DIFFERENCES IN PERIPHERAL ABERRATIONS BETWEEN EMMETROPES AND MYOPES AFTER A PERIOD OF SUSTAINED NEAR WORK

A thesis presented to the graduate faculty of The New England College of Optometry in partial fulfillment of the requirements for the degree of Master of Science.

Christine E. Beck

April, 2010

©Christine E. Beck
All rights reserved.

"The author hereby grants The New England College of Optometry permission to reproduce and to distribute publicly paper and electronic copies of the thesis document in whole or in part."

DIFFERENCES IN PERIPHERAL ABERRATIONS BETWEEN EMMETROPES AND MYOPES AFTER A PERIOD OF SUSTAINED NEAR WORK

Christine E. Beck

This manuscript has been read and accepted by the
Thesis Committee in satisfaction of the
thesis requirement for the degree of Master of Science

4/23/10
Date

Jane Gwiazda, Ph.D.
Graduate Faculty Advisor

Li Deng, Ph.D.

Ji He., Ph.D.

David Troilo, Ph.D.

5-19-10
Date

Nancy J. Coletta, O.D., Ph.D.
Director of Graduate Studies

The New England College of Optometry

DIFFERENCES IN PERIPHERAL ABERRATIONS BETWEEN EMMETROPES AND MYOPES AFTER A PERIOD OF SUSTAINED NEAR WORK

Christine E. Beck

The New England College of Optometry, 2010

PURPOSE

We studied the effects of one hour of sustained near work on peripheral aberrations in emmetropes and myopes in order to determine if there is a relationship between the change in peripheral aberrations after reading and refractive error.

METHODS

Aberrations were measured by the Complete Ophthalmic Analysis System (COAS) in 24 myopic and 24 emmetropic young adults. Measurements were taken centrally, and out to thirty degrees in both the nasal and temporal retina. The measurements were taken before reading and then immediately after one-hour of sustained reading. Changes in peripheral aberrations after reading were analyzed for each refractive group, and comparisons were made between refractive groups using ANOVA and t-tests

RESULTS

Myopes had significantly more Total RMS than emmetropes in the temporal retina both before and after reading. This difference is mainly due to main axis astigmatism which was found to be higher for emmetropes than myopes at all retinal positions both before

and after reading. Total RMS, main axis astigmatism, and oblique astigmatism were not found to change significantly after reading for either refractive group. Few significant differences were found between emmetropes and myopes for higher order aberrations, including vertical coma, horizontal coma, vertical trefoil, horizontal trefoil, and spherical aberration. There were also few significant changes after reading for either refractive group.

CONCLUSIONS

Emmetropes and myopes have significant differences in the amount of peripheral aberrations, so it is possible that peripheral aberrations are relevant to myopia. However, few significant changes in peripheral aberrations were found after reading for either refractive group, so it is unlikely that differences in peripheral aberrations induced by near work play a role in myopia development.

ACKNOWLEDGEMENTS

Throughout the years working on this thesis, I have achieved multiple personal and academic accomplishments. First and foremost I would like to thank Dr. Jane Gwiazda for all of her time, teachings, and encouragement. Without her, this would not have been possible. I would like to thank Dr. Ji He and Dr. Deng for their collaborations and advice. Also, I would like to thank David Kern and Sally Bittinger for all of the help they provided me during their time working in the COMET lab. Finally, I would like to thank my friends and family for their moral support of this endeavor over the past four years, including: Nicole Ross, Greg Lockwood, and my parents.

TABLE OF CONTENTS

Chapter 1 – Aberrations in Emmetropes and Myopes Before and After Reading……..…1

Introduction……..……1

Methods….……...……6

Subjects……6

Apparatus…….……6

Procedure……..…7

Statistical Analysis……...9

Results….……...……10

Total RMS……..10

Higher Order RMS…….....…14

Main Axis Astigmatism…….16

Oblique Astigmatism…….18

Vertical Coma……19

Horizontal Coma……19

Vertical Trefoil ……..……22

Horizontal Trefoil ……..…….…….…….22

Spherical Aberration……..23

Absolute Values…….23

Corneal Topography and Axial Length…….25

Discussion……..25

Corneal Topography and Axial Length…….29

Strengths and Limitations……..30

Conclusions……31

Chapter 2 – Pupil Size Differences in Emmetropes and Myopes……..33

Introduction……..…..33

Methods….……...……..34

Results……34

Discussion……..36

Appendices……..……...38

Appendix 1: Advertisements for NECO students and Craigslist…….……..38

Appendix 2: Subject Questionnaires for NECO and Non-NECO students……...41

Appendix 3: Informed Consent Forms for NECO and Non-NECO students……48

Appendix 4: P-values of Individual T-tests for Emmetropes vs. Myopes at

Each Retinal Location…….……...59

References…….....62

TABLES

TABLE NUMBER	TABLE TITLE	PAGE
1	Total RMS and higher order RMS values for each retinal position, before reading and after reading, for emmetropes and myopes	60
2	Main-axis astigmatism and oblique astigmatism values for each retinal position, before reading and after reading, for emmetropes and myopes	60
3	Trefoil, coma, and spherical aberration values for each retinal position, before reading and after reading, for emmetropes and myopes	61

FIGURES

FIGURE NUMBER	FIGURE TITLE	PAGE
1	Total RMS as a function of retinal position for emmetropes and myopes before reading	12
2	Total RMS as a function of retinal position for emmetropes and myopes after reading	12
3	Total RMS as a function of retinal position for emmetropes before and after reading	13
4	Total RMS as a function of retinal position for myopes before and after reading.	13
5	Higher order RMS as a function of retinal position for emmetropes before and after reading	15
6	Higher order RMS as a function of retinal Position for myopes before and after reading	15
7	Main axis astigmatism as a function of retinal position for emmetropes and myopes before reading	17

8	Main axis astigmatism as a function of retinal position for emmetropes and myopes after reading	17
9	Horizontal coma as a function of retinal position for emmetropes and myopes before reading	21
10	Horizontal coma as a function of retinal position for emmetropes and myopes after reading	21
11	Average Pupil Size for Emmetropes Before Reading	35
12	Average Pupil Size for Emmetropes After Reading	35

Chapter 1

Aberrations in the Peripheral Retina of Emmetropes and Myopes Before and After Reading

Introduction

Over the past several decades, myopia has become more prevalent in many countries (Zhao, Pan, Sui, Munoz, Sperduto, Ellwein, 2000; Dandona, Naduvilath, Srinivas, McCarty, Rao, 1999; Wong, Foster, Hee, Ng, Tielsch, Chew, Johnson, Seah 2000; Attebo, Ivers, & Mitchell, 1999; Vitale, Sperduto, Ferris 2009; Dandona Dandona, Srinivas, Sahare, Narsaiah, Munoz, Pokharel, Ellwein., 2002). Studies of populations in China (Zhao et al., 2000), India (Dandona et al., 1999; Murthy, Gupta, Ellwein, Munoz, Pokharel, Sanga, Bachani, 2002), Singapore (Wong et al., 2000), Australia (Attebo et al., 1999), and the United Sates (Vitale et al, 2009) have all provided evidence of the rise in the prevalence of myopia. Although the increases in myopia prevalence have been shown to be greater in urban than rural populations, it seems that nearly all communities are being affected (Dandona et al., 1999; Dandona et al., 2002; Saw, 2003).

There is evidence that the increase in myopia prevalence can partly be attributed to the growing amount of time people spend engaging in near work. One study looked at the difference in myopia development in school-aged boys. They found that boys who participated in reading and near-work were significantly more likely to develop myopia than boys who worked as skilled laborers (Hepsen, Evereklioglu, & Bayramiar, 2001). Another study looked at the degree of myopia in Jewish teenagers who were in Orthodox

schooling. It was found that students who participated in more near-work had a significantly greater degree of myopia than those who did not (Zylbermann, Landau, & Berson, 1993). Other recent research has compared amount of schooling and intelligence scores to amount of myopia. One study looking at 17 to 19 year old males found that myopia was significantly more prevalent in the males who had more schooling and higher intelligence (Rosner & Belkin, 1987). This provides evidence of near work contributions to myopia development. A study looking at adults compared amount of myopia in textile workers who had near-work tasks to those of workers who did not have a close-working distance (Simensen & Thorud, 1994). The study found that significantly more near workers had myopia than those who had other working tasks, despite the fact that eighty percent of the near workers had not been corrected for myopia before the age of twenty. However, the involvement of near work in myopia development recently has been questioned (Mutti & Zadnik, 2009).

It has been suggested that the association of near work and myopia may be related to accommodation (Goss & Wickham, 1995; Gwiazda, Thorn, Bauer, & Held, 1993). Myopic children have been found to have larger accommodative lags than non-myopes. Therefore, during near viewing these children may experience hyperopic retinal defocus leading to axial elongation, as in animal models. In a subgroup analysis of COMET data, children with large accommodative lags randomized to progressive addition lenses showed slowed myopia progression compared with children randomized to single vision lenses (Gwiazda, Hyman, Norton, Hussein, Marsh-Tootle, Manny, Want, Everett, & the COMET group, 2004).

Another possible explanation for the association of near work and myopia is that aberrations in the eye during near work may create defocus that could lead to increased eye growth. Studies have shown that after subjects engage in near work, corneal and whole-eye aberrations are higher (Buehren, Collins, & Carney, 2003; Collins, Buehren, Bece, & Voeta, 2006; Buehren, Collins, & Carney, 2005). The changes in corneal aberrations may be caused by eye-lid pressure (Buehren et al., 2003; Collins et al., 2006; Buehren et al., 2005). Some studies have shown that myopes have significantly more wavefront aberrations than emmetropes (He, Sun, Held, Thorn, Sun, & Gwiazda, 2002; Collins, Buehren, & Iskander, 2006). If intensive reading is a factor in the development of myopia, and myopes have more aberrations, aberrations might be a link in understanding the association between reading and myopia. However, other studies have shown that there is not a significant difference in aberrations between myopes and emmetropes (Llorente, Barbero, Cano, Dorronsoro, & Marcos, 2004; Cheng, Bradley, Hong, & Thibos, 2003). The difference in results found by these groups may be due to the fact that wavefront aberrations have been found to be constantly changing (Ginis, Plainis, & Pallikaris, 2004). Wavefront aberrations have also been found to vary with the pupil size used for calculations, which could be another reason for the differing results (Ginis et al., 2004; Wang, Zhao, Jin, Niu, & Zuo, 2003).

Eye shape also may be important. Many studies have shown differences in eye shape between emmetropes and myopes. It is known that, on average, myopes have a longer eye length than emmetropes and hyperopes (Atchison, Jones, Schimd, Pritchard, Pope, Strungnell, Riley, 2004; Llorente, et. al, 2004; Atchison, 2006; Atchison, Pritchard, & Schmid, 2006; Mutti, Sholtz, Friedman, & Zadnik, 2000; Logan, Gilmartin, Wildoset,

& Dunne, 2004; Atchison, Pritchard, Schmid, Scott, Jones, Pope, 2005; Schmid, 2003). Myopic eyes have been found to be more relatively hyperopic in the retinal periphery (Charman & Jennings, 1982; Atchison, Lucas, Ashman, Huynh, Schilt, Ngo, 2006; Mutti et al, 2000; Seidemann, Schaeffel, Guirao, Lopez-Gil, &Artal, 2002; Schmid, 2003). However, in contrast to these findings, one study found that myopic eyes had an overall enlargement, giving the same sphero-elliptical shape as that of emmetropes (Cheng, Singh, Kwong, Xiong, Woods, & Brady, 1992).

Recently, there has been strong interest in the role of the peripheral retina in myopia development. An early study looked at the relationship between peripheral refractive error in emmetropic pilots and the pilots' future refractive error. It was found that emmetropic pilots whose eyes were relatively hyperopic in the periphery were more likely to develop myopia (Hoogerheide, Rempt, & Hoogenboom, 1971).

Research on peripheral aberrations in humans has been limited. Emmetropes have been shown to have more peripheral astigmatism on average than myopes (Hoogerheide et. al., 1971; Calver, Radhakrishnan, Osubobeni, & O'Leary, 2007). Two studies were conducted in which aberrations were measured out to 10 degrees horizontally (Atchison et al., 2006; Read, Collins, Careny, and Franklin, 2006). Coma was found to vary systemically across the visual field (Atchison et al., 2006; Read, Collins, Carney, Franklin, 2006). Horizontal coma was found to be highest at the nasal retina and lowest at the temporal retina (Atchison et al., 2006).

Results from animal studies have demonstrated a role for peripheral form deprivation in the development of myopia. Monkeys raised with lenses that allowed the least amount of central vision had the largest amounts of myopia (Smith, Kee,

Ramamirtham, Qiao-Grider, & Hung, 2005). These results suggest that myopia may be caused by peripheral form deprivation and that peripheral signals might be able to overrule foveal signals in the process of emmetropization (Smith et al., 2005). A recent study raised nine moneys with lenses that eliminated form vision in the nasal field (Smith, Huang, Hung, Blasdel, Humbird, and Bockhorst, 2009). Six of the nine moneys exhibited relative myopia in the treated nasal field (Smith et al., 2009), providing additional evidence that the periphery may play a role in the development of myopia.

Form deprivation may lead to an increase in eye length in monkeys. One recent study raised monkeys with diffuser lenses secured in front of one eye (Huang, Hung, Ramamirtham, Blasdel, Humbird, Bockhorst, and Smith, 2009). The eye with the diffuser lens was found to exhibit relative peripheral hyperopia and be more prolate in shape than the non-treated eye (Huang et al., 2009). Another study used laser photocoagulation to ablate the fovea of monkeys, which were then raised with diffuser lenses or without any lenses. The monkeys raised with diffuser lenses had significantly longer eyes than the monkeys raised with no lenses, despite the fact that both groups had foveal ablation (Smith, Ramamirtham, Qiao-Grider, Hung, Huang, Kee, Coats, & Paysse, 2007). This study provides evidence that refractive error changes from peripheral form deprivation may be due to an increase in axial length. However, another study with chickens found that when the chickens wore defocus lenses with a central hole so that the fovea did not experience defocus, there was not a significant difference in refractive error or axial length (Schippert & Schaeffel, 2006).

Given the evidence from animal studies supporting the role of the peripheral retina in eye growth and the differences in peripheral aberrations between emmetropic

and myopic adults, we designed a study to investigate the link between near work and peripheral aberrations in young adults with different refractive errors. We measured aberrations out to 30 degrees nasally and temporally before and after a sustained period of near work.

Methods

Subjects

The subject population of this study consisted of 48 young adults recruited from the New England College of Optometry, Craigslist, and word of mouth (Appendix 1). Subjects were required to be between the ages of 18 and 35 years. There were 24 myopes (< –0.50D; mean -3.13 D) and 24 emmetropes (-0.50D to +0.75D; mean -0.07 D). Subjects were compensated $10 for expenses related to their participation in the study.

Subjects were excluded from the study if they had astigmatism greater than 1.50D, diseased eyes (e.g. glaucoma, amblyopia), previous corneal refractive surgery or therapy, or were unable to comply with study procedures or measurements.

Information on subjects' ocular and medical history was gathered through a questionnaire (Appendix 2).

Apparatus

Distance refractive error measurements were taken by the Complete Ophthalmic Analysis System (COAS) (WaveFront Science, Inc., Albuquerque, NM) which has been found to give refractive errors equivalent to those of the Grand Seiko autorefractor (Berntsen, Mutti, &Zadnik, 2008). The COAS was used to obtain central distance

refractive error measurements (used for classifying subjects into refractive error groups), and peripheral wavefront aberrations and refraction both before and after one hour of reading.

Procedure

The Institutional Review Board at the New England College of Optometry approved this study. Written informed consent was obtained from all subjects (Appendix 3), and all procedures adhered to the Declaration of Helsinki.

Subjects were asked to refrain from wearing contact lenses for at least twenty-four hours before the start of the study. If subjects had received a spectacle prescription within the last year, this was used for determining their refractive error group. If they did not have a recent prescription available, their distance refractive error was determined by the COAS.

Subjects were positioned in front of the COAS with their chin on the chinrest and their forehead against the headrest. The apparatus was aligned to their right eye so that they were able to see the internal target of the COAS, which is a red light surrounded by concentric circles. A small mirror was aligned to subjects' left eyes so that they were able to view a target with 20/100 black letters on a white background. The target letters were printed backwards to allow subjects to see the letters in the correct direction when viewed through the mirror. The target image was 33 centimeters from the subjects. Letters on the target were located centrally, 10, 20, and 30 degrees temporally, and 10 and 30 degrees nasally to the subject's right eye. Nasal 20 degrees was not tested due to complications arising from the optic nerve head often being at or near this location.

Testing began by aligning the mirror to the subject's left eye so that the image of the red dot and concentric circles in the COAS, seen with the right, would be superimposed on top of the central letter of the target seen with the left eye. After subjects were properly aligned, they were instructed to look to each of the letters, and three measurements were taken at each of the positions. It was assumed that the eyes were in parallel gaze. Subjects were asked to keep the letters in focus while the measurements were being taken. While measurements were taken myopic subjects were given a lens with the spherical equivalent of their prescription to hold in front of their left eye, which was viewing the target, to account for the difference in accommodative demand between the two refractive groups.

After measurements were taken, subjects were asked to read a book of their choice, without pictures, for one hour. At the conclusion of the one-hour reading task subjects were asked to place their chin back on the chinrest of the COAS and were immediately realigned so that once again the red light was seen on the central letter of the target, and three measurements were taken again at each of the positions. At most, the realignment after reading took approximately one minute.

Corneal Topography and Axial Length

Subjects were e-mailed and asked to return for additional measurements on a separate date (Appendix 3). The subset of subjects whom returned consisted of 8 myopes (< –0.50D) and 8 emmetropes (-0.50D to +0.75D. These subjects were compensated $7 for expenses related to their participation in the study. They were asked to complete the

same questionnaire they had completed at their first visit to determine if their information had changed.

The Humphrey Corneal Topography System-Model 995 was used to obtain corneal topography and the Zeiss IOLMaster was used to obtain axial length measurements from the subset of subjects. Subjects were asked to refrain from wearing contact lenses for at least twenty-four hours before the start of the study.

For corneal topography measurements, subjects were asked to sit in front of the Humphrey Corneal Topography System-Model 995 with their chin on a chinrest and their head against a headrest. They were asked to fixate on a central red dot while four measurements were taken on their right eye. Following the corneal topography measurements, subjects were asked to sit at the Zeiss IOLMaster with their chin on a chinrest and forehead against a headrest. Subjects were asked to fixate on a central orange/red dot while three measurements were taken for axial length.

Statistical Analysis

The mean of the three measurements for each of the six horizontal positions was calculated and analyses were performed. The calculations were done for 4.0 mm pupils, with adjustment for elliptical pupils (Lundstrom & Unsbo, 2007) due to the importance of accounting for the pupil shape when measuring peripheral aberrations (Atchison, Scott, & Charman, 2007). Only measurements where a subject's pupil was at least 3.90 mm were used. Therefore, any significant differences found between the two refractive groups can not be attributed to a difference in pupil size.

Repeated measures ANOVA were conducted to evaluate the refractive group differences, the retinal position differences and their interaction. When the interaction was significant ($p<0.05$), two-sample t-tests were applied to compare emmetropes and myopes at each retinal position (e.g. nasal 30 degrees). In addition, paired t-tests were performed to evaluate changes in aberrations after reading by refractive group. Total RMS, higher order (HO) RMS, and 7 Zernike aberration terms: (main axis astigmatism (Z_2^2), oblique astigmatism (Z_2^{-2}), vertical coma (Z_3^{-1}), horizontal coma (Z_3^1), vertical trefoil (Z_3^{-3}), horizontal trefoil (Z_3^3), and spherical aberration (Z_4^0) were investigated. We chose to analyze these specific terms due to the number of studies which had previously investigated these terms and reported results pertinent to the present study. Total RMS was determined by summing the square of each individual Zernike term, main axis astigmatism (Z_2^2) and higher, except for defocus (Z_2^0), and then calculating the square root. Higher order RMS was determined by summing the square of each individual Zernike term, vertical trefoil (Z_3^{-3}) and higher, and then calculating the square root. Statistical significance was taken as $p < 0.01$ for all of the post-hoc tests to account for multiple comparisons.

Results

Total RMS

The variation in the amount of total RMS across the retina was found to be significant for emmetropes and myopes both before reading (emmetropes $p<0.0001$; myopes $p<0.0001$) and after reading (emmetropes $p<0.0001$; myopes $p<0.0001$), with higher aberrations in the periphery.

Before reading, a significant interaction was found between myopes and emmetropes across the measured retinal positions ($p<0.0001$). Total RMS was found to be significantly higher for emmetropes than myopes at temporal 20 degrees (emmetropes=0.430μm; myopes=0.305μm ; $p=0.005$) and approached significance for temporal 30 degrees (emmetropes=0.637μm; myopes=0.497μm; $p= 0.038$) (Figure 1). No other significant differences were found between the two refractive groups.

After reading, there was also a significant interaction between myopes and emmetropes across the retina ($p<0.0004$). A similar result was found, with emmetropes having significantly more aberrations than myopes at temporal 20 degrees (emmetropes=0.439μm; myopes=0.304μm; $p=0.005$) and approaching significance at temporal 30 degrees (emmetropes=0.686μm; myopes=0.546μm; $p=0.020$) (Figure 2).

Within each refractive group, no significant changes were found in the amount of aberrations after reading, as shown in Figure 3 for emmetropes and Figure 4 for myopes.

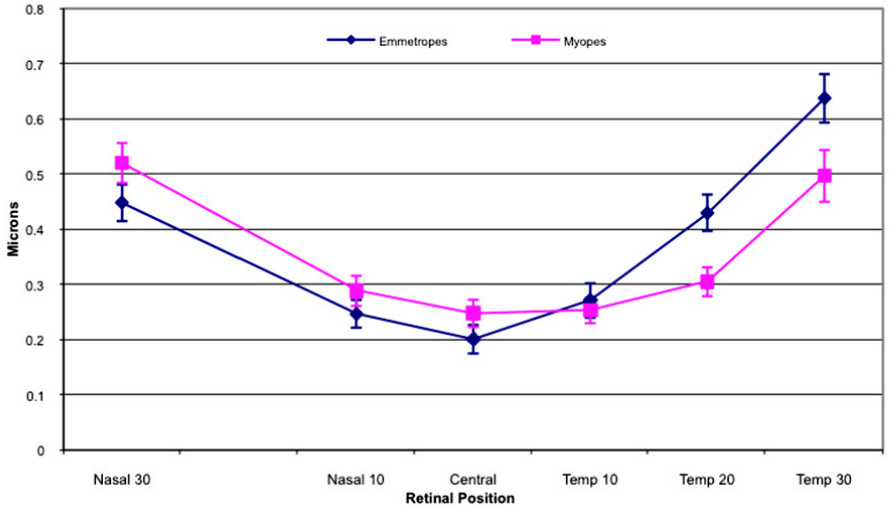


Figure 1: Total RMS as a function of retinal position for emmetropes and myopes before reading. Note that in this figure and all subsequent ones there are no data at nasal 20 deg, the approximate location of the optic disc, since no measurements were made there.

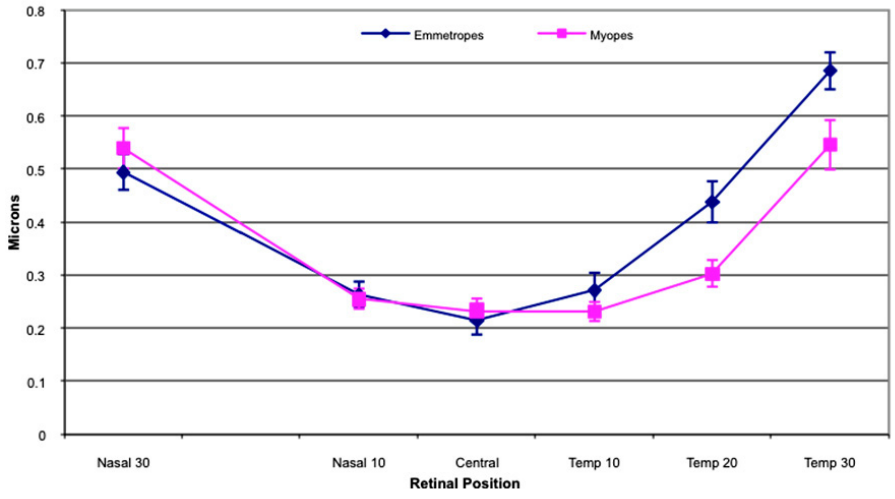


Figure 2: Total RMS as a function of retinal position for emmetropes and myopes after reading.

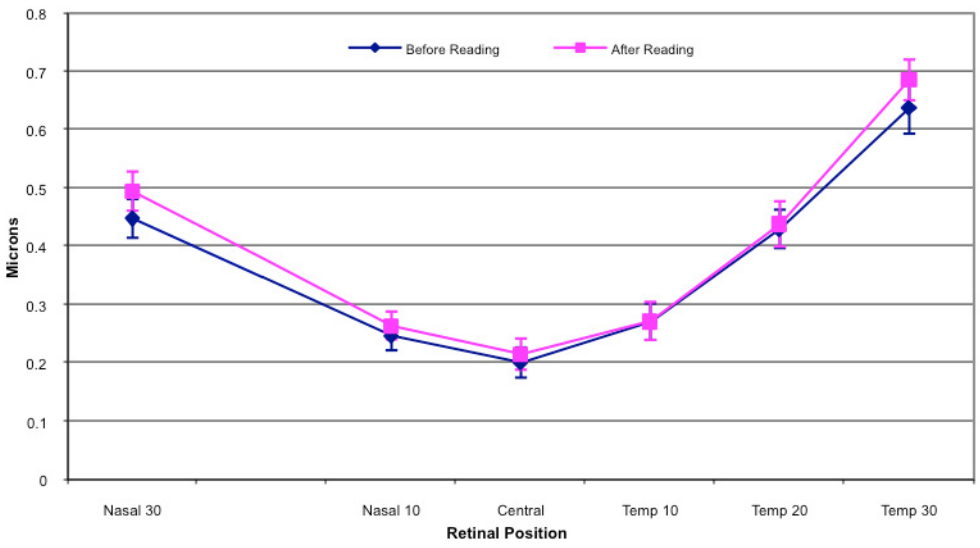


Figure 3: Total RMS as a function of retinal position for emmetropes before and after reading.

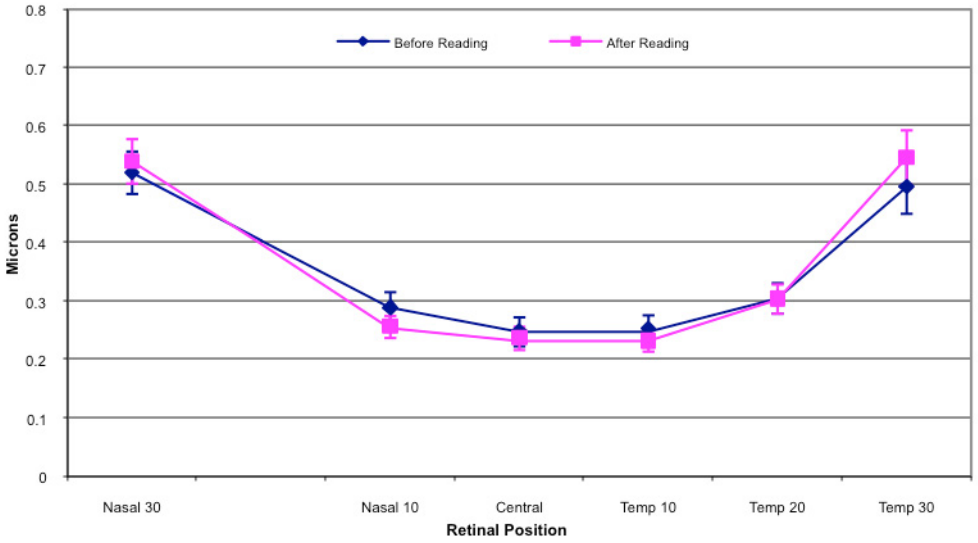


Figure 4: Total RMS as a function of retinal position for myopes before and after reading.

Higher Order RMS

The variation in the amount of higher order RMS across the retina was found to be significant for emmetropes and myopes both before reading (emmetropes $p<0.0001$; myopes $p<0.0001$) and after reading (emmetropes $p<0.0001$; myopes $p<0.0001$). No significant interaction between refractive group and retinal position were found either before reading or after reading for higher order (HO) RMS.

Emmetropes were found to have significantly more HO aberrations after reading at nasal 30 degrees (before=0.168μm; after=0.189μm; $p=0.001$) and at nasal 10 degrees (before=0.120μm; after=0.134μm; $p=0.004$), and approached significance centrally (before=0.101μm; after=0.111μm; $p=0.043$) and at temporal 30 degrees (before=0.171μm; after=0.192μm; $p=0.018$) as shown in Figure 5. Myopes were found to have significantly more HO aberrations after reading at nasal 30 degrees (before=0.143μm; after=0.168μm; $p<0.001$) as shown in Figure 6.

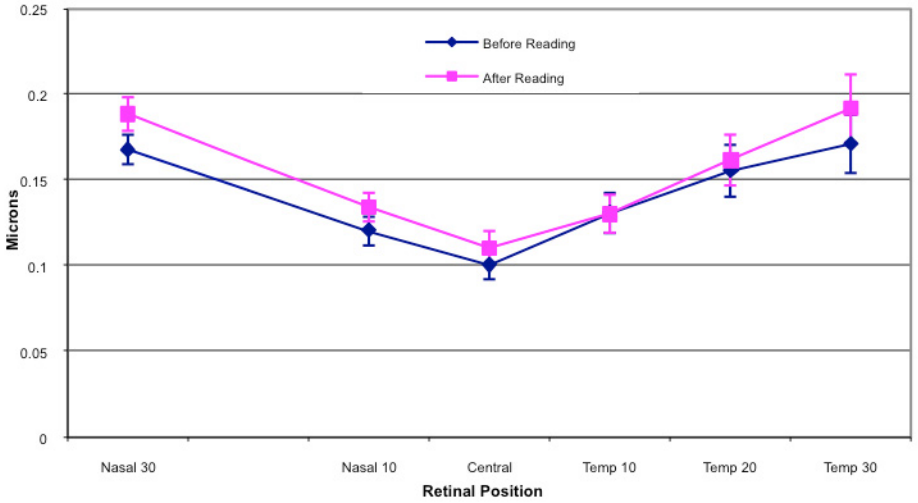


Figure 5: Higher order RMS as a function of retinal position for emmetropes before and after reading.

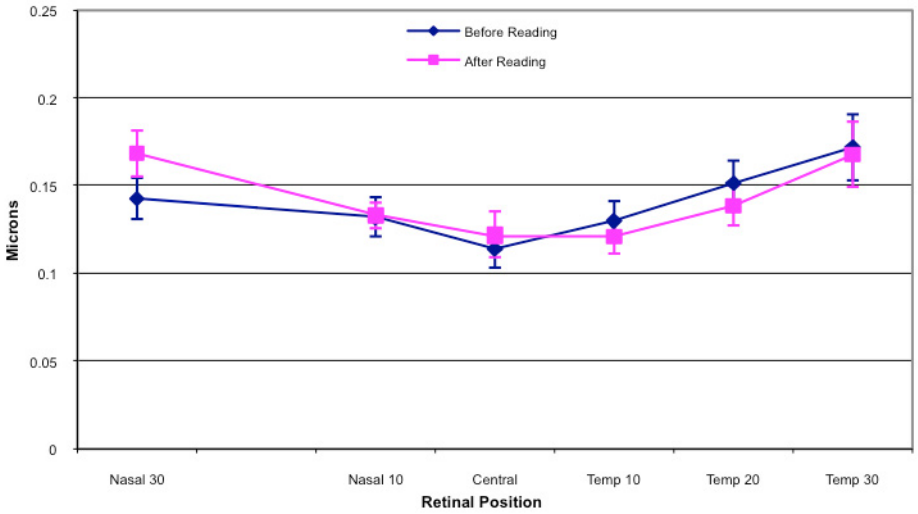


Figure 6: Higher order RMS as a function of retinal position for myopes before and after reading.

Main Axis Astigmatism (Z_2^2)

Variation in the amount in main axis astigmatism across retinal positions was found to be significant for both refractive groups before reading (emmetropes $p<0.0001$; myopes $p<0.0001$) and after reading (emmetropes $p<0.0001$; myopes $p<0.0001$). Both groups were found to have the highest amount of main axis astigmatism in the periphery, with the temporal retina being higher than the nasal retina as shown in Figure 7 and Figure 8.

A significant interaction was found for main axis astigmatism across retinal positions between refractive groups before reading ($p=0.005$). Emmetropes were found to have significantly more astigmatism than myopes at all retinal positions, as shown in Figure 7 (see appendix 4 for p-values).

After reading, similar results were found. There was a significant interaction across retinal positions between refractive groups

($p<0.0001$). Emmetropes once again had significantly more main axis astigmatism at all retinal positions, with the exceptions of nasal 10 degrees, which did approach significance ($p=0.042$), as shown in Figure 8.

Emmetropes were not found to have a significant change in main axis astigmatism after reading at any retinal position. Myopes were found to have a significant increase after reading at nasal 30 degrees (before=-0.051μm; after=0.056μm; $p=0.004$).

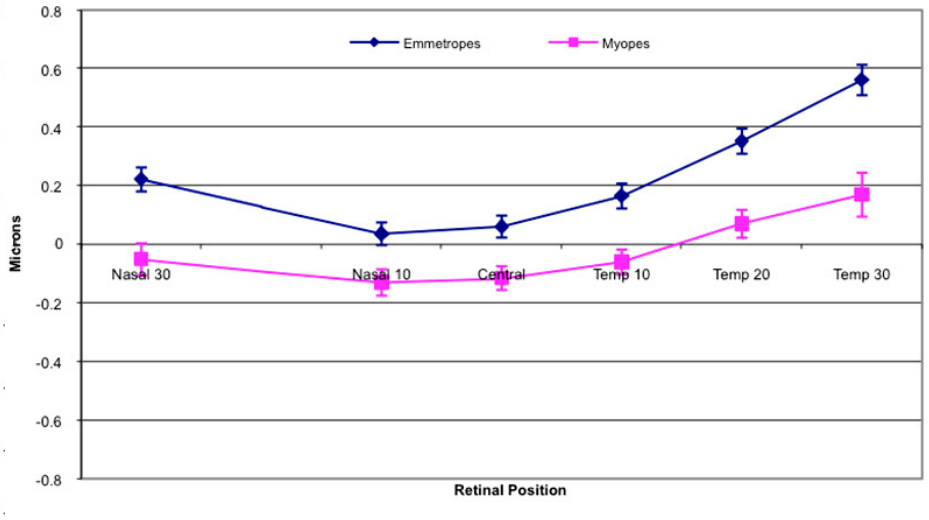


Figure 7: Main axis astigmatism as a function of retinal position for emmetropes and myopes before reading.

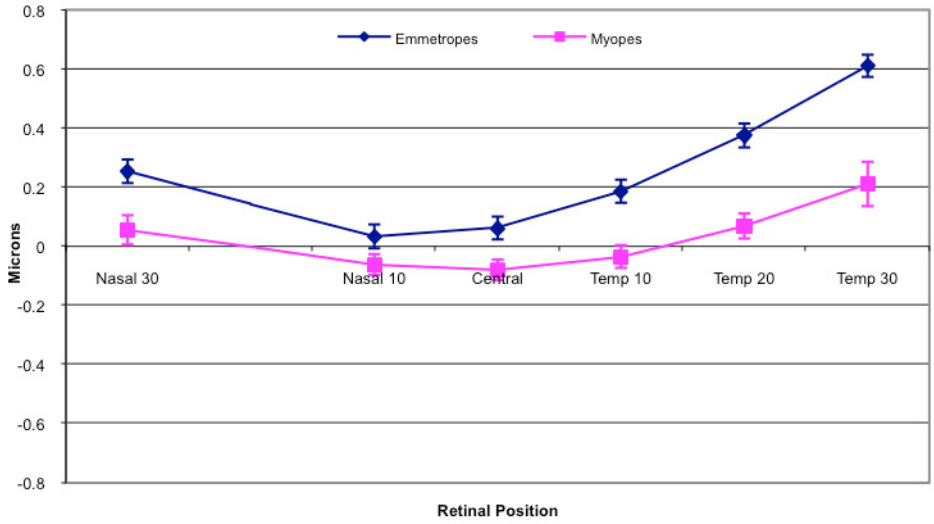


Figure 8: Main axis astigmatism as a function of retinal position for emmetropes and myopes after reading.

Oblique Astigmatism (Z_2^{-2})

Variation in the amount of oblique astigmatism across the retina was found to be significant for both emmetropes and myopes before reading (emmetropes $p<0.0001$; myopes $p<0.0001$) and after reading (emmetropes $p<0.0001$; myopes $p<0.0001$). Both groups were found to have higher oblique astigmatism in the periphery, with the nasal retina have the highest amount of positive oblique astigmatism and the temporal retina having the highest amount of negative oblique astigmatism.

Before reading, no significant interaction was found between myopes and emmetropes across retinal positions. However, emmetropes were found to have more aberrations than emmetropes, with the differences approaching significance, at nasal 10 degrees (emmetropes=0.119μm; myopes=0.054μm; p=0.023) and at temporal 30 degrees (emmetropes=-0.157μm; myopes=-0.295μm p=0.018).

A significant interaction between myopes and emmetropes across retinal positions was found after reading (p=0.0002). Emmetropes were found to have more aberrations than myopes, with the differences approaching significance, at nasal 30 degrees (emmetropes=0.311μm; myopes=0.056μm p=0.028) and at temporal 30 degrees (emmetropes=-0.169μm; myopes=-0.333μm p=0.016).

There were no statistically significant changes after reading for emmetropes. Myopes were found to have a significant increase in aberrations after reading at nasal 10 degrees (before=0.054μm; after=0.101μm; p=0.001), and increases that approached significance at nasal 30 degrees (before=0.322μm; after=0.432μm; p=0.032), centrally (before=0.026μm; after=0.101μm; p=0.047), at temporal 20 degrees (before=-0.080μm;

after=-0.115μm; p=0.025), and at temporal 30 degrees (before=-0.295μm; after=-0.333μm; p=0.031).

Vertical Coma (Z_3^{-1})

No significant interaction was found for vertical coma between emmetropes and myopes across retinal positions before or after reading, although before reading the p-value approached significance. Variation in the amount of vertical coma across the retina was found to be significant for emmetropes before reading ($p<0.0001$), but not for myopes. After reading, variation across retinal positions was found to be significant for both groups (emmetropes $p<0.0001$; myopes $p<0.0001$). Before reading, emmetropes were found to have significantly more vertical coma than myopes at nasal 30 degrees (emmetropes=0.033μm; myopes=-0.011μm; p=0.003). There were no significant differences between emmetropes and myopes after reading. Centrally, emmetropes were found to have a significant increase in vertical coma after reading (before=-0.010μm; after=-0.027μm; p=0.002). Myopes were found to have a significant increase after reading at nasal 30 degrees (before=-0.011μm; after=0.015μm; p=0.008).

Horizontal Coma (Z_3^{1})

Horizontal coma variation across retinal positions was found to be significant for emmetropes ($p<0.0001$) and myopes ($p<0.0001$) before reading. After reading, variation across retinal positions was once again found to be significant for both groups (emmetropes $p<0.0001$; myopes $p<0.0001$). Both groups had greater amounts of horizontal coma in the peripheral retina than in the central retina, with the nasal retina

having the greatest amount of positive horizontal coma and the temporal retina having the greatest amount of negative horizontal coma, as shown in Figures 9 and 10.

Before reading, a significant interaction between emmetropes and myopes was found across retinal positions ($p<0.0001$). Emmetropes were found to have significantly more horizontal coma than myopes at nasal 30 degrees (emmetropes=0.132μm; myopes=0.073μm; p=0.002) and at temporal 10 degrees (emmetropes=-0.054μm; myopes=-0.020μm; p=0.009). Differences approached significance at temporal 20 degrees (emmetropes=-0.078μm; myopes=-0.022μm ;p=0.015) and at temporal 30 degrees (emmetropes=-0.091μm; myopes=-0.025μm; p=0.024), as shown in Figure 9. A significant interaction between emmetropes and myopes across retinal positions was also found after reading (p=0.002). Emmetropes had significantly more horizontal coma than myopes at temporal 10 degrees (emmetropes=-0.054μm; myopes=-0.014μm; p=0.006), and differences that approached significance at temporal 20 degrees (emmetropes= -0.076μm; myopes=-0.032μm; p=0.028) and at temporal 30 degrees (emmetropes=-0.100μm; myopes=-0.024μm; 0.026) as shown in Figure 10.

Emmetropes had no significant differences in horizontal coma after reading at any of the retinal positions measured. Myopes has significantly more horizontal coma after reading at nasal 30 degrees (before=0.073μm; after=0.1144μm; p=0.003).

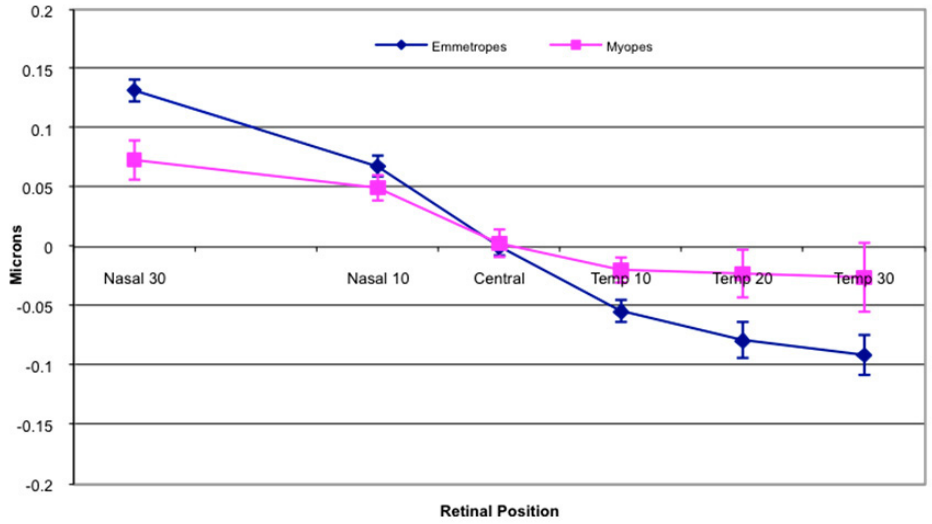


Figure 9: Horizontal coma as a function of retinal position for emmetropes and myopes before reading.

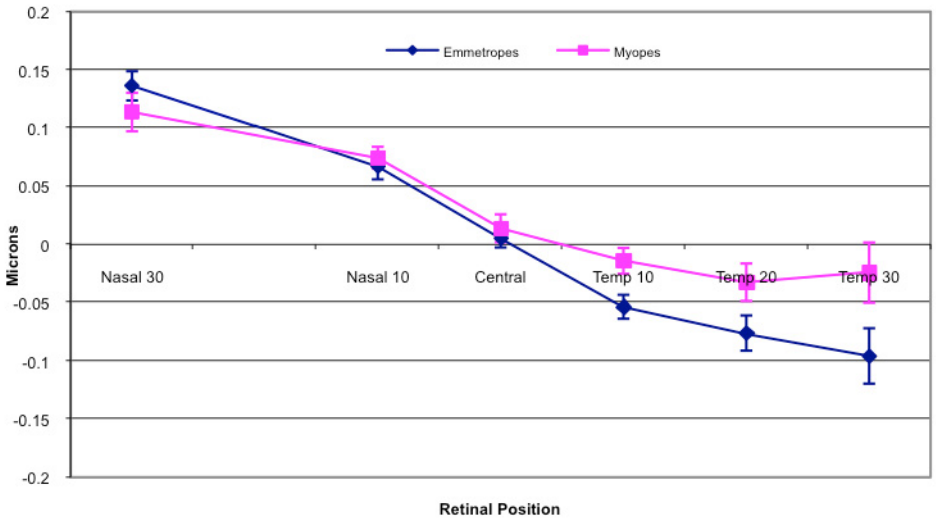


Figure 10: Horizontal coma as a function of retinal position for emmetropes and myopes after reading.

Vertical Trefoil (Z_3^{-3})

Variation in the amount of vertical trefoil (Z_3^{-3}) across retinal positions was found to be significant for both emmetropes before reading ($p<0.0001$) and after reading ($p<0.0001$). Both groups had greater amounts of vertical trefoil in the temporal retina than centrally, with the nasal and temporal retina having relatively equal amounts of aberration.

No significant variation in position was found across the retina for myopes before reading or after reading. No significant interaction was found for vertical trefoil (Z_3^{-3}) between refractive group and retinal position before reading ($p=0.013$), and there were no significant refractive group differences.

After reading there was a significant interaction between refractive groups across retinal positions ($p=0.005$). Emmetropes were found to have more vertical trefoil than myopes, approaching significance at temporal 30 degrees (emmetropes=0.062μm; myopes=0.021μm; $p=0.017$). Emmetropes were found to have a significant increase in trefoil after reading at the central position (before=-0.013μm; after=0.002μm; $p=0.007$) and at temporal 30 degrees (before=0.032μm; after=0.062μm; $p=0.002$). Myopes were found to have a significant increase in trefoil after reading at only the central position (before=0.003μm; after=0.017μm; $p=0.004$).

Horizontal Trefoil (Z_3^3)

Horizontal trefoil variations across retinal positions were not significant for emmetropes or myopes either before or after reading. In addition, no significant interaction between refractive groups across retinal positions was found for horizontal trefoil (Z_3^3) either before or after reading.

Spherical Aberration (Z_4^0)

Variation in spherical aberration across retinal positions was found to be significant for emmetropes before reading (p=0.001). Emmetropes had the greatest amount of positive spherical aberration centrally. Both nasally and temporally there were decreases in positive spherical aberration. The greatest amount of negative spherical aberration was found at temporal 30 degrees. Variation across the retina was not significant for emmetropes after reading. No significant variation in position was found across the retina for myopes before or after reading.

No significant interaction between refractive groups across retinal positions were found for spherical aberration before reading or after reading. There were no statistically significant differences in spherical aberration between refractive groups before or after reading. Emmetropes were found to have significantly less spherical aberration after reading centrally (before=0.022μm; after=0.014μm; p=0.007). Myopes were not found to have any significant changes in spherical aberration after reading.

Absolute Values

We chose to look at the absolute value of the aberrations to determine if there were any significant differences that were masked due to some subjects having high positive aberrations and some having high negative aberrations, averaging to zero, or if there were changes due to the refractive groups having opposite signs, which would be cancelled by looking at the absolute value. When using the absolute values instead of

signed values of each of the Zernike terms, fewer significant differences between the refractive groups were found.

Using absolute values, emmetropes were found to have significantly more main axis astigmatism than myopes before reading at temporal 20 degrees ($p<0.001$) and temporal 30 degrees ($p<0.001$). When the sign was respected, emmetropes were found to have significantly more main axis astigmatism at all retinal positions. The same pattern was found after reading with emmetropes still having significantly more main axis astigmatism at temporal 20 degrees ($p<0.001$) and temporal 30 degrees ($p<0.001$). Once again, this is a similar pattern as found when the sign was respected. When the sign was respected, emmetropes were found to have significantly more aberrations at all retinal positions except for nasal 10 degrees and the central position.

For oblique astigmatism, myopes were found to have significantly more aberrations than emmetropes at temporal 30 degrees ($p=0.001$) before reading. The same was found after reading with myopes still having greater aberrations ($p=0.001$). It is of interest to note that when the sign was respected, emmetropes were found to have significantly more oblique astigmatism than myopes in the temporal retina before and after reading.

Horizontal coma was found to be significantly higher after reading than before reading for myopes at nasal 30 degrees ($p<0.001$). The same difference was found when the sign was respected.

Vertical trefoil (Z_3^{-3}) was found to be significantly higher after reading than before reading in emmetropes at nasal 30 degrees ($p=0.002$). When the sign was

respected, this same significant increase in vertical trefoil was found; however a significant increase was also found at the central position.

Corneal Topography and Axial Length

Corneal topography and axial length data was analyzed for the subject of the original subjects which consisted of 8 emmetropes and 8 myopes. The corneal topography measurements were taken with subjects looking straight ahead before reading. No significant differences were found between refractive groups for total RMS, higher order RMS, main axis astigmatism (Z_2^2), oblique astigmatism (Z_2^{-2}), vertical coma (Z_3^{-1}), horizontal coma (Z_3^1), vertical trefoil (Z_3^{-3}), horizontal trefoil (Z_3^3), or spherical aberration (Z_4^0). As expected, axial length was found to be significantly longer for myopes than emmetropes ($p<0.001$). The average axial length was 23.27mm for emmetropes and 24.94mm for myopes.

Discussion

Aberrations differed between refractive groups both before reading and after reading, especially for main axis astigmatism. However, there were very few changes in aberrations after reading for either myopes or emmetropes. Overall, therefore, it is unlikely that differences in peripheral aberrations after reading contribute significantly to the development of myopia.

Before reading, emmetropes were found to have significantly more total aberrations than myopes at temporal 20 degrees and 30 degrees (borderline significant). These results are consistent with those of previous studies (Lundstrom, Mira-Agudelo, &

Artal, 2009; Atchison & Scott, 2002). After reading, emmetropes continued to have significantly more aberrations than myopes at temporal 20 degrees, and also had significantly more aberrations at temporal 30 degrees. Both refractive groups were found to have more aberrations nasally than centrally, which is consistent with previous literature (Atchison & Scott, 2002). During testing, there was difficulty obtaining measurements at temporal 30 degrees due to the pupil size at this position. Therefore, fewer subjects' data were used for this position (before reading emmetropes n=19, myopes n=15; after reading emmetropes n=19; myopes n=14). The fact that there was not a significant difference between the two groups at temporal 30 degrees could be attributed to a smaller sample size.

The differences in total RMS between the two groups are likely attributed to the differences in astigmatism, especially main axis. Emmetropes had significantly more main axis astigmatism than myopes at all retinal positions before reading. These results are consistent with previous studies, which have shown significant differences between emmetropes and myopes (Millodot, 1981; Seidemann et al., 2002; Charman & Jennings, 2006; Charman & Jennings, 1982; Hoogerheide et al., 1971), as well as an increase in astigmatism in the periphery for individual refractive groups (Gustafsson, Terenius, Buchheister, &Unsbo, 2001; Calver, et. al, 2007)**.** After reading, a similar pattern was found, with emmetropes having significantly more main axis astigmatism than myopes at all positions except for nasal 10 degrees (although emmetropes did have a great amount of main axis astigmatism at this position). Oblique astigmatism was found to be significantly higher for emmetropes than myopes before reading at temporal 30 degrees, and after reading at temporal 20 and temporal 30 degrees. These results may be predicted

by optical modeling due to the fact that myopes generally have longer eyes than emmetropes, which leads to an increase in peripheral astigmatism due to the fact that if the eye grows longer and all other components of the eye stay the same, it is expected for the oblique astigmatic image shell to stay constant (Charman & Jennings, 1982). In this scenario, there will be increased astigmatism due to the retina falling upon a different location of the astigmatic focal planes. Given that myopes often have longer eyes than emmetropes before they develop myopia (Mutti, Hayes, Mitchell, Jones, Moeschberger, Cotter, Kleinstein, Manny, Twelker, & Zadnik, 2007), the astigmatism differences produced by differences in eye shape may play a role in the development of myopia. Studies conducted with monkeys have shown that eyes with astigmatism emmetropize to the least-hyperopic focal plane as opposed to the circle of least confusion (Kee, Hung, Qiao-Grider, Roorda, & Smith, 2004). Other studies have shown that emmetropes have more mixed astigmatism in the periphery, while myopes have more compound myopic astigmatism (Hoogerheide, et. al, 1971; Millodot, 1981). This may mean that emmetropes' least hyperopic focal plane is less myopic than that of the myopes, leading to less myopia development if they emmetropize to the least myopic focal plane.

Higher order aberrations were found to be higher peripherally than centrally for both refractive groups, but no differences in aberrations were found between the two groups either before reading or after reading. Both groups had a significant increase in higher order aberrations at nasal 30 degrees after reading. This may be attributed to lens changes induced by convergence if tension from the nasal zonules during convergence leads to an increase in lenticular aberrations.

Few refractive group differences were found when looking at individual higher order Zernike terms. No significant differences were found between the two refractive groups for vertical trefoil (Z_3^{-3}) or horizontal trefoil (Z_3^{3}) either before reading or after reading. It has been noted previously that trefoil has less of an effect on visual acuity than coma (Applegate, Sarver, & Khemsara, 2002); therefore, one would not except as great a difference between the two groups as would be found with coma.

Horizontal coma was found to be more positive in the nasal retina and more negative in the temporal retina for both emmetropes and myopes before reading. These results are consistent with previous studies (Atchison, 2006; Atchison & Scott, 2002)**.** The same pattern was found after reading. Before reading, horizontal coma was found to be significantly higher for emmetropes than myopes at nasal 30 degrees, temporal 20 degrees, and temporal 30 degrees. After reading it was only found to be significantly higher for emmetropes than myopes at temporal 30 degrees. This may mean that horizontal coma differences do not play a role in myopia development, or it may be that since the coma causes more blur in the periphery, the emmetropes are more likely to emmetropize toward the area of retina with least blur. Given that emmetropes have the least amount of blur centrally, this may mean that they emmetropize to the central retina while myopes emmetropize to the peripheral retina, which has less blur. The idea may be supported by one recent study which found that central coma increases as myopia increases (Paquin, Hamam, & Simonet, 2002). For vertical coma, no significant differences were found between the two refractive groups.

Spherical aberration was found to be greater centrally than peripherally for emmetropes both before and after reading, which was also found in a previous study

(Atchison, 2006). In contrast to that study, we found that myopes had less spherical aberration centrally than peripherally before reading, but there were no significant changes across the retina after reading. This finding differs from one recent study which found myopes to have significantly more spherical aberration than emmetropes before reading, but not after reading due to an increase in spherical aberration by the emmetropes (Vasudevan, Ciuffreda, & Wang, 2007).

It should be noted that these results are for young adults. Given that many of the myopes tested were no longer progressing in their refractive error, different results may be expected in children with progressing myopia. There may be differences in the changes in peripheral aberrations after reading in myopes who are progressing that we did not see due to stability of the refractive status of our subjects. In the future, it would be interested to look at peripheral aberrations before and after reading in emmetropic and progressing myopic children.

Corneal Topography and Axial Length

No significant differences were found between myopes and emmetropes when looking at corneal aberrations before reading; this is in contrast to the significant differences that were found when looking at whole eye aberrations. The difference may have been due to the fact that only a small subset of the original subjects were used; 8 emmetropes and 8 myopes. However, it may also be that the differences found in aberrations between emmetropes and myopes were due to lenticular aberrations, or an interaction between the lenticular and whole eye aberrations.

Strengths and Limitations

A strength of this study is that it looked at the effects of reading under natural, everyday reading conditions. All subjects were advised to read as they normally do. If myopes read with glasses, they were able to do so for the reading period, and if they read without them they were able to take them off.

Another strength is that, based on the literature, the duration of the reading task of one hour is sufficient to see differences if they were present. One hour has been found by previous investigators to be an adequate amount of time to see corneal changes induced by reading (Collins, et. al, 2006; Vasudevan, et. al, 2007; Buehren et al., 2003; Collins, Kloevekorn-Norgall, Buehren, Voetz, &Lingelbach, 2005), refractive changes induced by reading (Ciuffreda& Lee, 2002; Walker &Mutti, 2002), and changes in whole eye aberrations (Buehren et al, 2005).

Testing conditions used in this study were similar to those in other studies. During testing, subjects moved their eyes to look at each of the letters. Previous studies have found that this provides similar results as found when subjects move their entire head (Radhakrishnan & Charman, 2008). Although only one eye was tested during the study, it has been found that there is symmetry between a person's two eyes in terms of monochromatic aberrations (Porter, Guirao, Cox, & Williams, 2001). Therefore we are confident that the aberrations measured for the right eye are consistent with those of the left eye, which was used to fixate on the near target.

Limitations of the study should be noted. As mentioned previously, there was some difficulty obtaining measurements in the far temporal retina for a few subjects due

to a decrease in pupil size and because some myopes were unable to position the lens in front of their eye in such a way that it did not block the letter on the target.

Although myopes were given a lens to account for the accommodative demand difference in myopes and emmetropes, there is the possibility that the myopes were not properly corrected at their last refraction. Also, not all emmetropes were plano. Therefore, some emmetropes might have accommodated less than others.

Subjects were allowed to read a book of their choosing. Therefore, print size and text varied. Subjects were also allowed to read the book at their normal reading position. Because these were natural positions, distance from the text as well as position of the eyes were not controlled. This may have led to a difference in accommodative demand between subjects. It has been previously found that the position of the near-work material makes a difference in corneal changes (Collins, et. al, 2006). During reading subjects were allowed to sit in a room alone. Although they were instructed not to stop reading until the end of the hour, there is the possibility that some subjects looked away from their reading more than others.

After reading, subjects were re-aligned with the COAS. Generally, this took only a few seconds, but for some subjects it took up to a minute. Subjects who took longer to be positioned in the COAS may have had dissipation in the effects of reading on aberrations.

Conclusions

Emmetropes and myopes have significant differences in the amount of peripheral aberrations, so it is possible that peripheral aberrations are relevant to myopia. However,

few significant changes in peripheral aberrations were found after reading for either refractive group, so it is unlikely that differences in peripheral aberrations induced by near work play a role in myopia development.

Chapter 2

Pupil Size in Emmetropes and Myopes

It is known that as pupil diameter increases, higher order aberrations increase, regardless of age (Applegate, Donnelly, Marsack, Koening, & Pesudovs, 2007). It has been thought that if myopes have larger pupils or less accommodative miosis than emmetropes, this may lead to greater amounts of aberrations and therefore more retinal blur (Charman & Radhakrishnan, 2009). However, the relationship between refractive error and pupil size has not been well established. Some studies have found that there is no difference in pupil size between myopes and emmetropes (Winn, Whitaker, Elliot, & Phillips, 1994; Jones, 1990; Netto, Ambrosia, & Wilson, 2004; Charman & Radhakrishnan, 2009), while others have found that myopes have larger pupils than emmetropes (Zinn, 1972; Alexandris, 1985). Two recent studies have looked at the differences between pupil size in myopes and emmetropes during accommodation and have found no significant differences (Subbaram & Bullimore, 2002; Charman & Radhakrishnan, 2009). While conducting our study on the difference in aberrations between emmetropes and myopes before and after reading, we noticed that data from some myopes could not be used due to the small pupil size. Therefore, we decided to analyze the data to determine if there were any statistically significant differences in the before-reading pupil size between the two groups.

Methods

The pupil size of each subject (emmetropes n=25; myopes n=33) at each retinal position was recorded by the COAS while measuring the aberrations as previously discussed. The average of the three before reading measurements was calculated for all subjects, including those whose data were not used due to their pupil size being smaller than the required 4.0mm. T-tests were performed to determine if there was a significant difference between the two groups. This is in contrast to the data analyzed for the peripheral aberrations. Here, we compared the pupil size measured by the COAS for each subject. When looking at peripheral aberrations we only analyzed the data for the central 4.0mm of each subjects, and those subjects with pupils smaller than 4.0mm were not used. Therefore, no differences found between refractive groups in the previous chapter can be attributed to differences in pupil size.

Results

At all retinal positions, emmetropes were found to have significantly larger pupils than myopes (nasal 30 degrees $p=0.004$; nasal 10 degrees $p=.002$; centrally $p<0.001$; temporal 10 degrees 0.001; temporal 20 degrees $p=<0.001$; temporal 30 degrees $p=0.002$). The average pupil size for each refractive group is shown in figure 11.

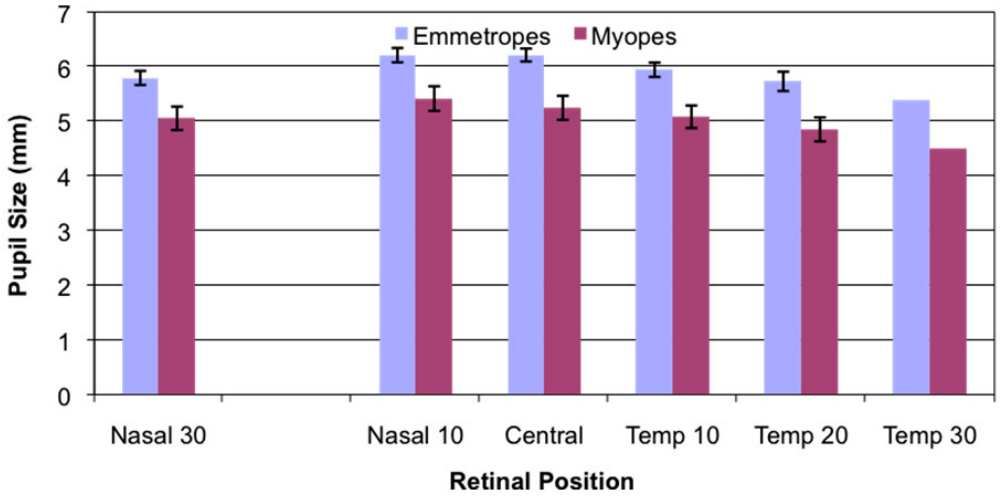


Figure 11: Average pupil size for emmetropes and myopes before reading

Another interesting observation we found was that higher myopes (<-5.99 D) tended to be the ones with the smaller pupils, as shown in Figure 12.

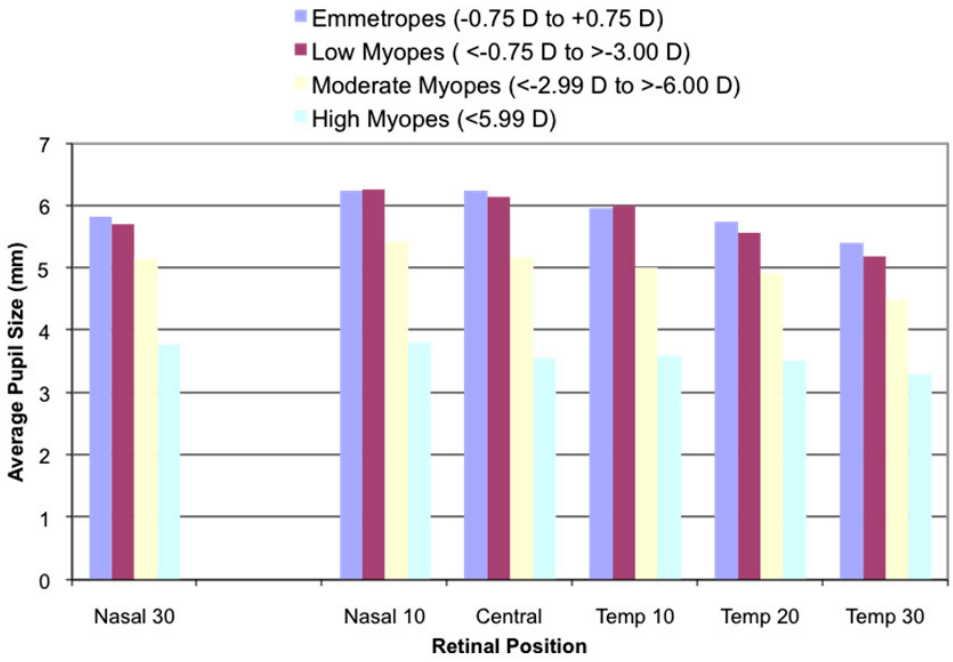


Figure 12: Average pupil size for emmetropes, low myopes, moderate myopes, and high myopes

Discussion

We found that before reading, emmetropes had significantly larger pupils than myopes while accommodating to a near target. Our results are consistent with one study that found myopic children had smaller pupils than emmetropes at both distance and near (Woung, Lue, & Shih, 1998). However, our results differ from studies that reported no significant differences between the pupil sizes of emmetropes and myopes during accommodation (Subbaram & Bullimore, 2002; Charman & Radhakrishnan, 2009).

This study was not designed to look at the differences in pupil sizes of subjects. Therefore, lighting and accommodation were not controlled. We also did not account for differences in corneal magnification when looking at pupil sizes. It has been found that it is important to account for this difference due to the fact that the corneal refractive power may cause the pupil in myopes to appear larger than the true size (Chaidaroon & Juwattanasomran, 2002). In consideration of this, these results showing differences in pupil size should be interpreted with caution. In the future it would be of interest to measure the pupil size of emmetropes and myopes of varying refractive errors under a controlled lighting condition.

These results may be of interest when comparing peripheral aberrations between emmetropes and myopes. In our study, we measured aberrations for the central 4.0mm of each subject. However, it is known that aberrations increase as pupil size increases (Wang et al, 2003; Applegate et al, 2007). If emmetropes have larger pupils than myopes, they may be experiencing more aberrations. It would also be of interest in the future to compare peripheral aberrations of emmetropes and myopes by analyzing the entire pupil

as opposed to the central 4.0mm for each subject. This may provide a more accurate assessment of the amount of retinal blur each group experiences.

Appendix 1:

Advertisements for NECO students and Craigslist

E-MAIL TO NECO STUDENTS:

To: All NECO Students
Subject: Participants Needed For Research Project ($10)

Are you an emmetrope (+0.75 D to -0.50 D) or a myope (-0.75 D to -10.00 D)? Are you between the ages of 18 and 30 years? If so, come participate as a subject in a research project examining the effects of reading on peripheral aberrations (e.g. astigmatism) and peripheral refraction in young adults. This study will be conducted in the Children's Vision Lab. The study will take approximately 1.5 hours, and you will be compensated $10 for your time. You will be asked to refrain from wearing soft contact lenses for twenty-four hours before the study. If you wear rigid contact lenses, have had corneal refractive surgery, or orthokeratology (CRT), you are not eligible to participate in this study. You are also not eligible to participate if you have more than 1.50D of astigmatism or any ocular diseases. During the study you will be asked to read a book of your choice for one hour. Nothing will come into contact with your eye. If you are interested, have any questions, or wish to make an appointment, please contact Christine Beck at christine_beck@neco.edu.

CRAIGSLIST POSTING:

Subject: Research participants needed for eye study – $10

The New England College of Optometry is conducting a study on the effects of reading on peripheral aberrations (e.g. astigmatism) and peripheral refraction (e.g. nearsightedness). The non-invasive study involves one visit to the New England College of Optometry in the Back Bay (free parking and T accessible). The total testing time is an hour and a half. You will be asked to refrain from wearing contact lenses for twenty-four hours before the study, and to bring a book which you will be asked to read for one hour. Measurements will be taken by an FDA-approved instrument which will not come into contact with your eyes. You will receive $10 compensation upon completion of the study.

We are currently looking for individuals with the following characteristics:

-Male or female
-Age 18 – 30 years
-Nearsighted
-Never had corneal refractive surgery (e.g. LASIK) or used orthokeratology
-Do not wear rigid contact lenses (soft contact lenses are acceptable)
-Do not have a history of eye disease

Please e-mail Christine_beck@neco.edu or call 617-236-6245 for further details and to make an appointment.

Appendix 2:

Subject Questionnaires for NECO and Non-NECO students

Subject Questionnaire for NECO Students

Instructions	Data Entry
Date. (month/day/year)	___ mm / dd / yyyy
Full Name. (First, middle initial, Last)	First MI Last
Date of Birth. (month/day/year)	___ mm / dd / yyyy
Gender. (male or female)	___
Ethnicity. **a.** Please select the category that you believe best describes your ancestral ethnic heritage, from the following: 1 American Indian/Alaska Native 2 Asian 3 Black or African-American 4 White/Caucasian 5 Indian 6 Native Hawaiian or Pacific Islander 7 Other **b.** Are you of Hispanic or Latino descent? (Yes/No) **c.** If you selected "Other" above, how would you describe your ethnic background?	**a.** ___ **b.** ___ **c.** ___
Place of Birth. Please specify the locality, region (if applicable) and nation of your birth. Example: Houston, Texas, United States Dholka, Gujarat, India.	___

Clinical Background

Instructions	Data Entry
General Health Status.	
a. Please list any medication that you are currently taking.	**a.** _____
b. Do you utilize prescription birth control (for instance "the pill" or "the patch")? (Yes/No)	**b.** _____
c. Have you ever suffered a serious injury or illness? If so, please specify the approximate date(s) and nature of the incident(s).	**c.** _____ _____
Ophthalmic History.	
a. Do you have any diseases of the eyes (Yes/No)? If 'yes', you are ineligible for this study.	**a.** _____
b. Do you regularly use eye drops? (Yes/No)	**b.** _____
c. Do you use corrective eyeware such as glasses or contact lenses (Yes/No)?	**c.** _____
d. Do you wear contact lenses (Yes/No)?	**d.** _____
i. If so, are your contacts considered "extended wear"? (Yes/No)	***i.*** _____
ii. When did you first start wearing refractive correction? (year and age)	***ii.*** _____ Year Age
e. Refractive Error. As best you can, please specify your spherical equivalent OD (right) and OS (left) refractive error measurements.	
i. OD	***i.*** **OD** _____
ii. OS	***ii.*** **OS** _____
f. CRT. Have you ever had Corneal Refractive Therapy (CRT) or Orthokeratology?	**f.** _____
i. If so, please specify the year(s) that you underwent CRT.	***i.*** _____

Ophthalmic History. (continued) **g. LASIK**. Have you had Laser Assisted In Situ Keratomileusis (LASIK) or Photorefractive Keratectomy (PRK)? ***i.*** If so, in what year was the surgery performed? **h. Injury**. Have you ever sustained injury to either eye? ***i.*** If so, for each injury please specify which eye and the nature and date of the injury.	**g.** _____ ***i.*** _____ **h.** _____ ***i.*** _____ _____ _____
Additional notes. Are there additional considerations of which you think we should be aware? If so, please specify as succinctly as you can.	_____ _____ _____ _____ _____ _____ _____ _____ _____ _____

Subject Questionnaire for Non-NECO Students

Instructions	Data Entry
Date. (month/day/year)	___ mm / dd / yyyy
Full Name. (First, middle initial, Last)	First MI Last
Date of Birth. (month/day/year)	___ mm / dd / yyyy
Gender. (male or female)	___
Ethnicity. **a.** Please select the category that you believe best describes your ancestral ethnic heritage, from the following: 1 American Indian/Alaska Native 2 Asian 3 Black or African-American 4 White/Caucasian 5 Indian 6 Native Hawaiian or Pacific Islander 7 Other **b.** Are you of Hispanic or Latino descent? (Yes/No) **c.** If you selected "Other" above, how would you describe your ethnic background?	**a.** _____ **b.** _____ **c.** _____
Place of Birth. Please specify the locality, region (if applicable) and nation of your birth. Example: Houston, Texas, United States Dholka, Gujarat, India.	___

Clinical Background

Instructions	Data Entry
General Health Status.	
a. Please list any medication that you are currently taking.	**a.** _____
b. Do you utilize prescription birth control (for instance "the pill" or "the patch")? (Yes/No)	**b.** _____
c. Have you ever suffered a serious injury or illness? If so, please specify the approximate date(s) and nature of the incident(s).	**c.** _____ _____
Eye History.	
a. Do you have any diseases of the eyes (Yes/No)? If 'yes', you are ineligible for this study.	**a.** _____
b. Do you regularly use eye drops? (Yes/No)	**b.** _____
c. Do you use corrective eyeware such as glasses or contact lenses (Yes/No)?	**c.** _____
d. Do you wear contact lenses (Yes/No)?	**d.** _____
i. If so, are your contacts considered "extended wear"? (Yes/No)	***i.*** _____
ii. When did you first start wearing refractive correction? (year and age)	***ii.*** _____ Year Age
e. Refractive Error. As best you can, please specify your prescription for your OD (right eye) and OS (left eye). ***i.*** OD ***ii.*** OS	***i.*** **OD** _____ ***ii.*** **OS** _____
f. CRT. Have you ever had Corneal Refractive Therapy (CRT) or Orthokeratology?	**f.** _____
i. If so, please specify the year(s) that you underwent CRT.	***i.*** _____

Ophthalmic History. (continued) **g. LASIK**. Have you had Laser Assisted In Situ Keratomileusis (LASIK) or Photorefractive Keratectomy (PRK)? ***i.*** If so, in what year was the surgery performed? **h. Injury**. Have you ever sustained injury to either eye? ***i.*** If so, for each injury please specify which eye and the nature and date of the injury.	**g.** _____ ***i.*** _____ **h.** _____ ***i.*** _____ _____ _____
Additional notes. Are there additional considerations of which you think we should be aware? If so, please specify as succinctly as you can.	_____ _____ _____ _____ _____ _____ _____ _____ _____ _____

Appendix 3:

Informed Consent Forms for NECO and Non-NECO students

CHILDREN'S VISION LABORATORY

Informed Consent for NECO Students

INFORMED CONSENT FOR STUDY OF CHANGES IN PERIPHERAL ABERRATIONS AND REFRACTION AFTER READING IN MYOPIC AND EMMETROPIC YOUNG ADULTS`

Investigators: Jane Gwiazda, PhD; Ji He, PhD; Christine Beck; David Kern

You have been asked to volunteer to participate in a research study to be conducted by the Children's Vision Laboratory of the New England College of Optometry. The purpose of this study is to measure peripheral aberrations of the human eye before and after near-work (reading), to gain understanding of their relationship to myopia (nearsightedness). The study will be conducted at the New England College of Optometry and requires one visit, which is expected to last approximately 90 minutes. There will be up to 40 subjects in this study.

INCLUSION/EXCLUSION CRITERIA:

You may be included in this study if you are between 18 and 30 years old and have the required refractive error. Refractive errors will be determined by an autorefractor, the Food and Drug Administration (FDA) approved Complete Ophthalmic Analysis System (COAS), at the beginning of your visit. To be included in the study you must be physically and psychologically capable of having the below described measurements of your eyes, and you must have non-diseased eyes (including the absence of glaucoma). You will be excluded from participating in the study if you have had corneal refractive surgery (eg. LASIK) or orthokeratology (Corneal Refractive Therapy) performed on your eyes.

CONTACT LENSES:

You cannot be included in the study if you wear rigid gas permeable (hard) lenses. You may be included in this study if you wear soft contact lenses, but we ask that you refrain from wearing your contact lenses for a full 24 hours before the scheduled time of your visit.

PROCEDURES:

A. Refraction and Aberration Measurements

a. You will sit in front of the COAS with your chin on the chinrest and your forehead against a headrest.

This test is non-invasive. The COAS is an FDA approved, Class 1 exempt device, with no known risks. This device is a commercially available clinical / research instrument.

b. The apparatus will be aligned to your right eye. You will be looking at a small red light.

c. You will be asked to fixate on a target with your left eye. The target will be a white background with small black letters, and will be seen reflected from a mirror. The target image will be 33 centimeters away as to simulate the distance most people hold books while they are reading.

d. The letters on the target will be located centrally, 10 degrees superiorly, 10, 20, and 30 degrees temporally, and 10 and 20 degrees nasally. Subjects will be asked to look at different letters depending on which measurement is being taken.

e. Three measurements will be taken for each direction of gaze.

f. You will be asked to read a book for one hour.

g. The above measurements will be taken immediately after reading.

RISKS:

There are no known risks involved in any of the testing procedures, and if significant new findings about risks become known you will be informed of them. There are no known discomforts.

POTENTIAL BENEFITS:

There are no expected direct benefits for you in this study. The information gathered will aid in the efforts to understand the optical properties of the eye and the development of myopia

COMPENSATION:

You will receive a small stipend for participation in this study ($10.00). Participation in this investigation is voluntary, and you may withdraw at any time during the study. If you refuse to participate or to complete this study or if you voluntarily withdraw from the study it will not involve any penalty or loss of benefits to which you are otherwise entitled, including as related to your position at NECO.

CONFIDENTIALITY:

Your medical records will be kept as confidential as possible within the limitations of state and federal law.

If you decide to be a subject in this study, both demographic and technical information about you will be collected. Demographic information will include, but will not be limited to, such things as name, date of birth, address, gender, ethnicity, etc. Technical information will include elements of your health history and results of all the tests and measurements related to the study. This information is collected in order to determine whether you are eligible to be a subject in the study; that is, to meet the inclusion/exclusion criteria and, if so, to allow the study investigators to gather the data from you that are necessary to support the study's purpose. The results from all of the subjects in the study can then be analyzed to develop the study's conclusion.

All study-related information will remain confidential with the study investigators or administrative staff. However, any regulatory authority or the Institutional Review Board may inspect the investigator's records pertaining to you as a subject. But they too should maintain confidentiality.

The results of the study may be used in health care education or in scientific publications. Your name and any information that specifically could identify you will not be used in any such presentation or publication.

PERSONAL HEALTH INFORMATION

Your personal health information (PHI), as related to this study is described in the "confidentiality" section above. If you sign this informed consent form, it grants permission to use your PHI as specifically discussed. This permission does not have an expiration date, but you can cancel it at anytime by writing to the principal investigator(s) at the address below.

If you cancel your permission to use your PHI after you have started the study but before your study participation would normally be concluded, you will not be allowed to continue in the study and the investigators will stop collecting data. However, they retain the right to use the information they have already collected to evaluate the study's results.

PRIVACY PRACTICES AND YOUR RIGHTS:

Health care providers are required by law to keep private any health information that identifies people. Federal Privacy Regulations require that you authorize the release of any health information that may reveal your identity. The persons and entities that you are authorizing to use or inspect all of the health information generated or collected about you during this study include the study doctor(s), the study staff, the Institution, any study Sponsor (or the authorized agents of the sponsor), the Food and Drug Administration (FDA), the Department of Health and Human Services (DHHS) agencies, and the Institutional Review Board. Because of the need to release information to these parties absolute confidentiality cannot be guaranteed. Once your personal health information is released it may be redisclosed, at which point your health information may no longer be protected by federal privacy regulations.

You may ask the study investigator to see a copy of your PHI related to the study. You may also request the study investigator to correct any information that you feel is incorrect. However, you may have to wait until the end of the study to see your records so that the study can be organized and conducted scientifically.

You must be given notice of your investigator's privacy policies. The Confidentiality, Personal Health Information, and Privacy Practices and your Rights sections of this form fulfill this requirement.

Unless you authorize the use and disclosure of your personal health information, you cannot participate in this research study. If you refuse to give your authorization, your medical care will not be affected.

Study investigators will try to answer any and all questions you may have regarding this study. Additional questions can be directed to Jane Gwiazda, Ph.D. (617-236-6234), or to Paul White, O.D. Chairman of the Institutional Review Board at the New England College of Optometry (627-236-6247), if you have questions about your rights as a research subject. In case of any problems (adverse reactions), you should contact Dr. Frank Thorn at 617-236-6237. If you need emergency care you can call the New England Eye Institute (NEEI) at 617-262-2020 for treatment or go to the emergency room of a nearby hospital. No funds are available to provide financial compensation for research-related injury or illness, even if the injury or illness is a direct result of this research study. Expense for your medical care may be covered by your medical insurance provider. If you do have any adverse reactions, you must also notify the Children's Vision Laboratory at 617-236-6245.

CONSENT:

I have read this consent form (or had it read to me) and I understand it. I understand the potential risks and benefits involved with this study and that I may withdraw at any time without affecting my future medical care. I understand that I must notify Dr. Jane Gwiazda immediately if I notice any medical problems that may be related to my participation in this study. I also understand that my participation in this study may be terminated at any time if the investigator or IRB feel it is in my best interests, or if I fail to keep the required study appointment or do not follow the study instructions. I will be made aware of any significant new findings that develop during the study, including any previously unforeseeable risks, which may affect my willingness to continue participation.

Any questions concerning this study have been answered to my satisfaction and I have received a copy of this consent form. By my signing this form, I voluntarily agree to participate in this study.

Principal Investigator:
Dr. Jane Gwiazda
Children's Vision Lab
424 Beacon Street
Boston, MA 02115
(617) 236-6245

_____
Your Name Printed

_____ _____
Your Signature Date

_____ _____
Investigator or Designee's Signature Date

CHILDREN'S VISION LABORATORY

Informed Consent for Non-NECO Students

INFORMED CONSENT FOR STUDY OF CHANGES IN PERIPHERAL ABERRATIONS AND REFRACTION AFTER READING IN MYOPIC AND EMMETROPIC YOUNG ADULTS`

Investigators: Jane Gwiazda, PhD; Ji He, PhD; Christine Beck; David Kern

You have been asked to volunteer to participate in a research study to be conducted by the Children's Vision Laboratory of the New England College of Optometry. The purpose of this study is to measure peripheral aberrations (i.e. astimgatism) of the human eye before and after near-work (reading), to gain understanding of their relationship to myopia (nearsightedness). The study will be conducted at the New England College of Optometry and requires one visit, which is expected to last approximately 90 minutes. There will be up to 40 subjects in this study.

INCLUSION/EXCLUSION CRITERIA:

You may be included in this study if you are between 18 and 30 years old and have the required refractive error. Refractive errors will be determined by an autorefractor, the Food and Drug Administration (FDA) approved Complete Ophthalmic Analysis System (COAS), at the beginning of your visit. To be included in the study you must be physically and psychologically capable of having the below described measurements of your eyes, and you must have non-diseased eyes (including the absence of glaucoma). You will be excluded from participating in the study if you have had corneal refractive surgery (eg. LASIK) or orthokeratology (Corneal Refractive Therapy) performed on your eyes.

CONTACT LENSES:

You cannot be included in the study if you wear rigid gas permeable (hard) lenses. You may be included in this study if you wear soft contact lenses, but we ask that you refrain from wearing your contact lenses for a full 24 hours before the scheduled time of your visit.

PROCEDURES:

B. Refraction and Aberration Measurements

a. You will sit in front of the COAS with your chin on the chinrest and your forehead against a headrest.

This test is non-invasive. The COAS is an FDA approved, Class 1 exempt device, with no known risks. This device is a commercially available clinical / research instrument.

b. The apparatus will be aligned to your right eye. You will be looking at a small red light.

c. You will be asked to fixate on a target with your left eye. The target will be a white background with small black letters, and will be seen reflected from a mirror. The target image will be 33 centimeters away as to simulate the distance most people hold books while they are reading.

d. The letters on the target will be located centrally, 10 degrees superiorly, 10, 20, and 30 degrees temporally, and 10 and 20 degrees nasally. Subjects will be asked to look at different letters depending on which measurement is being taken.

e. Three measurements will be taken for each direction of gaze.

f. You will be asked to read a book for one hour.

g. The above measurements will be taken immediately after reading.

RISKS:

There are no known risks involved in any of the testing procedures, and if significant new findings about risks become known you will be informed of them. There are no known discomforts.

POTENTIAL BENEFITS:

There are no expected direct benefits for you in this study. The information gathered will aid in the efforts to understand the optical properties of the eye and the development of myopia

COMPENSATION:

You will receive a small stipend for participation in this study ($10.00). Participation in this investigation is voluntary, and you may withdraw at any time during the study. If you refuse to participate or to complete this study or if you voluntarily withdraw from the study it will not involve any penalty or loss of benefits to which you are otherwise entitled.

CONFIDENTIALITY:

Your medical records will be kept as confidential as possible within the limitations of state and federal law.

If you decide to be a subject in this study, both demographic and technical information about you will be collected. Demographic information will include, but will not be limited to, such things as name, date of birth, address, gender, ethnicity, etc. Technical information will include elements of your health history and results of all the tests and measurements related to the study. This information is collected in order to determine whether you are eligible to be a subject in the study; that is, to meet the inclusion/exclusion criteria and, if so, to allow the study investigators to gather the data from you that are necessary to support the study's purpose. The results from all of the subjects in the study can then be analyzed to develop the study's conclusion.

All study-related information will remain confidential with the study investigators or administrative staff. However, any regulatory authority or the Institutional Review Board may inspect the investigator's records pertaining to you as a subject. But they too should maintain confidentiality.

The results of the study may be used in health care education or in scientific publications. Your name and any information that specifically could identify you will not be used in any such presentation or publication.

PERSONAL HEALTH INFORMATION

Your personal health information (PHI), as related to this study is described in the "confidentiality" section above. If you sign this informed consent form, it grants permission to use your PHI as specifically discussed. This permission does not have an expiration date, but you can cancel it at anytime by writing to the principal investigator(s) at the address below.

If you cancel your permission to use your PHI after you have started the study but before your study participation would normally be concluded, you will not be allowed to continue in the study and the investigators will stop collecting data. However, they retain the right to use the information they have already collected to evaluate the study's results.

PRIVACY PRACTICES AND YOUR RIGHTS:

Health care providers are required by law to keep private any health information that identifies people. Federal Privacy Regulations require that you authorize the release of any health information that may reveal your identity. The persons and entities that you are authorizing to use or inspect all of the health information generated or collected about you during this study include the study doctor(s), the study staff, the Institution, any study Sponsor (or the authorized agents of the sponsor), the Food and Drug Administration (FDA), the Department of Health and Human Services (DHHS) agencies, and the Institutional Review Board. Because of the need to release information to these parties absolute confidentiality cannot be guaranteed. Once your personal health information is released it may be redisclosed, at which point your health information may no longer be protected by federal privacy regulations.

You may ask the study investigator to see a copy of your PHI related to the study. You may also request the study investigator to correct any information that you feel is incorrect. However, you may have to wait until the end of the study to see your records so that the study can be organized and conducted scientifically.

You must be given notice of your investigator's privacy policies. The Confidentiality, Personal Health Information, and Privacy Practices and your Rights sections of this form fulfill this requirement.

Unless you authorize the use and disclosure of your personal health information, you cannot participate in this research study. If you refuse to give your authorization, your medical care will not be affected.

Study investigators will try to answer any and all questions you may have regarding this study. Additional questions can be directed to Jane Gwiazda, Ph.D. (617-236-6234), or to Paul White, O.D. Chairman of the Institutional Review Board at the New England College of Optometry (627-236-6247), if you have questions about your rights as a research subject. In case of any problems (adverse reactions), you should contact Dr. Frank Thorn at 617-236-6237. If you need emergency care you can call the New England Eye Institute (NEEI) at 617-262-2020 for treatment or go to the emergency room of a nearby hospital. No funds are available to provide financial compensation for research-related injury or illness, even if the injury or illness is a direct result of this research study. Expense for your medical care may be covered by your medical insurance provider. If you do have any adverse reactions, you must also notify the Children's Vision Laboratory at 617-236-6245.

CONSENT:

I have read this consent form (or had it read to me) and I understand it. I understand the potential risks and benefits involved with this study and that I may withdraw at any time without affecting my future medical care. I understand that I must notify Dr. Jane Gwiazda immediately if I notice any medical problems that may be related to my participation in this study. I also understand that my participation in this study may be terminated at any time if the investigator or IRB feel it is in my best interests, or if I fail to keep the required study appointment or do not follow the study instructions. I will be made aware of any significant new findings that develop during the study, including any previously unforeseeable risks, which may affect my willingness to continue participation.

Any questions concerning this study have been answered to my satisfaction and I have received a copy of this consent form. By my signing this form, I voluntarily agree to participate in this study.

Principal Investigator:
Dr. Jane Gwiazda
Children's Vision Lab
424 Beacon Street
Boston, MA 02115
(617) 236-6245

_____
Your Name Printed

_____ _____
Your Signature Date

_____ _____
Investigator or Designee's Signature Date

Appendix 4:

P-values of Individual T-tests for Emmetropes vs. Myopes at Each Retinal Location

	Before Reading	After Reading

		Before Reading			After Reading		
	Position	**Emmetropes**	**Myopes**	**P-value**	**Emmetropes**	**Myopes**	**P-value**
Total RMS	Nasal 30	0.448	0.520	0.150	0.495	0.534	0.381
	Nasal 10	0.247	0.289	0.267	0.264	0.256	0.783
	Central	0.201	0.248	0.197	0.215	0.237	0.529
	Temporal 10	0.271	0.253	0.643	0.272	0.232	0.286
	Temporal 20	0.430	0.305	0.005*	0.439	0.304	0.005*
	Temporal 30	0.637	0.497	0.038	0.686	0.546	0.020
Higher Order RMS	Nasal 30	0.168	0.143	0.090	0.189	0.168	0.220
	Nasal 10	0.120	0.132	0.397	0.134	0.133	0.908
	Central	0.101	0.114	0.321	0.111	0.122	0.475
	Temporal 10	0.131	0.130	0.955	0.131	0.121	0.531
	Temporal 20	0.156	0.152	0.840	0.162	0.139	0.218
	Temporal 30	0.171	0.172	0.980	0.192	0.168	0.200

Table 1: Total RMS and higher order RMS values for each retinal position, before reading and after reading, for emmetropes and myopes. The p-value for the difference between refractive groups at each position is also shown.

		Before Reading			After Reading		
	Position	**Emmetropes**	**Myopes**	**P-value**	**Emmetropes**	**Myopes**	**P-value**
Main Axis Astigmatism (Z_2^2)	Nasal 30	0.222	-0.051	<0.001*	0.254	0.056	0.002*
	Nasal 10	0.037	-0.130	0.003*	0.034	-0.062	0.042
	Central	0.061	-0.115	0.001*	0.062	-0.080	0.005*
	Temporal 10	0.166	-0.060	<0.001*	0.187	-0.034	<0.001*
	Temporal 20	0.353	0.071	<0.001*	0.375	0.069	<0.001*
	Temporal 30	0.562	0.170	<0.001*	0.611	0.211	<0.001*
Oblique Astigmatism (Z_2^{-2})	Nasal 30	0.274	0.322	0.256	0.311	0.432	0.028
	Nasal 10	0.119	0.054	0.023	0.114	0.101	0.343
	Central	0.055	0.026	0.114	0.064	0.047	0.253
	Temporal 10	0.021	1.933E-05	0.235	0.023	0.006	0.279
	Temporal 20	-0.053	-0.080	0.244	-0.071	-0.115	0.155
	Temporal 30	-0.157	-0.295	0.018	-0.169	-0.333	0.016

Table 2: Main-axis astigmatism and oblique astigmatism values for each retinal position, before reading and after reading, for emmetropes and myopes. The p-value for the difference between refractive groups at each position is also shown.

	Position	Emmetropes	Myopes	P-value	Emmetropes	Myopes	P-value
Vertical Coma (Z_3^{-1})	Nasal 30	0.033	-0.011	0.003*	0.022	0.015	0.320
	Nasal 10	-0.002	-0.027	0.096	-0.011	-0.009	0.448
	Central	-0.010	-0.024	0.193	-0.027	-0.027	0.499
	Temporal 10	-0.021	-0.018	0.445	-0.024	-0.018	0.371
	Temporal 20	-0.023	-0.016	0.391	-0.033	-0.026	0.368
	Temporal 30	-0.011	-0.039	0.157	-0.028	-0.048	0.240
Horizontal Coma (Z_3^{1})	Nasal 30	0.132	0.073	0.002*	0.136	0.114	0.142
	Nasal 10	0.068	0.050	0.096	0.067	0.075	0.307
	Central	0.001	0.003	0.422	0.005	0.014	0.269
	Temporal 10	-0.054	-0.020	0.009*	-0.054	-0.014	0.006*
	Temporal 20	-0.078	-0.022	0.015	-0.076	-0.032	0.028
	Temporal 30	-0.091	-0.025	0.024	-0.100	-0.024	0.026
Vertical Trefoil (Z_3^{-3})	Nasal 30	0.020	0.013	0.269	0.028	0.026	0.452
	Nasal 10	-0.013	0.010	0.034	-0.006	0.007	0.179
	Central	-0.013	0.003	0.103	0.002	0.017	0.134
	Temporal 10	-0.002	0.008	0.248	0.008	0.015	0.315
	Temporal 20	0.015	0.011	0.380	0.027	0.018	0.245
	Temporal 30	0.032	0.017	0.195	0.062	0.021	0.017
Horizontal Trefoil (Z_3^{3})	Nasal 30	-0.009	-0.008	0.465	-0.019	-0.015	0.345
	Nasal 10	0.003	-0.001	0.356	-0.002	-0.008	0.413
	Central	-0.006	-0.011	0.350	-0.013	-0.019	0.421
	Temporal 10	-0.013	-0.010	0.406	-0.017	-0.019	0.330
	Temporal 20	-0.0005	0.003	0.423	0.005	0.001	0.283
	Temporal 30	0.014	0.027	0.294	0.011	0.020	0.389
Spherical Aberration (Z_4^{0})	Nasal 30	0.003	0.011	0.240	0.007	0.010	0.429
	Nasal 10	0.012	0.007	0.327	0.011	0.003	0.257
	Central	0.022	0.004	0.065	0.014	0.009	0.323
	Temporal 10	0.012	-0.003	0.146	0.008	0.006	0.432
	Temporal 20	-0.002	-0.003	0.494	-0.001	0.006	0.307
	Temporal 30	-0.012	0.010	0.087	-0.014	0.010	0.050

Table 3: Trefoil, coma, and spherical aberration values are shown for each retinal position, before reading and after reading, for emmetropes and myopes. The p-value for the difference between refractive groups at each position is also shown.

References

Alexandris, E. (1985). *The Pupil, trans.* Telger, T. Springer-Verlag, New York, 11p.

Applegate, R.A., Donnelly, W.J., Marsack, J.D., Koenig, D.D., & Pesudovs, K. (2007). Three-dimensional relationship between high-order root-mean-square wavefront error, pupil diameter, and aging. *Journal of the Optical Society of America A: Optics and Image Science, and Vision 24*(3), 578-587.

Applegate, R.A., Sarver, E.J., & Khemsara, V. (2002). Are All Aberrations Equal? *Journal of Refractive Surgery, 18,* S556-S562.

Atchison, D.A. (2006). Higher order aberrations across the horizontal visual field *Journal of Biomedical Optics, 11(3),* 034026:1-5.

Atchison, D.A. (2006). Optical models for human myopic eyes. *Vision Research, 46,* 2236-2250.

Atchison, D.A., Jones, C.E., Schmid, K.L., Pritchard, N., Pope, J.M., Strugnell, W.E., & Riley, R.A. (2004). Eye Shape in Emmetropia and Myopia. *Investigative Ophthalmology & Visual Science, 45*(10), 3380-3386.

Atchison, D.A., Lucas, S.D., Ashman, R., Huynh, M.A., Schilt, D.W., & Ngo, P.Q. (2006). Refraction and Aberration Across the Horizontal Central 10° of the Visual Field. *Optometry and Vision Science, 83*(12), 213-221.

Atchison, D.A., Pritchard, N., & Schmid, K.L. (2006). Peripheral refraction along the horizontal and vertical visual fields in myopia. *Vision Research, 46,* 1450-1458.

Atchison, D.A., Pritchard, N., Schmid, K.L., Scott, D.H., Jones, C.E., & Pope, J.M. (2005). Shape of the Retinal Surface in Emmetropia and Myopia. *Investigative Ophthalmology & Visual Science, 46*(8), 2698-2707.

Atchison, D.A. & Scott, D.H. (2002). Monochromatic aberrations of human eyes in the horizontal visual field. *Journal of the Optical Society of America A: Optics and Image Science, and Vision 19*(11), 2180-2184.

Atchison, D.A., Scott, D.H., & Charman, W.N. (2007). Measuring ocular aberrations in the peripheral visual field using Hartmann-Shack aberrometry. *Journal of the Optical Society of America A: Optics and Image Science, and Vision 24*(9), 2963-2973.

Attebo, K., Ivers, R.Q.,& Mitchell, P. (1999). Refractive Errors in an Older Population: The Blue Mountains Eye Study. *Ophthalmology, 106*(6), 1066-1072.

Berntsen. D.A.,Mutti, D.O., & Zadnik, K. (2008). *Ophthalmic and Physiological Optics, 28*, 83-90.

Buehren, T., Collins, M.J.,& Carney, L. (2003). Corneal Aberrations and Reading. *Optometry and Vision Science, 80*(2), 159-166.

Buehren, T., Collins, M.J.,& Carney, L.G. (2005). Near work induced wavefront aberrations in myopia. *Vision Research, 45,* 1297-1312.

Calver, R., Radhiakrishnan, H., Osuobeni, E., & O'Leary, D. (2007).Peripheral refraction for distance and near vision in emmetropes and myopes. *Ophthalmic and Physiological Optics, 27*, 584-593.

Carney, L.G., Mainstone, J.C., & Henderson, B.A. (1997). Corneal Topography and Myopia. *Investigative Ophthalmology & Visual Science, 38*(2), 311-329.

Chaidaroon, W. & Juwattanasomran, W. (2002). Colvard Pupillometer Measurement of Scotopic Pupil Diameter in Emmetropes and Myopes. *Japanese Journal of Ophthalmology, 46,* 640-644.

Charman, W.N. (2005). Aberrations and myopia. *Ophthalmic and Physiological Optics, 25,* 285-301.

Charman, W.N. & Jennings, J.A.M. (2006). Longitudinal changes in peripheral refraction with age. *Ophthalmic and Physiological Optics,26*, 447-455.

Charman, W.N. & Jennings, J.A.M. (1982). Ametropia and Peripheral Refraction. *American Journal of Optometry, 59*(11), 922-923.

Charman, W.N. & Radhakrishnan, H. (2009). Accommodation, pupil diameter, and myopia. *Ophthalmic and Physiological Optics, 29,* 72-29.

Cheng, X., Bradley, A., & Thibos, L. (2003). Relationship between Refractive Error and Monochromatic Aberrations of the Eye. *Optometry and Vision Science, 80*(1), 43-49.

Cheng, H., Singh, O., Kwong, K., Xiong, J., Woods, B., & Brady, T. (1992). Shape of the Myopic Eye as Seen with High-Resolution Magnetic Resonance Imaging. *Optometry and Vision Science, 69*(9), 698-701.

Ciuffreda, K. & Lee, M. (2002). Differential refractive susceptibility to sustained nearwork. *Ophthalmic and Physiological Optics, 22*, 372-379.

Collins, M.J., Buehren, T., Bece, A., & Voetz, S.C. (2006). Corneal Optics after Reading, Microscopy and Computer Work. *ActaOpthalmologicaScandinavica, 84,* 216-224.

Collins, M.J.,Buehren, T., & Iskander, D.R. (2006). Retinal image quality, reading and myopia. *Vision Research, 46,* 196-215.

Collins, M.J., Kloevekorn-Norgall, K., Buehren, T., Voetz, S., & Lingelbach, B. (2005). Regression of Lid-Induced Corneal Topography Changes After Reading. *Optometry and Vision Science, 82*(9), 843-849.

Dandona, R., Dandona, L., Naduvilath, T.J., Srinivas, M., McCarty, C.A., & Rao, G.N. (1999). Refractive Errors in an Urban Population in Southern India: The Andhra Pradesh Eye Disease Study. *Investigative Ophthalmology & Visual Science, 40*(12), 2810-2818.

Dandona, R., Dandona, L., Srinivas, M., Sahare, P., Narsaiah, S., Munoz, S.R., Pokharel, G.P., & Ellwein, L.B. (2002). Refractive Error in Children in a Rural Population in India. *Investigative Ophthalmology & Visual Science, 43*(3), 615-622.

Ginis, H.S., Plainis, S., & Pallikaris, A. (2004). Variability of wavefront aberration measurements in small pupil sizes using a clinical shack-Hartmann aberrometer. *BMC Ophthalmology, 4*(1).

Goss, D.A., & Wickham, M.G. (1995). Retinal-image mediated ocular growth as a mechanism for juvenile onset myopia and for emmetropization. A literature review. *Documenta Ophthalmologica, 90*(4), 341-375.

Gwiazda, J.E., Hyman, L., Norton, T.T., Hussein, M.E.M., Marsh-Tootle, W., Manny, R., Want, Y., Everett, D., & COMET Group. (2004). Accommodation and Related Risk Factors Associated with Myopia Progression and Their Interaction with Treatment in COMET children. *Investigative Ophthalmology & Visual Science, 45*(7), 2143-2151.

Gwiazda, J., Thorn, F., Bauer, J., & Held, R. (1993). Myopic children show insufficient accommodative response to blur. *Investigative Ophthalmology & Visual Science, 34*(3), 690-640.

Gustafasson, J., Terenius, E., Buchheister, J., & Unsbo, P. (2001). Peripheral astigmatism in emmetropic eyes. *Ophthalmic and Physiological Optics 21*(5), 393-400.

He, J.C., Gwiazda, J., Thorn, F., Held, R., & Vera-Diaz, F.A. (2005). The association of wavefront aberration and accommodative lag in myopes. *Vision Research, 45,* 285-290.

He, J.C., Sun, P., Held, R., Thorn, F., Sun, X., & Gwiazda, J. (2002). Wavefront aberrations in eyes of emmetropic and moderately myopic school children and young adults. *Vision Research, 42*(8), 1063-1070.

Hepsen, I.F., Evereklioglu, C., & Bayramiar, H. (2001). The effect of reading and near-work on the development of myopia in emmetropic boys: a prospective, controlled, three-year follow-up study. *Vision Research, 19*(41), 2511-2520.

Hoogerheide, J., Rempt, F., & Hoogenboom, W.P.H. (1971). Acquired Myopia in Young

Pilots. *Ophthalmologica, 163,* 209-215.

Horner, D.G.,Soni, P.S., Vyas, N., & Himebaugh, N.L. (2000). Longitudinal Changes in Corneal Asphericity in Myopia. *Optometry and Vision Science, 77*(4), 198-203.

Huang, J., Hung, L.F., Ramamirtham, R., Blasdel, T.L., Humbid, T.L., Bockhorst, K.H., & Smith, E.L. (2009). Effects of Form Deprivation on Peripheral Refractions and Ocular Shape in Infant Rhesus Monkeys (Macaca mulatta). *Investigative Ophthalmology & Visual Science,* 50, 4033-4044.

Jiang, B., Schatz, S., &Seger, K. (2005). Myopic progression and dark focus variation in optometric students during the first academic year. *Clinical and Experimental Optometry, 88*(3), 153-159.

Jones, R. (1990). Do women and myopes have larger pupils? *Investigative Ophthalmology & Visual Science, 31*(7), 1413-1415.

Kee, C., Hung, L., Qiao-Grider, Y., Roorda, A., & Smith III, E.L. (2004). Effects of Optically Imposed Astigmatism on Emmetropization in Infant Monkeys. *Investigative Ophthalmology & Visual Science, 45*(6), 1647-1659.

Llorente, L., Barbero, S., Cano, D., Dorronsoro, C., & Marcos, S. (2004). Myopic versus hyperopic eyes: axial length, corneal shape and optical aberrations. *Journal of Vision, 4,* 288-298.

Logan, N.S.,Gilmartin, B., Wildsoet, C.F., & Dunne, M.C.M. (2004). Posterior Retinal Contour in Adult Human Anisomyopia. *Investigative Ophthalmology & Visual Science, 45*(7), 2152-2162.

Loman, J., Quinn, G.E., Kamoun, L., Ying, G.S., Maguire, M.G., Hudesman, D., & Stone, R.A. (2002). Darkness and Near Work: Myopia and Its Progression in Third-year Law Students. *Ophthalmology, 109*(5), 1032-1038.

Lundstrom, L., Mira-Agudelo, A., & Artal, P. (2009). Peripheral optical errors and their change with accommodation differ between emmetropic and myopic eyes. *Journal of Vision, 9*(6), 17.1-11.

Lundstrom, L & Unsbo, P. (2007). Transformation of Zernike coefficients: Scaled, translated, and rotated wavefronts with circular and elliptical pupils. *Journal of the Optical Society of America A: Optics and Image Science, and Vision, 24*(7), 569-577.

Millodot, M. (1981). Effect of Ametropia on Peripheral Refraction. *American Journal of Optometry & Physiological Optics, 58(9), 691-695.*

Murthy, G.V.S., Gupta, S.K., Ellwein, L.B., Munoz, S.R., Pokharel, G.P., Sanga, L., & Bachani, D. (2002). Refractive Error in Children in an Urban Population in New Delhi.

Investigative Ophthalmology & Visual Science, 43(3), 623-631.

Mutti, D.O., Sholtz, R.I., Friedman, N.E., & Zadnik, K. (2000). Peripheral Refraction and Ocular Shape in Children. *Investigative Ophthalmology & Visual Science, 41*(5), 1022-1030.

Mutti, D.O., Hayes, J.R., Mitchell, G.L., Jones, L.A., Moeschberger, M.L, Cotter, S.A., Kleinstein, R.N., Manny, R.E., Twelker, J.D., & Zadnik, K. (2007). Refractive Erorr, Axial Length, and Relative Peripheral Refractive Error before and after the Onset of Myopia. *Investigative Ophthlmology& Visual Science, 48*(6), 2510-2519.

Mutti, D.O. & Zadnik, K. (2009). Has Near Work's Star Fallen? *Optometry and Vision Science 86(2), 76-78.*

Netto, M.V., Ambrosio, R., & Wilson, S.E. (2004). Pupil size in refractive surgery candidates. *Journal of Refractive Surgery, 20*(4), 337-342.

Paquin, M., Hamam, H., & Simonet, P. (2002).Objective Measurement of Optical Aberrations in Myopic Eyes. *Optometry and Vision Science, 79*(5), 285-291.

Porter, J., Guirao, A., Cox, I.G.,& Williams, D.R. (2001). Monochromatic aberratiosn of the human eye in a large population. *Journal of the Optical Society of America A, 18*(8), 1793-1803.

Read, S.A., Collins, M.J., Carney, L.G., & Franklin, R.J. (2006). The Topography of the Central and Peripheral Cornea. *Investigative Ophthalmology & Visual Science, 47*(4), 1404-1415.

Radhakrishnan, H. &Charman, W.N. (2008). Peripheral refraction measurement: does it matter if one turns the eye or the head? *Ophthalmic and Physiological Optics 28,* 73-82.

Rosner, M. & Belkin, M. (1987). Intelligence, Education, and Myopia in Males. *Archives of Ophthalmology, 105*(11), 1508-1511.

Saw, S. (2003). A synopsis of the prevalence rates and environmental risk factors for myopia. *Clinical and Experimental Optometry, 86*(5), 289-294.

Schmid, G.F. (2003). Variability of retinal steepness at the posterior pole in children 7-15 years of age. *Current Eye Research, 27*(1), 61-68.

Schippert, R. & Schaeffel, F. (2006). Peripheral defocus does not necessarily affect central refractive development. *Vision Research 46,* 3935-3940.

Seidemann, A., Schaeffel, F., Guirao, A., Lopez-Gil, N., & Artal, P. (2002).Peripheral refractive errors in myopic, emmetropic, and hyperopic young subjects. *Journal of the Optical Society of America A, 19*(12), 2363-2373.

Smith, E.I., III, Kee, C., Ramamirtham, R., Qiao-Grider, Y., & Hung, L. (2005). Peripheral Vision Can Influence Eye Growth and Refractive Development in Infant Monkeys. *Investigative Ophthalmology & Visual Science, 46*(11), 3965-3972.

Smith, E.L., Ramamirtham, R., Qiao-Grider, Y., Hung, L., Huang, J., Kee, C., Coats, D., & Paysse, E. (2007). Effects of Foveal Ablation on Emmetropization and Form-Deprivation Myopia. *Investigative Ophthalmology & Visual Science, 48*(9), 3914-1104.

Smith, G., Atchison, D.A., Avudainayagam, C., & Avudainayagam, K. (2002). Designing lenses to correct peripheral refractive errors of the eye. *Journal of the Optical Society of America A: Optics and Image Science, and Vision 19*(1), 10-18.

Smith, E.L., Huang, J., Hung, L.F., Blasdel, T.L., Humbird, T.L., & Bockhorst, K.H. (2009). Hemiretinal form deprivation: evidence for local control of eye growth and refractive development in infant monkeys. *Investigative Ophthalmology & Visual Science, 50*(11), 5057-5069.

Simensen, G. & Thorud, L.O. (1994). Adult-onset myopia and occupation. *Acta Ophthalmologica (Copenh), 72*(4), 469-471.

Subbaram, M.V. & Bullimore, M.A. (2002). Visual acuity and the accuracy of the accommodative response. *Ophthalmic and Physiological Optics, 22*, 312-318.

Vasudevan, B., Ciuffreda, K.J.,& Wang (2007). Nearwork-Induced Changes in Topography, Aberrations, and Thickness of the Human Cornea After Interrupted Reading. *Cornea 26*(8), 917-923.

Vera-Diaz, F.A., Strang, N.C., & Winn, B. (2002). Nearwork induced transient myopia during myopia progression. *Current Eye Research, 24*(4), 289-295.

Vitale S, Sperduto RD, Ferris FL 3rd. (2009) Increased prevalence of myopia in the United States between 1971-1972 and 1999-2004. *Archives of Ophthalmology,* 127,1632-9.

Walker, T.W. & Mutti, D.O. (2002). The Effect of Accommodation on Ocular Shape. Optometry and Vision Science, 79(7), 424-430.

Wang, Y., Zhao, K., Jin, Y., Niu, Y., & Zuo T. (2003). Changes of Higher Order Aberration With Various Pupil Sizes in the Myopic Eye. *Journal of Refractive Surgery, 19*(2), S270-S274.

Winn, B., Whitaker, D., Elliot, D.B., & Phillips, N.J. (1994). Factors affecting light-adapted pupil size in normal human subjects. *Investigative Ophthalmology & Visual*

Science, 35, 1132-1137.

Whitmore, W.G., Curtin, B.J., & Fox, D. (1993). The Modulation of Ocular Growth in Rabbits with Peripheral Retinal Ablation. *Ophthalmology, 100*(7), 1003-1008.

Wong, T.Y., Foster, P.J., Hee, J., Ng, T.P., Tielsch, J.M., Chew, S.J., Johnson, G.J., & Seah, S.K.L. (2000). Prevalence and Risk Factors for Refractive Errors in Adult Chinese in Singapore. *Investigative Ophthalmology & Visual Science, 41*(9), 2486-2494.

Woung, L., Lue, Y., & Shin, Y. (1998). Accommodation and Pupillary Response in Early-Onset Myopia among Schoolchildren. *Optometry and Vision Science, 75*(8), 611-616.

Zhao, J, Pan, X., Sui, R., Munoz, S.R., Sperduto, R.D., & Ellwein, L.B. (2000). Refractive Error Study in Children: Results From Shunyi District, China. *American Journal of Ophthalmology, 129*(4), 427-435.

Zinn, K.M. (1972). *The Pupil.* Thomas, Springfield, 44p.

Zylbermann, R., Landau, D., & Berson, D. (1993). The influence of study habits on myopia in Jewish teenagers. *Journal of Pediatric Ophthalmology & Strabismus, 30*(5), 319-322.