrations of the horizontal visual field were measured at 0°, ±10°, ±20°, ±30°, and ±40° in the left and right eyes of eight subjects (age range: 25–32 years); four emmetropes and four myopes (sphere: −2.00 – −7.25 D, astigmatism ≤0.75 D). Zernike coefficients up to the fifth order were calculated for a circular wavefront circumscribing the entire elliptical pupil, and then shrunk to 4 mm diameter [24] to allow comparison. The subjects turned their eyes relative to the Hartmann–Shack sensor. The system had an open field of view and the accommodation was controlled by binocular fixation to a target at a distance of 2 m, except for the two most myopic subjects who used a fixation target at 25 cm distance instead.

2.2. COAS-HD-VR

The peripheral aberrations of the horizontal visual field were measured at 0°, ±20°, and ±35° in the left and right eyes of 14 subjects (age range: 22–31 years); seven emmetropes and seven myopes (sphere: −2.00 – −5.00 D, astigmatism ≤0.50 D). The standard software package of the instrument was used to calculate the Zernike coefficients up to the fifth order for a circular wavefront circumscribing the entire elliptical pupil, and then shrunk to 4 mm diameter [24] to allow comparison. The subjects turned their eyes relative to the Hartmann–Shack sensor. The system had an open field of view and the accommodation was controlled by binocular fixation to a target at a distance of 2 m, except for the two most myopic subjects who used a fixation target at 25 cm distance instead.

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3. Results

Figure 1 shows an example of the wavefront aberrations measured in two subjects for the horizontal angles of 0°, ±20°, and ±40° of the right and left eyes. The refractive errors (i.e. the second-order Zernike coefficients) have been removed to show more clearly the symmetry in the higher order aberrations that exist between the left and right eyes when comparing the same temporal/nasal angle (compare the same angle for the right eye and the left eye). The subjects have been chosen in order to show one subject (upper row) with a high mirror symmetry between the left eye and the right eye and one subject (lower row) with a lower symmetry.

The correlation of peripheral aberrations over the horizontal meridian between the right and left eyes for all subjects was quantified by calculating the correlation and the slope of the best fit regression lines between the two eyes for the second to fourth radial order Zernike coefficients (notation following the ANSI standard [25]). Table 1 gives the slope values for the fovea (denoted by 0°) as well as for the off-axis angles of ±10° (denoted by 10°), ±20° (denoted by 20°), and a combination of ±30°, ±35°, and ±40° (denoted by 30°–40°) for each Zernike coefficient separately. The last column shows the best fit slope when data from all angles are taken into consideration. Note that the number of subjects and measurements vary between the columns as the two instruments were measuring in different off-axis angles. The stars indicate that the correlation was statistically significant (p < 0.01). The slope values of Table 1 are for all
unaccommodated eyes, including both emmetropes and myopes. In Table 2, the slopes for all angles are given separately for the emmetropic and the myopic subjects as well as for the subgroup of 14 subjects who were also measured during accommodation with the COAS-HD-VR system.

Both tables show that defocus \((c_3^3)\) is highly correlated with the right and left eye for all angles and there is also some correlation for coma \((c_3^4)\) and spherical aberration \((c_4^2)\) over the whole horizontal visual field. When going off-axis, the number of significantly correlated coefficients increases and the slopes approach unity. This is especially obvious for the aberrations whose values depend on the off-axis angle, such as, for example, with/against-the-rule astigmatism \((c_3^2)\) and horizontal coma \((c_3^4)\); the slopes of the best fit line are very close to unity in off-axis angles and both coefficients increase with eccentricity as predicted by the Seidel theory and as shown in earlier studies [1–7].

A negative sign of the slopes in Tables 1 and 2 tells us that that aberration has a change in sign when comparing the same temporal/nasal angle of the left and right eyes. If the two eyes are mirror symmetric, such a change in sign is expected for the Zernike coefficients that are odd over the horizontal meridian. This is also what Tables 1 and 2 show; the significant slopes for the odd coefficients \(c_3^2, c_3^4, c_4^2, c_4^4\), and \(c_6^2\) are all negative, whereas the other significant slopes are all positive. Consequently, the right and left eyes are mirror symmetric over the horizontal field. The mirror symmetry can also be seen in Figure 2, where the same data as given in Table 1 are pictured with the Zernike coefficients of the right eye plotted against those of the left. The three graphs show defocus, astigmatism, and higher (third–fourth) order aberrations. The blue color is used for aberrations that are even over the horizontal meridian and red for the odd ones. An example of the even variation of astigmatism \((c_3^2)\), the odd variation of coma \((c_3^4)\), and the small variation in spherical aberration \((c_4^2)\) over the horizontal meridian of the right and left eye of one subject is shown in Figure 3. As can be seen, the nasal visual field generally has larger aberrations.

### 4. Discussion

The advantage of using two different instruments, one laboratory and one commercial, with separate analyzing software and located in two different laboratories is that the risk of systematic errors influencing the results is lower. In this study, it is difficult to compare the systems to find any potential bias since different subjects were measured in the different laboratories. However, when analyzing the results separately for the two systems, the slope of the regression line between the left and the right eyes was still close to one for defocus, with/against-the-rule astigmatism, and horizontal coma, although the overall correlation was somewhat weaker with the laboratory Hartmann–Shack sensor.

The instruments also differed in the accommodative stimuli presented to the subjects; the laboratory
sensor had a binocular fixation target with an accommodative demand of 0.5 D for the emmetropes, whereas the COAS-HD-VR was used together with a monocular target seen through a lens placed to give either 0 D or 4 D of accommodative demand. The choice of more than one accommodative demand was to investigate the symmetry for different viewing distances. As expected, we found equal symmetry in all three settings (see the previous paragraph, the last column of Table 1, and the last column of Table 2).

The mirror symmetry between the right and left eyes, which this study found over the whole horizontal meridian, has been noted earlier in a study on foveal aberrations of the right and left eyes [20]; in that study ten out of the 12 second- to fourth-order Zernike coefficients showed a significant correlation between the right and left eyes for the 109 subjects ($p < 0.01$). The fact that only four coefficients in Table 1 showed a significant correlation for the on-axis wavefronts can be explained by the lower number of subjects in the current study. However, the two studies agree on the most correlated aberrations (correlation coefficient of our foveal data compared with the correlation given in [20] in parentheses): defocus $c_0^2$ with 0.99 (0.98), spherical aberration $c_4^0$ with 0.79 (0.82), astigmatism $c_2^2$ with 0.78 (0.77), and coma $c_5^{1}$ with 0.54 (0.69).

The fact that there is a mirror symmetry between the two eyes also off-axis means that one can adopt the study protocol described in the introduction, i.e. it is enough to sample one of the subjects’ two eyes. However, when drawing this general conclusion, it is important to bear in mind that it applies to a population of subjects and that there can be individual differences, as shown by the wavefronts on the lower row of Figure 1. Additionally, the correlation between

Figure 2. The peripheral aberrations of the right eye plotted against those of the left for all subjects in the study (relaxed accommodation). The two first graphs show defocus and astigmatism in diopters and the third graph shows the third- and fourth-order Zernike coefficients in μm for a 4 mm pupil. The aberrations that are even over the horizontal meridian are plotted as blue stars and the odd are plotted as red circles. To guide the reader lines are plotted through zero with a slope of +1 (blue) and −1 (red). (The color version of this figure is included in the online version of the journal.)

Figure 3. The two graphs show how the with/against-the-rule astigmatism ($c_2^2$), horizontal coma ($c_1^3$), and spherical aberration ($c_4^0$) vary with the off-axis angle in the right and left eyes for one subject (three measurements per angle, pupil diameter of 4 mm). (The color version of this figure is included in the online version of the journal.)
the two eyes over a large part of the horizontal field suggests that the right and left eyes have similar properties, both regarding optics and shape of the retina. This might be one of the reasons why the emmetropization process and the prevalence of myopia are similar in both eyes.

While processing the wavefront data, some correlation was also found between the temporal and nasal fields of the same eye, especially for astigmatism (correlation coefficient 0.75). In spite of that, we recommend cautiousness when only sampling one half of the horizontal meridian, for two reasons. First, defocus showed large differences between individuals in how it varied with the off-axis angle over the temporal and nasal halves, as earlier noted by Gustafsson and co-workers and Ferree and colleagues [5,26]. Secondly, the higher-order aberrations tended to be larger in the nasal visual field, which can also be seen for astigmatism in Figure 3 and in the figures of references [2,3,21,23].

Generally, the amount of aberrations and their behavior with the off-axis angle in this study are in agreement with earlier studies [1–7]; i.e. a quadratic increase of astigmatism, close to linear increase of coma, and slightly lower spherical aberration in large off-axis angles. As both emmetropic and myopic coma, and slightly lower spherical aberration in large off-axis angles. As both emmetropic and myopic properties, both regarding optics and shape of the retina. This might be one of the reasons why the emmetropization process and the prevalence of myopia are similar in both eyes.

Acknowledgements

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References

Influence of Age on Peripheral Ocular Aberrations

Karthikeyan Baskaran*, Peter Unsbo†, and Jörgen Gustafsson‡

ABSTRACT

Purpose. To compare peripheral lower and higher order aberrations across the horizontal (±40°) and inferior (−20°) visual fields in healthy groups of young and old emmetropes.

Methods. We have measured off-axis aberrations in the groups of 30 younger (24 ± 3 years) and 30 older (58 ± 5 years) emmetropes. The aberrations of OD were measured using the COAS-HD VR Shack-Hartmann aberrometer in 10° steps to ±40° horizontally and −20° inferiorly in the visual field. The aberrations were quantified with Zernike polynomials for a 4 mm pupil diameter. The second-order aberration coefficients were converted to their respective refraction components (M, J_{45}, and J_{180}). Mixed between-within subjects, analysis of variance were used to determine whether there were significant differences in the refraction and aberration components for the between-subjects variable age and the within-subjects variable eccentricity.

Results. Peripheral refraction components were similar in both age groups. Among the higher order coefficients, horizontal coma (C_{31}) and spherical aberration (C_{40}) varied mostly between the groups. Coma increased linearly with eccentricity, at a more rapid rate in the older group than in the younger group. Spherical aberration was more positive in the older group compared with the younger group. Higher order root mean square increased more rapidly with eccentricity in the older group.

Conclusions. Like the axial higher order aberrations, the peripheral higher order aberrations of emmetropes increase with age, particularly coma and spherical aberration.

(Optom Vis Sci 2011;88:1088–1098)

Key Words: peripheral aberrations, off-axis refraction, aging, COAS-HD VR

Aging causes considerable changes in the optical and neural structures of the human eye. Visual acuity and contrast sensitivity decline with age, because of changes in both optical (increased monochromatic aberrations and intraocular light scattering) and neural factors. On-axis higher order monochromatic aberrations increase with age whereas the lower order aberrations (refractive errors) show small changes of the order of 1 D throughout life. Studies have also investigated the contributions of corneal and internal aberrations and found that the balance between the corneal and internal aberrations is lost with aging. Most of the above studies have concentrated on the age-related changes in the optics associated with central vision. Age-related changes in the optics affect both the central (on-axis) and peripheral vision (off-axis). In the periphery detection of pattern, movement and flicker are affected by the changes in the optical defocus, whereas changes in optical defocus or aberrations have little effect on resolution tasks in normal subjects. Peripheral resolution acuity is neurally limited. However, a recent study has shown that the low contrast resolution acuity declines with optical defocus in the periphery. Moreover, studies performed on subjects with central visual field loss have reported improvements in resolution acuity with peripheral (eccentric) refractive corrections at their preferred retinal locus. It would be interesting to know if resolution acuity in these subjects could be improved further by correcting both the lower and higher order aberrations for their eccentric fixation. It is possible that optical aberrations other than refractive errors could reduce peripheral image quality in these subjects. These subjects mostly correspond to an older age group whose preferred retinal locus can vary from 5 to 35° in the periphery. Therefore, it would be ideal to have normative data on the peripheral aberration profile of healthy older subjects.

There are few studies, which have explored age-related optical changes in the peripheral visual field. The influence of age on...
peripheral refractive errors along the horizontal visual field has been studied. The earlier studies by Millodot \textsuperscript{27,28} and Scialfa et al.\textsuperscript{29} had conflicting results about the peripheral astigmatism with no details regarding the central refraction. Charman and Jennings\textsuperscript{30} measured peripheral refraction in two subjects with an interval of 26 years and found an increase in relative peripheral myopia and a small increase in peripheral astigmatism. The recent cross-sectional studies by Atchison et al.\textsuperscript{31,32} found that younger and older subjects with similar central refractive corrections had similar peripheral refraction profiles. There is only one study available in the literature that has shown the effect of age on peripheral higher order aberrations. Mathur et al.\textsuperscript{33} measured peripheral aberrations up to $\pm 20^\circ$ eccentricity (matrix of 38 points in the 20° visual field) in a small group of young and older emmetropes. They concluded that peripheral higher order aberrations increase with age, but peripheral visual performance deficits observed in normal older people is not attributable to this increase. Because their study was restricted in both sample size and eccentricity, it would be reasonable to measure peripheral aberrations in a larger sample of

<table>
<thead>
<tr>
<th>Refraction components/ aberration coefficients</th>
<th>Age</th>
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<th>Age/eccentricity interaction</th>
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<td>0.97</td>
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</tr>
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<td>$C_{2}$</td>
<td>0.18</td>
<td>0.00*</td>
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</table>

*Statistically significant different values.

\textbf{TABLE 1.}
The p values of mixed between-within subjects analysis of variance for the refraction components (in bold) and aberration coefficients along the horizontal visual field.

\textbf{FIGURE 1.}
The refraction components $J_{45}$ (A), RPRE (B), and $J_{180}$ (C) along the horizontal visual field for both young and old groups. Both groups had a similar peripheral profile with a linear increase of $J_{45}$ astigmatism, myopic shift of RPRE, and quadratic increase in $J_{180}$ astigmatism. Note the y axis scales are different in the panels. The error bars represents standard error of mean. The plots for young and older eyes have been staggered horizontally so that error bars do not overlap.
subjects with more highly eccentric angles. Therefore, the aim of this study is to compare peripheral lower and higher order aberrations across the horizontal (±40°) and inferior (±20°) visual field in a group of young and old emmetropes.

**METHODS**

**Subjects**

A prospective study was performed on the OD of 60 healthy subjects (29 females and 31 males). They were divided into two groups based on age. Group 1 contained 30 younger emmetropes (24 ± 3 years; age range: 20 to 29 years) with a mean subjective refraction of −0.23 dioptr sphere (DS) (±0.39 DS) and −0.37 dioptr cylinder (DC) (±0.19 DC). Group 2 contained 30 older presbyopic emmetropes (58 ± 5 years; age range: 52 to 67 years) with a mean subjective refractions +0.31 DS (±0.65 DS) and −0.55 DC (±0.26 DC), respectively. All subjects had distance visual acuities of 0.0 logarithm of the minimum angle of resolution or better. The older subjects were evaluated for lens changes based on Age-Related Eye Disease Study scales. All the older subjects had a lens grading of grade 1 (no opacity) or better for nuclear, cortical, and posterior subcapsular cataract. The subjects had no history of ocular surgery or pathology. No cycloplegic drugs were used for measurements. The subjects gave their informed consent after the nature and the intent of the study had been explained. The study was approved by the local ethics committee, and the study protocol was designed in accordance with the tenets of Declaration of Helsinki.

**Experimental Procedures**

Monochromatic aberrations of the OD (OS occluded) were measured with a commercial open-view COAS-HD VR (AMO Wavefront Sciences, Albuquerque, NM) Shack-Hartmann aberrometer. The method used for measuring peripheral aberration with COAS-HD VR has been described in detail elsewhere. The

*FIGURE 2 (A–D).*

Zernike coefficients of third-order aberrations along the horizontal visual field for both young and old groups. Horizontal coma (Fig. 2C) differed most between the groups. Note the y axis scales are different in the panels. The error bars represent standard error of mean. The plots for young and older eyes have been staggered horizontally so that error bars do not overlap.
FIGURE 2 (E–I).
Zernike coefficients of fourth-order aberrations along the horizontal visual field for both young and old groups. Spherical aberration (Fig. 2G) differed most between the groups. Note the y axis scales are different in the panels. The error bars represent standard error of mean. The plots for young and older eyes have been staggered horizontally so that error bars do not overlap.
measuring wavelength was 840 nm, and the resulting Zernike coefficients were converted for a wavelength of 555 nm. The aberrations were measured with natural pupils in a dim room illumination. The subjects positioned their head in a chin rest and fixated at a target through a glass slide hot mirror. The target consisted of 3 mm diameter red light-emitting diodes (LED) placed 3 m from the subject. The LEDs were placed in a radial geometry subtending a visual angle of ±40° horizontally and +20° superiorly. The measurements were performed at 11 different visual field locations: fovea (on-axis), out to measure within subjects, repeated measures analysis of variance, with order aberrations for both groups were analyzed. The HO RMS from to third- to sixth-order was also computed. Mixed between- order root mean square (HO RMS) and the individual Zernike coefficients from second- to sixth-order were exported where. All the analyses were reported according to Optical Society of America recommended standards.37

**Data Analysis**

The higher order root mean square (HO RMS) and the individual Zernike coefficients from second- to sixth-order were exported from COAS-HD VR inbuilt software to Microsoft Excel (Microsoft, Redmond, WA). Statistical analysis was done with the SPSS software package version 17.0.0.235 for windows (SPSS, Chicago, IL). Graphs were plotted with GraphPad Prism software package version 5.0.3.477 for windows (GraphPad, San Diego, CA).

**Refraction Components**

The Zernike coefficients from the three repeated readings at each off-axis angle for all subjects were averaged. The spherical equivalent M was calculated from Eq. 1. The regular astigmatic component J180 and oblique astigmatism J45 were calculated from Eqs. 2 and 3.

\[
M = -4\frac{3 \times C_3 + 12 \times 5 \times C_5}{r^2}
\]

(1)

\[
J_{180} = \frac{-2 \times 6 \times C_6}{r^2}
\]

(2)

\[
J_{45} = \frac{-2 \times 8 \times C_8}{r^2}
\]

(3)

In the above equations C3, C6, C8, and C2 are Zernike coefficients for defocus, spherical aberration, regular astigmatism, and oblique astigmatism in micrometers (μm), and r is pupil radius in millimeter (mm). The relative peripheral refractive error (RPRE), the change in off-axis spherical equivalent relative to the on-axis spherical equivalent, was calculated for both groups.

**Aberration Components**

The nine individual Zernike coefficients of third- and fourth-order aberrations for both groups were analyzed. The HO RMS from to third- to sixth-order was also computed. Mixed between-within subjects, repeated measures analysis of variance, with Geisser-Greenhouse adjustments were used to determine whether there were significant differences in the refraction and aberration components for the between-subjects variable age and the within-subjects variable eccentricity (off-axis). A p value of <0.05 was considered statistically significant.

**RESULTS**

**Horizontal Visual Field**

**Refraction Components**

Age had significant effects on J45, J180 along the horizontal visual field, but no effect on RPRE. Eccentricity showed significant effect on all refraction components. There was a significant age-eccentricity interaction for J180 (Table 1).
J45 astigmatism increased linearly in both groups from the temporal to the nasal field. The rate of change was greater in the younger group (0.007 D/deg) than in the older group (0.003 D/deg). J45 astigmatism showed a very small variation (up to 0.5 D) across the visual field compared with J180 astigmatism (up to 2.35 D) (Fig. 1A, C). RPRE showed a myopic shift in the periphery for both groups with temporal-nasal asymmetry. Both the groups had maximum myopic shift of around 0.5 D in the temporal field whereas it was >1.5 D in the nasal field (Fig. 1B). J180 astigmatism increased quadratically along the horizontal visual field with temporal-nasal asymmetry for both groups. The older group had significantly higher astigmatism (up to 2.35 D) compared with the younger group (up to 2.1 D). This difference was more pronounced on the temporal field with the older group having astigmatism of 1.4 D compared with the 1.0 D of astigmatism in the younger group (Fig. 1C).

Aberration Components

The aberration coefficients that changed significantly with age were trefoil (C31), horizontal coma (C30), spherical aberration (C40), and secondary astigmatism (C42). Eccentricity showed significant effects on all coefficients except C42. There was a significant age-eccentricity interactions for most coefficients except C44 and C34 (Table 1).

Among the higher order coefficients, horizontal coma (C30) differed most between the groups and across the field. Horizontal coma (C30) increased linearly in both groups from the nasal to the temporal field. The rate of change across the field was greater in the older group (0.015 μm/deg) than in the younger group (0.007 μm/deg) (Fig. 2C). Spherical aberration (C40) was more positive in the older group than in the younger group. Spherical aberration was positive up to ±20° then shifted to negative values in the younger group whereas it remained positive across the field for the older group except at ±40° (Fig. 2G).

Higher Order Root Mean Square

Age and eccentricity had significant effects on HO RMS across the horizontal visual field (p < 0.05). HO RMS showed a qua-
dratic rate of change with temporal-nasal asymmetry across the field for both the groups. The rate of change was greater in the older group than the younger group (Fig. 3).

Inferior Visual Field

Refraction Components

Age had a significant effect on J45 astigmatism and no significant effect on RPRE and J180 astigmatism. Eccentricity showed significant effects on all refraction components. There was a significant age-eccentricity interaction for J45 (Table 2).

J45 astigmatism increased linearly in both groups with the rate of change higher in the younger group (0.015 D/deg) than older group (0.006 D/deg) (Fig. 4A). RPRE showed a myopic shift (up to −0.75 D) in both groups with no significant difference (Fig. 4B). J180 astigmatism increased toward the periphery in both groups with the young group having higher values (up to 0.72 D) than the old group (up to 0.58 D). However, this increase was not statistically significant (Fig. 4C).

Aberration Components

Among the aberration coefficients in the inferior visual field, only vertical coma (C3 1) demonstrated significant effects of both age and eccentricity. Age had significant effect on horizontal coma (C3 2), but there was no significant effect of eccentricity. All the other coefficients showed significant effect of eccentricity except C4 2 and C4 4. There were significant age-eccentricity interactions for most coefficients (Table 2).

Vertical coma (C3 1) changed linearly in both groups, with rate of change higher in the old group (0.009 μm/deg) than in the young group (0.005 μm/deg) (Fig. 5B). Spherical aberration (C4 0) was slightly positive for the younger group (up to +0.021 μm) and more positive in the older group (up to

FIGURE 5 (A–D).
Zernike coefficients of third-order aberrations along the inferior visual field for both young and old groups. Vertical coma (Fig. 5B) differed most between the groups. Note the y axis scales are different in the panels. The error bars represent standard error of mean. The plots for young and older eyes have been staggered horizontally so that error bars do not overlap.
FIGURE 5 (E–I).
Zernike coefficients of fourth-order aberrations along the inferior visual field for both young and old groups. Spherical aberration (Fig. 5G) differed most between the groups. Note the y axis scales are different in the panels. The error bars represent standard error of mean. The plots for young and older eyes have been staggered horizontally so that error bars do not overlap.

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with the earlier studies. The effect on J45 astigmatism. However, the amount of J45 astigmatism was only 0.22 D higher in the younger group (at nasal 40° and inferior 20°) than in the older group, which is a relatively small difference in the periphery.

As expected, RPRE showed myopic shift with no significant difference in both groups along the horizontal and inferior visual field. This finding is in line with earlier studies, which have shown emmetropes become relatively myopic in the periphery. The older subjects had slightly higher negative values of J180 astigmatism in the periphery than the younger group (−1.4 vs. −1.0 D at temporal 40°) along the horizontal visual field. However, there were no significant differences in J180 astigmatism between the groups in the inferior visual field. J180 astigmatism showed a significant quadratic increase with eccentricity in both groups along the horizontal visual field. Our results regarding J180 astigmatism agree with the results of Charman and Jennings study in which they reported slightly higher negative values in older eyes along the horizontal visual field. We also observed temporal-nasal asymmetry for RPRE and J180 along the horizontal visual field with greater changes in refraction for the nasal than for the temporal visual field in both groups. The nasal-temporal asymmetry is most probably attributable to the difference between the measurement axis (line of sight) and the eye’s optical axis.

In summary, the increases in peripheral refraction (lower order) with age across the horizontal and inferior visual field are relatively small. Even though we find no difference in peripheral refraction pattern between the two groups, it should be noted that refractive error in the periphery increases with eccentricity. Furthermore, it might be important to correct these peripheral refractive errors to achieve a better visual function in central visual field loss subjects.

### Aberration Components

The dominant higher order aberration in the periphery was coma, and this varied significantly between the groups and across the field. The horizontal coma C3 along the horizontal visual field and vertical coma C3 along the inferior visual field increased linearly in both groups in agreement with Seidel theory. Furthermore, the horizontal and vertical coma slopes were twice as large in the older group than the younger group. This finding is consistent with the previous study by Mathur et al. who also reported a rapid increase in coma slopes for older emmetropes. However, the reason for this rapid increase of coma slopes in older emmetropes is not clearly understood, and currently available eye models cannot fully reproduce the observed age-related changes in coma.

What is intriguing is why coma should increase with age—is this because of corneal, lenticular, or other changes? A recent axial study by Bierro et al. had found that in young eyes, the positive corneal coma is balanced by the negative internal (lenticular) coma. However, this balance is partly lost in the older eyes leading to increase of ocular (whole eye) horizontal coma. In addition, Atchison measured peripheral corneal and ocular aberrations in a middle-aged group and found that the corneal third-order coefficients were higher than the ocular third-order coefficients, indicating that the internal third-order coefficients provided a degree of balance to the corneal third-order coefficients. The studies by Bierro et al. and Atchison show that the balance between the corneal and internal third-order coefficients is present both axially and peripherally for the young and middle-aged groups. Furthermore, on-axis studies have shown that this balance is lost with aging thereby increasing the magnitude of ocular aberrations in old eyes. We could assume that the balance between corneal and lenticular coma is lost with aging also in the periphery. The loss of this balance could lead to both cornea and lens contributing to the increase of peripheral ocular coma in old eyes. This could be a reason for the increase in coma slopes that we observe in our study.

**FIGURE 6.**

HO RMS of the third- to sixth-order Zernike coefficients along the inferior visual field for both young and old groups. HO RMS increased from center to periphery in both groups with the old group having significantly higher magnitude of aberrations in the periphery. The error bars represent standard error of mean. The plots for young and older eyes have been staggered horizontally so that error bars do not overlap.

+0.038 μm) with significant changes across the inferior visual field (Fig. 5G).

**Higher Order Root Mean Square**

HO RMS showed significant variation across the inferior visual field for both groups. The old group had significantly higher values than the young group at 10° and 20° eccentricity (p < 0.05) (Fig. 6).
loss of balance may not only affect coma but also other aberration coefficients. However, this assumption of loss of balance between the corneal and lenticular aberrations, and the consequent increase in total ocular aberrations in the periphery with aging needs to be investigated.

Among the fourth-order coefficients, the peripheral spherical aberration was significantly higher in the old group than the young group along the horizontal and inferior visual fields. However, in our study, the on-axis spherical aberration between the young (0.009 ± 0.020 μm) and old (0.012 ± 0.038 μm) group for a 4 mm pupil showed no significant age dependence in agreement with previous studies with emmetropic subjects. The studies that reported increase in spherical aberration with age included large refraction ranges, which could have influenced their results. The remaining coefficients of the third- and fourth-order aberrations did not show any major variation between the groups.

HO RMS showed quadratic field dependence in both groups along the horizontal visual field. The young and old group showed on average 1.5 and 2.1 times increase in HO RMS from center to ± 20° eccentricity (horizontal and inferior). This shows that the older group had higher rate of change in HO RMS than the younger group across the horizontal and inferior visual field. These results are in agreement with the previous study by Mathur et al., who also reported a similar increase of RMS than the younger group across the horizontal and inferior visual fields. The young and old group showed on average 3.1 and 5.4 times increase in HO RMS in their old group for the 20° visual field. However, we have extended the horizontal visual field to ± 40° and therefore considering a larger part of the visual field, the young and old group showed on average 3.1 and 5.4 times increase in HO RMS from center to periphery. This suggests that the rate of change in HO RMS from ± 20° to ± 40° is much more rapid in both groups with greater increase in the older group than the young group. This increase in HO RMS across the horizontal visual field is mainly because of the increase in horizontal coma (compare Fig. 2C with Fig. 3).

Visual Performance

Does the increase in higher order aberrations influence visual performance in the periphery for old subjects? A previous study has shown that this amount of increase in higher order aberrations degrades the peripheral image quality. In addition, there are also other optical factors such as chromatic aberration, pupilary miosis, and intraocular light scattering, which could add to or partly mask the effect of increased monochromatic higher order aberrations. Nevertheless, some of the earlier studies have concluded that poor peripheral visual performance in older subjects is primarily neurally in origin and optical factors play a minor role. However, a recent study by Rosen et al. has demonstrated that low contrast resolution acuity declines with optical defocus in the periphery of healthy young subjects. Further studies are needed to ascertain whether the increased higher order aberrations in combination with lower order aberrations reduce peripheral visual performance in older healthy subjects. In particular, this amount of increase in higher order aberrations could further degrade the peripheral vision in older central visual field loss subjects, who use their preferred retinal locus for reading or other resolution tasks. To understand this better, correction of higher order aberrations and evaluation of the visual function should be performed in older subjects with central visual field loss.

In conclusion, the peripheral higher order aberrations increase with age particularly coma and spherical aberration. However, the question of whether this increase in higher order aberrations and the corresponding decrease in retinal image quality have any impact on peripheral vision needs to be investigated further.

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Clinical Impact of Objectively Determined Peripheral Refractive Error Correction on Low-Contrast Resolution Acuity

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Abstract

The purpose of this study was twofold: to find a fast, more clinically applicable method for improving peripheral visual function and to assess the impact of objectively obtained off-axis refraction on peripheral low contrast visual acuity. We measured peripheral low-contrast resolution acuity with Gabor patches both with and without off-axis correction at 20° in the nasal visual field of 10 emmetropic subjects; the correction was obtained using an open-field Hartmann-Shack wavefront sensor. The majority of subjects had simple myopic astigmatism, at 20° in the nasal visual field ranging from 1.00 DC to 2.00 DC, with axis orientations generally near 90 degrees. The mean uncorrected and corrected low-contrast resolution acuities for all subjects were 0.92 logMAR and 0.86 logMAR respectively. This shows an improvement in resolution acuity of 0.06 logMAR (\(p = 0.028\)) after off-axis refractive error correction. When grouped according to the amount of off-axis astigmatism, the \(-1.00 \text{ DC}\) group showed no difference in acuity with correction, the \(-1.25 \text{ DC}\), \(-1.50 \text{ DC}\) and \(-2.00 \text{ DC}\) groups improved on average by 0.05, 0.14 and 0.16 logMAR respectively. This is the first study to objectively determine peripheral refractive errors and compare low-contrast visual acuity with and without this refractive correction. This suggests that optical factors, such as off-axis astigmatism, do influence peripheral visual tasks involving low-contrast and that there are definite benefits in correcting even moderate amounts of off-axis refractive errors.

Keywords: Visual acuity; Low-contrast resolution acuity; Off-axis refractive errors; Peripheral vision; Off-axis astigmatism

1. Introduction

The visual environment is enormously complex; consisting of stationary and dynamic stimuli in a multitude of sizes, hues and contrast levels. As such, the human eye has evolved to make use of many of these attributes. The fovea is specialized in the resolution and identification of fine details in stationary objects, whereas the role of the peripheral retina in comparison is to detect changes occurring within the field of view. Once "detected", visual stimuli in the peripheral visual field are subsequently “foveated” to allow for improved resolution capabilities. Traditional tests of visual function generally employ high-contrast stimuli, which is somewhat surprising as the majority of visual tasks in a “real-world” setting involve the resolution of low-contrast objects (Jackson and Wolffsohn, 2007). Testing the visual performance of patients with central-field loss solely using high-contrast tests may therefore give an inadequate representation of true visual performance especially considering that this group must rely on eccentric viewing (peripheral vision) in order to see.

It is widely accepted that the limiting factor for visual resolution in the fovea is the optical quality of the eye (Anderson et al., 1991; Banks et al., 1991; Frisén and Glansholm, 1975; Green, 1970; Thibos et al., 1987; Thibos, 1998; Williams et al., 1996) relatively small errors in the refractive state of the eye result in reduced visual performance. In the peripheral retina it has been determined that visual performance, in particular high contrast resolution acuity, is constrained by neural sampling; the spacing between ganglion cell receptive-fields ultimately limiting most visual tasks (Anderson et al., 2002; Banks et al., 1991; Lundström et al., 2007b; Thibos et al., 1987; Williams, 1985; Williams and Coletta, 1987). In addition, it has been shown that there exists a clear asymmetry in ganglion cell density between the nasal and temporal retina, as well as along the vertical meridian. Peripheral visual acuity is in part paralleled by these anatomical differences (Curcio and Allen, 1990; Lewis et al., 2011). Due to these factors, peripheral high-contrast resolution acuity is relatively insensitive to optical defocus; requiring several diopters of defocus before resolution diminishes significantly (Anderson, 1996; Millodot and Lamont, 1974; Rempt et al., 1976; Rovamo et al., 1982; Wang et al., 1997).

Although the chief factor limiting high-contrast resolution acuity is neural in nature, one cannot however ignore...
the effects of reduced optical quality in the peripheral visual field seen with increasing eccentric viewing angles on other aspects of vision. The distribution of optical errors varies, not only with increasing eccentricity (Ferree et al., 1931; Jennings and Charman, 1981), but also depends upon position within the visual field (Atchison and Scott, 2002; Ferree et al., 1932; Gustafsson et al., 2001; Lotmar and Lotmar, 1974; Seidemann et al., 2002). The nasal visual field suffers from larger amounts of both higher- and lower-order aberrations than the temporal visual field. Of the lower-order aberrations, off-axis astigmatism has been shown to increase with increasing eccentricity (Atchison and Smith, 2000; Gustafsson et al., 2001); this increase being greater in the nasal visual field than in the temporal visual field (Ferree et al., 1932; Gustafsson et al., 2001). The average off-axis astigmatism at 20° in the nasal visual field of 20 emmetropic subjects in the study by Gustafsson et al. (2001) was −1.75 DC. The average spherical equivalent was −1.20 D showing that the subjects on average had a spherical component of little more than −0.25 D. Comparable values of sphere and cylinder at the same eccentricity, and likewise in emmetropic subjects, were also reported in a study by Atchison et al. (2005). Higher-order aberrations also show similar changes with respect to field angle (Atchison and Scott, 2002; Baskaran et al., 2010; Lundström et al., 2009, 2011; Mathur et al., 2008).

The measurement of these aberrations was difficult and time-consuming prior to the advent of Hartmann-Shack aberrometers. The first commercially available open-field Hartmann-Shack wavefront aberrometer, the COAS-VR was introduced by WaveFront Science (Albuquerque, NM) permitting rapid measurement of both on- and off-axis aberrations. Salmon and van de Pol (2005) found the COAS aberrometer to be similarly repeatable as subjective refraction for on-axis measurements, with an accuracy of approximately 0.25D for lower refractive errors; they concluded that the COAS aberrometer made for easy objective measurement of both lower- and higher-order aberrations. Off-axis measurement of higher-order aberrations was also found to be repeatable with the COAS-HD VR (Baskaran et al., 2010).

To what extent optical errors adversely affect visual performance depends largely on the specific visual task in question. Numerous studies examining peripheral visual function have shown the detrimental effect of optical defocus on detection acuity (Anderson, 1996; Anderson et al., 2001; Ferree et al., 1931; Leibowitz et al., 1972; Rosén et al., 2011; Wang et al., 1996, 1997), motion detection (Leibowitz et al., 1972), differential light sensitivity (Atchison, 1987; Funkhauser and Enoch, 1962; Koller et al., 2001) and contrast sensitivity (Coletta et al., 2002). A study by Rosén et al. (2011) showed that spherical defocus had a detrimental effect on peripheral low-contrast resolution acuity, but not high-contrast resolution acuity. In agreement with previous observations regarding high-contrast resolution acuity, greater amounts of defocus were required in order to significantly impair performance. On the other hand, a number of studies have shown that correction of off-axis refractive errors in patients with central field-loss can provide improved high-contrast resolution acuity (Baskaran et al., 2012; Gustafsson and Unsbo, 2003; Lundström et al., 2007a).

One commonality shared by many previous studies examining the effects of optics on peripheral visual function is that visual performance was examined after inducing varying amounts of optical defocus, a tiring and time-consuming procedure. No previous studies have however, specifically compared both corrected and unaided peripheral low-contrast resolution acuity on emmetropes. The aims of this study were to find a fast, more clinically applicable method for improving peripheral visual function and to assess the impact of objectively obtained off-axis correction on peripheral low contrast visual acuity.

2. Methods

2.1. Subjects

A total of 10 subjects (mean age 22 years ± 2 years, ranging from 19 to 24 years) participated in this study. All had right eyes that were emmetropic centrally; with unaided log MAR visual acuities of 0.0 or better, no known ocular disease, no strabismus nor significant distance phorias. Written informed consent was obtained from each subject after the nature and purpose of the experiment had been explained. The tenets of the Declaration of Helsinki were followed.

2.2. Measurement of refractive errors

Prior to acuity-measurement, central and peripheral refractive errors were acquired on the right-eyes of subjects using an open-field COAS-HD VR aberrometer. Measurements were taken under dim room illumination, so as to allow the use of natural pupils. Subjects were instructed to fixate a central red LED during measurement of on-axis refraction and to turn their eye to fixate a second LED situated 20° to the right for off-axis measurements (thus measuring in the temporal retina which corresponds to the nasal visual field). The distance from the subject to the LED was kept constant at 3.0 m. Refractive errors were obtained by using pupil plane metric (RMSw) as described by Marsack et al. (2004).

2.3. Subject alignment during acuity measurements

Subjects were seated at a distance of 3.0 m from the stimulus monitor and instructed to observe a fixation target (a cross subtending 0.5 degrees in the visual field) which was displayed on a small LCD display 20° to the right. The position and correct alignment of the subject was assured by using a chin- and forehead rest.
Two septums made of thin sheets of anodized aluminum were positioned so as to obscure the stimulus screen from the left eye, while still enabling the left eye to view the fixation target. In a similar fashion, the right eye was able to see the stimulus screen but was prevented from seeing the fixation cross. (See figure 1). These measures were taken in order to assure both fixation- and accommodation stability.

2.4. Stimuli

Stimuli used for the measurement of resolution thresholds consisted of low-contrast (10%) Gabor patches with a visible diameter of 2°. They were presented on a 17 inch CRT screen (Nokia 447Pro) which was positioned 20° to the left of the fixation display (relative to the right eye). The luminance of the CRT screen was 31 cd/m². The display had previously been calibrated and gamma-corrected with an i1Display 2 colorimeter from X-Rite. The mean luminance of the LCD fixation screen was 32 cd/m². Stimuli (Gabor patches) were generated using Matlab software with extensions supplied with the Psychophysics Toolbox (Brainard, 1997). Gabor patches were orientated obliquely; leaning either ±45° from the vertical so as to reduce the orientation-specific blurring effects of axis orientation of peripheral astigmatism in the horizontal visual field, as well as to minimize the superiority of vertical or horizontal gratings (Rovamo et al., 1982; Spinelli et al., 1984; Westheimer, 2003).

2.5. Optical correction

Off-axis sphero-cylindrical refractive errors, as measured with COAS-HD VR aberrometer, were corrected with full-aperture trial lenses after rounding to the nearest 0.25D. These were inserted in a modified lens-holder, mounted on the forehead rest and normal to the off-axis line of sight. The vertex distance from the right eye was 20 mm.

2.6. Psychophysical methodology

Resolution acuity was measured off-axis (20° nasal visual field), both with and without peripheral refractive correction. Low-contrast resolution thresholds were determined by a two-alternative forced-choice (2AFC) procedure, whereby the subjects had to decide the orientation of the grating. An adaptive Bayesian algorithm as proposed by Kontsevich and Tyler (1999) was used to calculate the probability density function for the threshold from a total of 40 trials. Full details of the psychophysical methodology are available in (Lewis et al., 2011; Rosén et al., 2011). Subjects initiated each measurement trial by pressing a key on a modified numerical keypad which also served to record responses during the trial. Stimulus presentation was preceded by a sound cue followed by a delay of 500 ms. To minimize saccadic fixational eye-movements, stimuli remained visible for a duration of 300 ms before disappearing.

3. Results

All subjects were emmetropic centrally (subjectively) and had astigmatism at 20° in the nasal visual field, ranging from −1.00 DC to −2.00 DC. The average uncorrected peripheral low-contrast resolution acuity was 0.92 logMAR. Following correction of off axis refractive errors this improved to 0.86 logMAR, a small however significant improvement of 0.06 logMAR (p = 0.028, Two-way Students T-test). A summary of these results is shown in table 1.

As the majority of emmetropic subjects in this study had simple myopic astigmatism, as was expected from previous studies (Atchison et al., 2005; Gustafsson et al., 2001), we grouped them according to the amount of off-axis astigmatism, (see figure 2). The group having −1.00 DC of astigmatism showed an insignificant decrease in resolution acuity. The other three groups showed improved resolution acuity with increasing degrees of astigmatism; the −1.25 DC group improved by 0.05 logMAR, the acuity of the subject with −1.50 DC improved by 0.14 DC and the two subjects with −2.00 DC improved on average by 0.16 logMAR.
The observed changes in low-contrast resolution acuity were strongly correlated with off-axis astigmatism (Pearson: \( r = 0.82; p = 0.0034 \)).

4. Discussion

Peripheral low-contrast resolution improved following the correction of off-axis refractive errors in the emmetropic subjects in this study. It is also evident that the degree of off-axis astigmatism is an important factor dictating the extent of improvement following its correction; the correction of larger amounts of astigmatism provides greater improvements in resolution acuity. One plausible explanation for slight decrease in resolution acuity for smaller cylinder-powers is that we did not compensate for spectacle magnification effects, and that we used standard uncoated trial-lenses, which will have given rise to slight transmission losses. The decision not to compensate for spectacle magnification was to generate more clinically applicable results, as spectacle magnification is not compensated for in a clinical setting, other than by fitting contact lenses. For the plano-concave trial lenses used, with a center-thickness \( = 2.2 \text{ mm} \) and vertex-distance \( = 20 \text { mm} \), spectacle magnification will be approximately \( -2 \% \) for \(-1.00 \text{ DC}, -3 \% \) for \(1.50 \text{ DC} \) and \(-4 \% \) for \(-2.00 \text{ DC} \). An off-axis contact lens correction would result in a larger retinal image and, in theory, give higher peripheral resolution thresholds as this would cause a shift in spatial frequency of the Gabor patches towards lower spatial frequencies.

Previous studies examining the effect of defocus on peripheral resolution acuity differ from the current study in two general ways.

1. Inducing both positive and negative spherical defocus to examine the effects on high-contrast resolution- and detection acuity (Wang et al., 1997), to examine the effects on high- and low-contrast resolution acuity (Rosén et al., 2011), or to maximize contrast-detection acuity (Wang et al., 1996).

2. Correcting off-axis refractive errors, as determined by static retinoscopy, and evaluating the effect on high-contrast resolution- and discrimination acuity (Millodot et al., 1975; Rempt et al., 1976).

Only in the studies by Millodot et al. (1975) and Rempt et al. (1976) was the peripheral high contrast resolution acuity evaluated with and without correction of off-axis refractive errors. They did not however observe any improvement in acuity, as only stimuli of high-contrast were used; such stimuli have since been proven to be insensitive to optical defocus in the periphery. While other studies induced defocus after peripheral refractive error correction they never compared unaided (or centrally corrected) peripheral visual acuity with acuity obtained after peripheral refractive correction. Rosén et al. (2011) used an autorefractor (PowerRefractor made by MCS, Germany) as a starting point for maximizing subjective high-contrast detection acuity with spherical lenses; thereafter spherical defocus was induced to examine the effect on high- and low contrast detection- and resolution acuity. Wang et al. (1996) compared their results of subjective contrast-detection acuity with off-axis retinoscopy, but did not assess visual acuity with objective refraction in place. Lundström et al. (2005, 2007a) showed that the method of choice for measuring off-axis refractive errors is wavefront aber-

Table 1: Distribution of on-axis and off-axis (20° nasal visual field) refractive error as measured with COAS, and peripheral low-contrast 10% resolution acuity (PLCVA) with- and without off-axis refractive correction. The difference between uncorrected- and corrected resolution acuity is shown in the final column; negative values show an improvement in acuity following correction of peripheral refractive errors.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Given off-axis refraction</th>
<th>Uncorr PLCVA (logMAR)</th>
<th>Corr PLCVA (logMAR)</th>
<th>Diff (Corr-Uncorr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM2</td>
<td>±/−1.00x95</td>
<td>0.89</td>
<td>0.91</td>
<td>0.02</td>
</tr>
<tr>
<td>EM6</td>
<td>±/−1.00x100</td>
<td>0.85</td>
<td>0.88</td>
<td>0.03</td>
</tr>
<tr>
<td>EM8</td>
<td>±/−1.00x65</td>
<td>0.90</td>
<td>0.86</td>
<td>−0.04</td>
</tr>
<tr>
<td>EM10</td>
<td>±/−1.00x80</td>
<td>0.80</td>
<td>0.82</td>
<td>−0.02</td>
</tr>
<tr>
<td>EM1</td>
<td>±/−1.25x95</td>
<td>0.88</td>
<td>0.84</td>
<td>−0.04</td>
</tr>
<tr>
<td>EM4</td>
<td>−0.50/−1.25x85</td>
<td>0.90</td>
<td>0.86</td>
<td>−0.04</td>
</tr>
<tr>
<td>EM7</td>
<td>−0.75/−1.25x100</td>
<td>0.94</td>
<td>0.87</td>
<td>−0.07</td>
</tr>
<tr>
<td>EM9</td>
<td>±/−1.50x75</td>
<td>0.93</td>
<td>0.79</td>
<td>−0.14</td>
</tr>
<tr>
<td>EM3</td>
<td>±/−2.00x90</td>
<td>1.04</td>
<td>0.88</td>
<td>−0.16</td>
</tr>
<tr>
<td>EM5</td>
<td>±/−2.00x95</td>
<td>1.10</td>
<td>0.94</td>
<td>−0.17</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.92±0.09</td>
<td>0.86±0.04</td>
<td>−0.06</td>
</tr>
</tbody>
</table>

Figure 2: Mean change in resolution acuity (logMAR) when subjects were grouped according to the degree of off-axis astigmatism present in the peripheral visual field. Negative values show an improvement in resolution acuity.
rometry, using a Hartman-Shack sensor. Off-axis retinoscopy was inherently difficult at larger angles, due to the presence of large aberrations.

The present study used a commercially available aberrometer to obtain values of off-axis refractive error; this correction was subsequently used in to evaluate the effect on low-contrast resolution acuity. Refractive corrections obtained with the COAS-HD VR aberrometer on our subjects were in agreement with other studies of peripheral aberrations in young emmetropic eyes (Atchison et al., 2005). The raw-data from the study of (Baskaran et al., 2011) on 30 young emmetropic subjects showed that the average off-axis astigmatism at 20° in the nasal visual field measured with a the COAS-HD VR aberrometer was −1.50 DC X90 with a range of −0.50 DC to −2.50 DC. Comparable degrees of astigmatism (approximately −1.25 DC) measured with a Shin-Nippon SRW5000 autorefractor were also reported by Atchison et al. (2005) in a group of 22 young emmetropes. The rationale in the present study for choosing only centrally emmetropic subjects was to avoid the necessity of a central refractive correction while evaluating peripheral visual acuity. Myopic and hyperopic subjects would first require a central correction to make them centrally emmetropic.

Rosén et al. (2012) showed a change in low-contrast acuity of up to 0.15 logMAR for every dioptr of spherical defocus which compares remarkably well with our results. Considering the two subjects with −2.00DC of off-axis astigmatism (EM3 and EM5) who showed an average improvement of 0.16 logMAR, the same amount of defocus would be induced with +1.00D spherical lens.

It is interesting to note that the average uncorrected low-contrast resolution was 0.92±0.09 and the corrected low-contrast acuity improved to 0.86±0.04 logMAR. The improved low contrast resolution is in close agreement with the results of Wang et al. (1997) who observed a maximal visual acuity of 4 to 5 cycles/degree at 20° in the nasal field for the high contrast resolution; this equates to an acuity of 0.78 to 0.88 logMAR. By correcting peripheral refractive errors, low-contrast acuity approaches a maximum set by the neural limitations of the eye and lies closer to the limit of high-contrast resolution acuity.

5. Conclusion

This is the first study to compare low-contrast visual acuity, both with and without objectively determined peripheral refractive error correction. This suggests that optical factors, such as off-axis astigmatism, do influence peripheral visual tasks involving low-contrast and that there are definite benefits in correcting even moderate amounts of off-axis refractive errors. For people who rely on optimal peripheral visual function, specifically those with central visual field loss, correction of off-axis refractive errors may be even more pertinent.

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References

Benefit of Adaptive Optics Aberration Correction at Preferred Retinal Locus

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ABSTRACT

Purpose. To investigate the effect of eccentric refractive correction and full aberration correction on both high- and low-contrast grating resolution at the preferred retinal locus (PRL) of a single low-vision subject with a long-standing central scotoma.

Methods. The subject was a 68-year-old woman with bilateral absolute central scotoma due to Stargardt disease. She developed a single PRL located 25° nasally of the damaged macula in her left eye, this being the better of the two eyes. High- (100%) and low-contrast (25 and 10%) grating resolution acuity was evaluated using four different correction conditions. The first two corrections were solely refractive error corrections, namely, habitual spectacle correction and full spherocylindrical correction. The latter two corrections were two versions of adaptive optics corrections of all aberrations, namely, habitual spectacle correction with aberration correction and full spherocylindrical refractive correction with aberration correction.

Results. The mean high-contrast (100%) resolution acuity with her habitual correction was 1.06 logMAR, which improved to 1.00 logMAR with full spherocylindrical correction. Under the same conditions, low-contrast (25%) acuity improved from 1.30 to 1.14 logMAR. With adaptive optics aberration correction, the high-contrast resolution acuities improved to 0.89/0.92 logMAR and the low-contrast acuities improved to 1.04/1.06 logMAR under both correction modalities. The low-contrast (10%) resolution acuity was 1.34 logMAR with adaptive optics aberration correction; however, with purely refractive error corrections, she was unable to identify the orientation of the gratings.

Conclusions. Correction of all aberrations using adaptive optics improves both high- and low-contrast resolution acuity at the PRL of a single low-vision subject with long-standing absolute central scotoma.

Key Words: eccentric viewing, preferred retinal locus, absolute central scotoma, adaptive optics, eccentric correction, aberrations
Moreover, coma is the dominant higher-order aberration, constituting 70 to 90% of the total higher-order root mean square (HO RMS) at eccentricities >10° in the periphery. Studies have also shown that the magnitude of coma is larger in older eyes than in young eyes, both centrally and peripherally.

The potential benefit of peripheral refractive error correction has previously been investigated, both in healthy subjects and in patients using a PRL, where an interesting difference between these two groups has been observed. Healthy subjects observe aliasing in the periphery (manifest as a significant difference between high-contrast detection and resolution acuity), and as a result, they show no improvement in high-contrast resolution acuity when peripheral refractive errors are corrected. Conversely, peripheral refractive error corrections have been shown to improve high-contrast resolution acuity in patients using a PRL. Additionally, peripheral refractive error corrections improve low-contrast resolution acuity in both healthy subjects and patients using a PRL. However, the effect of aberrations on the peripheral vision is less well known. One previous study using adaptive optics (AO) on healthy subjects showed a negligible improvement in high-contrast resolution at 20° eccentricity. Nevertheless, it is possible that correction of aberrations in patients using a PRL would improve their resolution acuity, as their high-contrast resolution has been shown to improve with solely refractive error correction. In this study, we have corrected eccentric refractive errors as well as higher-order aberrations using AO and evaluated both high- and low-contrast grating resolution acuity at the PRL of a single subject with a long-standing central scotoma.

METHODS

Subject

The subject was a 68-year-old Caucasian woman diagnosed with bilateral juvenile macular degeneration at the age of 17 years; this diagnosis was confirmed as Stargardt disease, with flavimaculatas changes in both eyes at a later stage in her life. She had bilateral central scotomas, with unaided visual acuity of 1.5 and 1.4 logMAR in the right and left eye, respectively, as measured using an Early Treatment Diabetic Retinopathy Study letter acuity chart at 1-meter distance. In her left eye, she developed a single PRL located 25° nasally from the damaged macula. According to her, she has been using the PRL consistently for all visual tasks during the past 40 years. In a previous study by Lundström et al., the same subject was prescribed a refractive error correction of −3.25/−1.75 × 80° at her PRL (based on the optimum Strehl ratio metric), which the subject used as her habitual correction. Her distance visual acuity in the left eye with this habitual correction was 1.3 logMAR. In addition to this correction, which she was using for the past 5 years, she used an 11× spectacle-mounted magnifier for spot reading. With this magnifier, near visual acuity was 0.2 logMAR at a working distance of approximately 1 cm. Slit lamp findings of the anterior segment were unremarkable and showed only mild age-related changes in the lens. Color fundus photographs were taken, showing geographic atrophy of the macular region in both eyes (Fig. 1A, B). Fixation stability was evaluated using a Spectral OCT/SLO scanning laser ophthalmoscope (OPKO Health, Miami, FL), whereby a fixation cross was projected on the PRL and the subject was instructed to fixate the cross for a duration of 20 s (Fig. 2). This specific subject was recruited because she had a relatively stable fixation (with a variation limited to approximately 2°) at the PRL and had a large central scotoma. She gave her informed consent after the nature and intent of the study had been explained. The local ethics committee approved the study, and the protocol was designed in accordance with the tenets of Declaration of Helsinki.

AO System

Fig. 3 shows the AO system combined with a system for visual psychophysics developed by the Visual Optics group at the Royal Institute of Technology in Stockholm. The principal components of the system are a Hartmann-Shack wavefront sensor, which uses...
a 32 × 32-microlenslet array (HASO 32, Imagine Eyes, France), an electromagnetic deformable mirror (MIRAO 52d, Imagine Eyes, France) with 52 actuators, and a CRT screen placed at the end of the system used for presenting visual stimuli. The pupil plane of the eye was conjugate to that of the deformable mirror using telescopes. The eye was aligned at the front focal plane of lens L1 with help of the pupil camera. The stimuli were imaged through the system by the telescopes formed by lens L4, L3, L2, and L1, with a total magnification of 1. The optimal defocus was −0.6 D after compensating for both wavelength (830–555 nm) and test distance (2.6 meter); this value was incorporated in the AO system before measurements. Aberrations were corrected by the AO system in a continuous closed loop throughout the visual testing. The subject was free to blink at any time, and a natural pupil size was used. Temporary lockups occurred occasionally when the subject moved her eye during AO correction. During those occurrences, the mirror would temporarily freeze, and the recorded aberrations would be identical for a given period. However, these periods were <1 s in duration, and the system was able to resume aberration correction automatically in all cases.

Visual Stimuli and Psychophysical Algorithm

The visual stimulus was a Gabor patch, a sine-wave grating multiplied with a Gaussian standard deviation of 0.6°, with an oblique orientation of ±45°. High- and low-contrast gratings corresponding to 100, 25, and 10% were used in this study. MATLAB (The MathWorks, Natick, MA) and the Psychophysics Toolbox20,21 were used to draw the stimuli and implement the psychophysical algorithm. The frequency of seeing was defined as the probability $P(x)$ of answering correctly, given a stimulus of size $x$, and was assumed to vary as a cumulative logistic function:

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

The guess rate $g$ was 0.5, as the experiments were based on a two-alternative forced choice paradigm. The lapse rate $\delta$ was set to 0.02, the slope $s$ was set to 0.04 logMAR, and threshold $\mu$, measured in logMAR, was the estimated quantity. The stimulus size $x$ could vary between 0.7 to 1.6 logMAR. The psychometric algorithm used in this study is based on the Bayesian adaptive estimation of the slope and threshold that is described in detail by Konstevich and Tyler.22 This algorithm requires only 30 trials to estimate the probability density function of the threshold; the advantage and accuracy of this algorithm in evaluating visual function are discussed in detail by Rosen et al.15

Optical Correction Conditions

We evaluated grating resolution acuity under four different optical corrections. The first two were solely spherocylindrical corrections, and the latter two were full correction of all the Zernike
coefficients up to sixth order (including the residual lower-order terms of sphere and cylinder) in a continuous closed loop at the PRL. The correction conditions were randomized, and the subject was unaware of the correction that could possibly benefit her. The correction conditions are as follows: Habitual spherocylindrical correction (Hab Spec): the subject used her habitual spectacle correction (−3.25/−1.75 × 80°) during vision evaluation. We recorded the residual aberrations over her habitual correction using the Hartmann-Shack sensor while the deformable mirror was actively flat. Full spherocylindrical correction (Full Spec): the correction was obtained by minimizing the RMS error of the wavefront. The correction was −2.00/−3.50 × 90° placed in the trial lens holder, and residual aberrations were recorded while the deformable mirror was actively flat. With this correction in place, the residual defocus and astigmatism terms were close to zero. The difference between habitual correction and this correction was −0.50 D and +1.25 D in the horizontal and vertical meridians, respectively. Habitual spherocylindrical correction plus higher-order correction (Hab Spec + AO): in this closed-loop situation, all Zernike coefficients were corrected continuously by the deformable mirror in real time under the entire duration of the vision evaluation procedure. She used her habitual spectacle correction, and the resulting residual aberrations and refractive errors over her spectacles were corrected by the deformable mirror in a closed loop. Full spherocylindrical correction plus higher-order aberration correction (Full Spec + AO): the full spherocylindrical correction was placed in the trial lens holder, and the resulting residual aberrations were corrected by the deformable mirror in a closed loop. The subject had a nearly diffraction-limited correction at her PRL.

Experimental Procedures

The subject positioned her head in a chin rest in front of the system. The CRT screen, on which visual stimuli were displayed, was located 2.6 m from the subject’s eye. She viewed the CRT screen through the AO system with her left eye. Fixation on the grating stimulus was aided by an equiluminant concentric circle with a diameter of 5°, displayed on the same screen (Fig. 3). By placing the edge of her scotoma on this circle, projection of the visual stimuli on her PRL during the procedure was facilitated. No cycloplegic drugs were used, and her right eye was occluded during the procedure. The psychophysical vision evaluation commenced once the desired correction condition was met. The subject was asked to determine the orientation of the grating, to the right or left in a two-alternative forced choice paradigm, by pressing the corresponding key on a numerical keyboard. At the end of the each measurement, the resolution acuity threshold was displayed in logMAR units. Three repeated measurements of high- (100%) and low-contrast (25 and 10%) grating resolution acuity were evaluated for each of the four different correction conditions and were subsequently recorded.

RESULTS

The AO system was successful in recording and implementing the four different correction conditions. The Zernike coefficients of the third- and fourth-order aberrations as well as total HO RMS (third–sixth order) measured at the PRL of the subject’s naked eye are shown in Table 1. Pupil diameter was 5 mm throughout the experiments, with only minor fluctuations. Resolution acuity at all contrast levels improved with AO aberration correction as shown in Fig. 4. The values presented in Fig. 4 show the mean visual acuity and individual values obtained with the four different correction conditions at all three contrast levels.

High-Contrast (100%) Grating Resolution Acuity

The mean high-contrast (100%) visual acuity with her habitual correction was 1.06 logMAR, and improved to 1.00 logMAR with full spherocylindrical correction. With AO aberration correction, the high-contrast visual acuity improved further to 0.89/0.92 logMAR. The mean HO RMS wavefront error, recorded by the Hartmann-Shack sensor, during the first two correction conditions was 0.91 and 0.92 μm, respectively. With both AO aberration corrections, the mean HO RMS wavefront error reduced further to 0.19 μm.

Low-Contrast (25%) Grating Resolution Acuity

The mean low-contrast (25%) visual acuity with her habitual correction was 1.30 logMAR, and this improved markedly to 1.14 logMAR with full spherocylindrical correction. With AO aberration correction, the low-contrast visual acuity improved further to 1.04/1.06 logMAR. The mean HO RMS wavefront error for the first two correction conditions was 0.92 and 1.00 μm, respectively. With both AO aberration corrections, the mean HO RMS wavefront error reduced further to 0.22 μm.

Low-Contrast (10%) Grating Resolution Acuity

The mean low-contrast (10%) resolution acuity was 1.34/1.51 logMAR with AO aberration correction; however, with purely refractive error corrections, she was unable to identify the gratings.

DISCUSSION

To our knowledge, this is the first time that resolution acuity has been evaluated after correction of all ocular aberrations using AO

<table>
<thead>
<tr>
<th>Zernike coefficients</th>
<th>Pre-correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{3}^{1}$</td>
<td>0.18</td>
</tr>
<tr>
<td>$C_{3}^{1}$</td>
<td>0.20</td>
</tr>
<tr>
<td>$C_{4}^{1}$</td>
<td>−0.85</td>
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<td>$C_{5}^{1}$</td>
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<td>$C_{4}^{2}$</td>
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<tr>
<td>$C_{5}^{2}$</td>
<td>−0.02</td>
</tr>
<tr>
<td>$C_{6}^{2}$</td>
<td>−0.05</td>
</tr>
<tr>
<td>$C_{7}^{2}$</td>
<td>−0.01</td>
</tr>
<tr>
<td>$C_{8}^{2}$</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Total HO RMS (third to sixth)</strong></td>
<td><strong>0.92</strong></td>
</tr>
</tbody>
</table>

All the Zernike coefficients up to sixth order were targeted for correction in the adaptive optics system.

Note that coma is the dominant aberration coefficient that constitutes 95% of the total HO RMS.
at the PRL of a low-vision subject. In this subject, there was an improvement in grating resolution acuity with full refractive error correction and a further improvement with aberration correction.

Considering the results in more detail, the high- (100%) and low-contrast (25%) resolution acuities improved by 0.06 and 0.16 logMAR, respectively, with full spherocylindrical correction as compared with values obtained with the habitual correction at her PRL. This finding is in agreement with a previous study by Lundström et al.,8 who also reported improvements in both high- and low-contrast resolution acuity after correction of eccentric refractive errors. However, they compared resolution acuity between central refractive correction and eccentric refractive correction. The greater improvement of low-contrast resolution with full spherocylindrical correction is in agreement with a previous study by Rosen et al.,15 in which they showed that low-contrast resolution is optically influenced in the peripheral vision even in normal healthy subjects. Based on our results, this subject has currently been prescribed new spectacles having a refractive correction of −2.00/−3.50 × 90° in the left eye.

With the AO, there was further improvement of 0.08 to 0.11 logMAR in both high- (100%) and low-contrast (25%) resolution. This shows that higher-order aberrations, primarily coma, play a role in degrading the image quality and that correction of these aberrations serves to further improve resolution acuity at the PRL. The relatively small difference in resolution acuity between the two AO corrections (which should theoretically be the same) could be explained by the reduction in light transmission through trial lenses compared with her habitual spectacle lens. The improvement in high-contrast resolution after AO correction suggests that this subject did not experience aliasing. One possible explanation for this is that her resolution in the PRL was much lower than that observed in healthy subjects at similar eccentricities. In her case, high-contrast resolution was 0.89 logMAR after AO correction, whereas Thibos et al.23 have reported high-contrast resolution acuity at a corresponding eccentricity of approximately 0.7 logMAR (six cycles per degree). Similar differences in peripheral resolution acuity between healthy subjects and age-related macular degeneration patients have previously been reported by Eisenbarth et al.24 Our subject may also have comparable degenerative changes in her PRL.

The low-contrast (10%) resolution task was difficult for the subject to perform even at the lowest spatial frequency available.
However, the AO correction improved the retinal image quality sufficiently, after which the subject was able to perceive the gratings and thereby respond to the task. The poor repeatability and variation in resolution acuity observed within and between AO corrections might be attributable to an increased frequency in eye movements with increasing task difficulty. The ability to perceive even very-low-contrast grating after aberration correction is owing to the improvement of image quality at the PRL, and this finding argues in favor of correcting the subject’s aberrations to help her in performing low-contrast visual tasks, such as recognizing faces in a better way.

Apart from the obvious advantages offered by aberration correction, there are also certain limitations in this study that need to be brought to attention. These are the use of gratings for determining resolution acuity, not correcting for chromatic aberration, and only evaluating the vision of a single low-vision subject. Studies have shown that the grating acuity consistently overestimates letter acuity both in normal eyes and in the PRL of patients with age-related macular degeneration. The visual acuity values obtained in this study would have, consequently, been slightly lower if we had instead adopted a letter identification task. Nevertheless, one could speculate that correction of eccentric refractive errors and aberrations may also improve visual performance even with a letter identification task. The improvements that we have observed under the four correction conditions apply for this subject only, and the results could be expected to vary in other subjects owing to variety of factors, such as the location of the PRL, size of the scotoma, underlying retinal disorder, and the magnitude of the eccentric refractive errors and higher-order aberrations. In addition, this technique may have limited usage in patients using multiple PRL’s for different visual tasks.

Further studies are required to investigate the degree of improvement in resolution acuity with aberration correction in a larger group of patients having central scotomas with an established PRL. Practical ways of correcting the aberrations at the PRL, particularly coma, for these patients should also be investigated. Until then, full correction of the eccentric refractive error, obtained by either using an open-view refractometer or an aberrometer, could be prescribed to these patients if an improvement in vision can be achieved with either a high- or low-contrast chart. This correction would also improve the detection acuity in these patients because studies have shown that detection is even more sensitive to optical errors.

In addition to the most common low-vision devices prescribed to these patients, such as magnifiers or CCTVs for reading and telescopes for distance, prescribing an eccentric correction could further help them to perform day to day visual tasks in a better way and thus improve their quality of life. In conclusion, correction of all aberrations using AO improves resolution acuity at the PRL of a single low-vision subject with longstanding absolute central scotoma.

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54. Fredrik Håkansson, 2011. Standing up to a Multinational Giant. The Saint-Gobain World Council and the American Window Glass Workers' Strike in the


People who lose their central vision have to rely on their peripheral vision for all visual tasks. The ability to resolve fine details in the periphery is reduced due to retinal limitations and the optical aberrations arising from the use of off-axis vision. The focus of this thesis has been to measure and correct peripheral optical errors, as well as to evaluate their impact on resolution acuity in both normal and central visual field loss subjects. In the different papers we have shown that the aberrometer used was repeatable and reliable in measuring peripheral ocular aberrations. There was mirror symmetry between the two eyes for most of the peripheral aberration coefficients. Age had a significant influence on peripheral ocular aberrations; there were larger amounts of higher-order aberrations in old eyes than in young eyes. Peripheral low contrast resolution acuity improved with peripheral refractive correction in subjects who had higher amounts of off-axis astigmatism. Finally, for the first time it was shown that adaptive optics aberration correction improved both high and low contrast resolution acuity measured at the preferred retinal locus of the single low vision subject. This thesis has shown that peripheral visual function can be improved by optical correction. The work presented in this thesis provides new insights regarding peripheral optical errors and their influence on vision.