Mathur, Ankit and Atchison, David (2009) *Effect of orthokeratology on peripheral aberrations of the eye*. Optometry and Vision Science, 86(5). pp. 476-484.

Manuscript Title: Effect of Orthokeratology on peripheral aberrations of the eye

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Number of Figures: 12

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Date: 13/10/08

Funding Details: The study was supported by Australian Research Council Discovery grant DP0558209.

Effect of Orthokeratology on Peripheral Aberrations of the Eye

Abstract

Purpose: To investigate the effect of orthokeratology on peripheral aberrations in 2 myopic volunteers.

Methods: The subjects wore reverse geometry orthokeratology lenses overnight and were monitored for 2 weeks of wear. They underwent corneal topography, peripheral refraction (out to ±34° along the horizontal visual field) and peripheral aberration measurements across the 42° x 32° central visual field using a modified Hartmann-Shack aberrometer.

Results: Spherical equivalent refraction was corrected for the central 25° of the visual fields beyond which it gradually returned to its pre-orthokeratology values. There were increases in axial coma, spherical aberration, higher order root mean square (RMS) and total root-mean-squared aberration (excluding defocus). The rates of change of vertical and horizontal coma across the field changed in sign. Total RMS showed a quadratic rate of change across the visual field which was greater subsequent to orthokeratology.

Conclusion: While orthokeratology can correct peripheral relative hypermetropia it induces dramatic increases in higher-order aberrations across the field.

Keywords: aberrations, coma, corneal refractive therapy, corneal topography, myopia, orthokeratology, peripheral aberrations, peripheral ocular aberrations, peripheral refraction.

Introduction

Orthokeratology is a reversible technique for correcting refractive error by altering the shape of cornea with contact lenses.[1] Currently reverse geometry design rigid gas permeable contact lenses are used which make correction of refractive error more predictable and efficient than do traditional rigid gas permeable lenses.[2, 3] Unlike traditional rigid gas permeable lenses, they have an additional back peripheral curve which is steeper than the back optic zone.[1] Their high oxygen permeability renders them safe for overnight wear.[1] The refractive error is corrected by overnight moulding of the cornea under the physical pressure of an optic zone flatter than the corneal curvature. Changes in corneal shape occur rapidly[4] and usually stabilize within a week.[3, 5] The regression of the changes after cessation of wear is just as rapid.[1]

Corneal shape is often described as a prolate ellipse (flattening of curve away from its vertex). Orthokeratology increases the vertex radius of curvature and makes the ellipse steepen away from its vertex (oblate ellipse).[1, 4] These changes in corneal shape correct low to moderate myopia but result in dramatic increases in the axial higher order aberrations, particularly spherical aberration.[6-8] Joslin et al.[7] found axial higher order aberrations increased 2.5 times for a 6mm pupil after 1 month treatment, with spherical aberration and horizontal coma increasing by 5 times and 7 times, respectively. Berntsen et al.[6] found 5 times increase in spherical aberration and 2 times increase in higher order root-mean-square aberrations for 5mm pupils after 1 month treatment. Losses in low contrast acuity[6] and contrast sensitivity[8, 9] were attributed to the high levels of spherical aberration produced by orthokeratology.

Aberration changes induced by orthokeratology are not limited to axial vision. Charman et al.[10] reported effects of orthokeratology on peripheral refraction out to ±34° along the horizontal visual field for 4 subjects, finding that myopia was corrected within ±10° of central visual field, but produced only minor changes at visual field angles larger than 30°. The treatment was effective in eliminating the relative peripheral hypermetropia of the subjects. This is of interest because relative peripheral hypermetropia is suspected of playing a role in development of myopia.[11, 12]

Refractive surgical interventions such as myopic laser in situ keratomileusis (LASIK) have considerable effects on central[13, 14] and peripheral aberrations.[15, 16]Atchison[15] compared aberrations for 2 patients who underwent myopic LASIK with 5 untreated subjects. The spherical aberration of the LASIK patients was much higher than the untreated subjects along the horizontal visual field out to 40° from fixation. The horizontal coma for the untreated subjects changed almost linearly across this field, and the LASIK patients showed approximately linear changes of the opposite sign between ±25° of the field.

As the changes in corneal shape due to orthokeratology are similar to those produced by myopic LASIK, that is flattening of the central cornea and relative steepening in the mid-periphery of the cornea, it is reasonable to anticipate changes in peripheral higher order aberrations similar to those produced by refractive surgeries. However, this cannot be assumed and in this study we investigated the effect of orthokeratology on peripheral refraction and higher order aberrations across the central 42° x 32° visual field.

Methods

This research study complied with tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology Human Research Ethics Committee. Informed consent was received from subjects after verbal and written explanations of the examination procedures.

Two healthy myopic subjects participated in the study. Subject 1 was a 53 year-old male with right eye refraction -2.00 DS/-0.12 DC x 89 and subject 2 was a 28 year-old female with right eye refraction -3.50 DS/-0.25 DC x 179. Only the right eyes were tested. A thorough lid and corneal assessment was done to ensure their suitability for overnight orthokeratology. Baseline corneal topography and dedicated orthokeratology software were used to estimate first trial lens parameters. Fitting assessment of the custom designed reverse geometry RGP contact lenses (Capricornia, Brisbane, Australia) was done from interpretation of dynamic fluorescein patterns.[1] Contact lens care procedures and insertion and removal techniques were explained to the subjects. They inserted the lenses just before bedtime and wore them for at least six hours each night. Subject 1 wore a lens in the right eye for the 2 weeks of the experiment only. He did not wear the lens for the 6th night due to presence of a foreign body between cornea and lens resulting in some corneal surface abrasions. Subject 2 wore lenses in both eyes and continued using them after the experiment.

Subjects were assessed prior to lens wear (baseline), and at 1 week and 2 weeks after commencing lens wear for corneal topography (Medmont E300 corneal topographer, Medmont Inc., Melbourne, Australia), peripheral refraction and peripheral aberration. In addition, subject 1 underwent corneal topography measurements after 1 night's lens wear and on-axis aberration measurements at days 1, 3 and 5 and at 1 week after cessation of lens wear. Since induced changes in corneal shape regress rapidly[1], at each visit the measurements were commenced no later than 2 hours after lens removal. All procedures were done without pupil dilation and with the left eye occluded.

Corneal topography

Corneal height data was used to estimate vertex radius of curvature R and corneal asphericity Q for the central 6mm of cornea, with pupil centre determined by the topographer as reference, using least squares fitting as described by Atchison et al.[17] using the following formula

$$X^2 + Y^2 + (1+Q)Z^2 - 2ZR = 0,$$

where the Z axis coincides with the line of sight. Four corneal topography images were captured at each visit and the means of vertex radii of curvature and corneal asphericities obtained from these images were used. These fits do not capture all the features of the corneal topography (e.g. radial symmetry is assumed), but they provide an indication of the changes taking place in surface shape with orthokeratology.

Peripheral refraction

Peripheral refraction was measured using an open-field Shin-Nippon SRW-5000 autorefractor (Tokyo, Japan). It is an open field instrument and allows subjects to fixate at any target behind the refractor through a beam splitter. It has been used previously for measuring peripheral refraction[10, 16, 18-20] and showed good correlation with results of Hartmann-Shack aberrometer.[21] The procedure was the same as described previously.[10, 16, 18, 19] A set of targets was mounted on a wall 3.3m from the subject's eye behind the autorefractor at 0° to ±30° in 5° intervals and at ±34° from fixation along the horizontal visual field. Five measurements were taken when the subject rotated his/her eyes to fixate each target. This was done twice and results averaged. Sphero-cylindrical refractions were converted to spherical equivalent (M), with/against the rule astigmatism (J_{180}) and oblique astigmatism (J_{45}).[10]

Peripheral aberrations

Aberrations were measured with a modified COAS-HD Hartmann-Shack aberrometer (Wavefront Sciences Inc. Albuquerque, USA) across 38 targets arranged in 6 rows x 7 columns matrix, projected on a back projection screen placed at 1.2m away from the eye. The targets covered about 42° x 32° of central visual field. Subjects fixated sequentially with their right eye at each point during the measurement through a beam splitter with their heads on the aberrometer's chin rest. The centre of the target matrix was aligned with the internal fixation target of the aberrometer. Prior to each measurement, the aberrometer was aligned such that the pupil was centered with respect to the aberrometer's measurement axis and the cornea was conjugate with the lenslet array. The alignment was done with the help of the aberrometer's alignment camera. Two measurements were taken for each target point. A detailed description of procedures has been given previously.[22]

Subject 1 also underwent peripheral aberration measurements at ±40° along the horizontal visual field during baseline measurements and at 2 weeks.

Pupils become elliptical when aberrations are measured away from the fixation axis. Assuming that pupils shorten according to the cosine of an off-axis angle, along the meridian of an off-axis location, Zernike polynomials for the elliptical pupils were estimated using a Matlab based algorithm which basically stretches the elliptical pupil along its minor axis to form a circular pupil.[23] Zernike coefficients were determined up to 6th order for 5mm pupils at 555nm using the OSA/ANSI system.[24] The contour plots for each Zernike coefficient were generated using triangle based cubic interpolation.

Raytracing

Out-of-eye raytracing was performed for model eyes using the raytracing program Zemax. Model eyes were adaptations of the Escudero-Sanz and Navarro[25] eye. The anterior corneal parameters of the two subjects derived from the corneal topography fits were used in the models and the ocular length adjusted in accordance with these and the refractions of the eyes. Raytracing was performed for a variety of object angles. For the raytracing, the stop was taken as the exit pupil of the eye (the usual entrance pupil for into the eye tracing) and was set to 5 mm, and rays were evenly spaced in relative values across this pupil. As mentioned before, the anterior corneal parameters do not give a full description of the corneal shape, and in the raytracing we assumed that the fits apply outside the 6mm zone over which they were made. Peripheral refractions along the horizontal meridian were determined from

2nd, 4th and 6th order Zernike aberration coefficients using the equations developed by Atchison and coauthors. [23]

Results

Following 2 weeks of orthokeratology, the cornea flattened over the central 4 mm and 5 mm for subject 1 and subject 2, respectively, similar to previous reports e.g. Charman et al. [10] Figure 1 shows the influence of orthokeratology on corneal vertex radius of curvature and asphericity (*Q*). From subject 1's results, it is evident that most of the change occurred following only 1 night of lens wear. The mean increases in corneal vertex radius and asphericity for subject 1 at 2 weeks were +0.31 mm and +0.95, respectively, and those for subject 2 were +0.57 mm and +1.30, respectively.

Figures 2 and 3 show refraction along the horizontal meridian at baseline (a), at 1 week (b), at 2 weeks (c), and the differences between 2 weeks and baseline (d). The spherical equivalent (*M*) was corrected for approximately the central ±10° of the visual field. After 2 weeks, central *M* was close to zero for subject 1, but subject 2 was still under-corrected by 1.0 D. The subjects were less myopic after two weeks than at baseline out to 25° to 34° from fixation. Ninety percent of the reduction in *M* (at fixation) occurring after 2 weeks for subject 2 was complete within 1 week whereas for subject 1 it was only 56%. This was likely because subject 1 did not wear the contact lens during the 6th night. Astigmatism J_{180} increased in the periphery at 2 weeks relative to baseline. The patterns of change in refraction for the subjects were similar to those reported by Charman et al.[10] in four subjects, including the correction of relative peripheral hypermetropia (Figures 2d and 3d).

Figure 4 shows the effect of orthokeratology on various axial higher-order aberration coefficients, higher-order root-mean-squared aberration and total root-mean-squared aberration (excluding defocus) for subject 1. All these terms increased considerably with orthokeratology. Due to the 6th night of no lens wear, the magnitudes of the terms on 7th day were very close to those seen on the 1st day. One week after ceasing lens wear, the terms were similar to their baseline values.

Figures 5 and 6 show higher order wavefront maps for subjects 1 and 2, respectively, across the pupil at each visual field location at baseline and at two weeks. At baseline, the combination of vertical and horizontal coma was the dominating aberration across the visual field. This increased in magnitude steadily from the centre to the periphery. Note its change in orientation with change in visual field meridian. After 2 weeks, positive spherical aberration dominated the visual field, although effects of coma can be seen clearly in the maps. The coma changed its direction at most visual field locations as a result of lens wear.

Figures 7 and 8 show some aberration coefficients and combinations of coefficients across the visual field for subject 1 and subject 2, respectively, at baseline and at 2 weeks of lens wear. While the color scales are different between aberrations and sometimes between the two subjects, the same color scale is used for a given aberration and subject at both baseline and two weeks. Other higher order coefficients are not shown as they were small and did not show any trends across the visual field. Consistent with Figures 2 and 3, defocus coefficient C_2^0 reduced substantially across most of the visual field at 2 weeks (Figures 7Ab and 7Bb, 8Ab and 8Bb). The rates of change of the astigmatism coefficients into the periphery were greater at 2 weeks than at baseline, which was consistent for the patterns for J_{180} shown in Figures 2 and 3 (Figures 7Aa and 7Ba, 7Ac and 7Bc for subject 1; Figures 8Aa and 8Ba, 8Ac and 8Bc for subject 2).

Trefoil coefficient C_3^{-3} (Figures 7Ad and 7Bd, 8Ad and 8Bd) did not show any trend across the visual field. The most noticeable changes at two weeks occurred for the vertical coma coefficient C_3^{-1} (Figures 7Ae and 7Be, 8Ae and 8Be) and the horizontal coma coefficient C_3^1 (Figures 7Af and 7Bf, 8Af and 8Bf). At baseline, the coma coefficients changed linearly across the visual field with C_3^{-1} increasing from the superior to the inferior visual field and C_3^{1} increasing from nasal to the temporal visual field. At two weeks, the direction of change was the opposite. Spherical aberration coefficient C_4^{0} did not show any particular pattern at baseline (Figures 7Ag, 8Ag), while at 2 weeks it had increased considerably in magnitude across the visual field together with a quadratic change across the field for subject 1 (Figure 7Bg) and higher values in the superior field than the inferior field for subject 2 (Figure 8Ag).

Higher order root mean square (HORMS) increased across the field for subjects at 2 weeks compared with baseline (Figures 7Ah, 7Bh and 8Ah, 8Bh). Total root mean square (Total RMS) showed a quadratic rate of change across the field for both subjects at baseline (Figure 7Ai and 8Ai), and increased in definition, magnitude and rate of change at 2 weeks (Figure 7Bi and 8Bi); the change at 2 weeks reflecting the increases in the peripheral astigmatism.

Figure 9 and 10 show coma coefficients along single meridians, the horizontal meridian for horizontal coma and the vertical meridian for vertical coma. Both coefficients had linear changes across the field (Figures 9a, 10a). Horizontal coma slopes were estimated only for ±21° of horizontal visual field. The coma slopes reverse at 1 week and 2 weeks compared with baseline, as seen in Figures 7Ae and 7Be and in Figures 8Ae and 8Be. For subject 1, between 20º and 40º eccentricity the coma coefficients at 2 weeks revert to values close to baseline (Figure 9b). Theoretical plots derived from theoretical raytracing are included; while quite understandably they are not excellent fits to the experimental values, they show similar trends.

Figures 11 and 12 show spherical aberration coefficients along the horizontal meridian for subject 1 and subject 2, respectively. Spherical aberration increased considerably in the centre of the visual field compared with baseline, and then declined more rapidly into the periphery for subject 1 (also Figures 7Ah, 7Bh). For subject 2, the spherical aberration showed an overall increase across the field (Figures 8Ah, 8Bh). The difference between the 2 subjects in the pattern of spherical aberration across the field was most likely because of the differences in the size of their treatment zones.

Discussion

Orthokeratology is an effective refractive treatment for correction of low to moderate myopia.[1, 5] It causes dramatic changes in corneal shape (e.g. Figure 3). Its effect on the axial aberrations and peripheral refraction has been investigated,[7, 10] but its effects on peripheral aberrations have not been reported previously. We found considerable effects on refraction and higher order aberrations. The refraction effects were similar to those we reported previously: correction of the spherical equivalent within the central ±10° visual field, outside of which it gradually approached the pre-treatment values. The most dramatic higher aberration changes were considerable increases in positive spherical aberration in the central visual field (e.g. Figures 11, 12) and reversals of the signs of coma slope across the visual field (Figures 9, 10).

There has been recent interest in the possibility of using orthokeratology to slow the progression of myopia by converting a relative hypermetropic periphery into relative myopic periphery (Figures 2 and 3). If this occurs, this process may be influenced by the changes in higher aberrations we have noted.

The changes in the higher order aberrations were predicted by simple modeling using the increases in anterior corneal radius of curvature and asphericity (Figures 9-12). While the modeling does not provide excellent fits to the experimental values, it shows similar trends. The modeling would also have predicted the changes in peripheral refraction, but these have not been shown. The changes in the peripheral refraction and higher order aberrations with orthokeratology were similar to those found previously with LASIK surgery;[15, 16] this is explained by the changes in anterior corneal shape. Some further raytracing investigation found that an increased anterior radius of curvature would decrease spherical aberration of the eye, but that this would be overwhelmed by the increasing positive asphericity; on the contrary the increased anterior radius of curvature and increased positive asphericity both contribute to reversing the coma slope.

The aberration changes due to orthokeratology seemed to be limited to the visual field region corresponding to the treatment zone on the cornea, with changes towards original values occurring beyond certain angles. This was found for spherical equivalent refraction, which provided good correction to 10º to 15º from fixation, and then reached baseline values at 25º to 34º from fixation (Figures 2d, 3d). Also horizontal coma and spherical aberration for subject 1 gradually returned to baseline values beyond 20º from fixation (Figures 9b, 11). Finally, subject 2 retained linearity of coma slopes further into the visual field than subject 1 (Figure 9 and 10), and this was probably because subject 2's treatment zone was larger than that of subject 1.

Increasing the treatment zone should increase the visual field size over which the spherical equivalent refraction is corrected. Assuming that a larger treatment zone gives a smaller effective positive asphericity *Q*, theoretical raytracing indicates that both increases in spherical aberration and the rate of change of coma across the visual field would be less marked. We do not know how these might affect the ability of using orthokeratology to slow the progression of myopia. The changes in corneal shape and aberrations after 1 week were closer to the final (2 week) results for subject 2 than for subject 1. This was largely because of subject 1's cessation of lens wear on the 6th night because of corneal abrasion and can be seen in the in the regression of his aberration coefficients between days 5 and 7 (Figure 4).

We measured peripheral aberrations with targets presented at 1.2 m away from the eye. Our younger subject 2 may have accommodated to a certain extent after her myopia was corrected, but some preliminary data indicates that accommodation less than 1 D will have only small effects on peripheral aberrations.

Forces of lids and/or extraocular muscles alter the shape of cornea[26, 27] and the eye.[28] We measured peripheral aberrations while the subjects rotated their eyes to fixate on the targets. Variation in extraocular forces during eye rotation may have altered ocular aberrations in our subjects to some extent. However, findings of Radhakrishnan and Charman[29] and us[30] suggest that these forces have little effect on peripheral refraction. Although the effects of extraocular forces on higher order aberrations are still unknown, their effect on our results should be minimal as we measure peripheral aberrations not more than 22° in any direction.

This study is limited by having only two subjects. We would not expect to find qualitatively different peripheral aberrations for other subjects as a) the basic changes in corneal shape (central flattening followed by peripheral steepening) and peripheral refraction due to orthokeratology are consistent with those for 4 subjects in a previous study[10] and b) the peripheral aberration changes are consistent with those in LASIK[15] in which cornea shape is changed in a similar way. A larger sample size would be required for correlation of changes in aberrations with changes in induced refraction, monitoring changes in aberrations over a longer time period, and to determine the influence of treatment zone size on the aberrations.

Conclusion

Orthokeratology has dramatic effects on refraction and higher-order aberrations across the visual field as well as at fixation. These changes are restricted to the region of the visual field corresponding to the corneal treatment zone.

Acknowledgement

The study was supported by Australian Research Council Discovery grant DP0558209. We thank Luke Arundel for the fitting and monitoring of contact lenses wear, and we thank Anna Tran-Nyugen for her participation.

Figure Captions

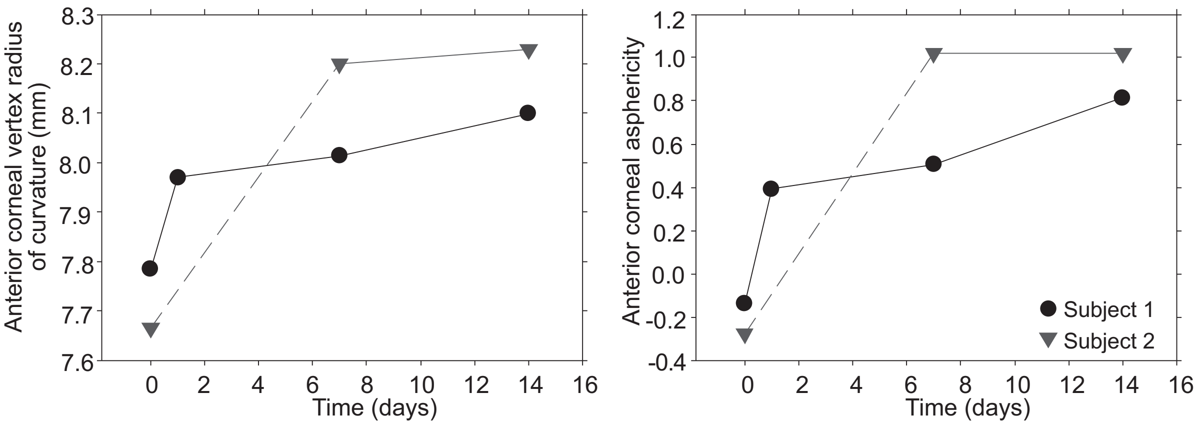

Figure 1. Effect of orthokeratology on (a) vertex radius of curvature and (b) asphericity of anterior cornea. Root-mean-squared errors of the fits for subject 1 ranged between 1.8 μm at baseline and 7.1 μm at 2 weeks. For subject 2 the errors were 2.6 μm and 6.8 μm at baseline and 2 weeks, respectively.

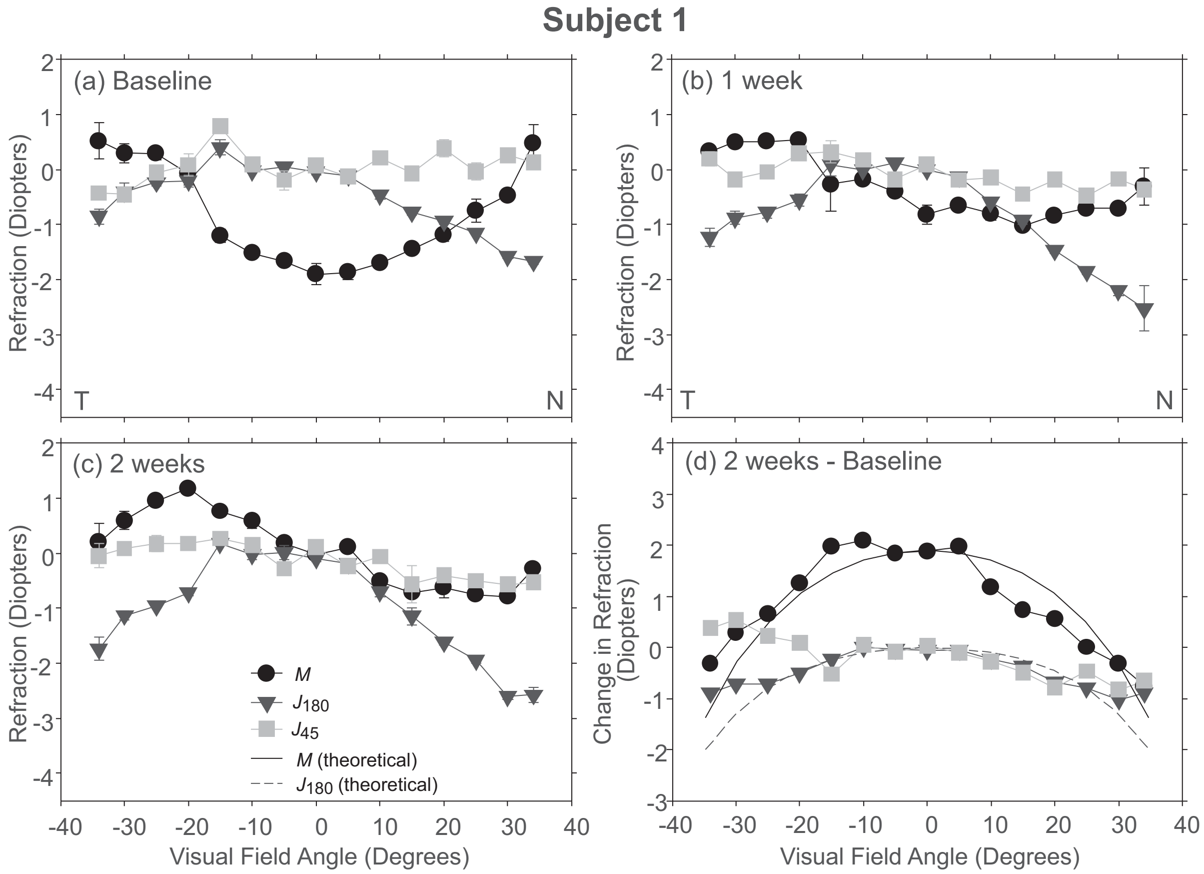

Figure 2. Refraction along the horizontal visual field for subject 1. (a) at baseline, (b) at 1 week; (c) at 2 weeks, and (d) differences between 2 weeks and baseline. The error bars represent the standard deviations of the mean refractive component for each visual field angle. In d), the dashed plots show model theoretical raytracing results.

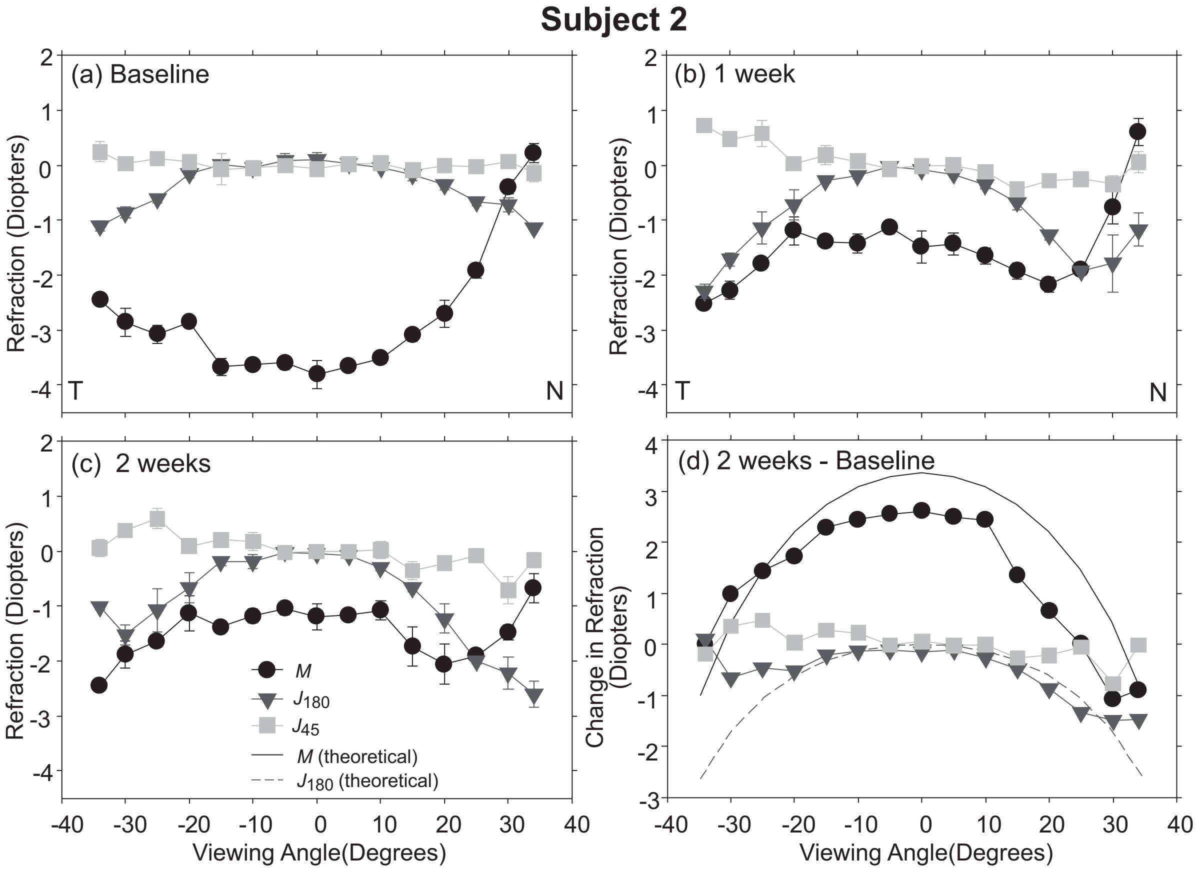

Figure 3. Refraction along the horizontal visual field for subject 2. Other details are as for Figure 2.

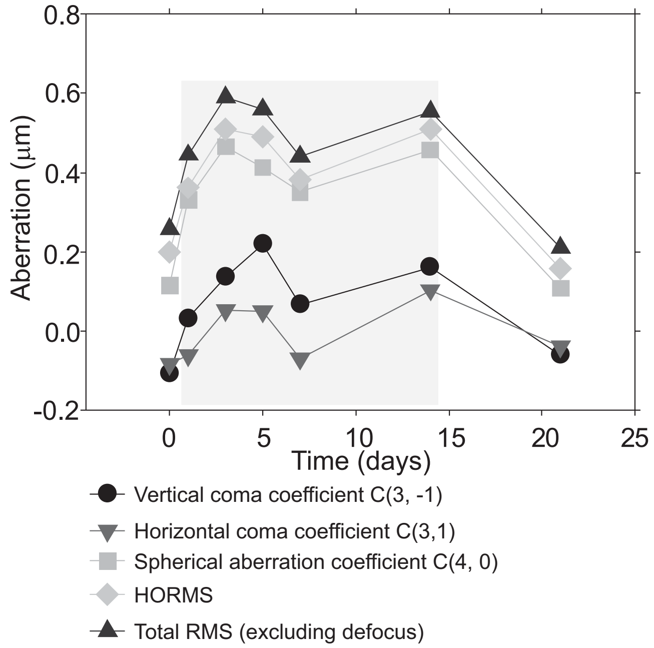

Figure 4. Axial horizontal coma coefficient (C_3^1), vertical coma (C_3^{-1}) coefficient, spherical aberration (C_4^0) coefficient, higher-order root-mean-squared aberration and total root-mean-squared aberration (excluding defocus) as a function of time from baseline for subject 1 (5mm pupil diameter). Lens wear ceased after 14 nights. The grey area represents the lens wear period.

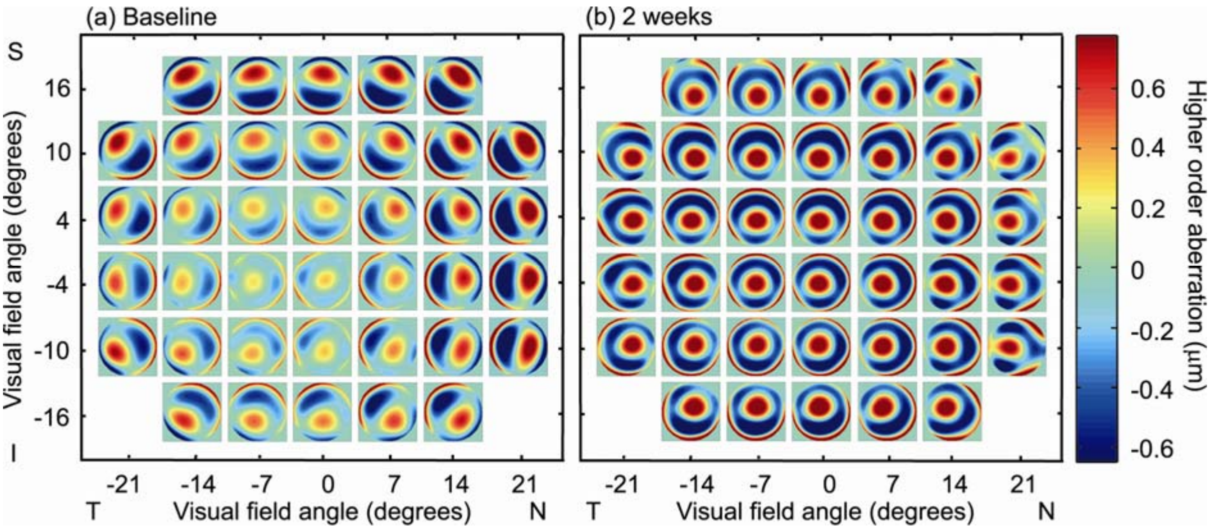

Figure 5. Higher order wavefront maps across the pupil at each visual field location for subject 1 at (a) baseline and (b) 2 weeks (5mm pupil diameter). T, N, S, I indicate temporal, nasal, superior and inferior visual fields.

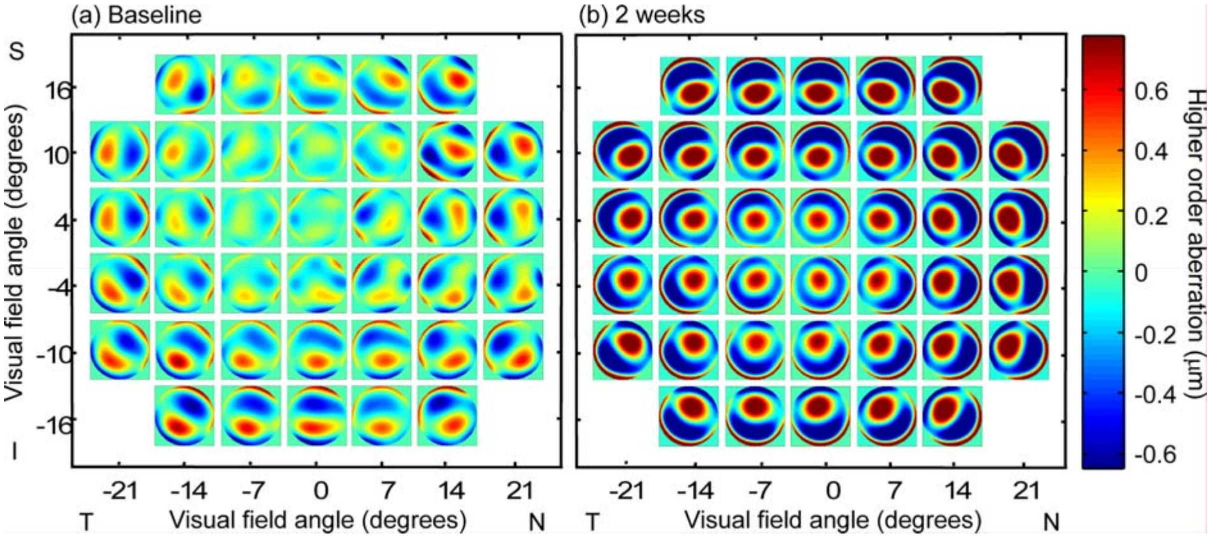

Figure 6. Higher order wavefront maps across the pupil at each visual field location for subject 2 at (a) baseline and (b) 2 weeks (5mm pupil diameter). T, N, S, I indicate temporal, nasal, superior and inferior visual fields.

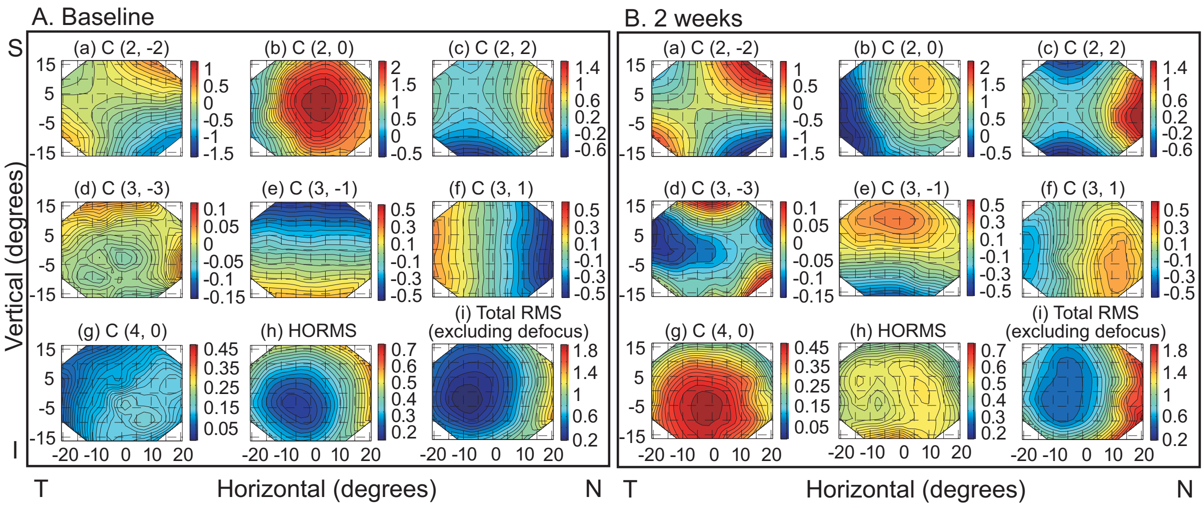

Figure 7. Individual aberration terms across the visual field for subject 1 (A) baseline and (B) at 2 weeks. (a) Oblique astigmatism coefficient C_2^{-2}, (b) defocus coefficient C_2^0, (c) with/against the rule astigmatism coefficient C_2^2, (d) trefoil coefficient C_3^{-3}, (e) vertical coma coefficient C_3^{-1}, (f) horizontal coma coefficient C_3^1, (g) spherical aberration coefficient C_4^0, (h) higher order root mean square (HORMS), (i) total root mean square excluding defocus (Total RMS). The color scales represent the magnitude of aberration term in μm and are common for a given aberration term at baseline and at 2 weeks. Pupil size 5 mm.

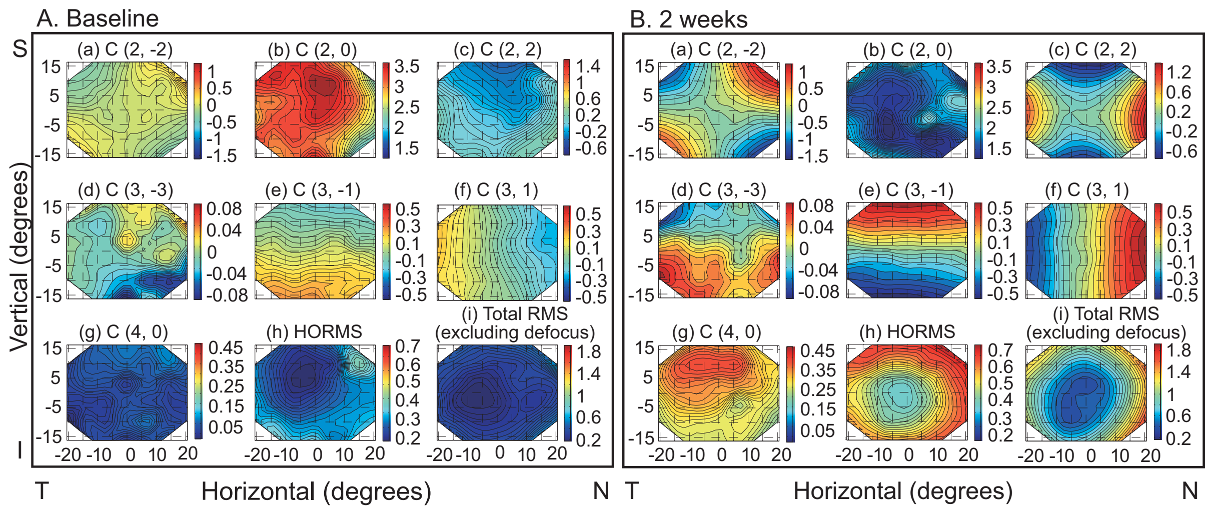

Figure 8. Individual aberration terms across the visual field for subject 2 (A) at baseline and (B) 2 weeks. Other details are as for Figure 7.

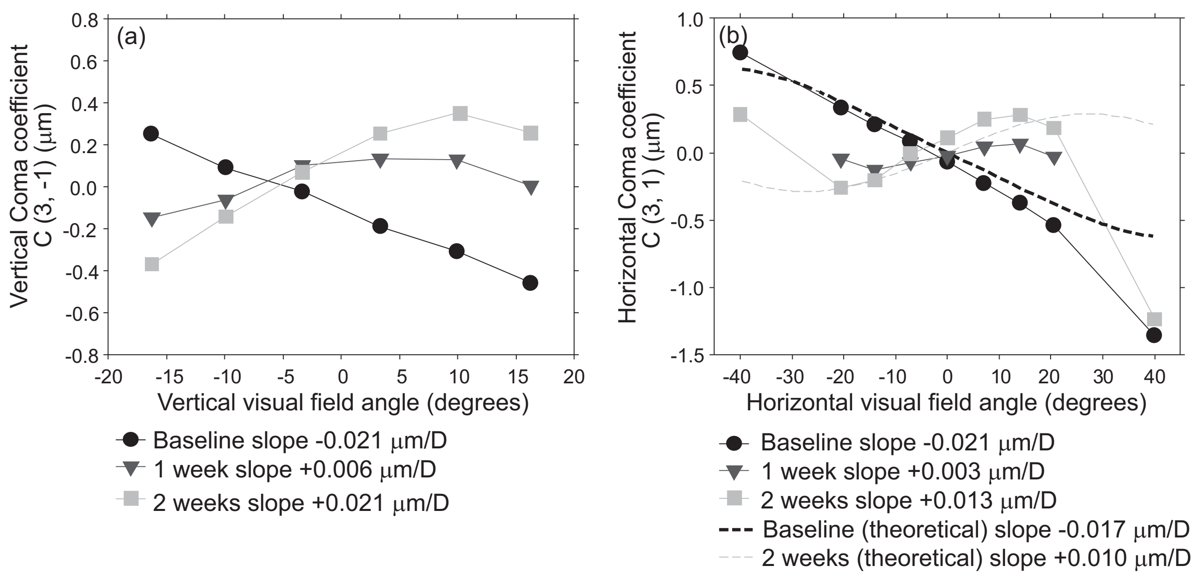

Figure 9. Subject 1's coma coefficients at baseline, 1 week and 2 weeks with 5 mm pupil: a) vertical coma coefficient along vertical visual field; b) horizontal coma coefficient along horizontal visual field. The horizontal coma coefficient at any given horizontal field angle was the mean of horizontal coma coefficients with the same horizontal field angle but with vertical field angles of -4° and +4°. Coma slopes were estimated by least squares linear fit. Horizontal coma slopes were estimated out to ±21°. In b), the dashed plots show model theoretical raytracing results at baseline and 2 weeks.

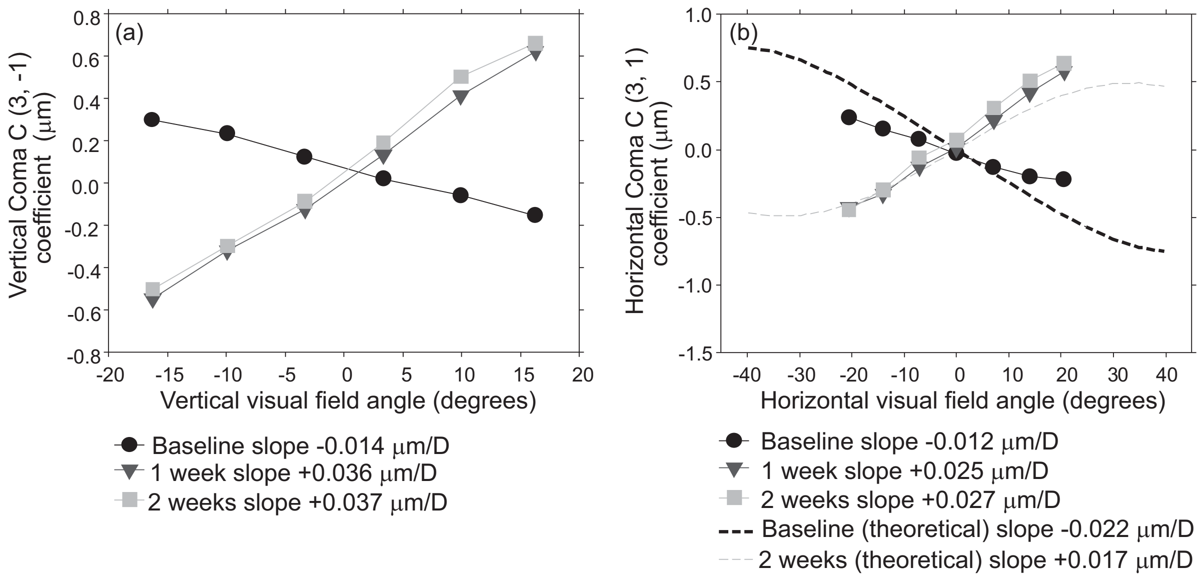

Figure 10. Subject 2's coma coefficients at baseline, 1 week and 2 weeks with 5 mm pupil: a) vertical coma coefficient along vertical visual field; b) horizontal coma coefficient along horizontal visual field. Other details are as for Figure 9.

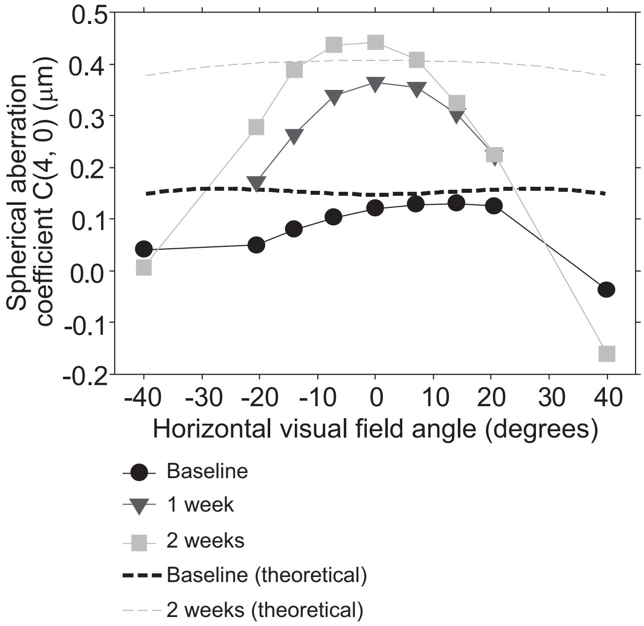

Figure 11. Subject 1's spherical aberration coefficient along the horizontal visual field at baseline, 1 week and 2 weeks with 5 mm pupil. In b), the dashed plots show model theoretical raytracing results at baseline and 2 weeks.

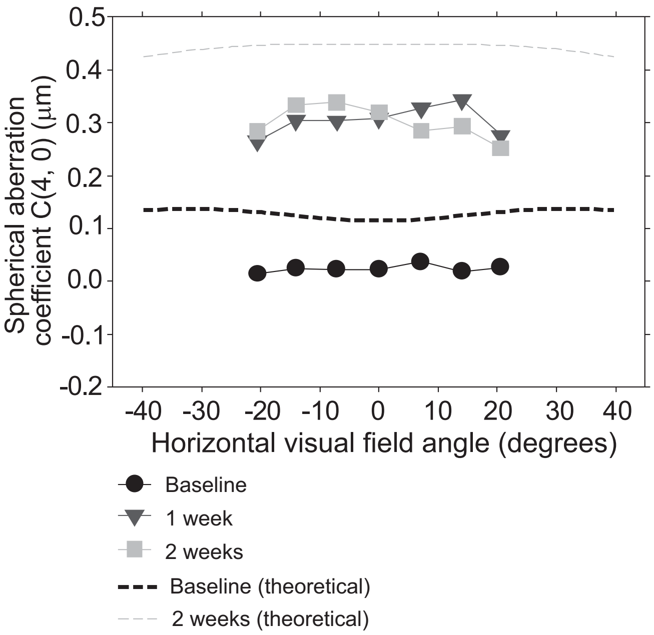

Figure 12. Subject 2's spherical aberration coefficient along the horizontal visual field at baseline, 1 week and 2 weeks with 5 mm pupil. Other details are as for Figure 11.

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