How to measure the Transverse Chromatic Aberration of the human eye in off-axis angles

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Abstract

Peripheral vision plays an important role for visually impaired people with central field loss. Furthermore, recent studies show that defocus in the image on the peripheral retina might influence the development of myopia. Apart from the refractive errors and astigmatism, off-axis aberrations such as coma and transverse chromatic aberration (TCA) also influence the image quality on the peripheral retina. Theory shows that the amount of TCA is quite large in peripheral vision especially in large off-axis angles. The aim of this study is to develop a method to measure the amount of TCA in the peripheral field of view of the human eye.

The method which was used for this study was subjective and the amount of TCA was measured in the left eye of the three volunteer adult subjects. The method was based on measuring the TCA as a chromatic difference of position outside of the eye. The measurements were done in the nasal retina of the eye in seven angles from 0 deg eccentricity (fovea) to 60 deg eccentricity. To compare the experimental results with theoretical values two schematic eye models were implemented in ZEMAX optical design software; a reduced eye model and a wide angle eye model.

The results showed the expected increase of TCA with off-axis angle. The measurements for two subjects were in good agreement with the eye models. The magnitudes for TCA varied between subjects, one reason for this can be related to the different shapes of the eye in different subjects. The third subject had different values for TCA. This difference led us to investigate the reliability and the repeatability of the method in more detail.
Introduction

1.1 Why measuring transverse chromatic aberration in off-axis angles?

The human eye is by nature optimized for central vision. The visual acuity and visual ability to recognize a stimulus decreases with retinal eccentricity from the fovea (center of vision) to the periphery (side vision). While foveal vision, with highest visual acuity, supports our need for identifying the objects, it is peripheral vision that alerts us of sudden events that need our foveal attention. Peripheral vision also plays an important role in keeping our balance and for orienting in the environment. But the role of peripheral vision becomes more significant for visually impaired people with central field loss or scotomas. Central scotoma (blind spot in the center of vision) is mainly caused by AMD (age-related macular degeneration). AMD is a medical condition in which the patient suffers from a loss of central vision as a result of nonfunctional central retina (macula). Figure 1.1 shows the difference in the images between a healthy eye and an eye with scotoma. For people with scotoma, although there is still peripheral vision for moving and keeping balance, reading or recognizing faces is difficult. If the peripheral visual acuity of these people could be improved, it will help them to read easier. We know that the decrease in visual acuity in the periphery has three main origins; decrease in the sampling density of the retina, refractive
errors (defocus and astigmatism), and off-axis aberrations such as coma and transverse chromatic aberration. We cannot do anything about the first limit, but for the last two limitations we can work on methods to decrease them. Although in the last decades the interests to investigate the characteristics of peripheral vision and peripheral refractive errors has increased a lot, there are still only a few studies on peripheral transverse chromatic aberration. Since theory shows a large amount of TCA in peripheral angles there is no doubt that TCA affects our peripheral image quality together with the refractive errors and coma.

The interest in studying peripheral refraction has also increased recently because of the idea that peripheral defocus might influence the development of myopia. There are several studies in this field since 70s. Recent studies on animals' eye (chickens) show that wearing a contact lens, which causes defocus on the peripheral retina, makes the eye grow to keep the best image (the focus) on the retina and thereby cause the development of myopia (Figure 1.2 a to c). So far there are no studies which have investigated the influence of TCA on the development of myopia but as it has been mentioned before, theory shows large amounts of TCA in off-axis angles and we know that TCA affects the peripheral image. The idea that the peripheral TCA might affect development of myopia needs to be investigated. The aim of this study is to develop a subjective method to measure the magnitude of the TCA in peripheral vision.

Figure 1.1) a) The image which the normal eye see. b) The image for the eye with scotoma

Figure 1.2) a) Studies on chickens' eye wearing contact lens. b) The contact lens causes defocus on the peripheral retina c) The eye tries to keep the focus on the retina by growing to the back direction.
1.2 Anatomy of the human eye

The human eye has a spherical shape with a diameter of ~24 mm. The first surface in the front part of the eye ball is called cornea. The cornea is a very thin transparent layer which covers the iris, the pupil and the lens. Although most of the people think that the eye’s lens has the main role for the refractive power of the eye, it is the cornea which has two third of the eye’s power. After the cornea is the anterior chamber; the space between the cornea and the iris that is filled with a water-like liquid called aqueous. The next important optical component is the pupil. The iris of the eye controls the size of the pupil and has different amounts of pigments in different people. The pupil is the aperture stop in the eye’s optical system. After the pupil there is the crystalline lens and between the last surface of the lens and the back part of the eye ball there is a gel called vitreous gel which consists of 98% water. The last surface is the retina. It consists of two kinds of photoreceptor cell; cones and rods. The distribution of these photoreceptors along the retina is not uniform. There are two special areas on the retina. The first one is an area with ~5 mm diameter closed to the center of the retina called macula lutea or yellow spot. In the center of the macula there is the fovea which has the highest concentration of cones. It is also called the center of vision. A little bit far from the center of the retina to the opposite side as fovea there is a spot where all the blood veins and the optical nerve of the eye go out of the eye ball. There is zero concentration of photoreceptors in this area. It is called the blind spot.

In figure 1.3 all the optical components of the eye from above are shown. The nose is located in the bottom of the page. The fovea divides the retina in two parts. The part which
is close to the nose is called nasal retina and the opposite part is called temporal retina. There are two important axes in the eye. One is the optical axis which goes from the center of the cornea to the center of the lens and meets the retina in the center. The other one is the visual axis which goes from the fovea to the nodal points of the eye's optical system. The visual axis in most of eyes is located approximately 5 deg from the optical axis on the temporal side of the retina. When we look at an object we turn our visual axis to that object and so that the image of the object falls on the fovea. But we still can see the other objects around the target which we choose to fixate. This side vision is called peripheral vision. In this study we investigated the amount of the transverse chromatic aberration of the eye in the nasal retina and at the fovea.
Theory on the optics of the eye

2.1 Limitations to retinal image quality

In any optical system getting an ideal image, i.e. an image that except in size is exactly identical to the object, is not possible because of two limits. First, the limitation of the optical system itself and second the intrinsic property of the light. The first limit, which is known as aberrations, rises from the fact that optical systems in general are not ideal. The geometry of the system, the surface quality and the material properties affect the image quality. The other limit, which is known as diffraction, rises from the wave nature of light and limits the focus size not to be infinitely small. To study any optical system like the human eye these two limits should be considered. If the effect of diffraction becomes more dominated than the effect of, the aberrations the optical system is called diffraction-limited. The human eye, with pupil size of 2 mm, is diffraction-limited in the center of vision (figure 2.1). In peripheral vision the effect of the aberration on the image quality is much higher than the effect of diffraction. So in this study we will focus on the aberrations of the eye since the effect of diffraction is negligible in comparison with the effect of aberrations. In this chapter we will discuss the general limitations which affect the image quality in the human eye. Then, since the focus of this study is on peripheral vision, we will discuss more about the limitations which affect the image quality in peripheral vision. And at the end we will discuss in more detail the transverse chromatic aberration of the eye.
2.2 Aberrations in the eye

The image quality of the eye is affected by errors in its optical system in three categories; refractive errors, monochromatic aberrations, and chromatic aberration. Since the refractive errors also are caused by the optics of the eye they can be consider as one type of aberrations. The graph in figure 2.2 briefly shows these three categories.
2.2.1 Refractive errors

Refractive errors in the eye are defocus and astigmatism. In defocus, because of mismatching between the optical power and the length of the eye, the light after passing the optical system is focused in front of the retina, in case of myopia, or behind the retina, in case of hyperopia (figure 2.3). In Foveal astigmatism (as corrected by spectacles), the eye has different optical powers in different meridians (cross-sections). It is often caused by the cornea not being spherical; having different radii of curvature in different meridians. In both cases defocus and foveal astigmatism, the results are blurry images on the retina.

![Figure 2.3] a) Hyperopia b) Myopia

2.2.2 Monochromatic aberrations

Monochromatic aberrations or third order aberrations which are also called Seidel aberrations are caused by the geometry of the optical system. They depend on the shape of the surfaces, the position of the object in respect to the system, the position of the aperture stop and so on. They affect both polychromatic and monochromatic light. In general the five monochromatic Seidel aberrations are; spherical aberration, coma, astigmatism, field curvature and distortion. In the eye field curvature is more or less compensated by having the curved retina as the image plane. Also the distortion is compensated by the brain. But the role of the other three aberrations is still noticeable in affecting the image quality of the eye. For example, spherical aberration is caused by the curved surfaces of the cornea and the lens. The rays of light which enter the eye through the edges of the pupil (marginal rays) have larger incident angle than those rays which enter close to the center of the pupil (paraxial rays) and inside the eye they are refracted more. So the result is different foci for marginal and paraxial rays (figure 2.4). Spherical aberration affects the image quality for central vision. The size of the pupil affects the amount of spherical aberration. With small pupil size the amount of spherical aberration is smaller.
Coma and astigmatism (off-axis astigmatism) affect the image quality of off-axis objects in the eye and we will talk about them in more detail later in the part related to the limitations to image quality in peripheral vision.

### 2.2.3 Chromatic aberration

The human eye, like any other optical system, suffers from chromatic aberration as well as monochromatic aberrations. In monochromatic aberrations the geometry of the optical system causes aberration but in chromatic aberration, the dispersion of the refractive media of the optical system is the origin of the aberration.

The refractive index of the eye varies with wavelength; \( n(\lambda) \). It means that the velocity of light inside the eye is depended on frequency. This phenomenon is usually referred to as dispersion. When a beam of light enters to the eye with an incident angle of \( i \), due to Snell’s law, it will refract with angle of \( i' \) inside the eye.

\[
\sin i = n(\lambda) \sin i'
\]

Since the refractive index of the eye varies with wavelengths, the refractive angle inside the eye is also depended on the wavelengths. The refractive index of most parts of the eye is...
close to the refractive index of water. So just as for water, the refractive index in the eye decreases with increasing wavelength. Therefore the refractive angle in figure 2.5 increases when the wavelength increases. In general, the variation in performance of the eye with wavelength is called chromatic aberration. There are two types of chromatic aberration; longitudinal and transverse chromatic aberration. The following section is about longitudinal chromatic aberration and in the next part, "Limitations to the image quality in peripheral vision" we will discuss the transverse chromatic aberration. In figure 2.5 for simplicity the reduced eye model (consists of cornea, vitreous gel, retina and has the pupil on the first surface) has been considered to describe the chromatic aberration of the eye. The same phenomenon happens in the real eye with its different optical components. The difference is that the light is refracted several times when it passes from one media to another with different indexes and dispersions. To describe the theory of longitudinal and transverse chromatic aberration we will for simplicity continue to use the reduced eye model.

2.2.3.1 Longitudinal chromatic aberration

The refractive power of the eye is depended on its refractive index. For example, in the reduced eye model, the cornea is a spherical surface that separates the air from the eye's media with refractive index of $n$. The power of a spherical surface, $K$, depends on the radius of the surface, $r$, and $n$.

$$K(\lambda) = \frac{n(\lambda) - 1}{r}$$

Since the refractive index is a function of wavelength, the refractive power of the eye also varies with wavelength, $K(\lambda)$. Figure 2.6 shows a reduced eye. When a beam of white light from an axial object enters to the eye, because of dispersion, the shorter wavelength (blue) is deviated in smaller angel than the longer wavelength (red) and meets the optical axis before the longer wavelength. It means that the blue wavelength has a shorter focal length than the red wavelength. So the refractive power of the eye becomes larger for shorter wavelength and it decrease with increase in wavelength. When the eye is focused to an axial object, because of the chromatic aberration, the focus for shorter wavelength (blue) is in front of the retina, the focused for the green-yellow wavelength is on the retina and for longer wavelength (red), the focus is behind the retina. The longitudinal chromatic aberration of the eye is defined as the variation in the refractive power of the eye or as the variation in the focal length of the eye along the optical axis with wavelength. It is also called the axial color or the chromatic difference of focus. Longitudinal chromatic aberration does not only exist for axial objects. For off-axis objects there is also chromatic difference of focus along the optical axis of the eye (Z axis in the figure below).
2.3 Limitations to the image quality in peripheral vision

When we go off the optical axis of the eye the role of three types of aberration becomes more dominant than the rest. In figure 2.7 these three types of aberration are highlighted. They are coma, off-axis astigmatism and transverse chromatic aberration. Moreover, there is also defocus that affects the image quality of peripheral vision. The magnitude of defocus depends on the shape of the eye and it varies from person to person. But for the other three aberrations the magnitudes depend on how large the angle is between the optical axis and the incident rays.

Figure 2.7) The limitation to the image quality in the eye. The red highlights show the limitation to the image quality in peripheral vision.
2.3.1 Coma

In coma, as shown in figure 2.8-a, when a beam of light enters the eye from an off-axis object, the magnification varies over the pupil. It means that those rays which go through the center of the pupil meet the cornea with the smaller refractive angles than those who are far from the center. The result is a blurred image with a shadow which is extended to the direction opposite to the direction of the entering beam. Figure 2.8-c,d shows coma in horizontal and vertical directions respectively.

![Figure 2.8](image)

**Figure 2.8** a) Coma in the eye caused by an off axis object. b) Image without coma, c) Image with horizontal coma, d) Image with vertical coma

2.3.2 Astigmatism (off-axis)

When a beam of light from an off-axis object enters the eye, no matter if the eye has refractive errors or not, the horizontal and vertical rays meet the curved surfaces of the eye with different incident angles and therefore they are focused in different points inside the eye. This kind of astigmatism which we here call off-axis astigmatism (just to separate it from the refractive error astigmatism) doesn't relate to the quality of the refractive surfaces of the eye and it is almost the same for all the eyes with the same off-axis angle for incident beams. Since it was complicated to show two directions for the entering beams and their focuses inside the eye, in figure 2.9 for simplicity a simple lens is shown. The same phenomenon happens in the optical system of the eye.

![Figure 2.9](image)

**Figure 2.9** a) Astigmatism caused by an off axis object in a lens. b) Image without off-axis astigmatism, c) Image with off-axis astigmatism
Figure 2.10 shows the point spread function calculated from wave front aberration measurements performed in an eye. The spot in the middle represent the image on the fovea. As we can see the effect of coma and astigmatism are obvious in higher degree eccentricities.

![Figure 2.10](image)

Figure 2.10) The PSF calculated from the wave front aberration measurements performed in an eye.

### 2.3.3 Transverse chromatic aberration

Transverse chromatic aberration is demonstrated in the figure below in the reduced eye model. When light from an off-axis object enters the eye, again because of dispersion, the path followed by the ray inside the eye varies with wavelength. Since the power of the eye is higher for the shorter wavelength (blue), the blue ray is refracted with a smaller refractive angle than the longer wavelength (red). Again the focus for the blue wavelength is in front of the retina and the focus for the red wavelength is behind the retina. But in this case the focuses for different wavelengths are not on the optical axis. They are further from optical axis and there is therefore also a difference in the image height for the two different wavelengths on the retina. This difference in the image height on the retina, which is shown in figure 2.11, is called the transverse chromatic aberration of the eye.

![Figure 2.11](image)

Figure 2.11) The transverse chromatic aberration of the eye, TCA
To describe the transverse chromatic aberration of the eye better, it is always useful to follow the principle ray, the ray that comes from an off-axis point and passes through the center of the entrance pupil. In the reduced eye model the entrance pupil is on the cornea. Since the principle ray for the red wavelength has larger refractive angle than the principle ray of the blue wavelength, it meets the retina further from the optical axis and makes a larger image than the image from the blue principal ray. Transverse chromatic aberration in the eye is defined as the variation of the image size with wavelength on retina. It is more common to define the TCA in the eye in terms of the angel between the two principle rays with different wavelengths (figure 2.12). It is also called chromatic difference of magnification, lateral color or angular dispersion. Transverse chromatic aberration is larger for off axis object but for axial object there is still transverse chromatic aberration since the fovea is located almost 5° from the optical axis.

![Figure 2.12](image.png) The transverse chromatic aberration of the eye in terms of the angle

### 2.4 Measurement of transverse chromatic aberration of the eye

The transverse chromatic aberration like the other kinds of aberration; longitudinal chromatic aberration and monochromatic aberration, is measured outside of the eye. As discussed in previous parts, transverse chromatic aberration happens because of the dispersion in the eye's media. Dispersion causes different wavelengths to refract with different angles inside the eye. So, as shown in figure 2.13, if two rays from two different off-axis sources with different wavelengths enter through the center of the eye's pupil with a certain difference between the incident angles, there will be an equal refractive angle inside the eye for both wavelengths. In this case both wavelengths meet the retina in the same position. So despite the differences in the objects' height outside the eye, the eye cannot recognize two different light sources since the images are overlapping on the retina. The angle outside the eye which is defined by the difference in the position of the two light sources, represent the transverse chromatic aberration of the eye. This idea is the base of our method to measure the TCA of the eye.
2.5 Other studies

Although there are several standard methods to measure the longitudinal chromatic aberration of the human eye such as: best focus method, laser speckle, vernier method, double pass technique, chromo-retinoscopy, so far there have been only few studies for experimentally measuring the transverse chromatic aberration of the eye\textsuperscript{10}. Most of these studies focused on measuring the TCA at the fovea\textsuperscript{11}. The only experimental data for measuring the TCA in peripheral vision has been reported by Ogboso and Bedell, university of Huston, 1987\textsuperscript{12}. They measured the transverse chromatic aberration across the retina in the right eyes of four subjects as the physical misalignment between perceptually aligned objects of two different wavelengths. The method was subjective and they used yellow (572 nm) and blue (435 nm) wavelengths. They proved that the magnitude of TCA increased with retinal eccentricity. They reported that for four subjects the TCA remained less than 10 arc min within 40 deg of the fovea and at 60 deg eccentricity the TCA increased to approximately 30 arc min. The experimental set up consisted of a screen in front of the subject and two lines with different wavelengths were projected onto the screen by different projectors. The subject was foveal fixating a point on the screen and viewed the two lines with his peripheral retina. The idea was to randomly flash the lower line (blue line) at nine known positions to the left and right of the upper fixed line (yellow line). And the subject task was to report whether the blue line was flashed to the right or to the left side of the yellow line. Figure 2.14 the result of their work.
The aim of our study was to develop a new method to measure the TCA in the peripheral retina of the eye with simpler set up and higher accuracy. The idea was to make a set up which instead of projecting the two lines on the screen used two light sources with different wavelengths and two slits in front of them to make the lines. And instead of randomly flashing one of the lines in a few marked positions, the set up was constructed to let the subject move one of the lines towards the other one until she/he see them aligned. In the next chapter, the experimental set up and the subject’s task will be presented in details. Then in chapter 5, our data and the result will be discussed.

Figure 2.14) Data represents TCA for four subjects. The horizontal axis represents the retina eccentricity in deg and the vertical axis represents the misalignment difference between the two lines in arc min. Dashed line is the predicted amount of TCA on a computer-simulated wide-angle model eye. Positive values refer to the misalignment on the right and the negative values refer to the misalignment on the left.
3.1 Principle of the measurements

The method which was used for this study was based on measuring the transverse chromatic aberration of the eye as a chromatic difference in the position outside of the eye. The method is demonstrated in figure 3.1. Two beams of light from two light sources with different wavelengths pass a positive lens before entering the eye. To have off-axis rays, the eye is turned to a foveal fixation target in certain angles. The light sources are placed in the focal plane of a positive lens to have the images of the lines at infinity for the subject. Since for each source the rays are parallel with their principal rays after passing the lens, the angle that the two principal rays make at the center of the lens is the same as the angle that they make at the center of the eye’s pupil (figure 3.1). As mentioned in the theory part, for a special distance between two light sources (angle between the two principal rays), both wavelengths will have the same refractive angle inside the eye. This means that the images of the two sources overlap in one position on the retina and for the eye it seems that the two rays come from the same position outside of the eye. This special angle between the two principal rays represents the transverse chromatic aberration of the eye. In figure 3.1 this angle is shown with large exaggeration.

\[
\text{TCA (arc min)} = \text{arc tan } \left( \frac{\text{misalignment (mm)}}{\text{Focal length (mm)}} \right) \times 60
\]

To measure TCA in terms of an angle, the physical misalignment between two sources should be measured. Since the misalignment between sources is in terms of a few tenths of millimeter, to make it possible to have two sources at almost the same place and to move one source with respect to the other on this small scale a beam splitter is used, as shown in
Figure 3.2. The whole geometry between the components is the same as in figure 3.1, except that the beam splitter folds the rays of the red source and makes it possible to move it in practice.

Figure 3.1) Shows the principal of the method for measuring TCA out of the eye by using two light sources and a lens and a fixed target.

Figure 3.2) Shows using a beam splitter for moving one of the sources easier while the whole geometry stays the same.
3.2 Experimental set up:

Figure 3.3 below schematically represents the experimental set up. The subject’s head was fixed by using a bite bar in front of the lens. The subject viewed monocularly two vertical lines through the lens while he was fovealy fixating a target. The lens was a 10 diopter achromatic lens with 30 mm diameter and the plane surface facing the slits to minimize aberrations. To have two vertical lines, one with short wavelength (blue) and one with longer wavelength (red) in the other side of the lens, two slits were used with two diodes as the light sources behind them and two diffusers in front of the slits. For the red line a 3 mm round type diode with wavelength of 660 nm and for the blue line the same type of diode with wavelength of 428 nm were used. Both had a luminous intensity around 1000 mcd at 30 mA. The slits were 100 mm from the lens, in the focal plane of the lens, and therefore the images of the slits were formed at infinity. A beam splitter was used between the lens and the slits to bend the beam from one of the slits and make it possible to move it. The two slits were placed on the same height so that, when the lines were aligned, the images were overlapping for the subject.

Figure 3.3) A schematic diagram of the experimental set up
As shown in the figure 3.3, the slit with the red light source was moved to the side of the set up and mounted on a translator stage to be able to move it sideways. The accuracy of the translator stage for moving the red line was 0.01 mm (~ 3.5 arc min). The subject viewed the two parallel lines through the lens; the blue line which was fixed in the center of the lens during the experiment and the red line which could be moved from the center of the lens to the two sides of it. The figure 3.4 and 3.5 shows the set up and the pictures below (3.6) show the situation of two lines viewed by the subject in two steps. First, when the red line was in
the center of the lens and overlapping the blue line. Second, when the red lined was moved to the left side of the lens where the two lines were completely separated. The foveal fixation targets were fixed on a wall 3 m from the bite bar. A camera, with a 12mm focal length objective and F-number of 1.2 at full aperture, was used in front of the subject to control the eye’s pupil and to align it with the set up during the experiment. More details about the usage of the camera are provided in alignment part.

![Figure 3.6](image)

Figure 3.6) Show the situation of two lines viewed by the subject in two steps: a) Overlapped. b) Separated

3.3 Alignment:

To align the set up three steps were followed. The first step was to place the two slits in the focal point of the lens with the help of a camera. The second step was aligning the set up by using a laser pointer to find the correct height for all components and correct direction for the lens and beam splitter. And the third step was to find the correct position for the eye with respect to the set up by using the camera.

Before starting these three steps the components of the set up were approximately mounted in their places as shown in figure 3.3. The measurements for the distances and the heights in this step were done by help of a ruler. After this step the set up was ready for more accurate alignment in the following three steps:

3.3.1 Step 1: Finding the focus

As mentioned before, to have the images of the two vertical lines at infinity the slits had to be placed in the focal plane of the lens. To find the correct position of the slits with respect to the lens, a camera was placed on the other side of the lens instead of the eye, figure 3.7. The camera's objective was set to infinity to only give a sharp image of distant objects. The
camera was connected to a TV. So the images of two slits were seen on the TV screen. Since the images were formed at infinity the distance between the camera and the lens wasn’t important. After mounting the camera in the correct height two steps were followed to place the slits in the focal plane of the lens; first the position of the lens with respect to the red slit was found. The red slit was fixed on top of the translator stage to the side of the set up and the lens was moved from the camera towards the beam splitter to find the position in which the image of the red slit became sharp on the TV. The lens was fixed and its position on the set up’s rail was marked. In the second step the position of the blue slit with respect to the lens was found by moving the blue slit back and forward on the rail to get a sharp image on the TV. Then the position of the blue slit was marked. After finding the accurate position of the lens and the slits on the set up's rail, the next step was to find the accurate height for all component of the set up and the accurate direction of the beam splitter and the lens by the help of a laser. For this purpose the camera was removed and replaced with a laser for the next aligning step.

![Figure 3.7](image.png) A schematic diagram of the set up in the step of finding the focus by using a camera

### 3.3.2 Step 2: Aligning with a laser pointer

A green laser pointer was used for alignment. First, everything except the red slit was removed from the set up to be put back one by one later. The laser was mounted parallel to the rail and approximately in the height where the eye was supposed to be placed later in the experiment. Then the laser spot on the wall was marked. First the lens was mounted on the position which had been found in previous step. To align the lens, finding the suitable height and direction for it, the laser spot on the wall had to be placed again on the same position as before. Then the beam splitter was mounted after the lens. To find the correct height and direction for it, the beam splitter was moved and tilted until that the laser spot on the red slit vertically and horizontally was placed in the center of the red slit. The same method was used to find the right height and direction for the blue slit. Then the laser was kept in its position for the next alignment step.
3.3.3 Step 3: Finding eye’s position

Aligning the eye’s pupil with the set up and keeping it in the correct position during the experiment is important because, as mentioned before, to get a correct value for TCA the beams from the two light sources have to enter through the center of the eye’s entrance pupil. The subject was asked to look to the different eccentricities while he was peripherally viewing two lines through the lens. In each eccentricity the subject needed to turn his visual axis to the foveal fixation target. In the case of large eccentricities the subject also needed to turn his head with bite bar. To keep the eye’s pupil in the correct position throughout the measurement, a reference point was needed. To find a reference point the previous camera was mounted in front of the bite bar so the position of the laser that had been used in the previous alignment step was marked on the TV’s screen as a reference point for the eye. Then the laser was removed and the subject’s eye was placed in front of the set up. To check the eye’s position with the reference point on the screen the same camera as before was used. This time the camera, as shown in figure 3.4 and 3.5, was placed on the right side of the set up lower than the position of the subject’s head. It was mounted in an oblique direction to face the eye and at the same time not to block the targets. During the experiment the camera was kept in the same position. So for all measurements in different angles the position of the pupil was checked by the reference point on the screen. To easily move the head of the subject in two directions and find the correct position of the eye, the bite bar was mounted on top of two perpendicular rails. Also the distance between the eye and the lens was measured. For higher eccentricities when the head needed to be turned, the eye moved away from the lens. Moving the head in two directions and keeping the eye again in the correct position just by using the camera and reference point sometimes was
tricky. Knowing the distance to the lens and keeping the eye at that distance helped to solve this problem.

3.4 Calibration

The calibration point or the zero point was the position of the red slit where the two lines were physically aligned, which was found by using a camera instead of the eye before the experiment, figure 3.7. All the overlapping points that were founded later by the subject in the experiment were compared to this zero point to measure the misalignment between the red and the blue lines.

3.5 Subjects

Three adult observers, ranging between 26 to 32 years of age from the Royal Institute of Technology Sweden, voluntarily participated in this study. All the measurements were done on their left eyes. Subject L.L had -3 D refractive errors in her left eye and the other two subjects, R.R and B.D, had no refractive errors in their tested eyes.

3.6 Experiment

The subject’s task was to move the red line from one side of the lens towards the center, where the blue line was fixed, and try to find a position where the two lines seemed to be overlapping. The procedure was different when the subject viewed the lines foveally, in 0 deg eccentricity, instead of using his peripheral vision in 10 to 60 deg eccentricities. In 0 deg the subject’s task first was to remove the red line from the calibration point to the left or right until the two lines looked completely separate (figure 3.6.b). Then the second step was to move it back towards the center and try to align them (figure 3.6.a). The measurement was repeated 10 times; 5 times from left side and 5 times from the right side of the blue line. At the end the misalignment between the two lines for 0 deg eccentricity was the difference between the position of the calibration point and the average value of all these measurements. In larger eccentricities, where the subject used his peripheral vision, the images of the two lines were not sharp enough to find a single position where the lines were aligned. Therefore there was a region in which the subject could move the red line but the two lines still seemed align to him. The aim was to find the border of this region from two sides of the blue line and then to find the position of the center of this area and compare it with the position of the calibration point to measure the misalignment between the two lines. The figure 3.9 schematically shows the subject’s task in four steps. First, the subject removed the red line from the calibration point until the two lines looked completely separate (step 1) then moved it back from the left side of the blue line towards it and tried to find the first position where the two lines seemed overlapped. The subject himself or a second person read the position of this point on the translator stage and recorded this
position (step 2). Then subject again continued to move the red line in the same direction until the two lines seemed recognizable again (step 3) then from the right side of the blue line started moving the red line towards the center to find the first point where the two lines overlapped again (but this time to the right side of the blue line) and recorded the position (step 4).

The difference between these two borders shows the width of the region where the two lines looked overlapped to the subject. In figure 3.9 these four steps are shown with big exaggeration in distances. In the experiment it was observed that the center of the overlapping region had a shift to the right side of the calibration point. The shift represents the misalignment between red and blue lines. By finding the center of this region and comparing it with the position of the calibration point the misalignment of two lines could be measured for different eccentricities. For each eccentricity the measurement were repeated 20 times, 10 times for finding the right border and 10 times for finding the left border. The average value of these 10 measurements was then compared to the calibration point to find the misalignment. The experiment was repeated for seven fixation targets from 0-deg eccentricity to 60 deg in the nasal retina for the left eye. To avoid the blind spot the measurement related to 20 deg eccentricity was done in 25deg instead. For the first 4 fixation target from 0 deg to 30 deg the bite bar was parallel to the axis of the set up. The subject’s task was to look to the fixation point by turning his eye while the head was facing straight towards the lens. For 40 deg to 60 deg the bite bar was turned around 25-30 deg to the left to make it easier for the subject to fix his visual axis to the higher eccentricities. The distance from the eye to the lens was kept the same throughout the entire experiment for all seven fixation targets.
3.7 Data Analysis

To go from the data which were recorded from the translator stage to the final results for TCA, some steps were followed for each set of measurements. As mentioned previously, the measurements for each subject were divided in two parts. First part was at the 0 deg eccentricity where the subject foveally looked through the lens and second when the subject was foveally fixating to the 10 deg to 60 deg eccentricities and viewed peripherally through the lens. In 0 deg eccentricity, the measurements were repeated 10 times. The average value and standard deviation for these set of measurements were calculated. The standard deviation showed the variation of the measurements. By comparing the average value of all measurements with the calibration point, the misalignment between the two lines was found. Also the difference between the calibration point and the average value plus standard deviation and minus standard deviation was calculated to show the variation in the misalignment between the two lines. As mentioned in the theory part, the transverse chromatic aberration is shown in terms of an angle. To translate the misalignment measured with the translator stage in mm to the angle in arc min the formula in part 3.1 was used. For eccentricities higher than 0 deg the measurements were done 20 times, 10 times for finding the left border and 10 times to find the right border. Then the average values and the standard deviations of the measurements for each border were calculated. Then by getting the mean value of the two average values, the position of the center of the overlapping region was found. Also the total standard deviation from the standard deviations of the two borders was calculated. The misalignment between the two lines was the subtraction of this mean value from the calibration point. To get the variation in the misalignment the subtraction of the mean value plus and minus the standard deviation were also calculated. The last step was to translate the misalignment in terms of the angle. Like 0 deg eccentricities the 3.1 formula was used. The result, that is the dependence of misalignment between two lines with eccentricity, is discussed in the result chapter.
To compare the experimental results with the predicted amount of TCA from theory, a schematic eye model is needed to reproduce the optical properties of the eye. There are several different eye models which are used for a wide variation of applications such as using the eye model in simulating the experiments, designing ophthalmic optical correction, predicting the result of refractive surgeries or studying better the properties of different optical components of the eye and etc. For example the Gullstrand eye model which was suggested by Allvar Gullstrand in 1911 and updated by Le Grand later was one of the useful eye models which has been highly used in studies and other application since it was designed. It is still in use mainly because the design was based on anatomy of the eye, it was simple and at the same time it can be used to reproduce the Gaussian properties of the eye. If we consider this eye model as a basic model, there will be two directions in designing the schematic eye models in respect to the basic model. One direction is to design very simplified reduced eye models like the famous Emsley eye model suggested in 1952. And the other direction is to design more advanced eye models which are following the anatomy of the eye more accurately with incorporation of a gradient-index (GRIN) crystalline lens like Liou-Brennan model. But since the distribution of the refractive index of the eye's media is not completely known yet, these eye models need to be adjusted by several parameters. These two opposite designs show that there is no general agreement in a specific eye.
model and depending on the application a suitable eye model is chosen. In this study we consider two different schematic eye models. First; a reduced eye model was used for qualitatively comparison between the experimental results and the theory and second; since the aim of this study was to measure TCA in peripheral retina, a wide angle schematic eye model, which was the suitable eye model for peripheral studies, was used. In section 4.1, the wide angle eye model, its properties and the reasons why we choose this model is discussed. The magnitude of the transverse chromatic aberration was computed for the modified and the reduced-eye model in ZEMAX, an optical design software. The results from the two eye models will be provided with the experimental data for TCA in the next chapter.

4.1 Reduced eye model

The reduced eye model which was used in this study is shown in the figure 4.1, table 4.1 and table 4.2. It consists of a spherical eye ball with 24 mm diameter and two surfaces; the cornea and the retina. The volume between these two surfaces is filled by vitreous gel with refractive index of 1.3428 for the blue wavelength and 1.3347 for the red wavelength. And the pupil is assumed to be at the cornea.

Figure 4.1) Reduced eye model used in this study

<table>
<thead>
<tr>
<th>Surface</th>
<th>Separation (mm)</th>
<th>Diameter (mm)</th>
<th>Radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornea</td>
<td>0</td>
<td>5</td>
<td>7.77</td>
</tr>
<tr>
<td>Pupil</td>
<td>24</td>
<td>1.25</td>
<td>Infinity</td>
</tr>
<tr>
<td>Retina</td>
<td>-</td>
<td>25</td>
<td>-12</td>
</tr>
</tbody>
</table>

Table 4.1) Properties of the reduced eye model used in the simulation
Refractive index for two wavelengths

<table>
<thead>
<tr>
<th>Medium</th>
<th>458nm</th>
<th>632.8nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitreous</td>
<td>1.3828</td>
<td>1.3747</td>
</tr>
</tbody>
</table>

**Table 4.2** Different refractive indexes of the reduced eye model for blue and red wavelengths

### 4.2 Wide-angle eye model

The advanced eye model used in this study is the wide-angle eye model proposed by I. Escudero-Sanz and R. Navarro et al in 1999\(^9\). The important feature of this model is that all parameters that define its geometry are anatomical and the curved image surface (the retina) has a simple spherical shape, with a 12 mm radius of curvature. This last property of the model makes it suitable to study the behavior of the eye model when the object is off axis. The schematic eye model is shown in figure 4.2 and the table 4.3 and 4.4 show the properties of the surfaces and the refractive indices, respectively. For 543 nm wavelength, the focal length of eye model is 22.03 mm in the image space and the refractive power is 60.7 D. The entrance pupil is placed in 3.04 mm from the first surface, and the exit is in -3.92 mm from the back surface of the eye model's lens. All ray tracing have been carried out with ZEMAX optical design software.

![Figure 4.2](image)

**Figure 4.2** a) A Schematic wide angle eye model, b) The wide angle eye model used in this study, implemented in ZEMAX.
### Wide angle eye model

<table>
<thead>
<tr>
<th>Surface</th>
<th>Type</th>
<th>Radius (mm)</th>
<th>Separation (mm)</th>
<th>Conic Constant</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conic</td>
<td>7.72</td>
<td>0.55</td>
<td>-0.26</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Spherical</td>
<td>6.50</td>
<td>3.05</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Stop</td>
<td>Plane</td>
<td>Infinity</td>
<td>0</td>
<td>0</td>
<td>1.25</td>
</tr>
<tr>
<td>4</td>
<td>Conic</td>
<td>10.20</td>
<td>4.00</td>
<td>-3.1316</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Conic</td>
<td>-6.00</td>
<td>16.3203</td>
<td>-1.0</td>
<td>5</td>
</tr>
<tr>
<td>Image</td>
<td>Spherical</td>
<td>-12.00</td>
<td>-</td>
<td>-</td>
<td>25</td>
</tr>
</tbody>
</table>

*Table 4.3* Properties of the wide angle eye model used in this study, adapted from 15

### Refractive index for two wavelengths

<table>
<thead>
<tr>
<th>Medium</th>
<th>458 nm</th>
<th>632.8 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>cornea</td>
<td>1.3828</td>
<td>1.3747</td>
</tr>
<tr>
<td>Aqueous</td>
<td>1.3445</td>
<td>1.336</td>
</tr>
<tr>
<td>Lens</td>
<td>1.4292</td>
<td>1.4183</td>
</tr>
<tr>
<td>Vitreous</td>
<td>1.3428</td>
<td>1.3347</td>
</tr>
</tbody>
</table>

*Table 4.4* The different refractive indexes of different part of the wide angle eye model for blue and red wavelengths

### 4.3 Implementation in ZEMAX

To follow the anatomic model both eye models were assumed to have the fovea located 5 degree from the optical axis of the eye on the temporal peripheral retina.

To simulate the same condition as in the experiment and find the amount of TCA outside of the eye for both the reduced and the wide angle eye models, the models were implemented
backwards. It means that instead of having the objects (light sources) outside of the eye and assuming that the rays enter to the eye from the first layer (cornea) and after passing the other layers meet the retina, the object's plane in ZEMEAX was placed on the retina and the ray tracing were done from the retina to the cornea and then to the outside of the eye. The angle which the light had with the normal of the last layer (cornea) was calculated for the two wavelengths. Figure 4.3 shows the implementation of the reduced eye model in ZEMAX. The main idea is that if the two rays with short and long wavelengths leave the retina from the same position, after passing through the eye's media because of the dispersion, they will leave the cornea with different angles. The difference between these two angles represents the TCA outside of the eye.

![Figure 4.3](image)

**Figure 4.3** The reduced eye model and the backward implementation of it in ZEMAX.

To have the two rays on the fovea, the object point was placed at 5 deg from the optical axis in the temporal side of the eye model. The external angle, the angle which the ray makes with the normal of the last surface (cornea) when it leaves the eye, was calculated for both wavelengths. For the off axis angles, the angles which were off from the visual axis (fovea), the object point was placed in the corresponding angle from the optical axis of the eye model. For example, for 10 deg off from the fovea in the nasal retina direction, the object point was placed in 5 deg from the optical axis but in the opposite direction as the fovea. The Table 4.5 and table 4.6 show the result for TCA in both eye models at 7 targets.
4.3.1 Reduced eye model in ZEMAX

<table>
<thead>
<tr>
<th>Eccentricity in retina from visual axis (Fovea)</th>
<th>Eccentricity in retina from optical axis</th>
<th>External angles of ray</th>
<th>Difference in angles (arc min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>5° in temporal retina</td>
<td>Blue ( \lambda = 458 \text{ nm} )</td>
<td>6.680157014</td>
</tr>
<tr>
<td>10°</td>
<td>-5° in nasal retina</td>
<td>Red ( \lambda = 632.8 \text{ nm} )</td>
<td>6.680157014</td>
</tr>
<tr>
<td>25°</td>
<td>20° in nasal retina</td>
<td>Blue ( \lambda = 458 \text{ nm} )</td>
<td>27.16112046</td>
</tr>
<tr>
<td>30°</td>
<td>25° in nasal retina</td>
<td>Red ( \lambda = 632.8 \text{ nm} )</td>
<td>34.33763778</td>
</tr>
<tr>
<td>40°</td>
<td>35° in nasal retina</td>
<td>Blue ( \lambda = 458 \text{ nm} )</td>
<td>49.95616722</td>
</tr>
<tr>
<td>50°</td>
<td>45° in nasal retina</td>
<td>Red ( \lambda = 632.8 \text{ nm} )</td>
<td>70.69557465</td>
</tr>
<tr>
<td>60°</td>
<td>55° in nasal retina</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 4.5* Predicted amount of TCA using the reduced eye model in ZEMAX

For 60 deg eccentricity in the reduced eye model, we had total internal reflection and it wasn't possible to calculate TCA. But in general it doesn't affect the result because the idea of using the reduced eye model was to qualitatively get an idea of how the TCA increases with eccentricity. Since at 50 deg off axis the amount of TCA predicted by the reduced eye model is more than 60 arc min it is clear that TCA will be larger than this value at 60 deg off-axis.
### 4.3.2 Wide-angle eye model in ZEMAX

<table>
<thead>
<tr>
<th>Eccentricity in retina from visual axis (Fovea)</th>
<th>Eccentricity in retina from optical axis</th>
<th>External angles of ray Blue $\lambda=458$ nm</th>
<th>Red $\lambda=632.8$ nm</th>
<th>Difference in angles (arc min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>5° in temporal retina</td>
<td>6.163964633</td>
<td>6.135668374</td>
<td>1.69777554</td>
</tr>
<tr>
<td>10°</td>
<td>-5° in nasal retina</td>
<td>6.163964633</td>
<td>6.135668374</td>
<td>-1.69777554</td>
</tr>
<tr>
<td>25°</td>
<td>20° in nasal retina</td>
<td>24.73967515</td>
<td>24.61890095</td>
<td>-7.24645194</td>
</tr>
<tr>
<td>30°</td>
<td>25° in nasal retina</td>
<td>30.98244391</td>
<td>30.83504617</td>
<td>-8.84386434</td>
</tr>
<tr>
<td>40°</td>
<td>35° in nasal retina</td>
<td>43.64015904</td>
<td>43.42413108</td>
<td>-12.96167706</td>
</tr>
<tr>
<td>50°</td>
<td>45° in nasal retina</td>
<td>56.6654697</td>
<td>56.36726506</td>
<td>-17.89227846</td>
</tr>
<tr>
<td>60°</td>
<td>55° in nasal retina</td>
<td>70.44873631</td>
<td>70.03975368</td>
<td>-24.53895738</td>
</tr>
</tbody>
</table>

*Table 4.6* Predicted amount of TCA using the wide angle eye model in ZEMAX
Results and discussion

5.1 Results

The results were evaluated in terms of the magnitude and the direction of the physical misalignment between the two vertical lines, with different wavelengths, as a function of the retinal eccentricity. The results are shown in figure 5.1.

Figure 5.1) Results for TCA from the experimental data on the left eye of three subjects and two eye models. Dashed lines correspond to result for each subject and the red and blue lines correspond to predicted amount of TCA in the wide angle eye model and the reduced eye model respectively.
The data represent the transverse chromatic aberration of the eye at the fovea and at the nasal retina. The vertical axis represents the physical misalignment between the two lines or the amount of transverse chromatic aberration of the eye in arc minutes. On this axis, zero shows the calibration point, the place where the two lines are physically aligned by using a camera. To understand the minus and plus sign on this axis better figure 5.2.a and 5.2.b are shown below. For simplicity we define positive and negative sign on the retina for the two sides of the eye’s optical axis. The positive part (+) on the retina is the side which contains the fovea and the negative part (-) is the other side of the optical axis on the retina (figure 5.2a,b). The minus sign (-) of TCA in object space is defined when the red line is offset to the left side of the blue line (figure 5.2.a) and positive sign (+) means that the red line is offset to the right side of the blue line (figure 5.2.b). The reason for this definition is related to the fact that when the refractive rays from the two slits meet the retina on the positive side, outside of the eye the ray from the red slit enters to the eye with a smaller incidence angle than the ray from the blue slit. So it means that the red line will appear on the right side of the blue line outside of the eye and vice versa for the minus sign.

The horizontal axis represents the nasal retina eccentricities in degrees and zero deg represents the fovea. The blue line is the predicted amount of the TCA for the reduced eye model in ZEMAX which shows an increase in TCA from +2.44 arc min at the fovea to more than -70 arc min at 60 deg eccentricity. The red line is the predicted amount of TCA for the wide-angle eye model in ZEMAX which shows an increase in TCA from +1.70 arc min at the fovea to -24.5 arc min at 60 deg eccentricity. The reason that the graphs for both eye models cross the horizontal axis at 5 deg eccentricity on the nasal retina is that, as discussed in the introduction and the eye model parts, the fovea is 5 deg offset from the optical axis to the temporal part of the retina.

**Figure 5.2) a)** Positive TCA means that the red line is on the right side of the blue line in object space and the refracted rays meet the retina on the positive side.
Dashed lines in figure 5.1 are the measured amount of TCA for the three subjects. The symbols for the subjects are: squares, L.L; circles, R.R; triangles, B.D. At the fovea, for all the subjects the positive misalignment was measured; it means that at the fovea the red line was offset to the right side of the blue line in object space for all three subjects. But the magnitude of the TCA varies from one subject to the other at the fovea. Both the reduced and the wide-angle eye model predict a positive TCA at the fovea. In larger eccentricities both eye models predict the increase in TCA with eccentricities in opposite direction as in the fovea. For two subjects; L.L and B.D the same direction of increase in TCA was measured. But for subject R.R the direction of TCA changed when increasing the angle. Subject L.L had an increase in the TCA from +3.16 arc min at the fovea to -11 arc min at 60 deg nasal retina. Subject B.D had also an increase in the TCA from +0.44 arc min at the fovea to -18.54 arc min at 60 deg eccentricity. Subject R.R had a different direction for TCA at 20 deg to 50 deg eccentricities than the eye models. This will be discussed more in the discussion part.

Table 5.1 shows the amount of TCA and the standard deviation for each set of measurements in different eccentricities for the different subjects. As predicted, the variation in the measurements increases with angle. The reason is the higher amount of refractive errors in higher eccentricities and also the lower sampling density of the peripheral retina.
<table>
<thead>
<tr>
<th>Retina Location (Deg)</th>
<th>Misalignments (arc min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subjects</td>
</tr>
<tr>
<td></td>
<td>B.D</td>
</tr>
<tr>
<td>0 deg fovea</td>
<td>0.45 ± 0.28</td>
</tr>
<tr>
<td>10 deg nasal</td>
<td>-2.23 ± 1.08</td>
</tr>
<tr>
<td>25 deg nasal</td>
<td>-1.36 ± 1.62</td>
</tr>
<tr>
<td>30 deg nasal</td>
<td>-1.92 ± 2.54</td>
</tr>
<tr>
<td>40 deg nasal</td>
<td>-5.62 ± 2.34</td>
</tr>
<tr>
<td>50 deg nasal</td>
<td>-13.77 ± 5.94</td>
</tr>
<tr>
<td>60 deg nasal</td>
<td>-18.54 ± 3.74</td>
</tr>
</tbody>
</table>

*Table 5.1* Experimental results for TCA in three subjects, at fovea and 6 eccentricities in nasal retina.

*Figure 5.3* Experimental results for TCA for three subjects are plotted in the figure. Also the standard deviation for each subject is shown with different color.
5.2 Discussion

The eye models predicted an increase in the transverse chromatic aberration of the eye with nasal retinal eccentricity. The results from the experiment also showed the increase of TCA with nasal retinal eccentricities. For the two subjects, L.L and B.D, the direction of TCA was well matched with the predicted direction from the eye models although the amount of TCA was different for each subject. For subject R.R the direction was different between 20deg to 50 deg eccentricities. This difference can be related to an inappropriate experiment situation for this subject. The bite bar which was used for subject R.R was not hard enough to fix his eye’s position in front of the set up. Although the position of the pupil was checked by the camera, it still seems that it was not completely possible to keep the eye in a correct and fixed position during the experiment. Also because it was difficult for subject R.R to do the measurements in larger eccentricities the measurements were done 10 times instead of 20 times for each off-axis angles. The difficulty could be caused by two reasons. One reason could be again related to the unsuitable bite bar which didn’t let the rays enter exactly to the center of the pupil. The other reason can be the shape of the subject’s eye. If the shape cause larger refractive errors (defocus), then it will be harder for subject R.R than the other subjects to recognize the lines. Also the method was highly subject dependent: it needed an experienced subject with a lot of practice of using his peripheral vision.

The difference in direction of TCA for subject R.R became the main reason to investigate two important questions about the method. First; how trustable is the method? And second; how repeatable is it? For the first question the idea was to use a similar wavelength instead of two different wavelengths for one subject to compare the two sets of data. If the new result with the same wavelengths is similar to the previous result with the different wavelengths, then it would show that the data for measuring TCA was false and we were measuring randomly an error in the eye caused by refractive errors. For the second question the experiment was repeated three times for subject B.D and the results were compared to each other.

5.2.1 Correction

Two light sources with the same 428 nm wavelength were used for subject B.D. The results are shown in figure 5.4.
The variation in measurements again grow with eccentricities, at 60 deg eccentricity the variation is quite large. But neglecting the data at 60 degree the results for all other angles were close to zero or were on the opposite direction as previous results with different wavelengths for subject B.D. At the fovea there is a small shift of +0.13 arc min. The result for two lines with the same wavelength has been used to correct the measurements with two different wavelengths for subject B.D. Figure 4.5 shows the experimental data of TCA for subject B.D with and without corrections. Dashed line shows the initial results for TCA and the solid line shows the result after considering the correction by using the data of the experiment with the two similar wavelengths.
5.2.2 Repeatability

Measurements with different wavelength were repeated three times for subject B.D. The results are shown in figure 5.6.

**Figure 5.6** Experimental data of TCA for subject B.D repeated three times. Each set of data is shown with different colors.

The repeatability for subject B.D at 0 deg to 30 deg is quite good, the large variation starts at 40 deg to 60 deg which is predicted since the amount of refractive errors increase with eccentricity. Figure 5.7.a to 5.7.c show the standard deviation in each set of measurements.
As we can see in figure 5.6.c the variation is larger than in the other figures. The reason for this difference is related to the experiment situation. For this set of measurement the eye was illuminated with a light source to keep the pupil size small, approximately with a diameter of 3 mm. The aim was to reduce the effect of optical errors by making the pupil’s size small and get more accurate result with smaller variations. But the data shows the
opposite result. The reason can be an unsuitable illumination. The slits were also illuminated by the same light source and it made the situation harder for the subject to recognize the lines. So the result was larger variation in measurements in each angle.

Table 5.2 shows the amount of TCA which was measured in the three set of measurements for subject B.D at fovea and also the predicted values from the two eye models.

**Foveal TCA**

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Values predicted by Eye models</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 arc min</td>
<td>Reduced eye model 2.24 arc min</td>
</tr>
<tr>
<td>0.82 arc min</td>
<td>Wide-angle eye model 1.70 arc min</td>
</tr>
<tr>
<td>0.96 arc min</td>
<td></td>
</tr>
</tbody>
</table>

*Table 5.2* Results for TCA at fovea from the measurements on the subject B.D and the two eye models.

The difference between the measurements and reduced eye model obviously is because of the approximation that we consider in the eye model. But the difference between the wide-angle eye model and the measurements can have different reasons. It can be because of the eye model or because of the shape of the subject’s eye or related to the method that we used in this study. The reason related to the eye model is because the eye model which was used in this study, the wide angle eye model, is not completely matched with the real eye. One of the differences is that in the real eye the pupil has a small horizontal shift towards the nose but in the wide angle eye model this shift hasn’t been considered. In other eye models like Liou Brennan advanced eye model which is more close to the anatomy of the eye the shift has been considered but the reason for choosing the wide angle eye model is that this model is more suitable for investigating off-axis angles in the eye. The reason related to the shape of the subject’s eye is the fact that the angle between the visual axis and the optical axis varies from one subject to another. The differences between the TCA from the experiment and the eye models can also be affected by this reason. The last reason can be the accuracy of the method to find the calibration point. In the following chapter further possible improvements will be discussed.
Outlook

6.1 What can be improved?

The improvements can be divided in two categories; first, the ones which affect the measurements at fovea and the other ones which affect the measurements at higher degrees of eccentricities.

6.1.1 Improving the result at the fovea

1) The calibration point, as mentioned before, has an important role for the measurement of TCA at the fovea. Making the slits as thin as possible can be one way to increase the accuracy of finding the calibration point. In this study the width of the slits was in order of millimeters. As shown in the experiment with the same wavelength, the calibration point which was found with available slits had a little shift to the positive value instead of having the zero value at 5 deg nasal retina (at the axial point). One way to increase the accuracy can be by using thinner slits in order of 0.01 mm. Also the width of the slits should be measured to be sure that they are exactly identical.

2) The optical errors also affect the accuracy of the measurement at fovea. Using the smaller pupil size can help to reduce the effect of the optical errors in measurements at the fovea. For this purpose, in one set of measurements in this study, a light source for illuminating the eye was used but as explained before the results were not improved.
6.1.2 Improving the result at off-axis angles

1) Using exactly the same luminance for both light sources with different wavelengths is also important to improve the set up. In this work the two diodes had 1000 cd luminous intensity at 30mA current. But they had different emitting angles. This angle was important for mounting the diodes behind the slits. For the blue diode with smaller angle it was necessary to be mounted far from the slit to illuminate the whole slit (otherwise we would have had a brighter area in the middle and darker areas at the two edges of the slit). Also for getting close to the same luminous intensity for the two lines it was necessary to work with the input voltage. All of these adjustments were done subjectively. It means that the position of the diodes and the applied voltage were changed up to that point that the luminous intensity of the two lines seemed approximately the same to the subject. To improve the accuracy for measurements in off axis angles the suggestion is to use exactly the same luminance for both light sources. The importance of having the same luminous intensity not approximately) became clear when accidently, after the experiment with the two blue diodes the red diode again was mounted behind the slits for repeating the measurement with different wavelengths for subject B.D, the voltage was forgotten to be changed for the red diode. There was therefore a small difference between the brightness of the red and blue lines. This difference was small enough that the subject didn't recognize it at first but the measurements were sensitive to this difference especially in larger eccentricities. In large angles, since the refractive errors and coma were large the images of the two lines were bluer and it was hard to recognize the lines’ shape. So the only way for the subject to do the task was by trying to align the lines when the blurry-reddish moving light turned to bluish white. When the blue light was a little brighter it affected the subject’s decision in aligning the lines and therefore affected the result in measurement of TCA.

2) Naturally, correcting the refractive errors (defocus and astigmatism) and also coma, in higher degrees of eccentricity also has an important role to improve the measurements.
Conclusion

The aim of this study was to develop a new method to measure the transverse chromatic aberration of the eye in the nasal retina eccentricity and at the fovea. The result showed the predicted increase of TCA in the eye with increases in eccentricities. Two eye models implemented in ZEMAX optical design software to compare the results of the experiment with the predicted values from the theory. The future work can be done to improve the method to find the more accurate calibration point by using the thinner slits. Also correction for the refractive errors and coma in higher deg eccentricities has an important role to get the more accurate result. Apart from the result it was turned out that the method was so subject dependence. It means that the method needs a well practice subject to use her/him peripheral vision and also highly motivated one to repeat the measurements over and over again. Therefore the method is not suggested for clinical applications or to test for large amount of subjects.
References


7. David A. Atchison, George Smith ," Optics of the human eye", Butterworth-Heinemann, chapter 1


