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OCULAR ABERRATIONS AND VISUAL QUALITY IN ASPHERIC AND MULTIFOCAL CONTACT LENSES

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To

-Erik, my star

-Sofia, my sunshine

-Ove, my love

ABSTRACT

Good visual quality and precise accommodation are required to be able to focus objects at distance and near, and are essential in order to be able to perform most tasks in life. Most eyes are not ideal eyes, i.e., they have different refractive errors which distort the produced image. The well-known refractive errors (lower order aberrations), myopia, hyperopia and astigmatism, have long been correctable. In addition to these common errors, irregularities in the refractive media create higher order aberrations, which are described by the Zernike polynomials. To achieve a higher level of visual quality, it is important to correct aberrations. Spherical aberration and chromatic aberration, present in polychromatic light, serve as cues for accurate accommodation in order to provide a clear image of the object. It is of interest to know how a reduction or increase of certain aberrations might affect visual quality and accommodation.

The aim of this project was to develop techniques to measure the changes in optical aberrations and accommodation in subjects while wearing standard contact lenses, and lenses with aberration control and to find new strategies to enhance the fitting of these lenses in order to achieve a higher level of visual quality.

Using an aberrometer, residual spherical aberration was evaluated with a standard contact lens and with a lens with spherical aberration control. Visual quality (i.e. visual acuity and contrast sensitivity) was also evaluated with the different contact lenses. Aberration and accommodation were measured with and without accommodative cues present. Accommodation was evaluated with a multifocal contact lens with a near reading addition.

The results show that it is possible to evaluate residual spherical aberration with contact lenses on the eye, but the change in aberration gave no difference in visual acuity or contrast sensitivity at distance or near with the methods used. Spherical aberration and chromatic aberration were shown not to be strong directional cues for accommodation, indicating that there are other cues more important for directional information. Since the multifocal contact lens, a centre distance design with reading addition +1.00, was not able to relax the accommodation for the subjects, it is therefore unlikely that subjects with reduced accommodative ability can effectively be treated with such a lens.

In conclusion, a wavefront measurement should be performed both with and without contact lenses, in order to know the amount of aberration in the eye and to note any change from a contact lens. The relatively small change in spherical aberration that non-customised lenses induce does not affect visual acuity, contrast sensitivity or accommodation. These lenses may then be fitted without worrying about affecting accommodation and they do not seem suitable to be fitted on young subjects with the ability to accommodate with the purpose of reducing their accommodative load. There is still reason to believe that there are subgroups of patients who can achieve better visual quality, but more sensitive clinical methods have to be developed.

Keywords: Contact lenses, Spherical aberration, Accommodation, Chromatic aberration, Visual acuity, Contrast sensitivity

LIST OF PUBLICATIONS

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CONTENTS

LIST OF ABBREVIATIONS

CA	chromatic aberration
CSF	contrast sensitivity function
D	diopter
DOF	depth of focus
HCVA	high contrast visual acuity
HCVN	high contrast visual acuity near
HOA	higher order aberration
HS	Hartmann-Shack
IOL	intra ocular lens
LCVA	low contrast visual acuity
LOA	lower order aberration
m.	muscle
MLCS	Mars Letter contrast sensitivity
MTF	modulation transfer function
n.	nerve
RAF	Royal Air Force
RMS	root mean square
SA	spherical aberration
SACL	spherical aberration-controlled contact lens
TFC	trial frame correction
UC	uncorrected
VA	visual acuity

1 INTRODUCTION

It is generally accepted that human vision is an extremely powerful information processing system that facilitates our interaction with the surrounding world and involves multiple areas of the brain (Wandell et al., 2007). It could be described as combination of an optical system which refracts the incoming light and creates an image on the retina, as well as an effective physiological process translating the image to nerve impulses and transmit them to the brain where they have to be interpreted in order for us to see, but even this complex account is a gross simplification of an intricate and multifaceted process. However, this "simple" model could be accepted when describing the influences of optical aberrations on visual quality in a healthy visual system. Good visual quality could, in the similar simplified way, be described in aspects of resolving the details, contrast and colour inherent in the image.

There are several factors influencing the visual optical system. The first refractive surface of the eye, the combination of the tear film and cornea, is highly important in refraction of the light; the pupil controls the amount of light through the system; the lens is able to change its refractive power, thus enabling focus at different distances. Each refractive component of the optical system of the eye suffers from aberrations that may degrade the image. At the retinal level, the spacing of the receptors determines resolution at this early stage in the visual process. The neural system's capability to resolve differences in contrast is also influenced by the clarity of the refractive surfaces and the resulting image.

Today there are several corrective means by which the aberrations of the eye can be changed, but do we get "super vision" by correcting aberrations with, e.g., contact lenses? Can we limit the movement of the contact lens on the eye to get sufficiently stable optics? Or does the lens-tear film interaction reduce the possible improvement in optical performance? Is the neural system capable of interpreting the improved image? Furthermore, when changing aberrations, do we alter the physiological cues for, e.g., accommodation? As indicated, there are several factors that limit visual quality.

This thesis covers some aspects of how aberration-controlled contact lenses interact with the optical system and how they can improve some of the critical defining elements of visual quality, namely measurable resolution ability and contrast sensitivity, and how changes in aberration might interfere with accommodation, the focusing mechanism of the eye. The combined field of visual optics, aberrations, contact lenses and visual quality is a broad field. This thesis therefore aims at giving a broad introduction to the field.

1.1 SHORT INTRODUCTION TO ABERRATIONS

A short introduction to aberrations is needed in order to understand the relationship between them and ocular anatomy and physiology. For a more detailed description of aberrations, see Section 1.3. Light is refracted in the eye mainly by the cornea and lens. Aberrations are, by definition, deviations from perfect refraction (Applegate, 2004; Jiang et al., 2006).

In normal visual tasks, with natural daylight, i.e., white light with different wavelengths, both chromatic aberrations and monochromatic aberrations will be present. Chromatic aberration is due to dispersion, since the refractive index will vary with the colour, i.e., the wavelength of the light. This will result in an extended image along the optical axis (longitudinal chromatic aberration) and will cause the size of the image of a point object to be extended by coloured fringes (lateral chromatic aberration), with a distorted retinal image as result, i.e., visual quality is decreased (von Helmholtz, 1924; Benjamin, 1998; Atchison & Smith, 2000).

The standard to describe monochromatic aberrations is by use of Zernike polynomials, which illustrates the shape of a wavefront (American National Standards Institute, 2004). The more common refractive errors such as myopia, hyperopia and astigmatism are classified as lower-order aberrations (LOA) and affect vision the most. But other imperfections in the system are also present and are classified as higher-order aberrations (HOA) in the Zernike polynomials. Spherical aberration (SA) is one of the HOA affecting vision most (Applegate et al., 2002; 2003; Applegate, 2004). SA refers to the lack of coincidence of focus between the peripheral rays and the central rays in the pupil. In this thesis, SA is of special interest since it is possible to correct SA with contact lenses.

1.2 OCULAR ANATOMY AND PHYSIOLOGY IN RELATION TO OPTICS OF THE EYE

The total refractive power of the eye needs to be about 60D (Liou & Brennan, 1997) to create an image on the retina that can be interpreted into a visual impression. Light passes many structures in the eye; some of them will refract the light, and others will not affect refraction but are important for image quality and consequently, vision. If we use the option to correct refractive errors with a contact lens, not only must the physical optics of the contact lens be known, but we also need to know how the contact lens affects the eye physiologically. A description of the eye´s anatomy and physiology in relation optical properties can help us to understand the influence of a contact lens on the eye. The main parts of the eye can be seen in figure 1.

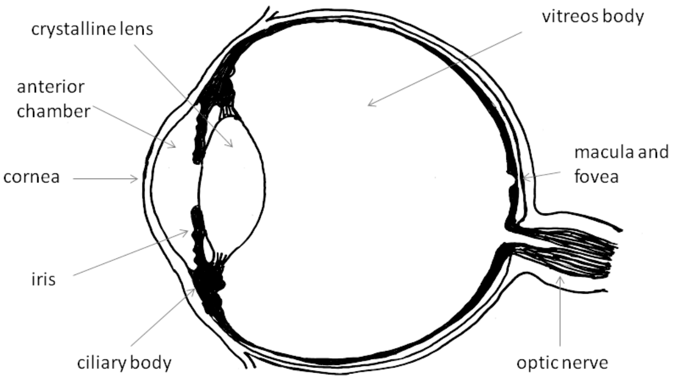

Figure 1. Cross-section of the eye. (Illustration by Annika Botes.)

1.2.1 The tear film

Maintenance of a smooth, intact tear film is essential for high-quality retinal images (Albarrán et al., 1997). The tear film also has a lubricating effect and contains antibodies, making it part of the immune system. In addition, the tear film supplies the cornea with oxygen and participates in corneal metabolism. Lachrymal thickness varies between blinks and is thickest immediately after a blink, about 9 µm, and thins out to about 4 µm before the next blink (Montés-Micó, 2007). Albarrán et al. (1997) and Hirji et al. (1989) also suggest that a normal tear film is stable for more than 8-10 seconds, and if the tear film breaks up completely in less time and dry patches are formed on the cornea, this can lead to deterioration of the optical properties and yield a feeling of dryness.

The tear film was previously described as three separate layers but Pflugfelder et al. (2000) has shown that sharp boundaries cannot be discerned, but rather there is a gradual diffusion between them. However, in a simplified description, a three layer description can still be used: the lipid layer, the aqueous layer and the mucous layer.

The outer surface of the tear film is comprised of the lipid layer, which is produced by the Meibomian glands located in the rims of the eyelids. The lipid layer covers the aqueous layer, preventing the evaporation of tears from the eye. Reduced production of Meibomian glands leads to increased evaporation from the eye and can give the feeling of having dry eyes, despite a high or normal production of aqueous (Johnson & Murphy, 2004; DEWS, 2007; King-Smith et al., 2010).

The aqueous layer is produced mainly by the lacrimal gland (*Glandula lacrimale*) temporally located in the upper temporal part of the orbit but also of the accessory glands (Wolfring and Krause), which produce a small amount of tears. Most often a contact lens will reduce the total amount of tear volume due to reduced reflex production of tears. (Johnson & Murphy, 2004). A contact lens will also divide the tear film, i.e., the aqueous layer, in two portions; pre-lens tear film and post lens tear film, and if the pre-lens film is too thin tear film break up time will decrease (Young & Efron, 1991; Little & Bruce, 1995) and cause a sensation of dryness due to increased friction and reduced optical quality (Wolfsson et al., 2010).

The posterior tear film has a strong interaction with the mucus layer. Mucus produced by the conjunctival goblet cells covers the corneal epithelium. The purpose of the mucous layer is to bridge the transition between the hydrophobic epithelium and the hydrophilic aqueous layer. This helps the tear film to spread over the cornea as a steady and sustained “structure”. Reduced function in conjunctival goblet cells leads to a decreased mucous layer which in turn leads to poor wettability of the cornea. This results in epithelial disruption, which can lead to both decreased comfort (Wolffsohn et al., 2010; Yeniad et al., 2010) and increased risk of infection in contact lens wear (Nilsson & Montan, 1994; Johnson & Murphy, 2004; Efron & Morgan, 2006).

Drying of the tear film has a major effect on the quality of the eye’s optical system. Based on results in studies using different methods, such as double-pass (Albarrán et al., 1997; Montés-Micó et al, 2005ab), retroillumination (Tutt et al., 2000), aberrometry (Thibos & Hong, 1999; 2008 Montés-Micó et al, 2004abc; Montés-Micó 2007) and interferometry (Szczesna et al., 2006;), optical aberrations created by tear film break-up contribute to a decline in image quality. Interaction between the tear film and contact lenses may also influence visual quality.

Xu et al. (2011) showed that subjects with tear film break-up time of more than 15 seconds had less changes in ocular aberrations than subjects with tear film break-up time less than 15 seconds, which supports the importance of careful tear film evaluation as part of a contact lens fitting examination to predict successful contact lens wear in terms of comfort and good optical quality.

When wearing a contact lens, the tear film reduces friction between the cornea and contact lens and between the tarsal conjunctiva and the contact lens. Reduced tear film production will, in addition to changes in aberrations, lead to discomfort and, in more severe cases, also lead to impaired surface of the cornea and tarsal conjunctiva (Korb et al., 2002; Pult et al., 2009; Yeniad et al., 2010). In cases with severe dry eyes contact lenses may not be recommended as a correcting alternative. Comfort problems for a contact lens wearer are often not due to reduced aqueous layer but due to excessive water loss from the exposed ocular surface, i.e., meibomian lipid deficiency, poor lid congruity and lid dynamics or low blink rate, in the presence of normal lacrimal secretory function (DEWS, 2007). A careful selection of the contact lens material and contact lens design should therefore be done to ensure optimal movement, minimal dehydration and friction of the lens (Wolfssohn et al., 2010) to avoid symptoms of ocular dryness and discomfort since these problems affect up to 75% of contact lens wearers (Begley et al., 2000; 2001; Chalmers & Begley, 2006; Doughty et al., 1997; Nichols et al., 2005ab).

Several studies have shown that contact lenses can change aberrations as intended. However, correction of ocular aberrations with aberration-controlled contact lenses may not yield the intended effect, if negative effects such as changes to tear film physiology and structure induced by the lenses may negate the potential positive effect. Consideration of the importance of the tear film should therefore be made when using all contact lenses. The examination procedure for contact lens fitting is described in Section 1.5.

1.2.2 Cornea

The next refractive surface is the cornea, which accounts for two thirds of the refractive power, ~40D. The cornea has a central thickness of about 0.5 mm and thickens towards the periphery (Doughty & Zaman, 2000). The cornea has a horizontal visible diameter of ~12 mm (11 to 12.5 mm) and a vertical diameter of ~11 mm (10.5-11.5 mm). The elliptical shape stems from the different radii in the horizontal and vertical front curve which are, on average, 7.8 and 7.7 mm, respectively at the apex (Kiely et al., 1984; Guillon et al., 1986; Lam & Loran, 1991). The corneal diameter and radii are used to determine the first trial lens in contact lens fitting.

Corneal shape flattens towards the periphery which creates an aspheric surface (Guillon et al., 1986). The aspheric curve and the thickening of the cornea towards the periphery give rise to increasing positive spherical aberration in the periphery (Wang & Dai et al., 2003). Fortunately, the lens almost neutralises the spherical aberration from the cornea by having spherical aberration of the opposite sign (Tomlinson et al., 1993; Artal et al., 2001). The optical medium behind the cornea is the aqueous humour with a refractive index of 1.34 (near that of water) compared to corneas refractive index of 1.376 (Liou & Brennan, 1997). Due to optical laws, the resulting refractive power is positive (Rabetts, 2007). Tomlinson & Schwartz (1979) described the position of the corneal apex to be located temporally but within 0.5 mm of the optical axis in the majority of eyes. The knowledge that the optical and visual axis are not aligned is important when fitting contact lenses with aberration control since the lens tends to centre on the apex and a decentred contact lens will affect the visual outcome.

The transparent tissue of the cornea absorbs almost no light in the visible region and scattering is minimal (Maurice, 1957; Doutch et al., 2008). The cornea consists of five layers: the epithelium, Bowman’s membrane, the stroma, Descemet’s membrane and the endothelium. To maintain transparency, the cornea’s five layers must be intact.

Superficial epithelial disruptions, due to dehydration from poor tear film quality or surface damage from, e.g., a contact lens, can lead to leakage of water into the hydrophilic corneal stroma and reduce the transparency of the tissue built of regularly organised lamellae of collagen fibres (Maurice, 1957). The epithelium, together with Bowman’s membrane, is the most important barrier in the eye's defence against invasion by microorganisms and an epithelial disruption increases the risk of infection considerably. The epithelium heals in a few hours by surrounding cells migrating in from the edges of the damaged area without leaving any visible scars (Bergmanson et al., 1985). The whole epithelium is regenerated in ~7-9 days (Hanna & O´Brien, 1960).

Descemet’s membrane, also part of the microbial barrier (Cheng et al., 1999), and the endothelium participate in the metabolic process. A damaged endothelium due to decreased oxygen supply from, e.g., long time of contact lens with low oxygen permeability, can cause hypoxia, followed by oedema and lost transparency, which will affect optical quality of the cornea and thereby the quality of vision.

Since the cornea is avascular, oxygen and nutrients are supplied by limbal vessels and via the tear film and the aqueous humour in the anterior chamber. A tightly fitted contact lens or a contact lens in a non-oxygen permeable material can cause hypoxia, which results in neovascularization in the limbal region (Chang et al., 2001).

The cornea is innervated by *n. trigeminus* (*n. ophthalmicus*), which reaches the cornea through the long ciliary nerve. There are 70-80 nerve branches around the cornea near the limbus, which create an overlapping plexus, making the cornea very sensitive (Lim & Ruskell, 1978; Cruzat et al., 2010). This high neural sensitivity can give rise to continuous foreign body sensation if the contact lens is decentred or has a loose fit.

1.2.3 Anterior chamber and iris

The anterior chamber is the space limited in front by the corneal endothelium and in the back by the iris and lens. It is filled with the clear aqueous humour and does not refract the light. In normal circumstances, i.e., in the healthy eye, it will be free of light-disturbing cells and flare.

Together, the iris and the crystalline lens form the posterior limits of the anterior chamber. The iris is a ring-shaped structure and acts as an aperture in the eye. Pupil size varies between 2.5 and 8 mm depending on light level, accommodation and convergence (Winn et al., 1994). Pupil size is also influenced by systemic or topical pharmacological agents. Both pupil size and flexibility decrease with age. Pupil size is assumed to be adjusted to give optimum visual acuity over a wide range of luminance (Laughlin, 1992). The pupil size affects depth of focus (DOF) which is the distance from the retina that an image could be located in order to perceive the image as clear and focused. Centration of the pupil does not always coincide with the optical axis but is normally decentres somewhat nasally (Liou & Brennan, 1997). The pupil is constricted by *m. sphincter pupillae* and dilated by *m. dilator pupillae*.

1.2.4 Crystalline lens and ciliary body

The crystalline lens contributes to about 1/3 of the refractive power of the eye, the remaining ~20D. It is a biconvex structure with a front radial curve of about 10 mm and a back curve of about 6 mm (Hart, 1992; Liou & Brennan, 1997). Like the cornea, the lens has an aspheric form and flattens at the periphery, which causes negative spherical aberration to counter the positive aberration from cornea as described above (Tomlinson et al., 1993; Artal et al., 2001). The lens consists of three structures: outermost is the lens capsule; inside the capsule at the front is the lens epithelium; and innermost the lens fibres (stroma), which can be further divided into the cortex and the nucleus. In order to accommodate, or focus at near, the lens has to increase its refractive power by changing the surface curvatures and the structure in the stroma. The lens has a gradient refractive index with highest value in the centre of the lens. Together with the shape of the lens the gradient index contributes to the negative spherical aberration (Liou & Brennan, 1997). During accommodation, it is mainly the front curve of the lens that changes to increase power. The change in shape will decrease the eye's total amount of positive spherical aberration and the resulting spherical aberration will change in negative direction (He et al., 2000; 2003; Cheng et al., 2004; Chin et al., 2009; López-Gil & Fernández-Sánchez, 2010). In younger years the lens is flexible; a young child can accommodate up to 20D. Over the years, the lens fibres grow and the lens loses flexibility; thus, the possibility to focus at near without correction will be lost (see Section 1.4). When the fibres accumulate in the nucleus, the lens also loses its clarity which can disturb optical quality and decrease visual acuity and contrast sensitivity. The lens is connected to the ciliary body via the *zonula zinnii*. The *zonula zinnii* originate from the ciliary body and are attached to the flexible lens capsule. The ciliary body is the circular part of the uvea between the *ora serrata* and the root of the iris. In addition to a stromal and endothelial component, the ciliary body houses the ciliary muscle. The action of the ciliary muscle is contraction, which moves the ciliary body forward and decreases the tension in the *zonula zinnii,* which leads to increased pressure on the stroma from the flexible lens capsule. This results in a thickening of the lens and a refractive power increase, due mainly to a change of the lens's front curve from 10 to 6 mm (Hart, 1992).

1.2.5 Vitreous body

The vitreous body consists of a colourless, transparent gel composed mainly of water and a loose network of collagen fibres (Hart, 1992). Outermost in the vitreous body, the fibres create a primitive membrane with connections to the posterior pole of the lens and to the retina. Sometimes a small channel can be observed from the posterior pole to the optic nerve head; it is an embryological remnant of the regressing hyaloid artery. The space between the lens and the vitreous body creates the posterior chamber and is filled with aqueous humour. Like the anterior chamber, the vitreous body and posterior chamber should be more or less free of light-disturbing cells and flare in normal circumstances. If present, they will decrease optical quality.

1.2.6 Retina

The retina is a complex structure with membranes and several specialised types of cells that interact closely. The retina is capable of transforming the incoming light to electrical nerve impulses through chemical processes for further transmission to the brain.

The retina contains five main classes of cell types (Masland, 2001). The photoreceptors cells are capable of phototransduction. When the photo pigment in a receptor absorbs light, i.e., photons, the structure of the molecule is changed and induces an electrical impulse.

There are two main types of photoreceptors. The cones are sensitive to different wavelengths in order to provide colour vision. They function best in relatively bright light. The rods are sensitive to less intense light, and outnumber the cones by a factor of 20: approximately 90 million rods compared to approximately 4.5 million cones (Curcio et al., 1990).

The photoreceptor cells are supported by the pigment epithelium, which protects the photoreceptors by absorbing stray light and preventing light scatter. It is also a part of the nutrition supply and creates the blood-retina barrier. Bipolar cells then link the photoreceptors to the ganglion cells. Horizontal cells allow the photoreceptors to interact while the amacrine cells allows the ganglion cells to interact and are activated in the feedback system which inhibits or activates the response from the photoreceptors (Eliott & Whitaker, 1991; Kolb 2003).

The ganglion cells send information through the parvo cellular and the magno cellular pathways. Parvo cells are specialised for resolution of fine details and colour, while magno cells are sensitive to contrast and motion (Murav'eva et al., 2009).

Anatomical factors limiting visual resolution are photoreceptor density and receptive fields. A receptive field is defined by the photoreceptors sending information through the same ganglion cell (Fischer, 1973). The size of the receptive field will determine the resolution, i.e., the ability to resolve fine details. In the central part of the visual field the resolution will depend on cone density, while the ganglion cell density will be the limiting factor in the peripheral parts of the retina. In the foveola, the ratio of ganglion cells and photoreceptors are close to 3:1, outside the foveal border the ratio decreases to 1:1 and even less in peripheral retina (Sjöstrand et al., 1999).

The diameter of the foveola is approximately 0.3 mm, which corresponds to ~1° of the visual field and the diameter of fovea is about 1.5-2.0 mm, corresponding to about 5° of visual field. The maximum resolution is further supported by the anatomical structure of the fovea. The inner layers of the retina are displaced in the central fovea to improve light transmission to the photoreceptors and retina, forming a small pit and the Henle fibre layer. Another optical aspect of the retina is that the photoreceptors are more sensitive to light that falls on the receptors parallel with the optic axis compared with stray light from more peripherally refracted rays. This phenomenon is called the Stiles-Crawford effect and has been proven to be important for quality of vision when pupil is large. (Stiles & Crawford, 1933; Fincham, 1951).

1.2.7 Optic nerve and visual pathway

The axons from the ganglion cells radiate towards the optic disc and leave the eye through the optic nerve. About half of the fibres from each eye cross at the optic chiasm and proceed in the optic tract to the lateral geniculate nucleus where there are synapses to axons leading to the primary visual cortex in the brain. The secondary visual cortex transforms the impulses to visual impressions (Hart, 1992).

1.3 REFRACTIVE ERRORS AND OPTICAL LIMITATION

All together, the refractive parts of the eye should give a good image on the retina and provide good visual quality, but the optics in the refractive system are not perfect. The main optical limitations of the eye are aberrations, scatter and diffraction.

1.3.1 Aberrations

Most eyes are not ideal eyes, i.e., different refractive errors will distort the image and it will not be perfectly focused on the retina. Due to different aberrations in the eye, as light is refracted a point source will not create a perfect point image on the retina and the experience will be blurred vision. Aberrations can be divided into chromatic aberration and monochromatic aberration. A description of the aberrations will follow.

1.3.1.1 Chromatic aberrations

Chromatic aberration (CA) is a distortion in which there is a failure of a lens or optical system to focus all colours to the same convergence point. CA is a result of the refractive index being different for different wavelengths, i.e., dispersion. The refractive index decreases with increasing wavelength. Light of different wavelengths forms images of different colours in slightly different places along the axis. For example, blue light with its short wavelength refracts more than red light with its longer wavelength.

Chromatic aberration can be both axial (longitudinal) and transverse (lateral). Longitudinal CA refers to the effect of different wavelengths being focused at different distances from the lens, i.e., at different points on the optical axis (focus shift). Transverse CA refers to the effect of different wavelengths being focused at different positions in the focal plane. The transverse CAs are small along the optical axis but increases with field angle. Thus, it is of less importance in respect to visual quality when the fovea is used for fixation. However, longitudinal CA is more pronounced in central vision. Theoretically, the total longitudinal CA, for all visible wavelengths will be more than 2D (von Helmholtz, 1924), but in practise it will be about 1D for wavelengths between 486-656 nm, and even less at lower luminance levels (Bradley &

Glenn, 1992). In polychromatic light and under photopic conditions, the eye is most sensitive to light of 555 nm (Liou & Brennan, 1997). The eye seems to be fairly well adapted to chromatic aberration. It is something we are hardly aware of, but chromatic aberration is used as one of the directional cues in accommodation control (He et al., 2000; Applegate, 2004; Cheng et al., 2004; Chin et al., 2009). The only way to avoid chromatic aberration is to use monochromatic light.

1.3.1.2 Monochromatic aberration

Monochromatic aberrations include the more common refractive errors we deal with every day like myopia, hyperopia and astigmatism. Monochromatic aberrations appear even when using monochromatic light, hence the name. Monochromatic aberration can be classified according to the Zernike polynomials (figure 2) based on the wavefront concept (Liang et al., 1994). The wavefront is a surface with uniform phase perpendicular to the light rays. The concept of rays, wavefronts and far points can be seen in figure 3. Wavefront aberrations are the measure of the distance from the ideal wavefront and the actual wavefront when they coincide in the pupil plane, and are usually measured in microns. Wavefront aberrations are a product of both the optical path and the refractive index (Charman, 2005). To get an idea of how the microns relate to dioptres, Marsack et al. (2004) have indicated that 0.25 microns defocus over a 6 mm pupil corresponds to 0.19D refractive error.

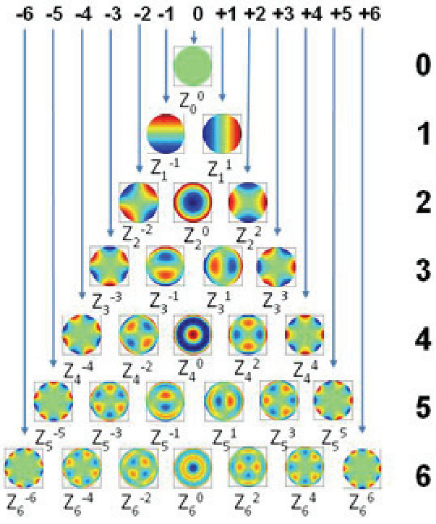

Figure 2. The Zernike polynomials. Order (n) 0 to 2 are the LOA and order 3 to 6 is the HOA. The picture is published with consents from the creator (Unsbo & Lundström).

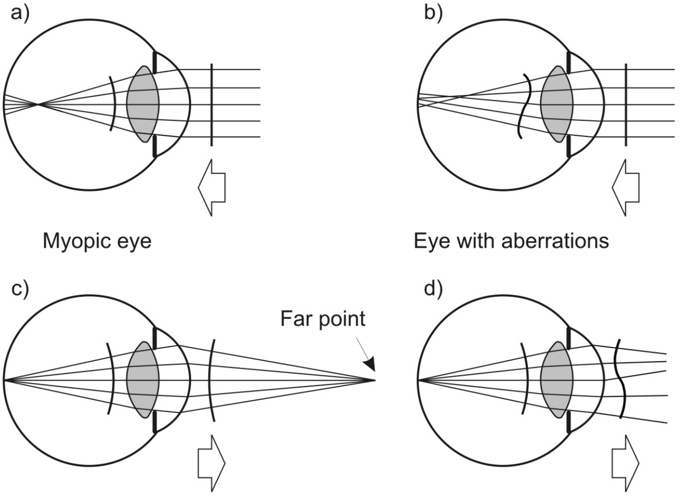

Figure 3. The concept of rays, wavefronts and far points. The picture is published with consents from the creator (Unsbo & Lundström).

From the Zernike polynomials, the aberrations can be divided into lower-order aberrations (LOA) and higher-order aberrations (HOA). When using the Zernike polynomials to describe aberrations, the zeroth-, first- and second- radial order are LOA (Thibos et al., 2002a). Zeroth- and first-order aberrations do not affect monochromatic image quality. In the second order we find the well-known refractive errors: myopia, hyperopia and astigmatism, which have long been correctable (Applegate, 2004). These are the ones we find and try to correct with spectacles or contact lenses during a normal eye exam, finding the spherical correction for myopia and hyperopia and the cylinder power including axis. The majority of the wavefront error, on average, is caused by these second-order aberrations (Atchison, 2005) and they will affect image quality the most. In addition to these common errors, irregularities in the refractive media create HOA which we find in the third order and higher in the Zernike polynomials.

However, it is important to remember that not all types of aberrations affect vision equally (Applegate et al., 2002; 2003; Applegate, 2004). A parallel to this is that 1D of astigmatism will not affect vision as much as 1D of defocus (sphere). The closer to the top of the Zernike pyramid, (lower-order) and those closer to the centre of the pyramid (lower frequency), the more the aberration will affect visual acuity. In contrast, aberrations further down and outwards toward the edges of the Zernike pyramid affect vision less. In a normal eye, aberrations of higher order than the 6th affects vision so little that they almost can be considered "retinal noise "(Catania, 2005).

Typically, the higher the order of the aberration, the smaller its magnitude. The total amount of higher-order aberrations, given by the root mean square (RMS), gives a rough estimation whether there is a large amount of aberrations or not. In normal vision RMS varies between 0.04 and 0.1 µm with a 3 mm pupil and between 0.2 and 0.5 µm with a 6 mm pupil (Howland & Howland, 1977; Walsh et al., 1984; Navarro et al., 1998; Porter et al., 2001; Atchison & Scott, 2002; Thibos et al., 2002b). Trefoil, coma and spherical aberration seem to be the HOAs affecting vision most (Applegate et al., 2002; 2003; Applegate 2004; Charman, 2005). A population distribution of the HOAs can be seen in figure 4 (Thibios et al., 2002b)

Spherical aberration is a fourth order, symmetrical aberration and can be seen as Z_4^0 in figure 2 and 4. Spherical aberration contributes substantially to the higher-order wavefront error (Applegate, 2004). Positive spherical aberration arises when the peripheral rays through a lens or optical system are refracted more than the central rays. Negative spherical aberration arises when the peripheral rays through a lens or optical system are refracted less than the central rays. Thus, the amount of SA will increase with increasing pupil size. The laws of geometrical optics show that for spherical surfaces, as in a spherical contact lens, a positive refraction power will induce positive spherical aberration and a negative refractive power will induce negative spherical aberration (Charman, 2003). Spherical aberration is by definition rotationally symmetrical (Dietze et al., 2004) and varies markedly within the population with a mean of about 0.1 ± 0.1 μm with a 6 mm pupil (Thibos et al., 2002b; Wang & Zhao et al., 2003; Wang & Koch, 2004) which means that SA is the only HOA having a mean value that significantly differs from zero Spherical aberration will increase with age leading to different mean in an older population. Since SA is one of the aberrations affecting vision the most, it would be of interest to correct SA to enhance image quality. It is possible to design contact lenses not only to correct second-order aberrations but also to correct spherical aberration. A standard lens should then have a value based on population average in order to fit as many individuals as possible.

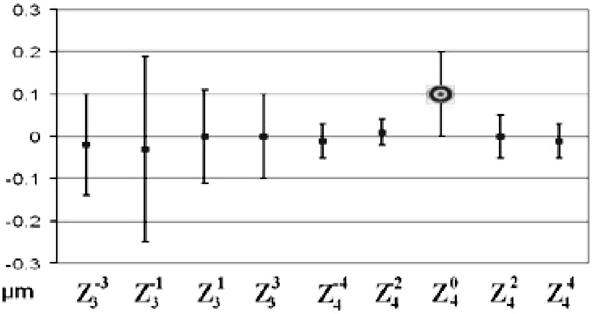

Figure 4. Population distribution (mean value and standard deviation) of third- and fourth-order Zernike coefficients , 6mm pupil (data from Thibios et al., 2002b ,the picture is published with consents from the creator (Unsbo & Lundström)).

1.3.1.3 Scattering and diffraction

The phenomenon of internal reflection in the eye is called scattering. This includes all light that reaches the retina after being deviated by reflection and will cause degradation of the retinal image. Scattering in the refractive media often arises when different refractive indices are present, such as in the lens in early stages of cataract or in opacities in corneal dystrophy. Scatter could also arise in the anterior chamber or vitreous body due to cell flare, remnants of the regressing hyaloid artery or by light reflected by the peripheral parts of the retina (Nam et al., 2011).

Diffraction arises when light waves pass the edge of an aperture or obstacle and bend around into the space behind. In the eye, the iris acts like an aperture and diffraction will become noticeable when the pupil is smaller than 2 mm (Howland & Howland, 1977; Porter et al., 2001; Thibos et al., 2002b). Taking diffraction, aberration and neural factors into account, optimum image quality can be achieved with a pupil diameter of 2-4 mm (Rabbets, 2007; Tunacliff, 1993) and can be seen in figure 5.

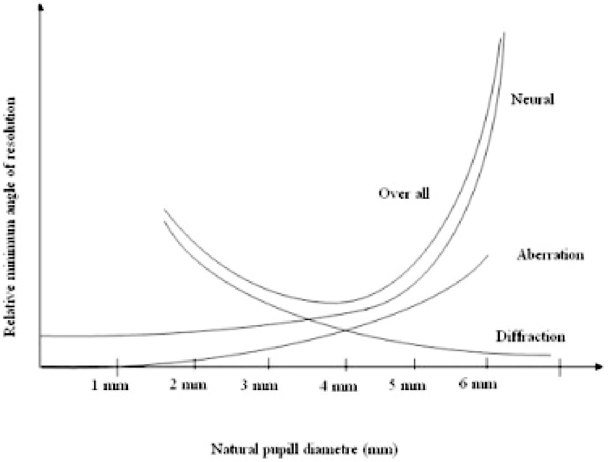

Figure 5. Image quality in relation to pupil size taking diffraction, aberration and neural factors into account (data from Freeman & Hull, 2003).

1.4 ACCOMMODATION AND PRESBYOPIA

1.4.1 Accommodation

Accommodation is the adjustment of the refractive power of the eye. When looking at an object closer to the eye than infinity, the eye needs to increase its refractive power. The eye will accommodate to bring a focused image to the retina. This is done through contraction of ciliary body, which will relax the tension on the lens, which in turn will change its curvature. This increase of power is called positive accommodation, and reduced power is called negative accommodation. In early theories (von Helmholtz, 1924; reprinted 1962), the unaccommodated eye was seen as the relaxed eye, but recent theories have shown that the eye's resting state of accommodation (also termed tonic accommodation) is slightly higher than zero, typically around one dioptre, corresponding to a distance of one meter (Culhane et al., 1999; Winn et al., 2002; Gilmartin et al., 2002).

1.4.1.1 Physiological and nervous mechanisms of accommodation

Already in the mid-1800s, Helmholtz (1854-1939) introduced his accommodation theory, which later was modified by Fincham (1951). This theory was modernised further by Weale (1962; 1989), Coleman (1970) and Fisher (1969; 1971; 1977) to become the most accepted theory today: When looking at distance, the lens has its flattest curve, during accommodation the lens adopt a steeper curve. Due to the changed shape of the lens, spherical aberration (SA) will change almost linearly from, on average, a positive value towards a more negative value in the accommodated eye (Atchison et al., 1995a; He et al., 2000; Cheng et al., 2004; Plainis et al., 2005).

Within the accommodative system, different components contribute to the final accommodative response. These components are normally described as reflex accommodation, tonic accommodation, proximal accommodation, convergence accommodation and adaptation of accommodation (Heath, 1956; Miles, 1985; Ciuffreda, 2002). However, when fixation is changed from one distance to another, reflex accommodation is the largest and most important component of accommodation in clearing the image because it acts in response to blur (Hung et al., 1996; Ciuffreda, 2002). The amount of blur is therefore a cue to reflex accommodation in order to determine the amount of change in accommodation that is needed. However, cues are also needed for direction, i.e., in order to know if accommodation has to be increased or decreased. The main directional cues for the accommodative system are thought to be chromatic aberration (CA) and spherical aberration (SA) (He et al., 2000; Applegate, 2004; Cheng et al., 2004; Chin et al., 2009,) but even proximity has been suggested. Under binocular conditions directional information is obtained through the convergence accommodative cross-link (Fincham, 1951; Ciuffreda, 1991). If all directional cues are removed, the accommodative system would have a 50/50 chance of responding in the correct direction (Ciuffreda, 1991). Previous studies of Troelstra et al. (1964) have shown that it is possible for the accommodative system to operate correctly on an error signal with the cues present (spherical and chromatic aberration, astigmatism and normal fluctuation of the lens) even if the direction or amount of the stimuli is unknown. Van der Wildt et al. (1974) have shown that the anticipation of the stimuli could act as a cue and guide the system in the right direction of accommodation.

The afferent pathway, which stimulates both accommodation and the direct and consensual light reflex, starts in the retinal receptors, continues through the optic nerve, optic chiasm, optic tract, the pretectal nucleus and to the Edinger-Westphal nucleus, which generates accommodation and miosis. A blurred retinal image serves as the sensory stimulus to accommodation, generating impulses which reach both the Edinger-Westphal nuclei (which are the parasympathetic nuclei of the oculomotor nerves) and travel through the oculomotor nerve to the ciliary ganglion in the orbit. The majority of the postganglionic parasympathetic fibres enter the globe through the short ciliary nerves, and some postganglionic fibres travel with the long ciliary nerves, and innervate the iris sphincter and the ciliary muscle to cause miosis and accommodation (Hart, 1992)

1.4.1.2 Aspects of accommodation

The maximum amount by which the eye can change its power is known as the amplitude of accommodation. In 1912 Duane presented results of the accommodative amplitude of 1000 subjects aged 8 to 70 years. The data are still used as normal values for accommodative amplitude in relation to age. By using Hofstetter's (1944) age-expected formula, which is based on Duane's table of amplitude of accommodation, it is possible to see if the amplitude is within normal values (see table 1). Many of the clinical methods used tend to give high readings on accommodation amplitude. One of the reasons for that is the DOF and the tolerance to blur as described above. Duane's (1912) values have long been generally accepted, but measurements of Hamasaki et al. (1956) shows that there is almost no accommodative response after about 60 years and less than 0.50 D at the age of 50. These results were confirmed by Dubbelman et al (2005). This means that the measured amplitude in this age group is due to the DOF and the tolerance to blur rather than actual accommodation and has therefore been called pseudo accommodation.

Expected values
Minimum amplitude = 15 – 0.25 * age in years
Expected amplitude = 18.5 – 0.3 * age in years
Maximum amplitude = 25 – 0.4 * age in years

Table 1. Expected values for amplitude of accommodation using the Hofstetter's formula (1944) based on a given age. The result is given in dioptres.

It also appears that both contrast and fine detail in the object influence control of accommodation. Charman and Tucker (1978) found the most accurate accommodation for fine details and high contrast. Ciuffreda and Hokoda (1985) found a larger spread in the results of response to fine or medium frequencies and this seems to be in line with the other findings. Maximum contrast sensitivity in the eye is in the range of 2-6 cycles per degree (Rabbetts, 2007; Tunacliff, 1993). Many factors such as defocus (=LOA) and chromatic and monochromatic aberrations can affect image quality and decrease the contrast and clarity of an image, but they also give important cues as to the amount and direction of accommodation required. (Rabbetts, 2007; Tunacliff, 1993).

The accommodative response is the amount of accommodation that is generated in response to a stimulus. Because of depth of focus, the accommodative response is not equal to the stimulus demand, but instead is usually less than the accommodative stimulus. The difference between the accommodative response and stimulus is the lag or lead of accommodation. When the accommodative response is smaller than the stimulus it is called a lag, and when it is greater, a lead.

The level of accommodation, in relation to the stimuli, cannot be regarded as a static condition. When viewing a near object, accommodation fluctuates within a range of about 0.2-0.3D (Mordi & Ciuffreda, 2004) with a frequency of about 2 Hz (van der Heijde et al., 1996). This fluctuation will decrease when looking at a distance target or viewing an "empty field", i.e., when there is a lack of stimuli for the eye. This is seen as evidence of the feedback mechanism to maintain a clear image on the retina. Since accommodation fluctuates, the eye is dependent on the DOF to perceive the image as continuously clear and focused. The pupil constricts somewhat for near vision, the smaller aperture this results in an increased DOF, which means DOF is also dependent on pupil size (Ciuffreda et al., 2007; Sergienko & Tutchenko, 2007; Milodot & Milodot, 1989). Since DOF is pupil dependent, illumination will also influence the results, so a standardised level of luminance would be preferable to optimize acuity.

1.4.2 Presbyopia and correction of presbyopia

Presbyopia occurs when a person can no longer see comfortably at a near distance, usually at working or reading distance. Millodot and Millodot (1989) showed that it is possible to use between half and two thirds of the accommodation amplitude for comfortable vision at near. Amplitude decreases continuously with age but the decline is often first noticeable around 45 years of age when the amplitude drops below 5 dioptres. As an example: if the reading distance is 40 cm and the amplitude is 5D, half of the amplitude is used for vision at close range, which can be tiring in the long run. In order to relive accommodation, plus lenses are added which means that less than half the amplitude is used.

The point at which the decrease in amplitude becomes noticeable can vary among individuals, but seems to occur for all people with minor variations depending on heredity and environment (Duane, 1922; Bito & Miranda, 1989).

Several theories have been launched over the centuries of which Hess-Gullstrand, described by Atchison (1995b), and Duane-Fincham are the best known (Duane, 1922). Hess-Gullstrand proposed that presbyopia occurs from changes in the lens and lens capsule, while the ciliary body remains unaffected in strength and structure. Duane-Fincham suggests that the ability to accommodate is lost due to a weakened force in the ciliary muscle and not due to the changes in cortex or nucleus of the lens.

These theories have been modified over the years, by adding extralenticular factors like changes in *zonula zinnii*. (Farnsworth & Shyne, 1979; Atchison, 1995b), but the most probable explanation is a combination of these factors.

Currently, there are several ways to correct for presbyopia:

1.4.2.1 Glasses

a) single vision reading glasses, with one focal distance for near fixation only

b) bifocal glasses, with two focal distances, one for distance and one for near (the presbyopic correction). Trifocal glasses are glasses with three focal distances: one for distance prescription, one for intermediate distance and one for near distance. The power of the intermediate portion of the lens could equal the near correction but be placed so that near vision also is available in upward gaze.

c) progressive lenses, which have a gradual change in power from top to bottom. Distance correction is ground into the upper part of the lens, and then there is a gradual change with downward gaze (for intermediate focus) until a full presbyopic correction is reached at the lowermost part of the lenses.

1.4.2.2 Contact lenses (rigid and soft)

a) Monovision in contact lens wear means fitting one eye for distance vision and one eye for near vision. This fitting modality is possible with both rigid and soft lenses.

b) Conventional aspheric lenses were initially designed to improve the fitting characteristics in single vision contact lens fitting. However, due to the aspherical surface, the lens gives rise to a "power-change" which can be used to correct presbyopia in its early stages. Aspheric lenses are available in both rigid and soft contact lens materials.

c) Multifocal contact lenses have a design with a mixture of that used in bifocal and progressive glasses. These lenses are available in both rigid and soft materials.

Soft lenses with aspheric design (b) and multifocal design (c) are used in this study and will be further described in 1.5.2.

1.4.2.3 Surgical correction

Using laser treatment to correct refractive error can be done in a way which achieves results similar to monovision with contact lenses. Laser treatment techniques to create corneas with multifocal refractive surfaces in order to correct both the underlying refractive error and presbyopia are now being used experimentally as well.

Intraocular lens implants capable of providing similar presbyopia solutions as with contact lenses are also a possibility: monovision and multifocal IOLs (intra ocular lens). Clinical trials are presently being carried out for accommodating IOLs (Cleary et al., 2010).

A more thorough description of the different correction possibilities available for presbyopia is outside the scope of this project. Furthermore, this project is mainly concerned with the formation of the image and the optical limits to vision in relation to aspheric and multifocal soft contact lenses and the remaining description of fitting and design of contact lenses will therefore be focused on soft lenses with aspheric and multifocal design.

1.5 VISUAL QUALITY

Visual quality might seem like a pretty wide concept, but is an attempt to describe vision and what a person really can perceive in a comfortable manner with optimal correction under variable conditions, such as at different distances, different light levels and in different environments. A clear image on the retina, based on an optimal refractive power (with or without corrective aids), is a fundamental component but is not the only condition that should be met. Factors that affect how an object is perceived are not only the image sharpness and contrast on the retina, but also how fast and accurate the focus can be altered from distance to near and how well the eyes work together to place the images in corresponding retinal points (Maddox, 1886; Ciuffreda, 1998). Additional factors affecting visual quality are the neural transmission from the retina to the brain and the interpretation of the image to visual stimuli in the brain (Norton et al., 2002). An attempt to evaluate visual quality is made in this project by using different objective and subjective measurements. Objective measurements have the advantage that they can be considered as subject independent but are in a way limited since they lack subjects' interpretation. Of course, the subjects' interpretation will have an impact on the subjective measurements in that the subjects' answers form the basis of the measurements. In this work, objective and subjective measurements have been performed with respect to aberrations (LOA and HOA), visual acuity, contrast and accommodation. Binocular vision and neural transmission have not been evaluated. Methods used in the study are described below.

1.5.1 Objective measurements

Objective measurements refer to measurements that can be performed without the response of the subject to determine the measurement endpoint. Objective measurements made in this project are autorefractor measurements, aberration measurements and objective accommodation measurements.

1.5.1.1 Autorefractors

Objective autorefractors are commonly based on the principle of analysing the vergence of reflected light rays returning to a camera after illuminating a point on the retina. (Choi et al., 2000; Abrahamsson et al., 2003; Hunt et al., 2003; Davies et al., 2003). Conventional autorefractors quantify second order aberrations, i.e., the spherical component (defocus) and astigmatism. The autorefractors used in this study are the PowerRefractor and the Shin-Nippon.

The PowerRefractor (MultiChannel Systems, Reutlingen, Germany – now manufactured by PlusOptix. Nürnberg, Germany) is a video refractometer with the ability to measure refractive errors and changes in both eyes simultaneously. The refractive power of the eye is presented as sphere, cylinder (in 0.25D steps) and axis for each eye (1° increments). The PowerRefractor allows continuous measurement (25 Hz) of refraction/accommodation, eye position and pupil size. For detailed information, see Choi et al. (2000). Several studies have shown that the PowerRefractor is a reliable instrument for measuring refractive errors in young children (Choi et al., 2000; Abrahamsson et al., 2003; Hunt et al., 2003; Satiani & Mutti, 2011). The instrument is placed at one meter from the subject and the target can be placed at any distance, however, the instrument is calibrated for fixation at one meter distance.

The Shin-Nippon N Vision-K 5001 Autoref-keratometer (Shin-Nippon, RyoSyo Industrial Co., Ltd, Japan) provides a binocular open-field view during the refraction measurement. That allows binocular measurements with external targets at distance or near. The refractive power of the eye is presented as sphere, cylinder and axis for each eye. The dioptric power-mode can be set on 0.12D or 0.25D steps. The Shin-Nippon model used in the study also features an automated keratometer and presents the radius of curvature corresponding to refractive power. For a more detailed description of the Shin-Nippon N Vision-K 5001 Autoref-keratometer, see Davies et al. (2003).

1.5.1.2 Aberrometry

Aberrations in the eye have been recognised since the beginning of the 19th century, first noticed by Young and further studied by Helmholtz, Seidel and Gullstrand (for a rewiev see Atchison & Charman, 2010). Early attempts to measure aberrations were done by Tscherning in 1894 (Rabetts, 2007). The Hartmann-test was developed in the early 20th century, and modified by Shack & Platt in 1971 to become the most widespread present-day principal used: the Hartmann-Shack (HS) wavefront sensor

(Liang et al., 1994). Over the last seventeen years, the methods to measure aberration in the eye have progressed and commercial instruments are now available and can be found in optometry and ophthalmology clinics.

The principle of an HS is an objective method which focuses a point source on the retina. The light reflected from the retina passes through the refractive parts of the eye on the way out and forms a wavefront comprised of both the refractive errors (LOA) and the higher-order aberrations (HOA) of the eye.

The light source is usually a laser diode with a wavelength near the infrared spectra creating a small spot on the retina acting like a secondary light source. From the retina, the light from the point source image is refracted back through the eye and exits the pupil. The wavefront, after having passed through the entire eye, then passes a lenslet array, which creates a pattern of points on a detector. The positions of the points are analysed by comparing their dislocation with the pattern of a perfect reference wavefront (Liang et al., 1994; Porter et al., 2001; Atchison, 2005). It is then possible to display the aberrations in the eye as a wavefront map, and the values of each aberration are referred to as the coefficient describing the amount of the respective Zernike polynomial present in the wavefront. Measuring techniques have been developed that can map the wavefront aberrations or calculate the modulation transfer function (MTF see Section 1.5.2.2) of individual eyes. The Zywave-instrument used in this thesis is based on Hartmann-Shack-technology and a schematic drawing can be seen in figure 6.

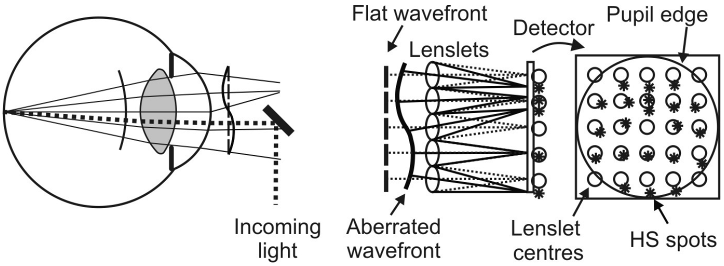

Figure 6.The principle of the Hartmann-Shack sensor. (The aberrations are exaggerated for clarity and the telescope, which images the wavefront from the exit pupil to the lenslet array, is omitted.) The picture is published with consents from the creator (Unsbo & Lundström).

1.5.1.3 Objective measurement of accommodation – dynamic retinoscopy

Amplitude and response accuracy of accommodation can be measured objectively with dynamic retinoscopy. The principle of all dynamic retinoscopy techniques is to determine when a neutral reflex occures while the patient is viewing a target at a close range. Only the Nott technique will be described in more detail here since it was used in this study. The Nott technique requires full distance correction, with the patient fixating an object of size 6/6 to 6/12 at a constant distance of 40 cm. The examiner observes the retinoscopy reflex by the retinoscope and adjusts the working distance until a neutral reflex is seen. The lag or lead of accommodation with the Nott technique is the dioptric difference between the stimulus and the endpoint for neutrality. The normal accommodative response at 40 cm is a lag of between 0.25D and 0.75D (Cacho et al., 1999; Garcia & Cacho, 2002).

1.5.2 Subjective measurements

Subjective measurements refer to measurements which are based on the subject's response and will therefore be influenced by the subject's interpretation of the task and his or her effort to perform. Subjective measurements in this study are visual acuity, contrast measurements and subjective accommodation measurements.

1.5.2.1 Visual acuity

Visual acuity (VA) is the ability to resolve fine details. To calculate the theoretical maximum resolution of the eye, there are two theories: one based on physiological conditions, the receptor theory, and the other based on the laws of physics, the wave theory (Rabbets, 2007). The receptor theory is based on the size of the photoreceptor. The weakness in this theory is the fact that the number, density and size of the human cones are highly variable between individuals (Curcio et al., 1990). However, the receptor theory is built upon the principles that the foveal receptors are 1.5μm in diameter with a gap of 0.5μm. In order for us to perceive two point sources as separate objects, a separate unstimulated receptor is needed between the stimulated receptors. The image detail must therefore be separated by a distance of 4 μm, which corresponds to a resolution of 49 seconds of arc, calculated at the neural level.

The wave theory assumes that even if the optics of the eye are optimized, diffraction will occur. The pupil acts as an aperture which provides a circular image that is most bright in the centre surrounded by rings, the Airy-disc formation (Rabbets, 2007). The central part of the Airy-disc contains 84% of the light. If two point-sources of light create images in the retina, a difference of light intensity is needed between the images to detect them as two separate points. If the Airy-discs are separated by a space corresponding to half the diameter, the difference in light intensity between the central and peripheral parts is big enough to perceive the light sources as two separate points. This is known as the Rayleigh criterion [$\Theta_{\min}= 1.22\lambda/g$ rad] (λ=wavelength, g=pupil size) (Rabbets, 2007). Calculated with a 3 mm pupil and a wavelength of 555 nm, it gives us a resolution of 47 seconds of arc, which is close to the value the receptor theory gives us. Due to anatomical factors and optical limitations described in Section 1.2 and 1.3, visual acuity will vary across the retina. The highest resolution will be in foveola where the density of cones are high and the gangion cell:cone ratio will be close to 3:1 (Sjöstrand et al., 1999). This results in receptive fields close to theoretical limitations. Visual acuity is often measured clinically but factors such as aberrations and neural factors will decrease visual acuity to a lower level than the theoretical smallest readable letter. Letter acuity is more than just a measurement of the ability to resolve fine details since it also involves the cognitive aspect of recognizing the letters presented. Letter acuity is therefore lower than, e.g., vernier acuity (the detection of line alignment) (McKee & Westheimer, 1978; Sun et al., 2008). To resolve a letter, the space between the strokes of the letter must be the same width as the strokes to create an unstimulated area between two receptors. Most commonly, charts present dark letters on a bright background, a near 100% contrast. Visual acuity is inversely proportional to the angle of resolution.

This gives us the formula for visual acuity as:

$V = 1/A$ (V=visual acuity, A=is the line width of the strokes of the letter expressed in minutes of arc)

Expressed in logMAR:

$\text{logMAR} = \log_{10}(A) = \log_{10}(1/V)$

For testing visual acuity there are a great number of different test charts available, varying in letter style, size and spacing, and for different testing distances. Using a chart with logarithmic scale would be most appropriate when determining visual acuity as the progression in letter size for each line is constant. One example is the Bailey-Lovie letter chart that doubles the letter size at every third line (Ferris et al., 1982). The ETDRS chart is a development of the Bailey-Lovie letter chart, which was used in this study.

Both the receptor theory and the wave theory give a maximum resolution of approximately 6/3. The reason for why those theoretical levels of visual acuity are rarely achieved is due to other factors influencing the optical quality like aberrations, scattering and diffraction. The neural system, including the retina and brain will also affect the result of visual acuity measurements since they are often of a psychophysical nature (Norton et al., 2002).

1.5.2.2 Modulation transfer function and contrast sensitivity function

Modulation Transfer Function (MTF)

MTF expresses the way in which any system degrades the modulation or contrast of the images of sinusoidal gratings of different spatial frequencies. Spatial frequency of a grating is defined by the number of full sine waves in each degree of angular subtense and is measured in cycles per degree, often being abbreviated to c/deg, c/º, or cpd. The advantage of using sine gratings is that even if the image is degraded it will still be sinusoidal (Walsh & Charman, 1989), only the contrast will be reduced.

The Michaelson contrast (C), or modulation (M) can be defined as:

$C = M = (L_{max} - L_{min})/(L_{max} + L_{min})$

where L is the luminance. If measuring the contrast in the object (M_o) and the image (M_i), the modulation transfer factor (T) will be defined as:

$T = M_i/M_o$.

When plotting the value of T against the transfer factors for different gratings of different spatial frequencies, the Modulation Transfer Function (MTF) is obtained.

Illustration of a sine-wave grating can be seen in Figure 7.

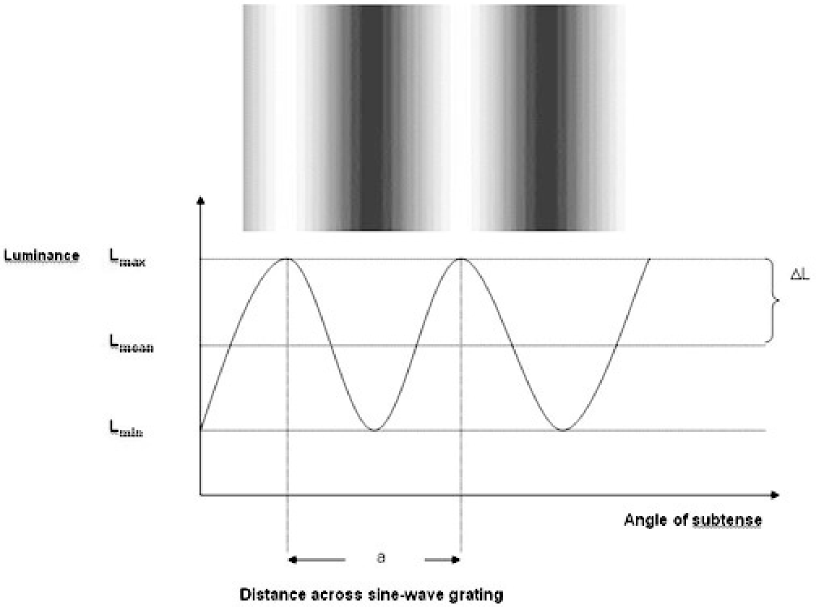

Figure 7. Schematic illustration of a sine-wave grating with the variables involved in specifying such a grating. a=1/spatial frequency

The contrast in the object will always be higher than the contrast in the image since the optical system will always degrade the image to some degree. Therefore, the MTF cannot be higher than 1. The higher value of MTF, the better the optical system. By measuring ocular aberrations, the retinal image quality can be calculated as MTF, although this is not necessarily how the subject perceives the object since both neural and cortical factors are involved.

Contrast Sensitivity Function (CSF)

In reality it is impossible to measure MTF in the retina but there is a possibility to measure contrast sensitivity, (S). By using low contrast sinusoidal gratings, it is possible to find the lowest identified contrast levels at different spatial frequencies S is then the reciprocal value of the threshold, or smallest distinguishable contrast (C_t). S is given by:

$S = 1/C_t$.

CSF is a plot of S against spatial frequencies and normally peaks between 2 to 6 cpd . When a subject has normal visual acuity but the history and symptoms indicates problems, an abnormal CSF curve can reveal ocular diseases or neurological injures, but also even uncorrected refractive errors like astigmatism or added aberrations in a contact lens, for example.

There is a wide range of digital and analog (distance and near) contrast sensitivity test charts available, which are based on both sinusoidal gratings (Ginsburg, 1984) and letters (Pelli et al., 1988; Elliott & Whitaker, 1992). In a clinical setting letter charts are preferred since they are easier to compare with visual acuity. In this study letter charts have been used since they were less time consuming and there was a need to shorten the total investigation time. The Test Chart 2000 (Thomson Software Solutions, Hatfield, UK) was used for distance measurements. The Test Chart 2000 is based on letters of different size at high- and low contrast. For near measurements the Mars Letter (The Mars Perceptrix Corporation, US) was used. The chart consists of letters in the same size but with different contrast levels. The test has been found reliable in several studies (Dougherty & Flom, 2005; Haymes et al., 2006; Thayaparan et al., 2007). Mars Letter is meant to be a more sensitive test than Vistech, for instance, which uses sinus gratings, and is a relatively imprecise test for CS. The intention was to use a more sensitive test. However, Mars Letter is not a full contrast sensitivity examination. In the study the aim was to test contrast sensitivity in healthy eyes under varying circumstances. Thus, a test that shows small differences was required. On the other hand, we did not want to have a test that showed differences so small that they were unlikely to affect visual quality. Examples of letter charts used in the study can be seen in figure 8.

Figure 8. Mars Letter Contrast Sensitivity chart, chart one.

To obtain high sensitivity during contrast sensitivity examinations, threshold testing is often required. However, the use of such stimulus like sinus gratings is often very demanding for the subjects compared to letter charts like Mars Letter chart. Since the frequency of correct responses is a function of the difficulty of the test a more sensitive test might give less reliable results and thereby decrease the specificity (Frizén, 1990). The clinical implication supported the decision to use the Mars Letter Contast Sensitivity Test.

1.5.2.3 Subjective measurement of accommodation – amplitude

The amplitude of accommodation is commonly measured subjectively. The “push-up” technique was used in the studies and is described here. In practice, the amplitude of accommodation is measured separately for each eye, but can also be measured binocularly. Distance correction is used while testing and the object is initially placed at ~50 cm from the subject’s eyes. The non-tested eye is occluded. An object with very small print (Rosenfield & Cohen, 1995) is brought towards the eye until blur is just noticeable. The onset of blur is the endpoint of the measurement because it demonstrates that accommodation is no longer changing (Ciuffreda, 1998). The distance from the spectacle plane, measured in meters, is inverted to provide the accommodation amplitude value in dioptres. If the RAF-rule is used, the amplitude can be read directly off the instrument. Normal values can be predicted by using Hofstetter's (1944) age-expected formula, which is based on Duane's table of amplitude of accommodation (Duane 1912; 1922) with an expected amplitude of [18.5 – (0.3 * age in years)], see also Chapter 1.4.1.2.

1.6 CORRECTION OF REFRACTIVE ERRORS WITH CONTACT LENSES

1.6.1 General soft contact lens fitting

To ensure good eye health, comfort and good visual quality when fitting contact lenses, it is necessary to conduct a series of examinations before the lens is placed on the eye (Young & Coleman, 2001) and to make an accurate evaluation of the lens when it is inserted. This section is a description of the instruments used in examinations and how to perform an evaluation.

1.6.1.1 Instruments in ocular examination for contact lens fitting

A careful evaluation of the eye with a slit-lamp biomicroscope is essential in contact lens fitting. To evaluate the health status of the eye, different illumination levels and illumination techniques as well as different magnifications are used, depending on the type of tissue being examined. Eyelids, eyelashes, the tarsal and bulbar conjunctiva, limbus, cornea and tear film should be examined because these factors can affect the lens fit. The slit lamp is not only used for the fundamental study of the eye, but also for evaluating the lens fit on the eye.

Keratometry measures the curvature of the central cornea. This measurement should be conducted to provide basic values and should be recorded even if the keratometer readings do not always predict the lens fit (Gundel, 1986). The flattening of the cornea, the shape factor, and location of the top of the cornea, corneal apex (Tomlinson & Schwartz, 1979), will be of greater influence and are best evaluated by the use of corneal topography (Garner, 1982; Young, 1992). This is valuable because the lens will be centred over the corneal apex rather than the geometric corneal centre. If the apex is displaced, the lens will decentre. The location of the apex will help to determine the best fit option to overcome a possible decentration (Bruce, 1994).Keratometry can also be used for evaluation of the tear film. By observing the mires, break-up time can be measured non-invasively, called NiBUT. This assessment of the value of lachrymal quality without invasive agents can be an advantage before a lens fitting (Hirji et al., 1989).

1.6.1.2 Initial trial lens

Modern contact lens fitting has been developed to a less complex procedure since there are fewer parameters to choose from, thanks to the development of lens materials and lens designs that allow each lens to cover a greater span of corneal shapes. The purpose of this chapter is to give an overview of the key aspects and parameters to take into account in single-vision contact lens fitting. Multifocal contact lens fitting strategies and designs follows the same basic principles regarding ocular evaluation and lens fit.

A good strategy is to choose a lens as close to the patient's refracted spectacle power as possible, compensated for vertex distance, to give the patient an optimal viewing experience without stimulating accommodation. Conventionally, spherical equivalent is used for astigmatism up to 0.75 D.

Back Optic Zone Radius (BOZR) or Base Curve (BC) is often based on the Keratometer-values even if they do not tell us much about lens movement (as mentioned above). A basic rule is still to choose a base curve approximately 1 mm flatter than the flattest Keratometer-value to obtain suitable movement. Modern disposable lenses are often only available in two to four base curves. When only two base curves are available it is recommended to fit the flatter base curve for flat Keratometer-readings and the steeper for steep Keratometer-readings. When four curves are available it is recommended to start in the middle of the available range of curves. However, it is always recommended to follow the manufacturer's guidelines if they deviate from the above.

Total Diameter TD should be about 2 mm greater than horizontal visible iris diametre (HVID) to provide complete coverage of the cornea in each position of gaze.

The thickness of the lens is often dependent on the lens material. A lens with high water content is generally thicker than a lens with low water content. The thickness has been shown to have little correlation with the movement, while there are various reports about comfort (Efron et al., 1986; Young, 1992), and modern materials like the silicone-hydrogel lenses are also dealing with modulus and friction (Tighe, 2004). Clinicians must consider the patient's eye status and wishes for wearing schedule and then choose a lens suitable for the patient in the available parameters.

1.6.1.3 Evaluation

The ideal soft contact lens should have the following characteristics after a suitable settling period: corneal coverage, good movement, alignment, centration and good patient response, which mean that both subjective evaluation by the patient and objective evaluation by the practitioner have to be done (Efron et al., 1986; McMonnies, 1997).

The lens should cover the cornea and remain approximately central on the cornea in the primary gaze at all times. If the cornea is exposed, dehydration will lead to desiccation and corneal staining. To allow tear exchange under the lens the lens must have good movement. Captured debris will work as metabolic agents and could cause toxic reaction in the cornea (Mertz & Holden, 1981; Zantos, 1984; Cheng et al., 1999). The lens should not show any signs of indentation on conjunctival vessels which may reduce the oxygen supply to the limbus and cause limbal neovascularization (Papas et al., 1997). It should also have an edge profile and a modulus appropriate for the cornea and conjunctiva and should show no edge standoff. Excessive movement is also not good as it could cause discomfort and lead to corneal staining. With modern materials and design it is now well established that soft contact lens movement plays only a minor role in corneal oxygenation, so corneal swelling or oedema is not a common problem with good patient compliance (Papas et al., 1997; Covey et al., 2001).

To judge movement, the lower edge of the lens can be observed during blink. If the lower lid covers the edge it can be observed at 4 or 8 o'clock. With modern materials an ideal movement is about 0.25-0.5 mm (Martin et al., 1989; Young et al., 1993; Little & Bruce, 1994ab; Le et al., 1996; Maldonado-Codina & Efron, 2004). In combination with judging movement and centration in when looking straight ahead, to the sides and upwards, a push-up test can be done.

A push-up test is a way of assessing the movement and mobility of the lens relative to the eye. It is an effective way to assess the dynamic fit. The practitioner pushes the lens in upward direction with the lower lid and observes the movement back to its original position. The significance of the push-up test has been described by Martin and Holden (1986) and Martin et al. (1989).

First assessment of the lens fit can be made after five minutes (Brennan et al., 1994*)* but it is ideal to wait 20 minutes, if possible, to allow the lens to stabilize on the eye. Several studies show the stabilization of the tear film between the lens and the eye as the main factor affecting lens movement the most (Bruce & Brennan 1988;1992; Little & Bruce, 1994ab; Golding et al., 1995). This is also in line with the new, less dehydrated silicone hydrogel material commonly used today.

A binocularly balanced over-refraction should be performed to achieve best visual acuity with maximum plus power. The refraction should have a clear endpoint.

Fluctuation in visual acuity could indicate a steep or flat lens fit and should be assessed with the slit lamp. A poor lens fit can also be detected with a retinoscope, which will give unstable reflexes, or by judging keratometer mires, which also will look unstable. In those cases a new trial lens should be chosen until refraction with a clear endpoint is reached.

The patient's subjective experience of the lens can be summarised in Ymanes triad: see good, feel good, look good (Yamane & Kuwabara, 1987). The patient should find the lens comfortable, but might have a sensation of the lens in the eye. After an over-refraction, the vision should be stable and clear, but initially the patient may have some difficulties in near work due to the change in prismatic effects compared with spectacles, especially myopes. There should not be any reaction in the eye after the adaptation period due to foreign body sensation from the lens (Dumbleton et al., 2008), or response to changes in pH or osmolarity from the lens storing solutions (Harris et al., 1990; Fletcher & Brennan, 1993).

All examinations and assessments described above are intended to give the patient comfortable lens wear with good visual quality, and also ultimately to ensure an unaffected eye.

1.6.2 Correction of presbyopia with contact lenses

There are several options to correct presbyopia with contact lenses (Bennett 2008; Morgan et al., 2011).

Monovision places a clear image on each retina, the confusion occurring at a higher part of the visual pathway (Collins & Goode, 1994). Alternating or translating bifocals have two different segments. The patient looks through the distance portion of the optic zone in primary gaze. On down gaze the lens is held up against the lower eyelid so the visual axis is directed through the near portion (Bennett, 2008). This type of presbyopic lens is mainly produced in rigid materials and will therefore not be discussed further.

Simultaneous vision bifocals are based on an optical system that places two images on the retina simultaneously and then relies on the visual system to select the clearer picture (Benjamin, 1991). In modern soft multifocal lens design, the power distribution across the lens surface is variable and lenses can be described as aspheric, multifocal or progressive.

Light pencils reaching a spherical lens in the peripheral section refract differently than pencils near the optical centre. This is known as spherical aberration. A spherical lens generates more spherical aberration when the distance to the optical centre increases.

To avoid spherical aberration, the curvature of the lens can be changed in the periphery, making the lens design “aspheric”. If the aim is to minimise the residual spherical aberration, the contact lens is an Spherical Aberration-controlled Contact Lens (SACL). (These types of lenses are used in Paper I, II and III.) The design of the lens curvature can also increase the amount of aberrations in the eye to increase the depth of focus at the retina and therefore provide an increased range of near vision. This type of lens is called a multifocal lens and is mainly used for correction of presbyopia but could possibly be used for other accommodative disorders.

1.6.2.1 Aspheric/Multifocal/Progressive - Centre-Near

The central portion of an aspheric centre-near lens focuses the light from a near object to a sharp retinal image. The surrounding area contains the power of lens required for distance vision. The required aspheric curve can be calculated to induce the required spherical aberration of the eye and the lens.

1.6.2.2 Aspheric/Multifocal/Progressive - Centre-Distance

The optical principle of aspheric centre-distance is the same as for centre-near but reversed. The central portion forms a sharp image on retina from distance objects and the surrounding area contains the power for near work. (This type of lens is used in Paper IV.)

1.6.2.3 Multi-zone concentric and diffractive bifocals

Lens design can also consist of a number of concentric zones or involve a combination of diffractive and refractive optics to achieve bifocal correction. Multi-zone concentric design relies on concentric zones alternatively powered for distance and near vision. The power in the centre of the lens can be chosen for either near or distance vision. These lenses are not used in the study, so they will not be discussed further.

Diffractive lenses work on the principle of placing a phase plate on the rear surface of the lens, which is able to split the light passing through into two discrete focal points, one for distance vision and one for near vision. These lenses will not be discussed further.

2 AIMS OF THE PROJECT

Since SACLs (spherical aberration-controlled contact lenses) in theory should improve vision and visual quality, the aim of this project was to investigate and implement methods to evaluate the influence of SACLs on vision and visual quality. Furthermore, since spherical aberration is involved in the control of accommodation it is also of interest to investigate the effect on accommodation that may be caused by changes in spherical aberration induced by SACL and multifocal lenses. The specific goals of the studies are:

Paper I: To evaluate the changes in spherical aberration induced by SACLs

Paper II: To evaluate the effect on vision and visual quality induced by SACLs

Paper III: To investigate the effect on accommodation when manipulating the assumed directional cues to accommodative response, i.e., spherical aberration and chromatic aberration.

Paper IV: To evaluate the effect that positive changes in spherical aberration induced by a multifocal centre distance contact lens has on the accommodative response

2.1 MATERIAL AND METHODS

2.1.1 Material/Data collection

Subjects for the studies were recruited among the students at the School of Optometry, Karolinska Institute, Stockholm, Sweden. To participate in the studies for Paper I, II, III and IV the subjects had to have (1) refraction within the limits for the contact lenses used in the studies to ensure that lenses were available in 0.25 DS steps of power; (2) astigmatism ≤0.75 DC to ensure adequate visual acuity with spherical lenses; (3) contact lens corrected (binocular and monocular) visual acuity of 6/6 (1.0) Snellen units or better and (4) no ocular pathology or systemic disorders. For Paper II, III and IV additional criteria were as follows: (5) age less than 35 to ensure that the subjects did not need reading addition; (6) not taking any medication with known effect on visual acuity or accommodation.

In Paper I, the number of subjects participating in part one and part two were 22 and 20, respectively. Their age was between 20 and 37 years. In Paper II, twenty subjects were included with a mean age of 22.3 years (±3.45 SD). In Paper III, twenty subjects were included with a mean age of 25.0 years (±2.37 SD). In Paper IV, twenty subjects with normal accommodation were included with a mean age of 25.9 years (±4.3 SD). None of the studies were conducted simultaneously. All subjects were recruited specifically for one study at the time; however, a limited number of subjects have participated in two studies.

2.1.2 Methods

In all papers, the subjects were carefully refracted, and baseline keratometry readings and slit lamp inspection of the eye were performed, all in line with a normal contact lens examination described earlier.

Wavefront aberrations and pupil size were measured with the Zywave^{TM} aberrometer (Bausch & Lomb) (Figure 9) in a dark room and the subjects were covered with a dark cloth to achieve maximum pupil size without the use of dilation. Based on the wavefront data for the maximum pupil size obtained with the Zywave, analytical scaling of the data was done using the method described by Lundström and Unsbo (2007) to calculate the aberrations for pupil sizes 4.0, 5.0 and 6.0 mm (i.e., for pupil sizes smaller than the subjects own pupil size while measuring). The power of the lenses fitted was chosen on the basis of refractive error (spherical equivalent). All lenses were inspected for acceptable movement, centration and corneal coverage.

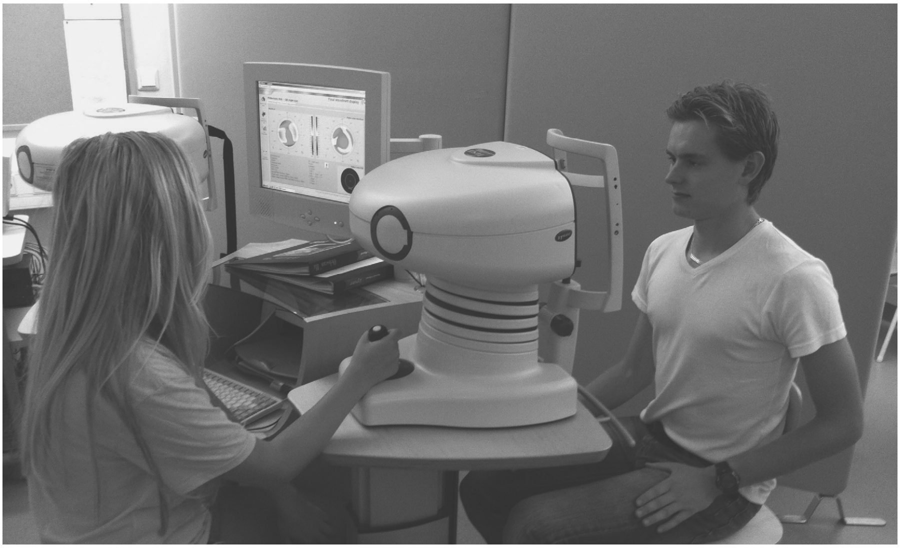

Figure 9. Zywave^{TM} aberrometer (Bausch & Lomb)

Paper I, Part One, compares the residual spherical aberrations with a standard daily disposable lens (Focus Dailies Disposable [8.6/14.2], Ciba Vision Inc.), with a daily disposable SACL (Definition AC Everyday [8.6/14.2], Optical Connection Inc.). Part Two evaluates the residual spherical aberrations with a monthly disposable silicone hydrogel lens (PureVision [8.6/14.0], Bausch & Lomb), which should reduce spherical aberration. Lenses were worn at least one hour before measurements were taken and at least half an hour of rest was given before the next lens was placed on the eye. Aberrations were measured both unaided as a baseline and while wearing the three different contact lenses.

Paper II evaluates the effect that changes in spherical aberration have on visual quality, i.e., visual acuity and contrast sensitivity, at distance and near. The study was a single masked randomised and controlled study with three daily disposable contact lenses: the spherical Dailies Aqua Comfort Plus (Ciba Vision Inc.), the aspheric Soflens Daily Disposable (Bausch & Lomb), and the Zeiss Contact Day 1 (Wöhlk GmbH).

After a short period of adaptation to the lenses, a spherical over-refraction was performed. If necessary, the lens power was adjusted to achieve best visual acuity.

Distance visual acuity (6 m) was measured binocularly and monocularly (in logMAR units) for the right and left eye using the Test-Chart 2000 with randomised letters to avoid learning effects. Low-contrast (10% contrast) visual acuity for distance was also measured binocularly and monocularly using the Test-Chart 2000. A Sloan two-sided ETDRS Near Point chart was used for high-contrast near visual acuity (100% contrast). The chart used for the worst eye was used for binocular measurements (Ferris et al., 1982). To evaluate near contrast sensitivity, the Mars letter contrast sensitivity chart was used at 40 cm. The value for near contrast sensitivity was in log contrast sensitivity units. For all measurements, monocular measurements were taken before binocular in order to avoid learning effects, and all notations were made in logMAR units, except for the Mars letter chart.

Paper III evaluates the effect that negative changes in spherical aberration induced by SACLs has on accommodation control. Wavefront measurements were performed on the unaided eye, with trial frame correction and with the contact lens. An SACL (PureVision [8.6/14.0], Bausch & Lomb), which should reduce spherical aberration, was fitted on the dominant eye and after twenty minutes of adaptation (Bausch & Lomb guidelines) to the lenses, a spherical over-refraction was performed. If necessary, the lens power was adjusted to achieve best visual acuity. PowerRefractor measurements were made in all subjects after aberrometry to measure velocity, response time and lag of accommodation. The subjects were instructed to look at printed text at a distance of 1.14 m (the measuring distance of the PowerRefractor with the 2x extension lens used to increase accuracy of the instrument) and to keep it clear at all times. The subjects fixated the target for four seconds to obtain a steady-state level of accommodation (Vasudevan et al., 2006). The accommodative stimulus, a –2.00 D lens, was then placed in front of the eye for four seconds and then taken away again while measurements were continued for another four seconds. This sequence was repeated three times with a total time of 28 seconds of continuous PowerRefractor measurement. Only data from the increase in accommodation, i.e., only when the –2.00 D was introduced and not when it was removed, was calculated. The sequence of 4 seconds of accommodative stimulation was used to reduce accommodative adaptation (Schor, 1979). The accommodation measurement sequence was performed under both polychromatic and monochromatic light conditions, i.e., with and without the possible directional cues from CA, and with trial frame correction and SACL, i.e., with reduction of the possible directional cue of SA, which gives four different accommodation measurements for each subject.

Paper IV evaluates the effect that positive changes in SA induced by multifocal lenses has on accommodation response. In this paper the subjects were wearing a plano multifocal contact lens with a centre distance design (Proclear™ Multifocal Centre Distance, CooperVision Ltd, Hamble, UK) with an addition power in the periphery of +1.00 D in combination with their own distance spectacle correction. The design of the lens can be seen in figure 10. After aberration measurements, accommodation response was measured with a Shin-Nippon N Vision-K 5001 Autoref-Keratometer with the subject's habitual spectacle correction only. After four hours of adaptation to the lens, accommodation response with both habitual spectacle correction and the plano multifocal contact lens was measured. The left lens was removed before the measurement. This was done in order to make it possible to measure the near response of the eye alone and not the eye and contact lens as an optical system. The right eye only (still wearing the lens) was fixating a near target at 40 cm. A physical septum prevented the left eye from seeing the near target during the measurement and the accommodative response was measured in the left eye only. Measurements were based on the assumption that accommodation is equal in the two eyes even under conditions in which only one eye is fixating (Hart, 1992).

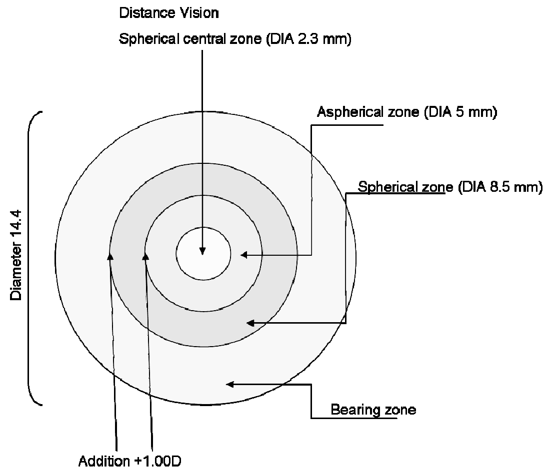

Figure 10. Proclear^{TM} Multifocal lens design.

2.1.3 Contact lenses used in the study

Details of the lenses used:

	Used in:	Optics:	Replacement:
Focus Dailies Disposable	Paper I	Spherical	Daily
Definition AC Everyday	Paper I	Aspheric	Daily
PureVision	Paper I + III	Aspheric	Monthly
Dailies Aqua Comfort Plus	Paper II	Spherical	Daily
Soflens One Day Disposable	Paper II	Aspheric	Daily
Zeiss Contact Day 1	Paper II	Aspheric	Daily
CooperVision Multifocal D +1.00	Paper IV	Aspheric multifocal	Monthly

2.1.4 Ethics

Ethical approval was given by the local ethical committee and the studies adhered to the Declaration of Helsinki. The subjects received written information and informed consent was obtained from all the participants before the study.

2.2 RESULTS

2.2.1 Paper I

Part One showed that spherical aberration was on average positive for all pupil sizes in the uncorrected eye. With the standard lens (Dailies) spherical aberration was on average close to zero for all pupil sizes. The SACL made spherical aberration negative for all pupil sizes. Statistical analysis showed that the difference in the amount of spherical aberrations was statistically significantly ($p < 0.05$) for all pupil sizes when comparing the uncorrected eye, the standard lens and the SACL.

The results of Part Two showed that the monthly disposable lens with aberration reduction lowered the spherical aberration by about 0.19 µm (±0.08 SD) with a 6 mm pupil rather than the 0.15 µm as indicated by the manufacturer. The lens resulted in negative spherical aberration with all pupil sizes. Statistical analysis of the results showed that aberrations were statistically different ($p < 0.05$) with and without the lens with all three pupil sizes and can be seen in figure 11.

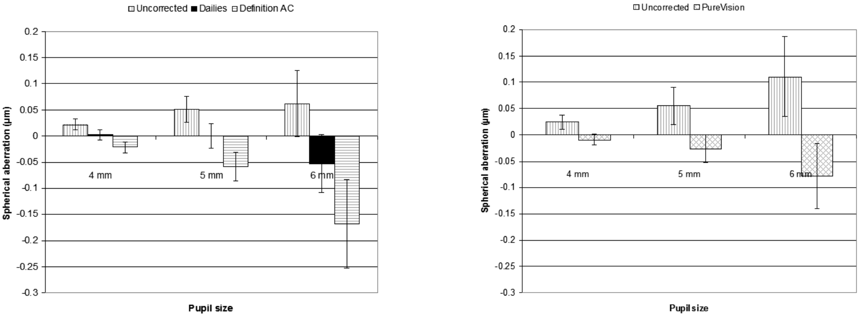

Figure 11. Mean (µm 95% confidence intervals) with Focus Dailies Disposable and with Definition AC Everyday for three different pupil sizes.

2.2.2 Paper II

The results from the aberration measurements in Paper II were in line with the results in Paper I. On average, spherical aberration was positive for all pupil sizes in the uncorrected eye, and close to zero for all pupil sizes with the Dailies disposable. The lenses from Bausch&Lomb and Zeiss made spherical aberration more negative for all pupil sizes with no statistically significant difference ($p < 0.05$) in the amount of change between the two lenses. Statistical analysis showed that the difference in the amount of spherical aberrations was significantly different ($p < 0.05$) for all pupil sizes when comparing the uncorrected eye and the three lenses.

Data for binocular visual acuity and contrast measurements with trial frame and contact lenses can be seen in table 2. There was no significant difference in high- and low-contrast visual acuity between trial frame correction and contact lenses, or between the three lenses. Data for high-contrast Sloan near visual acuity and Mars letter contrast visual acuity showed no significant difference between trial frame and contact lens or between the three lenses.

Table 2	Distance		Near	
Correction	HCVA	LCVA	HCVN	MLCS
Trial frame	-0.12 ± 0.07[a]	0.19 ± 0.08	-0.16 ± 0.08	1.75 ± 0.04
Dailies	-0.14 ± 0.09	0.17 ± 0.08	-0.18 ± 0.06	1.76 ± 0.05
Soflens	-0.12 ± 0.08	0.13 ± 0.08	-0.16 ± 0.05	1.75 ± 0.05
Zeiss	-0.14 ± 0.07	0.16 ± 0.09	-0.19 ± 0.06	1.74 ± 0.06

[a] Mean ±standard deviation

Table 2. Visual acuity and contrast measurements with trial frame and with the three soft contact lenses at distance and near. High contrast visual acuity (HCVA), logMAR; low contrast visual acuity (LCVA), logMAR; high contrast visual acuity near (HCVN); logMAR; Mars Letter contrast sensitivity, (MLCS), log Contrast Sensitivity (log CS).

2.2.3 Paper III

Statistical analysis showed no difference in the amount of SA comparing UC (uncorrected) and TFC (trial frame correction) ($p>0.05$) for all three pupil sizes. However, SA with SACL correction was found to have a statistically significant negative shift ($p>0.001$) as compared with both UC and TFC over all three pupil sizes. The analysis of the time for the subjects to accommodate from 2% to 98%, i.e., accommodation response time, showed no significant difference ($p>0.05$) between TFC and SACL corrections, neither in chromatic nor monochromatic light. Furthermore, no statistically significant difference could be found for the peak velocity and the size of the accommodative lag between TFC and SACL corrections under the two light conditions and can be seen table 3. Using the data for individual subjects, linear regression fits were made for SA/velocity and total RMS/velocity under both polychromatic and monochromatic conditions. The aberration values used were those for the uncorrected eye over a 5 mm pupil. For SA/velocity, the R^2 values were 0.02 and 0.06 in white and monochromatic light, respectively, the corresponding R^2 values for RMS/velocity being 0.005 and 0.08.

	Lag of accommodation	**Response time**	**Velocity**
	Diopters	Seconds	Diopters/seconds
TFC – polychromatic	0.47±0.44	1.52±0.86	2.48±1.22
TFC – monochromatic	0.30±0.34	1.33±0.56	2.27±1.14
SACL – polychromatic	0.90±0.81	1.23±0.77	1.94±1.19
SACL – monochromatic	0.34±0.56	1.27±0.47	2.27±1.07

Table 3. Mean (±SD) values of accommodation. Lag of accommodation: the difference between maximal accommodation and the strength of the accommodation stimulus. Response time: time between 2% and 98% of accommodation response. Velocity: the peak velocity calculated from the fitted sigmoid curve. Trial frame correction (TFC), Spherical aberration controlled contact lens (SACL).

2.2.4 Paper IV

In the normal subject group, the aspheric contact lens changed the amount of SA on average by 0.093 μm (±0.110 SD). Average pupil size was 5.72 mm (±1.17 SD). The mean lag of accommodation for the subject group was 0.85D (±0.57SD) and 0.75D (±0.52SD) without and with the multifocal lens, respectively. Statistical analyses showed no difference in lag ($t = 0.8479$, $p = 0.407$) with and without the lens. There was no correlation ($R^2 = 0.011$) between pupil size and the amount of SA, nor was there any correlation ($R^2 = 0.001$) between aberration and lag of accommodation while wearing the aspheric lens.

2.3 DISCUSSION

The purpose of this project was to investigate whether non-custom-made aberration-controlled and multifocal lenses can improve visual quality. In order to do this, methods to evaluate the influence of different contact lenses were used. Since accommodation control is a part of visual quality and spherical aberration is considered to affect accommodation, accommodation was also examined.

In Study I, the purpose was to evaluate changes in spherical aberration induced by SACLs. It was found that the average amount of spherical aberration in the uncorrected eye is positive and similar in amount to that found in previous publications (Thibos et al., 2002 b; Wang & Dai et al., 2003; Wang & Koch, 2004). The alleged advantage of using the SACLs in these studies is to reduce spherical aberration and not to increase other aberrations, i.e., the intention is to create as perfect a wavefront as possible and thereby improve image quality regardless of the power needed to correct refraction. With a 6.0 mm pupil, as found in Part One and Two of Paper I, SACLs overcorrected the positive spherical aberration. This resulted in the average spherical aberration shifting from positive to negative. Smaller pupil sizes (5.0 and 4.0 mm) showed the same shift. On an individual level, some subjects still had positive spherical aberration with the lenses, and some obtained close to zero, but most subjects had induced negative spherical aberration. On the other hand, the standard lens in part one also shifted the average spherical aberration from positive to negative, but with this lens almost all subjects obtained a spherical aberration close to zero, which should optimize image quality.

Spherical standard lenses induce increased negative spherical aberration with increasing negative lens power, about 0.15 μm for a 5.0 DS lens (Bausch & Lomb Product Information, 2006). The subjects in Part One had a mean myopia of -2.63 DS and a spherical standard lens with this power will, because of its geometric shape, reduce the positive spherical aberration by about 0.075μm with a 6.0 mm pupil. This reduction in spherical aberration is well matched with aberrations found in the subjects tested.

With increasing age, the amount of positive spherical aberration increases as a result of changes in the crystalline lens (Porter et al., 2001). The overcorrection of spherical aberration obtained with the SACLs in Part Two is not surprising since the lens design is based on the average spherical aberration of an older age group than the subjects in our study.

Besides the variation in spherical aberration with age and size of refraction, the results of the studies show that different contact lenses also will affect spherical aberration differently. Consequently, the resulting residual spherical aberration with contact lens correction is often unknown. If the purpose is to change the spherical aberration in a particular direction to provide the best possible image quality or to facilitate accommodation, the selection of the lens should be based on the measurement of aberrations in the uncorrected and corrected eye. To evaluate this commercial aberrometers work well for clinical measurements both with and without the contact lens on the eye.

In Paper II, the aim was to evaluate the visual quality, i.e., visual acuity and contrast, with SACLs and standard lenses, which change spherical aberration.

The results of Paper II confirmed the findings of Paper I, i.e., that spherical aberration in the unaccommodated eye shifts toward zero or negative values with both spherical and aspheric lenses compared to the uncorrected eye. In this study, the results were comparable with previous studies with patients in the same age group (Thibos et al., 2002b; Wang & Dai et al., 2003; Wang & Koch, 2004). Spherical aberration has been suggested as one of the higher-order aberrations with the greatest influence on visual acuity (Applegate et al., 2002). Despite the reduction of spherical aberrations, no difference in high- and low contrast visual acuity at distance in the unaccommodated eye could be found. This result is consistent with previous studies evaluating visual quality of the photopic levels of illumination with aspheric lenses similar to those used in this study (Morgan et al., 2005; Efron et al., 2008). Even under mesopic conditions, when the pupil is larger and the amount of spherical aberration is more pronounced, Efron et al. (2008) found no difference in image quality with aspheric lenses compared to spherical lenses. Efron et al. (2008) also showed that subjects cannot distinguish between spherical and aspheric lenses based on grading of subjective visual performance. Although Rae et al. (2009) could detect a slight improvement of high-and low-contrast visual acuity with customized contact lenses that made spherical aberration negative with a value of 0.1 μm, they pointed out that it probably was not of clinical significance (half a line or more of improvement on a logMAR chart (Morgan et al., 2005). These studies with contact lenses are also in line with results from Johansson et al. (2007) with two different IOLs. Overall, these results indicate that non-customized aspheric lenses do not have any clinically measurable positive effect on the visual quality of the unaccommodated eye in an average population. This is probably due to the low level of spherical aberrations found in most subjects and relatively small pupil sizes under photoptic conditions. The results also show that the clinical tests used in these studies are insensitive to the possible improvements made by aspheric lenses. There is reason to believe that at least a subgroup of patients, i.e., patients with naturally large pupils and a larger amount of spherical aberrations, may have improvements in visual acuity with non-customized aspheric lenses (Plakitsi & Charman, 1997; Liang &Williams., 1997).

When near tasks are performed, accommodation will be needed if no reading addition is used. Previously published data have shown that spherical aberration is positive in the unaccommodated eye and will change linearly towards negative values with increasing accommodation (He et al., 2000; Dietze et al., 2004). For visual quality at near it should therefore not be advantageous to have a large negative spherical aberration in the unaccommodated eye since this will result in substantial amounts of negative SA in near vision (Ivanoff, 1956; Ninomiya et al., 2003; He et al., 2003; Cheng et al., 2004). Correction of spherical aberration in the unaccommodated eye using aspheric lens design can result in an increased amount of negative spherical aberration. In this study the change in spherical aberration due to the accommodation was not measured, and therefore it can only be assumed that the experimental group followed the general trend of a negative change in spherical aberration. With this assumption, it follows that all subjects would have a larger amount of negative spherical aberration for near vision when they wore contact lenses, especially aspheric, compared with the measurements in the trial frame. Naïvely, one would therefore assume that visual quality would decrease in near vision with aspheric lenses. However, the measurements of high-contrast visual acuity and contrast sensitivity at near yielded no difference in visual quality when compared between the lenses, nor when compared to the trial frame measurements. On the other hand, the induced negative spherical aberration causes an increased depth of field, which can reduce the need for accommodation.

It appears that a shift in spherical aberration with accommodation is a cue of fine-tuning of accommodation response (He et al., 2000; Applegate, 2004; Cheng et al, 2004; Chin et al., 2009). It is therefore interesting to evaluate other parameters of the accommodative system to search for possible beneficial effects induced by the lens during near visual tasks. The overall impact of changes in spherical aberration on accommodation is unknown and it may perhaps be better to fit lenses that provide the eye with the aberrations to which the visual system is already adapted to if the intention is to achieve the best possible quality of vision (Chen et al, 2007).

In general, SA and CA are thought to be directional cues for accommodative control. In Paper III, the aim was to evaluate the effect on accommodative control by inducing a negative change in spherical aberration with SACLs and perform measurements in both poly- and monochromatic light, i.e., with and without CA present. In the first part, it was found that the average spherical aberration for distance in the uncorrected eye was positive and the average RMShoa was similar to results from Paper I & II and others' studies (Thibos et al., 2002b; Wang & Dai et al., 2003; Chen et al., 2007). The same result was found with trial frame correction, i.e., trail frame correction does not change the aberrations of the eye. For all pupil diameters, SA with SACLs shifted to a more negative value. These results are also consistent with Paper I & II. The results are also close to what the manufacturer claims (Bausch & Lomb Product Info, 2006) over a 6 mm pupil. Accommodation measurements were carried out with two different levels of spherical aberration and a pupil size of about 5 mm. Measurements of accommodation showed no significant differences in time, speed and lag of accommodation after reducing the SA with SACLs in both monochromatic and polychromatic light. This indicates that the role of SA and CA as cues for directional control of accommodative is doubtful.

The PowerRefractor method was used for all measurements of accommodative response in this paper. The method had weakness in that the same fixation object was used all the time. This object was a single word which might not keep the subjects attention during the whole period of measurement. Furthermore, the accommodative stimulus used was a lens of -2.00D during all measurements. This means that the change in the stimulus was predictable in both size and direction. It is possible that subjects were able to learn what sort of change of accommodation they had to do and it may help to maintain the same dynamic response profile. Therefore, this may have influenced the results. In order to avoid this learning effect, several lenses with different negative power could be used, so that patients cannot predict whether a positive or negative response is required. A pilot study with five patients was done before the main experiment with accommodation stimuli of 1D step and random direction. We could not find any learning trends in the pilot study, which is why the stimulus of 2D, in only one direction, for accommodation, was selected. It is therefore unlikely that a learning effect in this regard has falsified the results. Fernandez & Artal (2005) used a 2.0D and a 1.5D lens when accommodation was stimulated in the direction from far to near, known by the subjects, which is similar to the stimuli used in this study. Fernandez& Artal's results are similar to the results of Troelstra et al. (1964) who found that the average error is about 50% and that there is no indication of trends or learning. In addition, the response time, speed and latency of accommodation found in Paper III was very much in line with previous findings, so the potential limitations of the method should be very small and insignificant (Tucker & Charman, 1978; Heron & Winn, 1989; He et al., 2005).

The change in SA induced in Paper III does not change the accommodative response, a finding that is in line with Atchison et al. (1995b) and He et al. (2005), and indicates that the spherical aberration is not a strong directional clue for accommodation, at least when accommodation changed in large steps. This is not in line with the recent results of Theagarayan et al. (2009) who found that the accommodative lag was affected when the spherical aberration changed. On the other hand, the negative change in SA induced by Theagarayan et al. (2009) was much larger than those induced in the present study and had a magnitude far greater than is normally found in the human eye. Since SA is the optical effect of the peripheral rays not focused on the same point as the central rays, it is difficult to see how this can guide the direction for the accommodation of a target that is 2.0D unfocused, because SA refraction patterns are small and far out of focus. This may be the reason why we and others have not found any effect on accommodation when the size of normal levels of SA changes. Therefore it may be that in most eyes in which the amount of SA is low, SA is rather a cue to maintain a steady state level of accommodation rather than a directional cue for major changes in accommodation (Li et al., 2009). Fernandez and Artal (2005) found that correction of aberrations increased response time and reduced peak velocity but the accuracy of accommodation was not affected. In the present study, the amount of SA was about a quarter of the total RMShoa in the uncorrected eye and about one-tenth or less with SACLs. Contact lenses nearly corrected SA but had little effect on the total RMShoa, indicating that it is possible to change the SA with a SACLs but accommodation will still be largely unaffected.

When comparing the response, velocity and lag of the accommodation during monochromatic and chromatic conditions, no differences were found in this study. These results are in line with Troelstra et al. (1964) who found that the spherical and chromatic aberration were not important to determine the initial direction of accommodation. In contrast, Aggarwala and colleagues (1995ab) found that accommodation under monochromatic conditions was not as accurate as accommodation under chromatic conditions which indicates the importance of CA as a cue for accommodation. As mentioned earlier, the difference in our results may be due to use of step stimuli rather than oscillating stimuli, which were used by Aggarwal et al.

(1995 ab). In a situation with step stimuli, voluntary accommodation may be the strongest directional cue (Charman, 2010 – personal communication). Our use of a mid-spectrum monochromatic light source, rather than 10 different wavelengths as used by Aggarwal et al. (1995ab), may also have influence the outcome of the accommodation in relation to CA. On a side note, it is at least good to know that accommodation seems unaffected under conditions of night driving with street lighting since the monochromatic light source used in Paper III is a standard street lamp.

In combination, our results indicate that both SA and CA most likely do not contribute as the only or main directional cues for accommodation when accommodation is changed in larger steps, since eliminating one or both of them does not alter the accommodative response. It is therefore likely that the accommodative system uses other cues for directional control. Under monocular conditions, the most probable cue for directional control is proximal information, i.e., monocular cues to judge distance such as parallax motion, perspective, overlap, etc. Under binocular conditions, these monocular cues are combined with input from the vergence system, i.e., convergence-accommodation cross-link information, to yield the directional cues to accommodation.

In Paper IV, the aim was to evaluate the effect on accommodative response by inducing changes in spherical aberration with multifocal lenses in order to evaluate accommodative behavior in young subjects.

The main finding of this study was that pre-presbyopic subjects with normal accommodation do not relax their accommodation when they are fitted with aspheric multifocal centre distance contact lenses. This was shown by an unchanged accommodation lag with and without the lens. This is similar to the conclusions that Tarrant et al. (2008) made.

Reading addition, multifocal- or progressive spectacles are commonly used to reduce the amount of blur and thereby the amount of accommodative effort in young subjects with conditions such as (1) reduced accommodation; (2) high AC/A; (3) pseudo-myopia; and (4) myopia.

The aetiology of myopia has been studied extensively, with the relative importance of hereditary vs. environmental influences being the subject of ongoing debate. However, the well-established association between myopia progression and near work, i.e., accommodation, has led to several attempts to reduce myopia progression through prescribing near addition in order to reduce accommodation (Leo & Young, 2011). The use of progressive addition lenses is widely used and has produced some treatment effect (Leung & Brown., 1999; Edwards et al., 2002; Gwiazda et al., 2003).

Based on our findings, the aspheric contact lens used does not seem to achieve the same treatment effect that reading spectacles have on young subjects with the ability to accommodate in order to reduce blur and their accommodative load, and consequently are not suitable to be fitted for this purpose (Tunnacliffe, 1993; McCormack , 1998; Leung & Brown., 1999; Edwards et al., 2002; Gwiazda et al., 2003; Brautaset et al., 2008; MacEwen et al., 2008; Wahlberg et al., 2010; Nilsson & Brautaset, 2011; Leo & Young, 2011). Even if the lenses used in the study did not affect accommodation, it cannot be excluded that they may be used for other purposes such as counteracting myopia progression, which ongoing studies have shown (Smith et al., 2010; Sankaridurg et al., 2010; Anstice & Phillips, 2011)

However, a larger study should be conducted to fully evaluate this. In the condition in which decreased blur and hence decreased accommodation is sought for treatment purposes, it might be that only the condition of decreased accommodative ability could benefit from these lenses is number (1), reduced accommodation, as described above. Further studies are ongoing to evaluate this. In addition, it might be worthwhile to evaluate the effect on accommodation with an aspheric multifocal centre near lens, since the subjects would then need to use the more peripheral part of the lens to see clearly at distance and the reading addition would occupy the central part of the pupil. The reading addition will then be dominant since the pupil constricts as a part of the accommodative reflex, and a center near addition will therefore might relax accommodation. Relaxation of accommodation could be related to pupil size, because the aspheric design used in the study gives increased addition with increasing diameter. However, no correlation in lag and pupil diameter could be found. The average pupil size in the subject group was larger than the zone of aspheric addition in the lens. It has been previously shown that accommodation is affected by the amount of spherical aberration (Theagarayan et al, 2009), but no correlation could be found between the amount of SA and the lag of accommodation in this study. Thus, it appears that young healthy people do not accommodate less when they are provided with aspheric lenses like Proclear^{TM} (CD add +1.00). This is probably because these subjects are able to accommodate and the fact that the accommodation is driven by the central part of the visual field. The light from the more peripheral part of the contact lenses will also strike the cones at an angle that is not along their axis and this effect, the Stiles-Crawford effect, has been proven to be important for accommodation (Fincham, 1951). This may explain why the subjects do not relax their accommodation in near vision when they wear these lenses.

2.4 CLINICAL GUIDELINES

In order to know the level of the aberrations in the eye and to note any change from a contact lens, a wavefront measurement should be performed both with and without contact lenses.

The methods used clinically today are not sufficient to determine which patients could benefit from aberration-controlled contact lenses, which are based on average population values. There is still reason to believe that there are subgroups of patient who can achieve better visual quality but more sensitive clinical methods have to be developed. In order to evaluate whether some patients may benefit from these lenses, a careful history of symptoms and follow-up would be the best approach.

The relatively small change in spherical aberration that non-customised lenses induce does not affect accommodation. These lenses may then be fitted without worrying about unwanted affects on accommodation.

Multifocal, center distance, contact lenses, (addition+1,0), do not seem suitable to be fitted on young subjects with the ability to accommodate in order to reduce blur and their accommodative load, as they do not achieve the same treatment effect that reading spectacles have.

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4 REFERENCES

Abrahamsson, M., Ohlsson, J., Björndahl, M., Abrahamsson, H. Clinical evaluation of an eccentric infrared photorefractor: the PowerRefractor. *Acta Ophthalmol. Scand.* 2003; 81:605-610.

Aggarwala, K., Kruger, E., Mathewa, S., Kruger, P. Spectral bandwidth and ocular accommodation. *J. Op.t Soc. Am.* 1995b; 12:450-455.

Aggarwala, K., Nowbotsing, S., Kruger, P.B. Accommodation to monochromatic and white-light targets. *Invest Ophthalmol Vis Sci.* 1995a; 36:2695-2705.

Albarrán, C., Pons, A.M., Lorente, A., Monte´s, R., Artigas, J.M. Influence of the tear film on optical quality of the eye. *Contact Lens Anterior Eye.* 1997; 20:129–135

American National Standards Institute, "Methods for reporting optical aberrations of eyes," ANSI Z80.28-2004 (ANSI, 2004)

Anstice, N.S. Phillips, J.R. Effect of dual-focus soft contact lens wear on axial myopia progression in children. *Ophthalmology.* 2011; 118:1152-61.

Applegate, R.A. Glenn Fry Award Lecture 2002: wave-front sensing ideal corrections and visual performance. *Optom Vis Sci.* 2004; 81:167-177.

Applegate, R.A. Marsack, J.D. Ramos, R. Sarver, E.J. Interaction between aberrations to improve or reduce visual performance. *J Cataract Refract Surg*. 2003; 29:1487-95.

Applegate, R.A. Sarver, E.J. Khemsara, V. Are all aberrations equal? *J Refract Surg.* 2002; 18:556–62.

Artal, P. Guirao, A. Berrio, E. Williams, D.R. Compensation of corneal aberrations by the internal optics in the human eye. *J Vis.* 2001; 1:1-8.

Atchison, D.A. Charman, W.N.Thomas Young's contribution to visual optics: the Bakerian Lecture "on the mechanism of the eye". *J Vis*. 2010; 10: 1-16.

Atchison, D. A. Smith, G. Optics of the human eye. Butterworth-Heinemann. Oxford. 2000.

Atchison, D.A. Accommodation and presbyopia. *Ophthalmic Physiol Opt.* 1995b; 15:255-72.

Atchison, D.A. Collins, M.J. Wildsoet, C.F. Christensen, J. Waterworth, M.D. Measurement of monochromatic ocular aberrations of human eyes as a function of accommodation by the Howland aberroscope technique. *Vision Res.* 1995a; 35:313-323.

Atchison, D.A. Recent advances in measurements of monochromatic aberration of human eyes. *Clin Exp Optom.* 2005; 88:5–27.

Atchison, D.A. Scott, D.H. Monochromatic aberrations of human eyes in the horizontal visual field. *J Opt Soc Am A Opt Image Sci Vis.* 2002; 19 :2180–4.

Bausch & Lomb Product Information SofLens daily disposable BL 73457 SE. 2006.

Begley, C.G. Caffery, B. Nichols, K.K. Chalmers, R. Responses of contact lens wearers to a dry eye survey. *Optom Vis Sci.* 2000; **77:** 40–46.

Begley, C.G. Chalmers, R.L. Mitchell, G.L. Nichols, K.K. Caffery, B., Simpson, T. DuToit, R. Portello, J. Davis, L. Characterization of ocular surface symptoms from optometric practices in North America, *Cornea.* 2001; 20: 610–618

Benjamin, W.J. Borish, I.M. Physiology of aging and its influence on the contact lens prescription *J Am Optom Assoc.* 1991; 62:743-53.

Benjamin, W.J. Borish's Clinical Refraction; Saunders: Chicago, 1998; pp 77–120.

Bennett, E.S. Contact lens correction of presbyopia. *Clin Exp Optom.* 2008; 91:265-78.

Bergmanson, J.P. Ruben, C.M. Chu, L.W. Epithelial morphological response to soft hydrogel contact lenses. *Br J Ophthalmol.* 1985; 69:373-9.

Bito, L.Z. Miranda, O.C. Accommodation and presbyopia. In Reinecke, R.D. (Ed.), Ophthalmology Annual. 1989; 103-128; New York, Raven Press.

Bradley, A. Glenn A. Fry Award Lecture 1991: Perceptual manifestations of imperfect optics in the human eye: attempts to correct for ocular chromatic aberration. *Optom Vis Sci.* 1992; 69:515-521.

Brautaset, R. Wahlberg, M. Abdi, S. Pansell, T. Accommodation insufficiency in children: Are exercises better than reading glasses? *Strabismus*. 2008; 16: 1-5.

Brennan, N.A. Lindsay, R.G. McCraw, K. Young, L. Bruce, A.S. Golding, T.R. Soft lens movement: temporal characteristics. *Optom Vis Sci*. 1994 ;71:359-63.

Bruce, A. S. Brennan, N. Clinical observations of the postlens tear film during the first hour of hydrogel lens wear. *Int. Contact Lens Clin*. 1988; 15: 304-309.

Bruce, A.S. Influence of corneal topography on centration and movement of low water content soft contact lenses. *Int. Contact Lens Clin.* 1994; 21: 45-49

Bruce, A.S., Brennan, N.A. Hydrogel lens binding and the post-lens tear film. *Clin.Eye Vis.Care*. 1992; 4: 111-116

Cacho, P. Garcia-Munoz, A. Garcia-Bernabeu, J.R. Lopez, A. Comparison between MEM and Nott dynamic retinoscopy. *Optom Vis Sci*. 1999; 76:650-655.

Catania, L. Wavefront technology and Higher-Order Aberrtions. *Optometric Management.* 2005; 9:1-2

Chalmers, R.L. Begley, C.G., Dryness symptoms among an unselected clinical population with and without contact lens wear, *Cont Lens Anterior Eye.* 2006; 29: 25–30.

Chang JH, Gabison EE, Kato T, Azar DT. Corneal neovascularization. *Curr Opin Ophthalmol.* 2001; 12:242-9.

Charman, W.N. Optical aberrations and the eye. *Optician.* 2003; 5898:18–23.

Charman, W.N. Tucker, J. Accommodation and colour. *J Opt Soc Am*. 1978; 68:459-71.

Charman, W.N. Wavefront technology: past, present and future. *Cont Lens Anterior Eye*. 2005; 28:75-92.

Chen L, Artal P, Gutierrez D, Williams DR. Neural compensation forthe best aberration correction. *J Vis*. 2007; 7: 9.1–9.

Cheng, H. Barnett, J.K. Vilupuru, A.S. Marsack, J.D. Kasthurirangan, S. Applegate, R.A. Roorda, A. A population study on changes in wave aberrations with accommodation. *J Vis*. 2004; 16:272-280.

Cheng, K.H. Leung, S.L. Hoekman, H.W. Beekhuis, W.H., Mulder, P.G. Geerards, A.J. Kijlstra, A. Incidence of contact-lens-associated microbial keratitis and its related morbidity. *Lancet*. 1999; 354:181-5.

Chin, S.S. Hampson, K.M. Mallen, E.A.H. Role of ocular aberrations in dynamic accommodation control. *Clin Exp Optom*. 2009; 92:227-237.

Choi, M. S. Weiss, S. Schaeffel, F. Seidermann, A. Howland, H.C.Wilhelm, B. Wilhelm, H. Laboratory, clinical, and kindergarten test of a new eccentric infrared photorefractor (PowerRefractor). *Optom Vis Sci*. 2000; 77 537-548.

Ciuffreda, K.J. Accommodation, the pupil, and presbyopia. In: Borish´s Clinical refraction,1st ed. Benjamin, W.J., Eds.; W.B. Saunders company: Philadelphia, 1998; 77-120.

Ciuffreda, K.J. Hokoda, S.C. Effect of instruction and higher level control on the accommodative response spatial frequency profile. *Ophthalmic Physiol Opt*. 1985; 5:221-3.

Ciuffreda, K.J. The scientific basis for and efficacy of optometric vision therapy in nonstrabismic accommodative and vergence disorders. *Optometry*. 2002; 73:735-762.

Ciuffreda, K.J. Vison and Visual Dysfunction. In: Visual Optics and Instrumentation, vol 1. Chairman, N., Eds.; The Macmillan Press: UK, 1991; Chapter 11.

Ciuffreda, K.J. Wang, B. Vasudevan, B. Depth-of-focus: control system implications. *Comput Biol Med*. 2007; 37:919-23.

Cleary, G. Spalton, D.J. Gala, K.B. A randomized intraindividual comparison of the accommodative performance of the bag-in-the-lens intraocular lens in presbyopic eyes. *Am J Ophthalmol*. 2010; 150:619-627.

Coleman, D. J.: Unified model for accommodative mechanism. *Am. J. Ophthalmol*. 1970; 69:1063-79.

Collins, M.J. Goode, A. Interocular blur suppression and monovision. *Acta Ophthalmol Scand*. 1994; 72: 376–380.

Covey, M. Sweeney, D.F. Terry, R. Hypoxic effects of high Dk softcontact lens wearers are negligible. *Optom Vis Sci*. 2001; 78:95-99.

Cruzat, A. Pavan-Langston, D. Hamrah, P. In vivo confocal microscopy of corneal nerves: analysis and clinical correlation. *Semin Ophthalmol*. 2010; 25:171-7.

Culhane, H.M. Winn, B. Gilmartin, B. Human dynamic closed-loop accommodation augmented by sympathetic inhibition. *Invest Ophthalmol Vis Sci*. 1999; 40:1137-43

Curcio, C.A. Sloan, K.R., Kalina, R.E., Hendrickson, A.E. Human photoreceptor topography. *J Comp Neurol*. 1990; 292:497-523.

Davies, L.N. Mallen, E.A.H. Wolffsohn, J.S. Gilmartin, B. Clinical evaluation of the Shin-Nippon NVision-K 5001/Grand Seiko WR-5100K autorefractor. *Optom Vis Sci*. 2003; 80:320-324.

Dietze, H.H. Cox, M.J. Douthwaite, W.A. Correcting ocular spherical aberration with soft contact lenses. *J Opt Soc Am A Opt Image Sci Vis*. 2004; 21:473–85.

Dougherty, B.E. Flom, R.E. An evaluation of the Mars Letter Contrast Sensitivity Test. *Optom Vis Sci*. 2005; 82:970-5.

Doughty, M.J. Fonn, D. Richter, D. Simpson, T. Caffery, B. Gordon, K. A patient questionnaire approach to estimating the prevalence of dry eye symptoms in patients presenting to optometric practices across Canada, *Optom Vis Sci*. 1997; 74 624–631

Doughty, M.J. Zaman, M.L. Human corneal thickness and its impact on intraocular pressure measures: a review and meta-analysis approach. *Surv Ophthalmol*. 2000; 44:367-408.

Doutch, J. Quantock, A.J. Smith, V.A. Meek, K.M. Light transmission in the human cornea as a function of position across the ocular surface: theoretical and experimental aspects. *Biophys J*. 2008; 95:5092-9.

Duane, A. Normal values of the accommodation at all ages. *Jour. Amer. Med. Assoc*. 1912; 21:1010-1013.

Duane, A. Studies in monocular and binocular accommodation with their clinical application. *Trans Am Ophthalmol Soc*. 1922; 20:132-157.

Dubbelman, M. Van der Heijde, G.L. Weeber, H.A. Change in shape of the aging human crystalline lens with accommodation. *Vision Res*. 2005;45:117-32.

Dumbleton, K.A. Woods, C.A. Jones, L.W., Fonn, D. Comfort and adaptation to silicone hydrogel lenses for daily wear. *Eye Contact Lens*. 2008; 34:215-23.

Edwards, M.H. Li, R.W. Lam, C.S. Lew, J.K. Yu, B.S. The Hong Kong progressive lens myopia control study: Study design and main findings. *Invest Ophthalmol Vis Sci*. 2002; 43:2852-8.

Efron, N. Brennan, N.A. Currie, J.M. Fitzgerald, J.P., Hughes, M.T. Determinants of the initial comfort of hydrogel contact lenses. *Am J Optom Physiol Opt*. 1986; 63:819-23.

Efron, N. Morgan, P.B. Rethinking contact lens associated keratitis. *Clin Exp Optom*. 2006; 89:280-98.

Efron, S. Efron, N. Morgan, P.B. Optical and visual performance of aspheric soft contact lenses. *Optom Vis Sci*. 2008; 85:201–10.

Elliott DB, Whitaker D. Changes in macular function throughout adulthood. *Doc Ophthalmol*. 1990-1991; 76:251-9.

Elliott, D.B. Whitaker, D. Clinical contrast sensitivity chart evaluation. *Ophthalmic Physiol Opt*. 1992; 12:275-80.

Farnsworth, P.N. Shyne, S.E. Anterior zonular shifts with age. *Experimental Eye Research.* 1979; 28: 291-297.

Fernández, E.J. Artal, P. Study on the effects of monochromatic aberrations in the accommodation response by using adaptive optics. *J Opt Soc Am A Opt Image Sci Vis.* 2005; 22:1732-8.

Ferris 3rd, F.L. Kassoff, A. Bresnick, G.H. Bailey, I. New visual acuity charts for clinical research. *Am J Ophthalmol.* 1982; 94:91–6.

Fincham, E.F. The accommodation reflex and its stimulus. *Br. J. Ophthalmol.* 1951; 35: 381-393.

Fischer, B. Overlap of receptive field centers and representation of the visual field in the cat's optic tract. *Vision Res.* 1973; 13:2113-20.

Fisher, R. F. The force of contraction of the human ciliary muscle during accommodation. *The Journal of Physiology.* 1977; 270, 51-74.

Fisher, R.F. Elastic constants of the human lens capsule. *Journal of Physiology.* 1969; 201, 1-19.

Fisher, R.F. The elastic constants of the human lens. *Journal of Physiology.* 1971; 212, 147-180.

Fletcher, E.L. Brennan, N.A. The effect of solution tonicity on the eye. *Clin Exp Optom.* 1993; 76:1 17–21.

Frizén, L. Clinical tests of vision. Raven Press, USA, 1990.

Garcia, A. Cacho, P. MEM and Nott dynamic retinoscopy in patients with disorders of vergence and accommodation. *Ophthal. Physiol. Opt.* 2002; 22:214-220.

Garner, L.F. Sagittal height of the anterior eye and contact lens fitting. *Am J Optom Physiol Opt.* 1982; 59:301-5

Gilmartin, B. Mallen, E.A. Wolffsohn, J.S. Sympathetic control of accommodation: evidence for inter-subject variation. *Ophthalmic Physiol Opt*. 2002; 22:366-71.

Ginsburg, A.P. A new contrast sensitivity vision test chart. *Am J Optom Physiol Opt*. 1984; 61:403-7.

Golding, T.R. Harris, M.G. Smith, R.C. Brennan, N.A.Soft lens movement: effects of humidity and hypertonic saline on lens settling. *Acta Ophthalmol Scand.* 1995; 73:139-44.

Guillon, M. Lydon, D.P. Wilson, C. Corneal topography: a clinical model. *Ophthalmic Physiol Opt*. 1986; 6:47-56.

Gundel, R. Peripheral keratometry and soft lens fitting. *Int Eyecare*. 1986; 2:611-613.

Gwiazda. J. Hyman, L. Hussein, M. Everett, D. Norton. T.T. Kurtz D. A randomized clinical trial of progressive addition lenses versus single vision lenses on the progression of myopia in children. *Invest OphthalmolVis Sci*. 2003; 44:1492-500.

Hamasaki, D. Ong, J. Marg, E. The amplitude of accommodation in presbyopia. *Am J Optom Arch Am Acad Optom.* 1956; 33:3-14.

Hanna, C. O´Brien, J.E. Cell production and migration in the epithelial layer of the cornea. *Arch Ophthalmol.* 1960; 64:536-9.

Harris, M.G. Higa, C.K. Lacey, L.L. Barnhart, L.A. The pH of aerosol saline solution. *Optom Vis Sci.* 1990; 67:2 84–88.

Hart, W. Adler´s Physiology of the eye, 9th ed. Mosby year book: St Louis, 1992.

Haymes, S.A. Roberts, K.F. Cruess, A.F. Nicolela, M.T. LeBlanc, R.P. Ramsey, M.S. Chauhan, B.C. Artes, P.H. The letter contrast sensitivity test: clinical evaluation of a new design. *Invest Ophthalmol Vis Sci.* 2006; 47:2739-45.

He, J.C. Burns, S.A. Marcos, S. Monochromatic aberrations in the accommodated human eye. *Vision Res*. 2000; 40:41-48.

He, J.C. Gwiazda, J. Thorn, F. Held, R. Vera-Diaz, F.A. The association of wavefront aberration and accommodative lag in myopes. *Vision Res*. 2005; 45:285–290.

He, JC. Gwiazda, J., Thorn, F. Held, R. Huang, W. Change in corneal shape and corneal wave-front aberrations with accommodation. *J Vis.* 2003; 3:456–63

Heath, G.G. Components of accommodation. *Am. J. Optom. Arch. Am. Acad. Optom.* 1956; 33:569-579.

Heron, G. Winn, B. Binocular accommodation reaction and response times for normal observers. *Ophthalmic Physiol Opt.*1989; 9: 176-183.

Hirji, N. Patel, S. Callander, M. Human tear film pre-rupture phase time (TP-RPT)--a non-invasive technique for evaluating the pre-corneal tear film using a novel keratometer mire. *Ophthalmic Physiol Opt*. 1989; 9:139-42.

Hofstetter, H.W. A comparison of Duane´s and Donders´ tables of the amplitude of accommodation. *Am. J. Optom. Arch. Am. Acad. Optom*. 1944; 21:345-363.

Howland, H.C. Howland, B. A subjective method for the measurement of monochromatic aberrations of the eye. *J Opt Soc Am.* 1977; 67:1508–18.

Hung, G.K. Ciuffreda, K.J. Rosenfield, M. Proximal contribution to a linear static model of accommodation and vergence. *Ophthal. Physiol. Opt*. 1996; 16:31-41

Hunt, O.A. Wolffsohn, J.S. Gilmartin, B. Evaluation of the measurement of refractive error by the PowerRefractor: a remote, continuous and binocular measurement system of oculomotor function. *Br J Ophthalmol.* 2003; 87:1504-1508.

Ivanoff, A. About the spherical aberration of the eye. *J Opt Soc Am. 1956*; 46:901–3.

Jiang, H. Wang, D. Yang, L. Xie, P. He, J.C. A comparison of wave-front aberrations in eyes wearing different types of soft contact lenses. *Optom Vis Sci.* 2006; 83:769–74.

Johansson, B. Sundelin, S. Wikberg-Matsson, A. Unsbo, P. Behndig, A. Visual and optical performance of the Akreos Adapt Advanced Optics and Tecnis Z9000 intraocular lenses: Swedish multicenter study. *J Cataract Refract Surg*. 2007; 33:1565-72.

Johnson, M.E. Murphy, P.J. Changes in the tear film and ocular surface from dry eye syndrome. *Prog Retin Eye Res.* 2004; 23:449–474

Kiely, P.M. Smith, G. Carney, L.G. Meridional variations of corneal shape. *Am J Optom Physiol*. 1984; 61:619-26

King-Smith, P.E. Hinel, E.A. Nichols, J.J. Application of a novel interferometric method to investigate the relation between lipid layer thickness and tear film thinning. *Invest Ophthalmol Vis Sci*. 2010; 51:2418-23.

Kolb, H. How the Retina Works. *American Scientist.* 2003; 91:1-2

Korb, D.R. Greiner, J.V. Herman, J.P. Hebert, E. Finnemore, V.M. Exford, J.M. Glonek, T. Olson, M.C. Lid-wiper epitheliopathy and dry-eye symptoms in contact lens wearers. *CLAO J.* 2002; 28:211-6.

Lam, C. Loran, D.F.C. Designing contact lenses for oriental eyes, *J BCLA.* 1991; 14:109-114.

Laughlin, S.B. Retinal information capacity and the function of the pupil. *Ophthalmic Physiol Opt*. 1992; 12:161-4.

Le, A.H. Liem, S.E. Su, J.L. Harris, M.G. Fitting characteristics of 1-day and 14-day Acuvue disposable contact lenses. *Optom Vis Sci*. 1996; 73:750-3.

Leo, S.W. Young, T.L. An evidence-based update on myopia and interventions to retard its progression. *J AAPOS*. 2011; 15:181-9.

Leung, J.T. Brown, B. Progression of myopia in Hong Kong Chinese schoolchildren is slowed by wearing progressive lenses. *Optom Vis Sci.* 1999; 76:346-54.

Li, J. Xiong, Y. Wang, N. Li, S. Dai, Y. Xue, L.Zhao, H. Jiang, W. Zhang, Y. J. Effects of spherical aberration on visual acuity at different contrasts. *Cataract Refract.Surg.* 2009; 35, 1389–1395.

Liang, J. Grimm, B. Goelz, S. Bille, J.F. Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor. *J Opt Soc Am A Opt Image Sci Vis*. 1994; 11:1949-57.

Liang, J. Williams, D.R. Aberrations and retinal image quality of the normal human eye. *J Opt Soc Am A Opt Image Sci Vis.* 1997; 14: 2873–83.

Lim, C.H. Ruskell, G.L. Corneal nerve access in monkeys. *Albrecht Von Graefes Arch Klin Exp Ophthalmol.* 1978; 208(1-3):15-23.

Liou, H.L. Brennan, N.A. Anatomically accurate, finite model eye for optical modeling. *J Opt Soc Am A Opt Image Sci Vis.* 1997; 14:1684-95.

Little, S.A, Bruce, S.A., Hydrogel (Acuvue) lens movement is influenced by the postlens tear film. *Optom Vis Sci.* 1994a; 71: 364-370

Little, S.A, Bruce, S.A.,Postlens tear film morphology, lens movement and symptoms in hydrogel lens wearers. *Ophthalmic and Physiological Optics*. 1994 b; 14 :65–69.

Little, S.A. Bruce, A.S. Role of the post-lens tear film in the mechanism of inferior arcuate staining with ultrathin hydrogel lenses. *CLAO J.* 1995; 21:175-81.

López-Gil, N. Fernández-Sánchez, V. The change of spherical aberration during accommodation and its effect on the accommodation response. *J Vis.* 2010; 12;10:12

Lundström, L. Unsbo, P. Transformation of Zernike coefficients: scaled, translated, and rotated wavefronts with circular and elliptical pupils. *J. Opt. Soc. Am. A.* 2007; 24:569-577.

MacEwen, C. Lymburn, E. Ho, W. Is the maximum hypermetropic correction necessary in children with fully accommodative esotropia? *Br J Ophthalmol.* 2008; 92: 1329–1332.

Maddox, E.E. Investigations in the relation between convergence and accommodation of the eyes. *J. Anat. Physiol*. 1886; 20:475-508, 565-584.

Maldonado-Codina, C. Efron, N. Impact of manufacturing technology and material composition on the mechanical properties of hydrogel contact lenses. *Ophthalmic Physiol Opt.* 2004; 24:551-61.

Marsack, J.D. Thibos, L.N. Applegate, R.A. Metrics of optical quality derived from wave aberrations predict visual performance. *J Vis.* 2004; 4:322-8.

Martin, D.K. Boulos, J. Gan, J. Gavriel, K. Harvey P. A unifying parameter to describe the clinical mechanics of hydrogel contact lenses. *Optom Vis Sci*. 1989; 66:87-91.

Masland, R.H. The fundamental plan of the retina. *Nat Neurosci*. 2001; 4:877-86.

Maurice, D. M. The structure and transparency of the cornea *J Physiol*. 1957; 136: 263–286.

McCormack, G.L. Fusion and binocularity. In: Benjamin WJ, ed. Borish's Clinical Refraction. London: WB Saunders Company, 1998; 121–158.

McKee, SP. Westheimer, G. Improvement in vernier acuity with practice. *Percept Psychophys*. 1978; 24:258-62.

McMonnies, C.W. The critical initial comfort of soft contact lenses. *ClinExp Optom.* 1997; 80:53-58.

Mertz, G.W. Holden, B.A. Clinical implications of extended wear research. *Can J Optom.* 1981; 43: 203-205.

Miles, F.A. Adaptive regulation in the vergence and accommodation control systems. *Rev Oculomot Res*. 1985; 1:81-94.

Millodot, M. Millodot, S. Presbyopia correction and the accommodation in reserve. *Ophthalmic Physiol Opt*. 1989; 9:126-32.

Montés-Micó R, Alio´ JL, Muñoz G, Charman WN. Temporal changes in optical quality of air-tear film interface at anterior cornea after blink. *Invest Ophthalmol Vis Sci.* 2004b; 45:1752–1757

Montés-Micó R. Role of the tear film in the optical quality of the human eye. *J Cataract Refract Surg.* 2007; 33:1631–1635

Montés-Micó R, Alio´ JL, Charman WN. Dynamic changes in the tear film in dry eyes. *Invest Ophthalmol Vis Sci.* 2005a; 46:1615–1619

Montés-Micó R, Alio´ JL, Charman WN. Postblink changes in the ocular modulation transfer function as measured by a doublepass method. *Invest Ophthalmol Vis Sci.* 2005b; 46:4468–4473

Montés-Micó R, Alio´ JL, Mun˜oz G, Pe´rez-Santonja JJ, Charman WN. Postblink changes in total and corneal ocular aberrations. *Ophthalmology*. 2004a; 111:758–767

Montés-Micó R, Ca´ liz A, Alio´ JL. Wavefront analysis of higher-order aberrations in dry eye patients. *J Refract Surg.* 2004c; 20:243–247

Mordi JA, Ciuffreda KJ. Dynamic aspects of accommodation: age and presbyopia. *Vision Res.* 2004; 44:591-601.

Morgan PB, Efron N, Woods CA; International Contact Lens Prescribing Survey Consortium. An international survey of contact lens prescribing for presbyopia. *Clin Exp Optom.* 2011; 94:87-92.

Morgan PB, Efron SE, Efron N, Hill EA. Inefficacy of aspheric soft contact lenses for the correction of low levels of astigmatism. *Optom Vis Sci*. 2005; 82:823–8.

Murav'eva SV, Deshkovich AA, Shelepin YE. The human magno and parvo systems and selective impairments of their functions. *Neurosci Behav Physiol.* 2009; 39:535-43.

Nam J, Thibos LN, Bradley A, Himebaugh N, Liu H. Forward light scatter analysis of the eye in a spatially-resolved double-pass optical system. *Opt Express.* 2011; 19:7417-38.

Navarro R, Moreno E, Dorronsoro C. Monochromatic aberrations and point-spread functions of the human eye across the visual field. *J Opt Soc Am A Opt Image Sci Vis.* 1998; 15:2522–9.

Nichols J.J., C. Ziegler, G.L. Mitchell and Nichols, K.K., Self-reported dry eye disease across refractive modalities, *Invest Ophthalmol Vis Sci.* 2005b; 46:1911–1914.

Nichols, J.J. Mitchell, G.L. King-Smith, P.E. Thinning rate of the precorneal and prelens tear films. *Invest Ophthalmol Vis Sci*. 2005a; 46:2353-61.

Nilsson, M. Brautaset, R.L. Vergence adaptation in subjects with convergence excess. *Strabismus*. 2011; 19:5-11.

Nilsson, S.E. Montan, P.G. The hospitalized cases of contact lens induced keratitis in Sweden and their relation to lens type and wear schedule: results of a three-year retrospective study. *CLAO J.* 1994; 20:97-101.

Ninomiya, S. Fujikado, T. Kuroda, T. Maeda, N. Tano, Y. Hirohara, Y. Wave-front analysis in eyes with accommodative spasm. *Am J Ophthalmol.* 2003; 136:1161–3.

Norton, T.T., Corliss, D.A., Bailey, J.E. The pdychophysical measurement of visual function. Butterworth-Heinemann, New York, 2002.

Papas, E.B. Vajdic, C.M. Austen, R. High-oxygen-transmissibilitysoft contact lenses do not induce limbal hyperaemia. *Curr Eye Res*. 1997; 16:942-948.

Pelli, D. G. Robson, J. G. Wilkins, A. J. The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences*. 1988; 2:187-199

Pflugfelder, S.C. Liu, Z. Monroy, D. Li, DQ. Carvajal, M.E. Price-Schiavi, S.A. Idris, N. Solomon, A. Perez, A. Carraway, K.L. Detection of sialomucin complex (MUC4) in human ocular surface epithelium and tear fluid. *Invest Ophthalmol Vis Sci.* 2000; 41:1316-26.

Plainis, S. Ginis, H. S. Pallikaris, A. The effect of ocular aberrations on steady-state errors of accommodative response. *J Vis*. 2005; 23:466-477.

Plakitsi, A. Charman, W.N. Ocular spherical aberration and theoretical throughfocus modulation transfer functions calculated for eyes fitted with two types of varifocal presbyopic contact lens. *Cont Lens Anterior Eye.* 1997; 20:97–106.

Porter, J. Guirao, A. Cox, I.G.Williams, D.R. Monochromatic aberrationsof the human eye in a large population. *J Opt Soc Am AOpt Image Sci Vis.* 2001; 18:1793–803.

Pult, H. Murphy, P.J. Purslow, C. A novel method to predict the dry eye symptoms in new contact lens wearers. *Optom Vis Sci*. 2009; 86:E1042-50.

Rabbetts RB, Clinical Visual Optics, 4rd edition. Butterworth-Heinemann, Oxford, 2007

Rae, SM. Allen, P.M. Radhakrishnan, H. Theagarayan, B., Price, H.C. Sailaganathan, A. Increasing negative spherical aberration with soft contact lenses improves high and low contrast visual acuity in young adults. *Ophthalmic Physiol Opt.* 2009; 29:593–601.

Rosenfield, M. Cohen, A.S. Push-up amplitude of accommodation and target size. *Ophthal. Physiol*. Opt. 1995; 15:231-232.

Rouse, M.W. Management of binocular anomalies: efficacy of vision therapy in the treatment of accommodative deficiencies. *Am J Optom Physiol Opt* 1987; 64: 415-420.

Sankaridurg, P. Donovan, L. Varnas, S. Ho, A. Chen, X. Martinez, A. Fisher, S. Lin, Z. Smith, EL 3rd. Ge ,J. Holden, B. Spectacle lenses designed to reduce progression of myopia: 12-month results. *Optom Vis Sci*. 2010; 87:631-41. Erratum in: Optom Vis Sci. 2010t; 87:802.

Satiani, N.G. Mutti, D.O. Screening for Hyperopia in Infants Using the PowerRefractor. *Optom Vis Sci*. 2011; May 19. [Epub ahead of print]

Schor, C.M. The influence of rapid prism adaptation upon fixation disparity. *Vision Res*. 1979; 19:757-765.

Sergienko, N.M. Tutchenko, N.N. Depth of focus: clinical manifestation. *Eur J Ophthalmol*. 2007; 17:836-40.

Sjöstrand, J. Olsson, V. Popovic, Z. Conradi, N. Quantitative estimations of foveal and extra-foveal retinal circuitry in humans. *Vision Res*. 1999; 39:2987-98

Smith, EL 3rd. Hung, L.F. Huang, J. Blasdel, T.L. Humbird, T.L. Bockhorst, K.H. Effects of optical defocus on refractive development in monkeys: evidence for local, regionally selective mechanisms. *Invest Ophthalmol Vis Sci*. 2010; 51:3864-73

Stiles, W. S., Crawford, B. H. The Luminous Efficiency of Rays Entering the Eye Pupil at Different Points. Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character, Vol. 112, No. 778 (Mar. 2, 1933), pp. 428-450

Sun, H. Lee, B.B. Baraas, R.C. Systematic misestimation in a vernier task arising from contrast mismatch. *Vis Neurosci*. 2008; 25:365-70.

Szczesna, D.H. Jaron´ski, J. Kasprzak, H.T. Stenevi, U. Interferometric measurements of dynamic changes of tear film. *J Biomed Opt.* 2006; 11: 034028

Tarrant, J. Severson, H.Wildsoet ,C.F. Accommodation in emmetropic and myopic young adults wearing bifocal soft contact lenses. *Ophthalmic Physiol Opt.* 2008; 28: 62-72.

Thayaparan, K. Crossland, M.D. Rubin, G.S. Clinical assessment of two new contrast sensitivity charts. *Br J Ophthalmol.* 2007; 91:749–52

The Definition and Classification of Dry Eye Disease: Report of the Definition and Classification Subcommittee of the International Dry Eye Work Shop (2007) *The Ocular Surface.* 2007; 5:65-204 / www.theocularsurface.com

Theagarayan, B. Radhakrishnan, H. Allen, P.M. Calver, R.I. Rae, S.M. O'Leary, D.J. The effect of altering spherical aberration on the static accommodative response. *Ophthalmic Physiol Opt.* 2009; 29: 65-71.

Thibos, L.N. Hong, X. Bradley, A. Cheng, X. Statistical variation of aberration structure and image quality in a normal population of healthy eyes. *J Opt Soc Am.* 2002b; 19:2329–48.

Thibos, L.N. Hong, X. Clinical applications of the Shack-Hartmann aberrometer. *Optom Vis Sci.* 1999; 76:817–825

Thibos, L.N., Applegate, R.A., Schwiegerling, J.T. Webb, R. Standard for reporting the optical aberrations of the eye. *J Refract Surg.* 2002a; 18:52–60.

Tighe, B. In SiliconeHydrogels: Continius wear contact lenses Ed: D. Sweeney: Butterworth-Heinemann, Edingburg, 2004

Tomlinson, A. Hemenger, R.P. Garriott, R. Method for estimating the spheric aberration of the human crystalline lens in vivo. Investigative *Opthalmology and Visual Science*. 1993; 34, 621–629.

Tomlinson, A. Schwartz, C. The position of the corneal apex in the normal eye. *Am J Optom Physiol Opt.* 1979; 56:236-40.

Troelstra, A. Zuber, B.L. Miller, D. Stark, L. Accommodative tracking: a trial-and-error function. *Vision Res.* 1964; 4:585-594.

Tunnacliffe, A.H. Introduction to visual optics. The Association of Brithis Dispensing Opticians, London, 1993.

Tutt, R. Bradley, A. Begley, C. Thibos, L.N. Optical and visual impact of tear break-up in human eyes. *Invest Ophthalmol Vis Sci.* 2000; 41:4117–4123

van der Heijde, G.L. Beers, A.P. Dubbelman, M. Microfluctuations of steady-state accommodation measured with ultrasonography. *Ophthalmic Physiol Opt*. 1996; 16:216-21.

Van der Wildt, G.J.; Bouman, M.A.; Van De Kraats, J. The Effect of Anticipation on the Transfer Function of the Human Lens System. *Opt. Acta.* 1974; 21, 843–860.

Vasudevan, B. Ciuffreda, K.J. Wang, B. An objective technique to measure the depth-of-focus in free space. *Graefes. Arch. Clin. Exp. Ophthalmol*. 2006; 244, 930–937.

von Helmholtz, H. A Treatise on Physiological Optics, Vol. 3; Optical Society of America: Southall, New York, 1924; reprinted Dover Publication: New York, 1962

Wahlberg, M. Abdi, S. Brautaset, R. Treatment of accommodative insufficiency with plus lens reading addition: is +1.00 D better than +2.00 D? *Strabismus.* 2010; 18: 67-71.

Walsh, G. Charman, W.N. Howland, H.C. Objective technique for the determination of monochromatic aberrations of the human eye. *J Opt Soc Am A.* 1984; 1:987–92.

Walsh, G. Charman, W.N. The effect of defocus on the contrast and phase of the retinal image of a sinusoidal grating. *Ophthalmic Physiol Opt*. 1989; 9:398-404.

Wandell, B.A. Dumoulin, S.O. Brewer, A.A. Visual field maps in human cortex. *Neuron*. 2007; 56:366-83.

Wang, L. Dai, E. Koch, D.D. Nathoo, A. Optical aberrations of the human anterior cornea. *J Cataract Refract Surg*. 2003; 29:1514-21.

Wang, L. Koch, D.D. Age-related changes in corneal and ocular higherorder aberrations. *Am J Ophthalmol.* 2004; 137:988–92.

Wang, Y. Zhao, K. Jin, Y. Niu, Y. Zuo, T. Changes of higher-order aberration with various pupil sizes in the myopic eye. *J Refract Surg.* 2003; 19:270–4.

Weale, R.A. Presbyopia towards the end of the 20th century. *Survey of Ophthalmology.* 1989; 34, 15-30.

Weale, R.A. Presbyopia. *Br J Ophthalmol.* 1962; 46:660-8.

Winn, B. Culhane, H.M. Gilmartin, B. Strang, N.C. Effect of beta-adrenoceptor antagonists on autonomic control of ciliary smooth muscle. *Ophthalmic Physiol Opt*. 2002; 22:359-65.

Winn, B. Whitaker, D. Elliott, D.B. Phillips, N.J. Factors affecting light-adapted pupil size in normal human subjects. *Invest Ophthalmol Vis Sci*. 1994; 35:1132-7.

Wolffsohn, J.S. Hunt, O.A. Chowdhury, A. Objective clinical performance of 'comfort-enhanced' daily disposable soft contact lenses. *Cont Lens Anterior Eye.* 2010; 33:88-92

www.thomson-software-solutions.com/.

Xu, J. Bao, J. Deng, J. Lu, F. He, J.C. Dynamic changes in ocular Zernike aberrations and tear menisci measured with a wavefront sensor and an anterior segment OCT. *Invest Ophthalmol Vis Sci*. 2011 May 25. [Epub ahead of print]

Yamane, S. J. Kuwabara, D. M. Ensuring compliance in patients wearing contact lenses on an extended-wear basis. *Int. Cont. Lens Clin.* 1987; 14, 108–112

Yeniad, B. Beginoglu, M. Bilgin, L.K. Lid-wiper epitheliopathy in contact lens users and patients with dry eye. *Eye Contact Lens*. 2010; 36:140-3.

Young, G. Coleman, S. Poorly fitting soft lenses affect ocular integrity. *CLAO J.* 2001; 27:68-74.

Young, G. Holden, B. Cooke, G. Influence of soft contact lens design on clinical performance. *Optom Vis Sci*. 1993; 70:394-403.

Young, G. Ocular sagittal height and soft contact lens fit. *J Br Contact Lens Assoc.* 1992; 15:45-49.

Young, G., Efron, N. Characteristics of the pre-lens tear film during hydrogel contact lens wear. *Ophthalmic Physiol Opt*. 1991; 11:53-8.

Zantos, S.G. Corneal infiltrates, debris and microcysts. *J Am Optom Assoc.* 1984; 55:196–198.