Objective changes in astigmatism during accommodation

Francisco Lara-Lacárcel1 | Iván Marín-Franch1,2 | Vicente Fernández-Sánchez1 | Resurrección Riquelme-Nicolás1 | Norberto López-Gil1

1Faculty of Optics and Optometry, University of Murcia, Murcia, Spain
2Computational Optometry, Atarfe, Spain

Correspondence
Norberto López-Gil, Faculty of Optics and Optometry, University of Murcia, Murcia, Spain.
Email: norberto@um.es

Funding information
Fundación Séneca de la Región de Murcia, Grant/Award Number: 15312/PI/10

Abstract

Purpose: Previous studies have shown small but clinically significant changes in the power and axis of astigmatism when the eye accommodates. Monocular objective measurements of the eye during accommodation, when the object approaches the eye without convergence, also reveal small astigmatic changes. Moreover, it is known that the eye exhibits ocular cyclotorsion at different gaze angles. Since accommodation and convergence normally occur simultaneously, we studied the change in the magnitude and axis of astigmatism during accommodation for different convergence angles.

Methods: The left eye of 15 subjects between 20 and 49 years old (mean 28.5 ± 9.7 years) having ≤1.5 D astigmatism was evaluated. Measurements were made using a Shack-Hartmann aberrometer for an accommodation range of +0.50 D to −10 D in 0.50 D steps, and for four monocular convergence demands: 0°, 5°, 10° and 15°. Statistical analysis used power vectors to quantify the change in cylinder power and axis for each accommodation and convergence demand with age.

Results: Jackson cross-cylinder component J45 did not change during accommodation for all vergences tested. However, J0 changed by an average of −0.02 D per dioptre of accommodation (D/Dacc) for convergence demands of 0°, 5° and 10° and −0.03 D/Dacc for the 15° demand. This corresponds to an average cylinder power change of −0.05 D/Dacc for convergences of 0°, 5° and 10° and −0.08 D/Dacc for 15° of convergence. The cylinder axis always changed towards 90° (against-the-rule), and age did not play a significant role.

Conclusions: Except for accommodation demands >4 D, we did not find a clinically significant change in astigmatism for convergence angles up to 15°. The small changes in cylinder power and axis may be due to shifts in the position of the crystalline lens during accommodation.

Keywords
accommodation, accommodative astigmatism, astigmatism, monocular convergence
INTRODUCTION

It is common to find young patients with active accommodation whose objective refraction exhibits small and fluctuating degrees of astigmatism (typically against-the-rule). Hyperactive accommodation associated with stress from near work produces accommodative excess, yet despite the change in astigmatism, the same cylindrical correction is prescribed for both near and far vision. Changes in power and direction of astigmatism during accommodation and eye rotation have been termed accommodative astigmatism.

One might consider that variations in astigmatism due to accommodation are not due to changes in the optics of the eye, but rather to an optical artefact resulting from a shift in the relative positions of the correcting spectacles and the corneal plane with accommodation. Hoffstetter developed formulae to calculate the amount of astigmatic correction required for near vision in presbyopes, which would depend on the astigmatism for distance vision, spectacle vertex distance, distance of the fixation target and the accommodative response. However, his formulae do not explain the changes in power and direction of astigmatism with accommodation and therefore consider that these must be, at least partially, due to natural changes in the optics of the eye. Estimates of overall change in the magnitude of astigmatism with accommodation are typically small, ranging from −0.04 to 0.02 D per D of accommodation (D/Dacc). The direction of change was inconsistent across studies, with some finding an increase in with-the-rule astigmatism and others observing against-the-rule astigmatism.

However, none of the aforementioned studies considered that cyclotorsion, produced during accommodative convergence, might change both the magnitude and axis of astigmatism. Small changes in the astigmatic axis resulting from cyclotorsion were observed in early studies using subjective measures in presbyopic subjects and even in patients with amblyopia or strabismus. Some of these changes show an increase in with-the-rule astigmatism, others found greater against-the-rule astigmatism, and some noted oblique changes. A more recent study examining the change in astigmatism for a convergence demand of 30° found large variability between subjects.

The aim of this study was to quantify objectively the combined effect that accommodation has on the power and direction of astigmatism at varying convergence demands during monocular viewing. Simple optical modeling and simulations based on ray tracing were developed to explain the results.

METHODS

Subjects

This was a retrospective study with data extracted from a multipurpose dataset exploring the effects of ocular aberrations on accommodation. The left eyes of 15 subjects (8 female, 7 male) were selected. The mean age (SD) was 28.5 (9.7) years, and ranged from 20 to 49 years. The average spherical equivalent of the subjects was −1.5 (1.4) D. All observers had less than 1.5 D of astigmatism and distance visual acuity lower than logMAR 0.00 (as measured with a high contrast acuity chart). The only inclusion criterion was between 18 and 50 years of age. Exclusion criteria were no history of amblyopia or strabismus, no accommodative anomaly, no history of ophthalmic surgery and no keratoconus or other corneal abnormalities. In addition, subjects were excluded if they wore gas permeable contact lenses that could affect the anterior corneal surface and modify the aberrations of the eye. This study was approved by the University of Murcia institutional review board and followed the tenets of the Declaration of Helsinki.

Experimental procedure

All objective measurements of accommodation, as well as low- and higher-order aberrations, were taken with a Shack–Hartmann aberrometer (irx3, Imagine Eyes, imagine-eyes.com) without any optical correction. Measurements were taken monocularly and on-axis at four convergence demands: 0° (no convergence), 5°, 10° and 15°. Measurements for the 0°, 5° and 10° convergence demands were evaluated for all 15 subjects. Measurements for the 15° convergence demand were evaluated for only nine subjects.

For each subject, the far point was determined objectively with the aberrometer. Then, aberrations of the eye were measured for up to 21 accommodative stimuli from −0.5 D to 10 D in 0.5 D steps. The Badal system within the irx3 aberrometer was used to change the vergence of the stimulus. There was a 1.5-second pause between the change in accommodative demand and the measurement in order to allow time for the subject to accommodate. This procedure was repeated three times for each subject and accommodation demand.

During the trials, the only instructions given were to try and keep the stimulus as clear as possible. Subjects were reminded that they could blink at any time, and as often as they needed. To obtain measurements at different convergence demands, the chin rest of the aberrometer was rotated with respect to the device (Figure 1).
protractor was added to control the angle of rotation and thus the convergence demand. In order to keep the head steady during the trials, an elastic band was attached to the forehead rest (not shown in Figure 1). All measurements for a given subject were made in a single session. The contralateral eye was occluded with a patch (not shown in Figure 1).

**Data processing and analysis**

Even though three repeated trials were performed for each convergence and accommodation demand, only the one that yielded the greatest amplitude of accommodation (i.e., the one for which the difference in accommodative responses between 10 D and −0.5 D of demand was greatest) was used for analysis. Further, data for the 9.5 and 10.0 D accommodative stimuli were removed from the analysis because the measurements became unreliable and had low reproducibility. Additionally, a series of wavefront data for the 15° convergence demand were unreliable for six subjects (four female, two male). Therefore, for 0°, 5° and 10° convergence demands, data for 15 subjects were available, whereas for the 15° stimulus, data were only available for nine subjects.

The accommodative response for each demand was computed as the root mean square (RMS) of the wavefront measurement. Astigmatism was analysed after converting the Zernike coefficients obtained from the measured wavefront aberrations to power vectors, i.e., the spherical equivalent M and the Jackson cross-cylinder components J₀ and J₄⁵. For each participant and convergence demand, linear regression was performed for each component of the power vectors with respect to the accommodative response. The rates estimated by linear regression were specified as diptres of change in M, J₀, and J₄⁵ for each diptre of accommodative response and are denoted here. The regression lines were used to smooth out noise by predicting the power vector values for accommodative responses from zero to 8 D in 1 D steps before they were used to compute the conventional negative cylinder power and axis.

We looked at the overall change in the power vectors J₀ and J₄⁵ for all subjects and at each convergence demand, and considered whether the rates of change varied with age. We then looked at the corresponding overall changes in the conventional negative cylinder powers and axes for each individual subject.

Data processing and statistical analysis was done with Microsoft Excel (Microsoft.com), the open-source statistical environment R (R Project for Statistical Computing, r-project.org), Igor Pro (v 8.04; WaveMetrics, wavemetrics.com) and Zemax OpticStudio (v15; zemax.com).

**RESULTS**

**Experimental results**

Similar values of mean accommodative miosis were found for all angles of convergence, with mean pupil diameters of 2.63 ± 0.73; 2.49 ± 0.77; 2.64 ± 0.72 and 2.58 ± 0.76 mm at 0°, 5°, 10° and 15°, respectively.

Figure 2 shows the rate of change of J₀ and J₄⁵ with accommodative response. The rate of change of J₀ was small and negligible for J₄⁵. The mean estimated rate of change for J₀ was about −0.02 D/Dacc for 0°, 5° and 10° of convergence and −0.03 D/Dacc for 15° of convergence. These values may be influenced by multiple factors, such as a small misalignment of the visual axis with respect to the

**FIGURE 1** Modifications made to the irx3 wavefront aberrometer. The left panel shows a subject being measured with zero convergence demand. The right panel shows the same person for a convergence demand of 15° after rotation of the chin rest, as can be seen by comparing the rod in the bottom part of each image or the black lines in the upper region (added to show the effect more clearly)
measuring beam, microfluctuations in accommodation, changes in pupil size, etc. To assess the effect of these factors on intrasubject variability, we computed the 95% Gaussian confidence interval for 10 repeated measurements for an individual subject. The half-length of the confidence interval (twice the standard error of the mean) was 0.02 D, showing moderate to negligible effect of the aforementioned factors. However, it must be noted that the values shown in Figure 2 for \( J_0 \) and \( J_{45} \) are average findings. These would be 0.00 D/Dacc except for sampling error if no real change in \( J_0 \) occurred. The error bars in the left panel indicate that the mean negative slopes for \( J_0 \) are significantly different from zero for all four vergence stimuli. In contrast, the average slopes for \( J_{45} \) were not significantly different from zero.

Figure 3 shows the individual rates of change as a function of age for \( J_0 \) and \( J_{45} \). Except for the unusually low \( J_0 \) value for the 49-year-old subject, there does not seem to be any remarkable trend with age. That is, the magnitude of change in astigmatism with accommodation appears independent of age.

Figure 4 shows the changes in the magnitude and axis of astigmatism with accommodation, corresponding to the changes in the power vectors shown in Figure 2. The small rates of change in the magnitude of the power vectors \( J_0 \) and \( J_{45} \) corresponded to increases in the cylinder from \(-0.05\) D/Dacc to \(-0.08\) D/Dacc. The apparently anomalous axis for 15° convergence is due to the large cylinder value of one subject (out of the nine who were able to provide reliable data at this vergence demand) that changed the sign of the \( J_{45} \) value. There was, however, a clear trend in the change of cylinder axis toward 90 degrees (see lower panel of Figure 4). The overall direction of change in astigmatic axis was towards 88°, 89°, 93° and 83° for convergence demands of 0°, 5°, 10° and 15°, respectively.

To show the large inter-subject differences in the change of astigmatic power and axis with accommodation, and to facilitate direct comparisons with the results obtained by Radhakrishnan and Charman, we replicated their Figure 5 with our data for convergence demands of 0°, 5°, 10° and 15°. Each panel in our Figure 5 shows individual changes in astigmatism expressed as the negative correcting cylinder. After accommodation, the final axis position fell between 60° and 120° for two-thirds of the subjects at all convergence demands. There seems to be a small, yet systematic change in the astigmatic axis towards the against-the-rule direction.

**DISCUSSION**

We carried out measurements for four different monocular convergence demands over a wide range of accommodative stimuli in 15 observers. Our results indicate that the power vectors \( J_0 \) and \( J_{45} \) change little with accommodation at different angles of convergence. In particular, changes in \( J_{45} \) were practically negligible and indistinguishable from measurement error. The greatest change in \( J_0 \) was found for a 15° convergence demand (Figure 2). When converting these values into the more conventional sphero-cylindrical notation, it becomes clear that most changes in astigmatism with accommodation are towards an against-the-rule orientation.

While some studies have evaluated the change in astigmatism with accommodation using an autorefractometer, we are only aware of three groups have studied this change using a Shack-Hartmann aberrometer, and none with a convergence demand as high as 15°. Cheng studied wavefront aberrations up to the sixth order for a
LARA-LACÁRCEL et al. found a change in third order aberration (astigmatism) of 0.013 µm/Dacc, which corresponds to 0.021 D/Dacc.

Radhakrishnan and Charman evaluated 31 subjects between 17 and 37 years of age over an accommodation range from 0 to 4 D. They found a change in astigmatism of −0.036 D/Dacc. Therefore, the magnitude of the results of their study were comparable to our findings without monocular convergence, i.e., −0.06 D/Dacc. However, their changes were typically towards with-the-rule, whereas our results were mostly towards against-the-rule. In a subsequent study, Radhakrishnan and Charman evaluated 20 normal subjects (both emmetropic and myopic) to determine if the distance refraction changed during 30° of monocular convergence with respect to the primary gaze position. Although half of the myopic individuals showed refractive changes, the mean shifts were small and there was great variability in the results, although all showed pupillary miosis in oblique gaze. The authors concluded that for some individuals, the pressure of external structures affected the refractive state when oblique vision was maintained over a considerable period. Additionally, they observed no systematic changes in refraction after 20 min

**FIGURE 4** Astigmatic magnitude (upper panel) and axis (lower panel) for different accommodative demands calculated from the linear regression models of the power vectors $J_0$ and $J_{45}$, whose slope is shown in Figure 2. The lines in the upper panel were fitted using simple linear regression. Other details as for Figure 3

**FIGURE 5** Individual mean changes in astigmatism per dioptre of accommodation for 0°, 5°, 10° and 15° convergence demands. The radial length of the vector represents the negative power of the change and the angle the direction of the cylinder axis. To emphasize the largely vertical orientation of the cylinder axes, each change is shown both with its axis and at an axis rotated by 180°. The concentric rings represent 0.05 D change in power.
of reading. In a more recent investigation, Liu and Thibos used a Shack-Hartmann aberrometer to evaluate the change of axial and oblique astigmatism (J₀ and J₄₅) during accommodation (up to 6 D). In agreement with our results, J₀ and J₄₅ showed little change with accommodation, and the change in axis was towards against-the-rule. These authors indicated that the axis of astigmatism was practically independent of accommodation, suggesting that the changes in zonule tension during accommodation were uniform across the lens.

Besides the pressures of external structures proposed by Radhakrishnan and Charman there are other possible explanations for the small changes in the axis and magnitude of astigmatism during accommodation. Variations in astigmatism will occur when fixing a near object through spectacle lenses due to changes in the “effectiveness” of the lens at that viewing distance, and Hofstetter presented formulae to quantify these changes. However, the objective changes measured by aberrometers or refractometers require an alternative explanation based on the change in the optics of the cornea or the crystalline lens. A change in astigmatism during accommodation as a result of changes in corneal topography during accommodation seems unlikely. Alternatively, optical differences could come from changes in crystalline lens shape or position produced by differential zonular tension.

Through a system of phakometry Purkinje imaging for measurement of the tilt and decentration of the lens, Rosales and Marcos offered a hypothetical explanation of the variations in astigmatism with accommodation in the primary gaze position that were found in their experiments. This explanation is based on the progressive increase in the relaxation of the zonule with accommodation, due to the effects of gravity and the vertical inclination of the lens around the horizontal axis. During accommodation, the eye increases its power and the curvature of the lens surfaces alter in terms of radius and asphericity, resulting in a general change in optical aberrations. Modelling of the eye during accommodation is usually based on radially symmetrical changes, so no changes in astigmatism will be apparent. However, during accommodation, zonules lose tension and the lens may move downward due to gravitational forces, generating asymmetry. It is well known that a displacement of two elements, one with positive (cornea) and one with negative (crystalline lens) spherical aberration generates coma, astigmatism and tilt. In particular, a vertical displacement of the lens with rotational symmetry and negative spherical aberration will result in a decrease in J₀ while J₄₅ remains constant, thus generating against-the-rule astigmatism. The value of the generated astigmatism will depend on the square value of the displacement. Figure 6 shows image formation by a commercial ray tracing software (Zemax OpticsStudio) for an accommodating model eye based on the experimental parameters of the cornea and the lens found by Dubbelman and collaborators using a wavelength of 587 nm and a 4-mm entrance pupil.

The astigmatism generated by a 0.35-mm vertical displacement of the lens is −0.10 D and 0.0 D for J₀ and J₄₅, respectively, which corresponds to a mean change in J₀ for 5 D of accommodation with no convergence of −0.02 D per dioptre of accommodation. The astigmatism generated by this displacement is −0.19 D at a 90° axis, which is close to the measured astigmatism (around 0.25 D).

The change in J₀ when convergence varied from 5° to 15° could be explained by tilting of the crystalline lens. Figure 2 shows a small decrease in J₀ from 0° to 5° of convergence. Such a decrease falls with the intersubject standard deviation (0.03 D), but can also be explained by the fact that with zero convergence there is a small misalignment between the corneal axis and the lenticular axis (lines connecting the centres of curvature of their surfaces) of 2°–3° in the nasal direction, which can be eliminated by 5° of convergence. The particularly large change in J₀ found in the 44 year old subject for 15° of convergence (Figure 3) might be explained by a larger crystalline lens tilt when the zonules are relaxed. This change could be responsible for the anomalous mean axis values shown in Figure 4.

Therefore, factors such as tilting and/or translation of the lens during accommodation could produce changes in the power and/or axis of astigmatism. These ad hoc explanations should be treated as hypotheses rather than confirmed results, and should be studied in detail using technology that allows in-vivo direct observation of the lens during accommodation and convergence, such as Optical Coherence Tomography.

The results of this study may have clinical application. In clinical practice, it is common to find young patients with highly active accommodation, in whom there are small increases in against-the-rule astigmatism. However, based on the results presented here, these changes will only have clinical relevance for accommodation demands exceeding 4D.

![Figure 6](image-url) Ray tracing through a model eye with a target vergence of 5 D, a 4-mm entrance pupil and downward vertical displacement of the lens of 0.35 mm
ACKNOWLEDGEMENTS
Funded by Fundación Séneca, Murcia, Spain.

CONFLICT OF INTEREST
The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

AUTHOR CONTRIBUTIONS
Francisco Lara-Lacárcel: Conceptualization (supporting); Data curation (lead); Formal analysis (lead); Investigation (equal); Methodology (equal); Project administration (lead); Supervision (lead); Validation (equal); Visualization (equal); Writing—original draft (lead); Writing-review & editing (lead).

Iván Marín-Franch: Data curation (supporting); Formal analysis (lead); Methodology (equal); Software (equal); Supervision (supporting); Visualization (equal); Writing—review & editing (equal).

Vicente Fernández-Sánchez: Conceptualization (equal); Data curation (lead); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (equal); Supervision (supporting); Validation (supporting); Visualization (supporting); Writing—original draft (supporting); Writing-review & editing (supporting).

Norberto López-Gil: Conceptualization (lead); Data curation (equal); Formal analysis (supporting); Funding acquisition (lead); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (equal); Supervision (equal); Writing—review & editing (supporting).

Resurrección Riquelme-Nicolás: Investigation (supporting); Supervision (supporting); Writing—review & editing (supporting).

LARA-LACÁRCEL et al.

REFERENCES
1. Scheiman M, Wick B. Clinical management of binocular vision. Philadelphia: Lippincott Williams & Wilkins; 2002.
2. Bannon RE. A study of astigmatism at the near point with special reference to astigmatic accommodation. Am J Optom Arch Am Acad Optom. 1946;23:33–75.
3. Hoftstetter HW. The correction of astigmatism for near work. Am J Optom Arch Am Acad Optom. 1945;22:121–134.
4. Tsukamoto M, Nakajima T, Nishino J, Hara Y, Uozato H, Saishin M. Accommodation causes with-the-rule astigmatism in emmetropes. Optom Vis Sci. 2000;77:150–155.
5. Byakuno IE, Okuyama F, Tokoro T, Akizawa Y. Accommodation in astigmatic eyes. Optom Vis Sci. 1994;71:323–331.
6. Ukai K, Ichihashi Y. Changes in ocular astigmatism over the whole range of accommodation. Optom Vis Sci. 1991;68:813–818.
7. Cheng H, Barnett JK, Vilupuru AS, et al. A population study on changes in wave aberrations with accommodation. J Vis. 2004;4:3. https://doi.org/10.1167/4.4.3
8. Park H, Park IK, Shin J-H, Chun YS. Objective verification of physiology changes during accommodation under binocular, monocular, and pinhole conditions. J Korean Med Sci. 2019;34:e32. https://doi.org/10.3346/jkms.2019.34.e32
9. Liu T, Thibos LN. Variation of axial and oblique astigmatism with accommodation across the visual field. J Vis. 2017;17:24. https://doi.org/10.1167/17.3.24
10. Radhakrishnan H, Charman WN. Changes in astigmatism with accommodation. Ophthalmic Physiol Opt. 2007;27:275–280.
11. Mutti DO, Enlow NL, Mitchell GL. Accommodation and induced-with-the-rule astigmatism in emmetropes. Optom Vis Sci. 2001;78:6–7.
12. Enright JT. Ocular translation and cyclotorsion due to changes in fixation distance. Vision Res. 1980;20:595–601.
13. Hughes WL. Change of axis of astigmatism on accommodation. Arch Ophthalmol. 1941;26:742–749.
14. Radhakrishnan H, Charman WN. Refractive changes associated with oblique viewing and reading in myopes and emmetropes. J Vis. 2007;7:5. https://doi.org/10.1167/7.8.5
15. López-Gil N, Fernández-Sánchez V, Thibos LN, Montés-Micó R. Objective amplitude of accommodation computed from optical quality metrics applied to wavefront outcomes. J Optom. 2009;2:223–234.
16. Thibos LN, Hong X, Bradley A, Applegate RA. Accuracy and precision of objective refraction from wavefront aberrations. J Vis. 2004;4:9.
17. Thibos LN, Wheeler W, Horner D. Power vectors: an application of fourier analysis to the description and statistical analysis of refractive error. Optom Vis Sci. 1997;74:367–375.
18. R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2020; Available at: r-project.org/index.html
19. Bayramlar H, Sadigov F, Yildirim A. Effect of accommodation on corneal topography. Cornea. 2013;32:1251–1254.
20. He JC, Gwiazda J, Thorn F, Held R, Huang W. Change in corneal shape and corneal wave-front aberrations with accommodation. J Vis. 2003;3:456–463.
21. Rosales P, Marcos S. Phakometry and lens tilt and decentration using a custom-developed Purkinje imaging apparatus: validation and measurements. J Opt Soc Am A. 2006;23:509–520.
22. López-Gil N, Fernández-Sánchez V. The change of spherical aberration during accommodation and its effect on the accommodation response. J Vis. 2010;10:12. https://doi.org/10.1167/10.13.12
23. López-Gil N, Howland HC, Howland B, Charman N, Applegate R. Generation of third-order spherical and coma aberrations by use of radially symmetrical fourth-order lenses. J Opt Soc Am A. 1998;15:2563–2571.
24. Bonaque-González S, Bernal-Molina P, López-Gil N. Amount of aspheric intraocular lens decentration that maintains the intraocular lens’ optical advantages. J Cataract Refract Surg. 2015;41:1110–1111.
25. Dubbelman M, Weeber HA, Van Der Heijde RGL, Völker-Dieben HJ. Radius and asphericity of the posterior corneal surface determined by corrected Scheimpflug photography. Acta Ophthalmol Scand. 2002;80:379–383.
26. Dubbelman M, Van Der Heijde GL, Weeber HA. Change in shape of the aging human crystalline lens with accommodation. Vision Res. 2005;45:117–132.
27. Chang Y, Wu HM, Lin YF. The axial misalignment between ocular lens and cornea observed by MRI (I)-At fixed accommodative state. Vision Res. 2007;47:71–84.
28. Venables WN, Ripley BD. Modern applied statistics with S. 4th ed. New York, New York: Springer; 2002.

How to cite this article: Lara-Lacárcel F, Marín-Franch L, Fernández-Sánchez V, Riquelme-Nicolás R, López-Gil N. Objective changes in astigmatism during accommodation. Ophthalmic Physiol Opt. 2021;41:1069–1075. https://doi.org/10.1111/opo.12863