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Corneal refractive changes due to short-term eyelid pressure in downward gaze

Running head: Corneal changes due to eyelid pressure

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ABSTRACT

Purpose: To assess corneal refractive changes after visual tasks of 15 minutes duration and their association with eyelid morphology.

Setting: Contact Lens and Visual Optics Laboratory, School of Optometry, Queensland University of Technology, Brisbane, Queensland, Australia.

Methods: Eighteen young subjects with normal ocular health were recruited. Corneal topography was measured with a videokeratoscope prior to and after four conditions consisting of two downward gaze angles (20° and 40°) and two types of visual tasks (reading and steady fixation). Anterior eye photography in downward gaze was used to determine the eyelid angle, tilt and position with respect to the cornea.

Results: There were significant changes in corneal refractive power after the 15 minute downward gaze tasks. The largest group mean corneal sphero-cylindrical change was +0.33/-0.30x84 after reading in 40° downward gaze (4 mm corneal diameter). The refractive changes after the 40° tasks were significantly larger than the changes after the 20° tasks ($p<0.001$). The changes in refractive RMSE were significant for all conditions, except the 20° steady fixation task, for 4 and 6 mm analysis diameters ($p<0.05$). Significant correlations were found between some aspects of eyelid morphometry and corneal refractive change.

Conclusion: The pressure of the eyelids on the cornea in short-term downward gaze resulted in optically and clinically relevant corneal changes. Correlation between the refractive corneal changes and eyelid parameters suggests that the angle, shape and position of the eyelids influence the nature of the corneal changes. When high accuracy is required, refraction should be qualified in terms of the visual tasks undertaken prior to assessment.

INTRODUCTION

The regularity and stability of the corneal surface is important for clear vision. It is well known that the application or change in pressure on the cornea can alter its surface shape with examples including digital pressure [1, 2], a modified tonometer probe [3] and orthokeratology contact lenses [4]. The eyelids also influence the shape of the corneal surface. Increased or altered pressure from abnormal eyelids can produce topographical corneal changes. Ptosis [5, 6], chalazia [7] and eyelid haemangiomas [8] often cause changes to corneal astigmatism and surgery for these conditions usually partially reverses the induced change [6, 9-11].

However altered pressure from normal eyelids also influences corneal astigmatism, with examples including eyelid retraction [12, 13] and narrowing of the palpebral aperture [12-15]. Typically the presence of the eyelids on the cornea causes a 90/180 astigmatic change [13, 14]. The narrowed palpebral aperture associated with downward gaze induces corneal topography changes that are wave-like horizontal bands of distortion parallel to the eyelid margin [16-18].

Corneal irregularity after reading has been linked with the visual symptom of vertical monocular diplopia [1, 18-25]. Using a number of clinical techniques including keratometry and vision with pinholes and with rigid contact lenses, it has been established that monocular diplopia symptoms can be of corneal origin. With the use of modern videokeratoscopes these corneal changes can be accurately studied.

Previously corneal optical changes have been analysed after continuous reading sessions of one hour [26]. In this study, we examined corneal optical changes after 15-minute downward gaze tasks, which is a common reading duration. Digital photography was used to allow analysis of eyelid morphometry in downward gaze and associations with the corneal optical changes were explored.

METHODS

Subjects

Eighteen subjects, aged between 19 and 29 years with an average age of 23 ± 3 years, were recruited for this study. There were equal numbers of males and females and eight were emmetropes (± 0.25D) and ten were myopes (≤-0.50D). The average refractive error was -1.22 ±0.66 D and ranged from +0.25 to -5.75 D with -0.75 D or less astigmatism. The subjects were required to have a corrected acuity of 0.0 log MAR or better and a slit lamp biomicroscopy examination ensured normal anterior ocular health. Only the left eye was tested for each subject to avoid issues associated with enantiomorphism in eyelid morphometry and corneal topography [27, 28]. To minimise previous topographical alterations from contact lens wear, subjects were excluded if they were rigid gas permeable contact lens wearers and soft contact lenses wearers were asked to refrain from wearing their lenses for at least 32 hours prior to testing [29-34]. Additionally all subjects were asked to avoid any substantial reading on the morning of the experiment to avoid prior corneal changes due to the eyelids [17, 26].

Protocol

The protocol fulfilled the requirements of the university human research ethics committee and all participants gave their informed consent. The Medmont E300 Corneal Topographer (Medmont Pty. Ltd., Victoria, Australia) was used for all topography measurements as it not only has a high level of accuracy and precision for spherical and aspherical test surfaces [35] but also has a high level of repeatability on human subjects [36]. Corneal topography changes were measured prior to and after four different tasks. The post-task measurements were made within two minutes following the near task as it is known that there is a sharp decline in the magnitude of the eyelid-induced corneal distortions immediately following the cessation of a near task [37].

The tasks were 15 minutes in duration and were completed in random order on separate days in the morning. The downward gaze conditions were combinations of two downward gaze angles (20° and 40°) and two visual tasks (reading with gaze shifts and steady fixation without gaze shifts). In both task conditions there were eyelid movements associated with blinking. While the rate of blinking can vary for different task conditions [38-41] and between individuals, it is unlikely to be a significant factor on the corneal changes. A blink lasts approximately 0.26 seconds [42] and on average there are 11.1 blinks per minute [43]. So with less than 5% of the time spent blinking, natural variations in blink rate are unlikely to have a large influence on the corneal changes.

The four conditions were: reading at 20° downward gaze; steady fixation at 20° downward gaze; reading at 40° downward gaze; and steady fixation at 40° downward gaze. A downward eye gaze angle of approximately 25° has been reported for recreational and study-related reading [44]. So the 20° downward gaze conditions of this study most closely represent the vertical eye gaze angle adopted during reading, while the 40° conditions examine a more extreme angle.

The subjects were positioned in a head rest to ensure consistency of eye and head position. It has been shown that head movements contribute only approximately 5% of the total head and eye movement during reading [45], so it is predominantly eye movements that are responsible for horizontal gaze alterations. This set-up also ensured that the subject's eye movements were primarily in the horizontal plane. For the reading tasks, three lines of N12 text were visible on a computer monitor at approximately 40 centimetres distance (Figure 1A). The participants could scroll for further text using the mouse or keyboard for continuous reading. During the steady fixation tasks, a fixation cross was visible in the centre of a cut-out window. Subjects were instructed to blink naturally during all four tasks.

This same subject positioning was used for the anterior eye photography to ensure consistency between the eyelid morphometry and corneal topography changes (Figure 1A and B). The digital images were recorded using a Canon 300D 6.3 megapixel SLR camera with a 100 mm macro lens. Three custom built camera mounts allowed images to be taken in primary gaze and 20° and 40° downward gaze (Figure 1 shows the 40° version). This set-up allowed the subject to be positioned in a head rest with their eye at a known height of 37.5 cm above the table. Horizontal adjustments could be made for inter-subject variations of the inset of the eye. This meant that when the camera was mounted at the chosen angle of either 20° or 40°, the camera was at a known distance of 37 cm from the eye. With the vertical height and angle of the camera fixed and the horizontal distance adjustable for fine tuning of alignment, every image had the same scale ratio (i.e. real eye to digital image scale).

Data analysis

Corneal refractive power maps were exported from the videokeratoscope and a mean of 6 maps were averaged for each condition according to the method of Buehren et al.[26]. The changes in refractive power (post-task minus pre-task) and the average change for each condition were calculated. A best-fit sphero-cylinder was fitted to the pre-condition and post-condition refractive maps for 4 mm and 6 mm diameters using the method of Maloney et al. [46]. These corneal diameters were chosen to approximate average pupil sizes in photopic and mesopic conditions. The sphero-cylindrical analysis was calculated around the videokeratoscope axis. Some topography data within the selected corneal diameters was missing due to shadows from the eyelashes. An average of 0.05% and 0.81% of the data was missing for the 4 mm and 6 mm analysis diameters respectively, which would not have any significant influence on the results. During the sphero-cylinder best-fit process, if a data point was missing the calculation was made using the available points in that meridian. The sphero-cylindrical change between pre-task and post-task was calculated using power matrices [47].

For statistical analysis, the sphero-cylindrical change was separated into vector components M (best sphere), J0 (difference between vertical and horizontal meridians) and J45 (oblique astigmatism). The vector changes were analysed with one-sample t-tests to indicate which changes were significant compared to baseline. The combined change of these vector components for each condition was analysed using a MANOVA with two repeated within-subject factors (downward gaze angle and type of visual task). The change in the vector components was also analysed for a correlation with spherical refractive error.

The calculated best-fit sphero-cylinders from the average refractive power maps were used to examine the influence of eyelid-induced corneal changes in terms of higher order aberrations. The best-fit sphero-cylinder was subtracted from the corresponding average refractive power map to leave the residual error at every data point. The RMSE (a statistical measure of variation) was calculated for each map, using the data points in the residual error topography map, to provide a single value estimate of the corneal higher order aberrations. The difference between pre-task and post-task RMSE was analysed with a 2-sample t-test for each condition. The changes in RMSE for the conditions were compared with a two-way repeated measures ANOVA.

The digital images of the anterior eye in primary, 20° and 40° downward gaze were analysed, using a previously published method and custom written software, to approximate the morphometry of the limbus and upper and lower eyelids [48]. As the camera was manually focussed and positioned at a known distance from the eye, each image had a resolution of 68.7 pixels per mm. For the limbus and pupil outlines, 10 and 8 points respectively were used for the ellipse functions fitted to the outlines. For the upper and lower eyelid margin, a total of 9 points were selected which were then fit with a polynomial function $Y = AX^2 + BX + C$ [49], with respect to the limbus centre. These terms describe different aspects of the eyelid with coefficient A being the curvature, coefficient B the angle or tilt and coefficient C the distance from the geometric corneal centre. The coefficient C values (distance from corneal geometric centre) of the upper and lower eyelids were added together to estimate the size of the palpebral aperture. The corneal changes were matched to the eyelid morphometry in downward gaze (Figure 2). The upper and lower eyelid parameters (A, B, and C and palpebral aperture size) were analysed for correlation with the change in corneal astigmatic vectors J0 and J45 and the spherical component, M.

RESULTS

The group means and standard deviations for the changes in vector components (M, J0 and J45) for each of the task conditions and for the 4 and 6 mm pupil diameters are presented in Table 1. The consistent direction of astigmatic change for all task conditions was against-the-rule (positive J0) and was statistically significant ($p<0.05$) for all conditions and over both analysis diameters. Spherical corneal changes reached statistical significance for the 40° tasks over both 4 and 6 mm diameters ($p<0.001$). The change in the oblique component of astigmatism (J45), although small, was closer to 45° for the 20° downward gaze tasks and closer to 135° for the 40° downward gaze tasks.

A repeated measures MANOVA examining the combined changes in M, J0 and J45 within 4 and 6 mm, found the downward gaze angle (20° versus 40°) to be a significant factor ($p<0.001$), with the 40° downward gaze producing larger corneal changes than 20°. However, there was not a significant difference between the changes due to reading and steady fixation.

There were no correlations between the corneal refractive change and the subject's spherical refractive error for either M ($r=-0.05$, $p=0.67$), J0 ($r=-0.09$, $p=0.46$) or J45 ($r=-0.20$, $p=0.10$). So there does not seem to be an association between the degree of refractive error and the magnitude of the corneal change.

For a clinical interpretation of the corneal changes the mean sphero-cylindrical corneal changes were considered. Over a 4 mm pupil diameter the mean sphero-cylindrical changes were +0.06/-0.07x97 and +0.05/-0.09x109 for the 20° downward gaze reading and 20° downward gaze steady fixation conditions respectively. The group mean changes were substantially larger for the extreme 40° downward gaze reading and 40° downward gaze steady fixation conditions, being +0.33/-0.30x84 and +0.24/-0.25x87 respectively. Similar refractive changes were measured over 6 mm pupil diameter: +0.06/-0.07x97 (20° reading), +0.05/-0.07x95 (20° steady fixation), +0.29/-0.28x93 (40° reading) and +0.25/-0.26x88 (40° steady fixation).

Over both analysis diameters the astigmatic changes for the 40° tasks were approximately 0.25 D, reaching clinical significance. While the group mean sphero-cylindrical changes for the 20° conditions were smaller, individually there were often clinically relevant changes. Over a 4 mm analysis diameter, the maximum sphero-cylindrical changes were +0.29/-0.29x81 (20° reading) and +0.30/-0.24x88 (20° steady fixation). The mean refractive power difference maps highlight the corneal regions that experienced the greatest refractive change for each condition (Figure 3).

The corneal RMSE, which represents the higher order aberrations, increased post-task for all conditions (Table 2). Similar to the refractive vector analysis, the downward gaze angle was a significant factor affecting the magnitude of change in RMSE ($p<0.01$) (40° downward gaze greater than 20° downward gaze), but the type of visual task was not a significant factor. Results from two-tailed paired t-tests between pre-task and post-task RMSE show that the increase in RMSE was significant for all conditions except the 20 degrees steady fixation condition, when analysed for both 4 and 6 mm corneal diameters (Table 2).

The vector J0 which described most of the corneal refractive change was not significantly correlated to any of the eyelid morphometry parameters. Despite the average changes in M and J45 being small, significant correlations were found with some of the upper and lower eyelid morphometry parameters after the 40° tasks. The best sphere (M) changes after the 40° reading task, had a statistically significant correlation with the lower eyelid curvature (coefficient A) in 40° downward gaze ($R^2=0.22$, $p<0.05$). This indicated that straighter lower eyelids were associated with greater changes in best sphere than curved lower eyelids. The best sphere changes after the 40° steady fixation task were correlated with the 40° downward gaze upper eyelid curvatures ($R^2=0.40$, $p<0.01$). However, in this case a curved eyelid produced a greater best sphere change. The change in vector J45 after the 40° reading task was correlated with the lower eyelid tilt in 40° downward gaze ($R^2=0.28$, $p=0.025$). A downward slant of the lower eyelid (down towards the temporal) produced a negative J45 change, while an upward slanting eyelid was more likely to produce a more positive J45 change. For the 40° steady fixation condition, there was some evidence that the palpebral aperture size was associated with the change in best sphere ($R^2=0.29$, $p=0.077$), with a narrow palpebral aperture more likely to be associated with a larger refractive change.

DISCUSSION

We have shown that significant corneal optical changes can occur from short periods (15 minutes) of near work. The average astigmatic change was in the direction of against-the-rule astigmatism (i.e. with-the-rule astigmatism decreased or against-the-rule astigmatism increased). This is the direction of astigmatic change recorded by others that have measured eyelid-induced corneal changes [17, 26]. There are two main differences in the protocol used in this study compared to previous work. The participants were positioned in fixed angles of downward gaze rather than adopting a natural reading posture and the task duration was 15 minutes compared to 60 minutes used in previous research [17, 26]. The refractive changes after the 20° downward gaze conditions of this study are comparable with the previously measured corneal sphero-cylindrical changes after reading [17]. This suggests that in the natural reading posture used in previous research, the eye's vertical downward gaze angle was on average approximately 20°. This is consistent with other investigations concerning visual posture which have recorded an average 26.3° downward eye gaze during reading [44]. The extreme 40° downward conditions produced larger changes than both the 20° task conditions. For extreme downward gaze angles such as 40°, both the upper and lower eyelids are in contact with the central 6 mm of the cornea. So it can be expected that in comparison to the 20° conditions, when only the upper eyelid is in contact with the central cornea, the refractive changes will be larger.

Using the assumption that greater than 1/8 D change would alter the refractive outcome by at least 0.25 D, the group mean refractive change for the 20° tasks was not clinically significant. However for both the 20° reading and steady fixation conditions, 8 of the 18 subjects had spherical corneal changes greater than 1/8 D. For the 40° conditions, the group mean sphero-cylindrical changes were in the order of 0.25 D, which is a clinically significant change. The maximum corneal sphero-cylindrical change observed at this downward gaze angle was +0.87/-0.75x90. The magnitude of these corneal changes is potentially important for clinical research or assessment prior to refractive surgery and it offers a likely source for some of the day-to-day variability in refraction.

It has been recorded that the magnitude of eyelid-induced corneal changes increases with the length of time spent reading [37]. This study considered corneal changes after 15 minutes of downward gaze and it is therefore likely that the changes would be greater for longer reading durations. The cumulative effect of multiple near tasks over the course of a day may also increase the magnitude of corneal changes, as diurnal changes to the cornea have been found in adults whose work involved significant reading [50].

The results of this study are from a sample of eighteen subjects and may not be representative of a larger population. The subjects in the study had a range of refractive errors but this factor was not correlated with the corneal changes we found. However other factors such as ethnicity and eyelid tension may contribute to differences in the corneal change between individuals.

Refractive changes were analysed over both 4 and 6 mm corneal diameters to simulate photopic and mesopic pupil sizes. Similar changes were seen over both analysis diameters. Examination of the difference corneal topography maps revealed that in 40° downward gaze only the upper eyelid-induced changes were within the central 4 mm diameter while both the upper and lower eyelid-induced changes were within the central 6 mm. This accounts for the comparable changes over the 4 mm and 6 mm analysis diameters (Figure 3).

Using wavefront aberration analysis, the “wave-like” corneal distortion can be described primarily as a change in vertical coma, trefoil x 30 and 90/180 astigmatism [17, 26]. In this study the change in RMSE provided an estimate of the change in higher-order aberrations. While there was less than 0.1 D RMSE change for the 20° tasks, the largest group mean change was 0.23 D (4 mm diameter, 40° steady fixation condition). The corneal distortions described by higher-order aberrations are responsible for the visual symptom of monocular diplopia which has been reported after downward gaze reading [1, 18, 20-24, 51].

There is also evidence that the morphometry of the eyelids is associated with the induced corneal changes. In particular, the J45 astigmatic changes after the 40° tasks were correlated with the lower eyelid tilt. The important influence of the lower eyelid on corneal topography has been previously highlighted with an association between lower eyelid tilt and the natural level of corneal astigmatism (i.e. not after reading) in a group of 100 young subjects [52]. So not only does eyelid pressure cause temporary corneal changes but the cumulative effect may be associated with the natural astigmatism of young healthy subjects. The shape of the eyelids (eyelid curvature) showed correlations with the magnitude of best spherical change (vector M). A narrow palpebral aperture (eyelid position) was associated with larger corneal changes, as previously reported [26, 53]. These associations are moderate and account for between 20 to 40% of the variation in corneal refractive change. This suggests that there are other factors involved in eyelid-induced corneal changes that were not measured in this investigation, such as eyelid tension and corneal modulus.

In summary, we have shown that eyelid tilt, curvature and position are influential in the magnitude of eyelid-induced corneal changes. These corneal changes are optically and clinically significant with up to 0.25 D group mean change after only 15 minutes of the downward gaze task. This offers a possible explanation for some of the variation in refraction observed from day-to-day. Considering the magnitude of these changes and previous work on their regression [37], it is recommended that sustained tasks performed in downward gaze should be avoided for at least 30 minutes prior to corneal and refractive assessment requiring high accuracy.

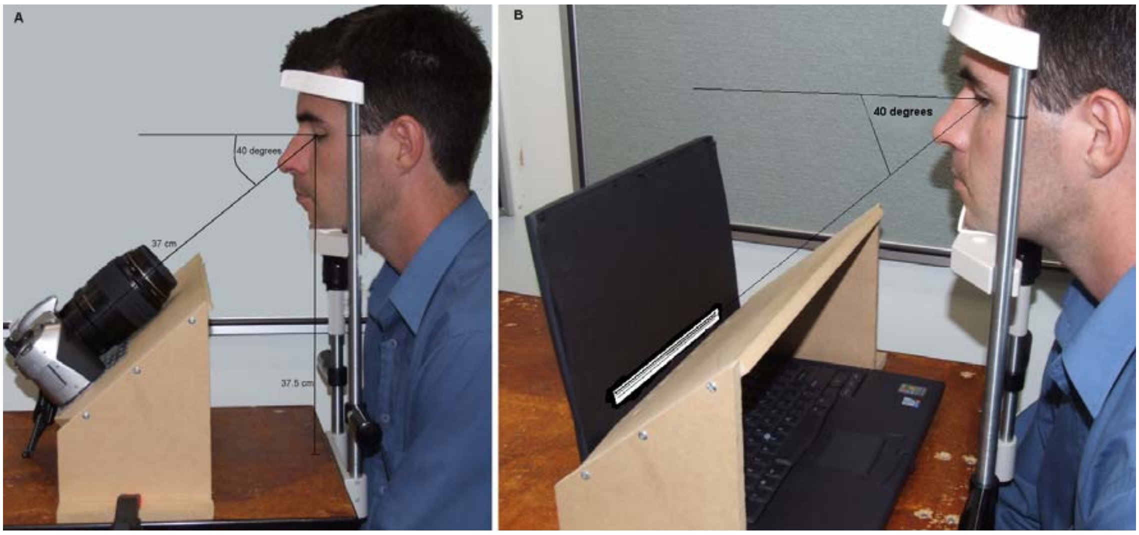

Figure 1: A) Camera and subject fixating at 40° downward gaze; B) Visual task positioned at 40° downward gaze, approximately 40 cm from the subject.

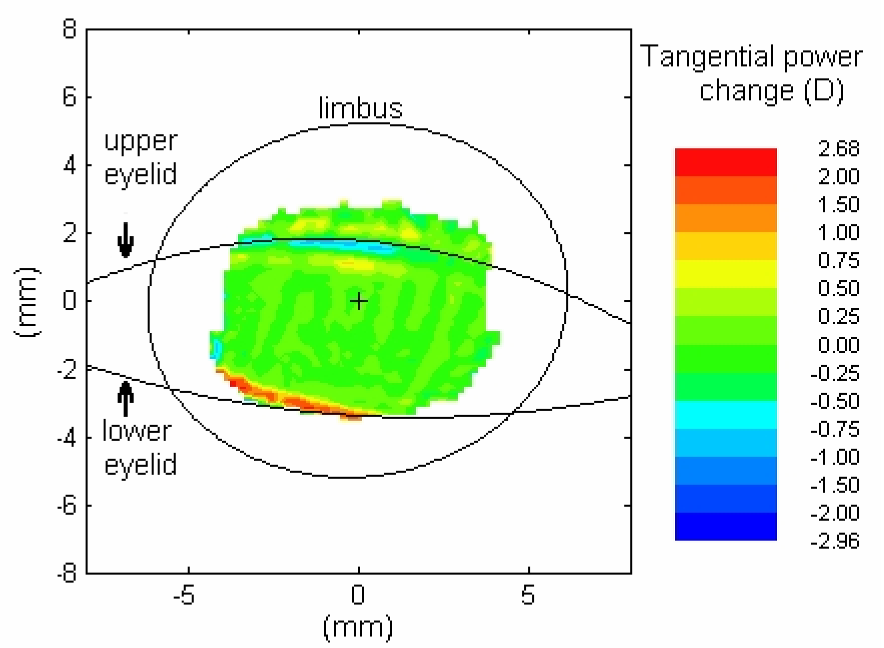

Figure 2: Relationship between the position of the eyelids and the induced corneal topography change. Tangential power difference map (post task minus pre task) after 40° downward gaze steady fixation task overlayed with the eyelid morphometry in 40° downward gaze (subject 5).

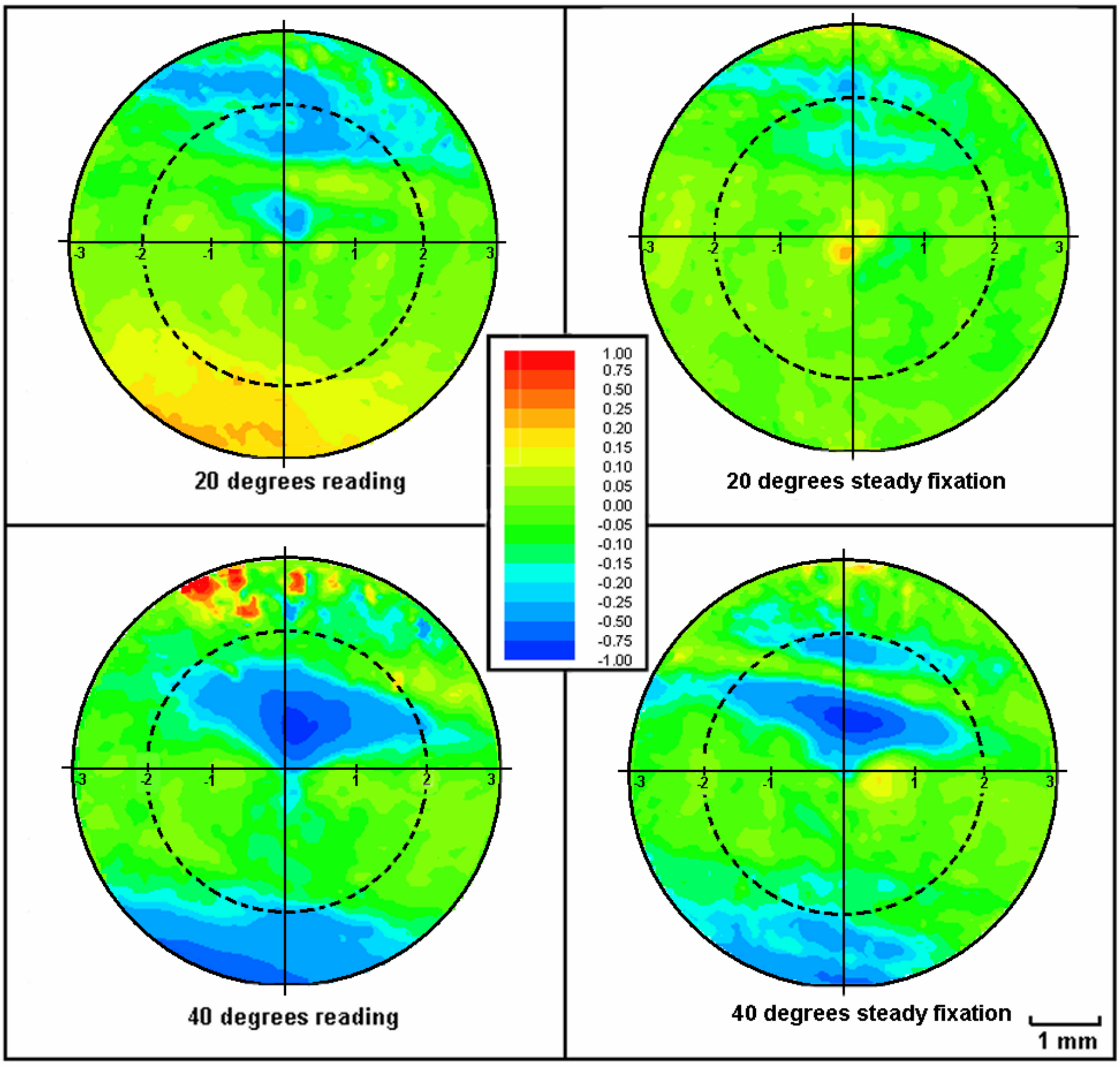

Figure 3: Mean refractive power difference maps for each task condition. Outer circle 6 mm corneal diameter, inner dashed circle 4 mm diameter.

Corneal refractive vector change

Pupil size (mm)	Downward gaze angle (degrees)	Task	M (D)	J0 (D)	J45 (D)
4	20	reading	0.02 ± 0.05	**(0.03 ± 0.07)***	0.01 ± 0.06
		steady fixation	0.01 ± 0.09	**(0.04 ± 0.06)***	**(0.03 ± 0.05)***
	40	reading	**(0.18 ± 0.16)****	**(0.15 ± 0.15)****	-0.03 ± 0.09
		steady fixation	**(0.12 ± 0.10)****	**(0.13 ± 0.08)****	-0.01 ± 0.05
6	20	reading	0.02 ± 0.06	**(0.03 ± 0.06)***	0.01 ± 0.06
		steady fixation	0.02 ± 0.09	**(0.04 ± 0.05)****	0.02 ± 0.04
	40	reading	**(0.16 ± 0.10)****	**(0.14 ± 0.10)****	**(-0.03 ± 0.06)***
		steady fixation	**(0.11 ± 0.09)****	**(0.11 ± 0.07)****	-0.02 ± 0.05

Table 1: Group mean changes and standard deviations of M, J0, and J45 within 4 and 6 mm corneal diameters for each condition. M represents the spherical corneal power, J0 is the 90/180° astigmatic power and J45 is the 45/135° (oblique) astigmatic power. Comparison of vector change with no change (0D) using t-tests (* = significant, $p<0.05$ and ** = highly significant, $p<0.001$).

Corneal refractive RMSE change

Corneal diameter (mm)	**Downward gaze angle (degrees)**	**Task**	**Pre - task RMSE (D)**	**Post - task RMSE (D)**	**Change in RMSE (D)**	**p-value**
4	20	reading	0.32	0.39	0.07 ± 0.11	**(0.016)***
		steady fixation	0.36	0.38	0.02 ± 0.17	0.535
	40	reading	0.33	0.53	0.20 ± 0.23	**(0.022)***
		steady fixation	0.34	0.57	0.23 ± 0.18	**(<0.001)****
6	20	reading	0.50	0.57	0.06 ± 0.08	**(0.002)****
		steady fixation	0.51	0.55	0.05 ± 0.07	0.35
	40	reading	0.52	0.59	0.07 ± 0.05	**(0.003)****
		steady fixation	0.51	0.64	0.13 ± 0.11	**(<0.001)****

Table 2: Group mean refractive RMSE change for the four task conditions within 4 and 6 mm corneal diameters. Comparison of pre-task versus post-task RMSE with t-tests (* = significant, $p<0.05$ and ** = highly significant, $p<0.001$)\

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