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Meridional Anisotropy of Foveal and Peripheral Resolution Acuity in Adults With Emmetropia, Myopia, and Astigmatism

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Purpose. To quantify astigmatism-related meridional anisotropy in visual resolution at central, nasal, and inferior visual fields.

Methods. Three groups of young adults (range, 18–30 years) with corrected-to-normal visual acuity (logMAR 0) were recruited: (1) myopic astigmats (MA): spherical-equivalent error (SE) < -0.75D, with-the-rule astigmatism ≥ 2.00D, $n = 19$; (2) simple myopes (SM): SE < -0.75D, astigmatism ≤ 0.50D, $n = 20$; and (3) emmetropes (EM): SE $\pm$ 0.50D, astigmatism ≤ 0.50D, $n = 14$. Resolution acuity was measured for the horizontal and vertical gratings at central and peripheral visual fields (eccentricity: 15°) using a 3-down 1-up staircase paradigm. On- and off-axis refractive errors were corrected by ophthalmic lenses.

Results. The MA group exhibited meridional anisotropy preferring vertical gratings. At the central field, the MA group had better resolution acuity for vertical than horizontal gratings, and their resolution acuity for horizontal gratings was significantly worse than the SM and EM groups. At peripheral visual fields, both the SM and EM groups showed better resolution acuity for the *radial* (i.e., nasal field: horizontal gratings; inferior field: vertical gratings) than *tangential* orientation. However, the MA group tended to have better resolution acuity for the *tangential* orientation (i.e., vertical gratings), and their resolution acuity for horizontal gratings was significantly lower than the SM and EM groups at the nasal field. No significant differences were found in the inferior field among the three groups.

Conclusions. This study provided evidence of astigmatism-related meridional anisotropy at the fovea and nasal visual fields, underscoring the significant impact of astigmatism on orientation-dependent visual functions.

Keywords: astigmatism, meridional anisotropy, peripheral vision

Astigmatism is a common refractive error that affects over 20% (cylindrical power > 0.75D) of Native American[1] and Asian Chinese populations.[2–6] When a beam of light passes through an astigmatic surface, it forms two line foci, perpendicular to each other, at separate image planes along the optical axis. Unless the circle of least confusion (dioptric midway of the two image foci) falls directly on the retinal plane producing symmetric blur, astigmatism continuously degrades the retinal image quality for one orientation more than the other. If early astigmatism is not corrected by ophthalmic aids, this orientation-dependent blur may interrupt vision development, leading to a permanent meridional visual deficit in resolution acuity[7,8] and contrast sensitivity.[9,10] However, previous studies have considered only how astigmatism affects visual performance at the fovea; the effect of astigmatism on peripheral vision remains unknown.

Peripheral vision is usually more sensitive to visual stimuli oriented radially from the fovea.[11,12] If the fovea is imagined as the hub of a wheel, the radial orientation refers to the orientation of the wheel spokes. For instance, when visual stimuli are oriented horizontally, they are more resolvable than those oriented vertically in the temporal and nasal visual fields. In contrast, those oriented vertically are more resolvable in the superior and inferior fields. Such a bias to radial orientation has been consistently reported in various visual tasks, including resolution acuity,[13] vernier acuity,[14] contrast sensitivity,[15] and horizontal-vertical illusion.[16]

The orientational bias of peripheral vision is, in fact, accordant with the anisotropic visual input at the peripheral visual fields. In natural scenes, the radial orientation from the peripheral retinal images exhibits the highest power spectral density compared with other orientations.[17,18] In contrast, the tangential orientation (i.e., perpendicular to the radial orientation), especially for high spatial frequency components, is smeared by the off-axis rotational-asymmetric aberrations of the human eye (e.g., off-axis astigmatism, coma, and trefoil).[15] Of note, uncorrected refractive astigmatism, which creates an orientation-dependent blur across the entire visual field, can disturb radially biased visual processing of certain visual field regions. However,

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how the orientational bias of peripheral vision is affected has yet to be determined.

This study aimed to investigate the meridional anisotropy of astigmatic participants at the central, nasal, and inferior visual fields. Myopic adults with with-the-rule (WTR) astigmatism (negative cylindrical axis at 180° ± 20°), which is the most common astigmatism subtype (>80%) in the young myopic population,[3,19] were recruited. When viewing distant objects, the presence of myopic WTR astigmatism smears the horizontal component of retinal images and degrades retinal images oriented horizontally (e.g., horizontal gratings) more than those in other orientations (e.g., vertical gratings). Because the presence of WTR astigmatism not only creates an orientation-dependent blur at the fovea, but also disrupts the anisotropic visual input at the nasal and temporal fields, it can be hypothesized that WTR astigmatism affects radially biased visual processing at the horizontal visual fields but spares that of the vertical visual fields.

To isolate the additional effect of astigmatism on meridional anisotropy, a myopic astigmatic group was compared with two age-matched nonastigmatic refractive groups of simple myopes and emmetropes. It was found that myopic WTR astigmats exhibited meridional anisotropy that preferred vertical gratings.

Methods

Young adults aged 18 to 30 years, with corrected-to-normal visual acuity (logMAR 0 or better) in both eyes were recruited from three refractive groups: compound myopic astigmatism (MA, $n = 19$), simple myopia (SM, $n = 20$), and emmetropia (EM, $n = 14$). Myopia was defined as a spherical-equivalent error of <-0.75D, and emmetropia as a spherical-equivalent error within ±0.50D. All participants in the MA group had WTR astigmatism of ≥2.00D (minus cylinder correcting axis of 180° ± 20°), whereas those in the SM and EM groups had no or very mild astigmatism of ≤0.50D. None of the participants had anisometropia greater than 2.00D, manifest ocular disease, strabismus, or eye surgery.

All participants underwent subjective refraction, using an endpoint of maximum plus/minimum minus power providing maximum distance visual acuity. Peripheral refraction (in the nasal and inferior visual fields) was determined using an open-field autorefractor (Shin-Nippon NVision-K 5001, Rexxam Co., Ltd., Kagawa, Japan), with participants fixating on a small LED light placed 3 m away at 15° eccentricity. Five consecutive readings were taken. The *representative value* generated automatically by the autorefractor was used to correct peripheral vision for peripheral acuity measurements.

A resolution acuity test was developed using Psykinematix (KyberVision Japan LLC, Sendai, Japan). The visual stimuli were displayed on a 22-inch gamma-corrected CRT flat screen monitor at 1920 × 1440 resolution and 90 Hz refresh rate. On each trial, a high-contrast sinusoidal grating patch, oriented either horizontally or vertically, was presented briefly for 200 ms (diameter: 1.2°; contrast: 99%; background luminance: 54 cd/m^2). The stimulus edge was blurred with a half Gaussian ramp function ($\sigma = 0.1°$) to eliminate any abrupt contrast cues. The background was enclosed by a black shield cover, leaving a 2° diameter window at the center (Fig. 1). The visual task was to identify the grating orientation: that is, horizontal (H) or vertical (V). The onset and offset of stimuli were temporally modulated by a Gaussian window (σ: 33 ms).

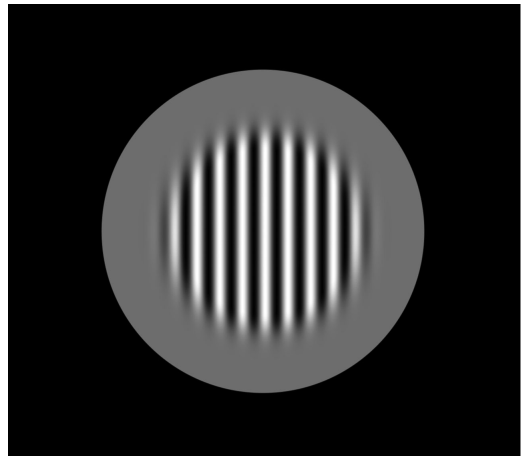

Figure 1. Visual stimulus. Participants were asked to identify the orientation of the grating. The background was enclosed by a black shield cover with a 2° diameter window at the center to indicate the location of the visual stimulus.

The viewing distances were 6 and 3 m when testing the central and peripheral visual fields, respectively. All measurements were performed with the participants wearing best optical correction; central and peripheral refractive errors were fully corrected using full aperture trial lenses placed 12 mm in front of the cornea, with the untested eye being occluded by a standard black opaque eye patch. Even though high-contrast resolution acuity at peripheral visual fields is known to be largely unaffected by optical blur,[20] peripheral refractive errors were corrected to ensure that the outcomes of psychophysical measurements arose from neural rather than optical factors.

The psychophysical paradigm was implemented to measure resolution acuity for both horizontal and vertical gratings. The grating bar width (GW_1, GW_2) and orientation (V, H) of grating stimuli were controlled using four randomly interleaved staircases: GW_{1H}, GW_{1V}, GW_{2V}, and GW_{1V}. The bar width, that is, half the reciprocal of spatial frequency in arcmin, was decreased by 1-unit step after three consecutive correct responses and was increased by 1-unit step after one incorrect response (3-down 1-up; converged towards 79% correct). The step sizes were 0.05 and 0.125 minute of arc for the measurements undertaken in the fovea and periphery, respectively. Resolution acuity was taken as the average of the last eight reversal points (3rd to 12th) of each staircase. The resolution acuity measurements reported in the following figures were based on an average of four measurements. Note that all resolution acuities, in arcmin, were multiplied by the spectacle magnification to control for potential optical magnification differences among refractive groups.

$$Spectacle\ magnification = \frac{1}{1 - d\left[Fs + Fc\ sin^2\left(\theta - \alpha\right)\right]}$$

where Fs, Fc, θ, and α represent the spherical refractive error, cylindrical refractive error, azimuth angle (180° or 90°), and astigmatic axis, respectively; and d denotes the distance from the back vertex of the lens to the entrance pupil, assumed to be 15 mm.[21]

Resolution acuity was measured first in the fovea and then the periphery. The test sequence of the peripheral visual fields, that is, nasal and inferior, was randomized. When testing the inferior peripheral field, participants fixated on a letter X located at 15° eccentricity above the monitor. When testing the nasal peripheral field, participants fixated on a letter X located at 15° eccentricity on the side of the monitor. Participants faced the monitor, with their head position stabilized in a head-chin rest, for all testing conditions and only their eyes directed towards the fixation targets. Thus, the optical axes of the corrective lenses were maintained along the relevant visual field direction. The temporal and superior visual fields were omitted to avoid potential interference from the physiological blind spot and the upper eyelid. Eye position during fixation was carefully monitored using a digital camera (NCB541W Night Vision Camera, Wansview Technology Co. Ltd., Shenzhen, China).

The experimental procedures were approved by the ethics committee of The Hong Kong Polytechnic University (HSEARS20150602001-02), and the research was conducted according to the principles expressed in the Declaration of Helsinki. The experiments were undertaken with the understanding and written consent of each participant.

Results

Participants

A total of 53 participants were recruited in the three refractive groups. Table shows their demographic information. All three groups were age- and gender-matched, with no significant difference in age (1-way ANOVA, $F(2, 50) = 1.30$, $P = 0.28$) or gender (chi-square test: $\chi^2 = 0.79$, $P = 0.67$) among the three groups. Although there were significant group effects on cylindrical error, spherical error, and spherical-equivalent error (1-way ANOVA, $F(2, 50) \geq 19.49$, $P < 0.001$), the spherical error and spherical-equivalent error were not significantly different between the MA and SM groups (unpaired $t < 2.40$, $P > 0.07$), nor was the difference in cylindrical error between the SM and EM groups (unpaired $t = 0.74$, $P = 1.00$). The characteristics of astigmatism are summarized in Supplementary Figure S1.

Meridional Anisotropy in Foveal Resolution Acuity

The findings revealed a significant meridional difference in foveal resolution acuity for horizontal and vertical gratings in the MA group (Fig. 2a, 2-way ANOVA mixed design, orientation [within-subjects factor] × group [between-subject factor] interaction: $F(2, 50) = 19.44$, $P < 0.001$). These astigmatic participants had significantly lower resolution acuity, by 33% for horizontal gratings than vertical gratings (Fig. 2a, V: 0.71 ± 0.03 arcmin or Snellen approximately 20/14; H: 0.94 ± 0.06 arcmin or Snellen approximately 20/19; paired $t = 4.45$, $P < 0.001$). Compared to the SM and EM groups, resolution acuity for horizontal gratings was significantly lower in the MA group, by 39% and 31%, respectively (Bonferroni-Holm post hoc test, unpaired $t \geq 3.18$, $P \leq 0.005$). In contrast, resolution acuity measured with vertical gratings was similar among the three groups (Bonferroni-Holm post hoc test, unpaired $t \leq 1.35$, $P \geq 0.56$). Data for individual participants are presented in Supplementary Fig. S2a.

In contrast to the myopic astigmats, no significant difference in resolution acuity for the two grating orientations was found in simple myopes (V: 0.69 ± 0.03 arcmin, H: 0.68 ± 0.03 arcmin; paired $t = -1.03$, $P = 0.31$). In emmetropes, a slightly, but significantly lower resolution acuity by 6%, for vertical gratings than for horizontal gratings was observed

Table. Demographic Information

	MA	SM	EM
Gender (female/male)	8/11	9/11	8/6
Age (years)	22.11 ± 0.50	21.50 ± 0.37	21.14 ± 0.29
Spherical error (D)	−5.20 ± 0.68†	−4.53 ± 0.60#	−0.14 ± 0.10†#
Cylindrical error (D)	−2.67 ± 0.15*†	−0.29 ± 0.05*	−0.18 ± 0.06†
Spherical-equivalent error (D)	−6.53 ± 0.68†	−4.67 ± 0.61#	−0.23 ± 0.09†#

The symbols indicate statistically significant differences between groups in Bonferroni post hoc tests ($P < 0.05$). *MA vs. SM; †MA vs. EM; #SM vs. EM. MA, myopic astigmats. SM, simple myopes. EM, emmetropes.

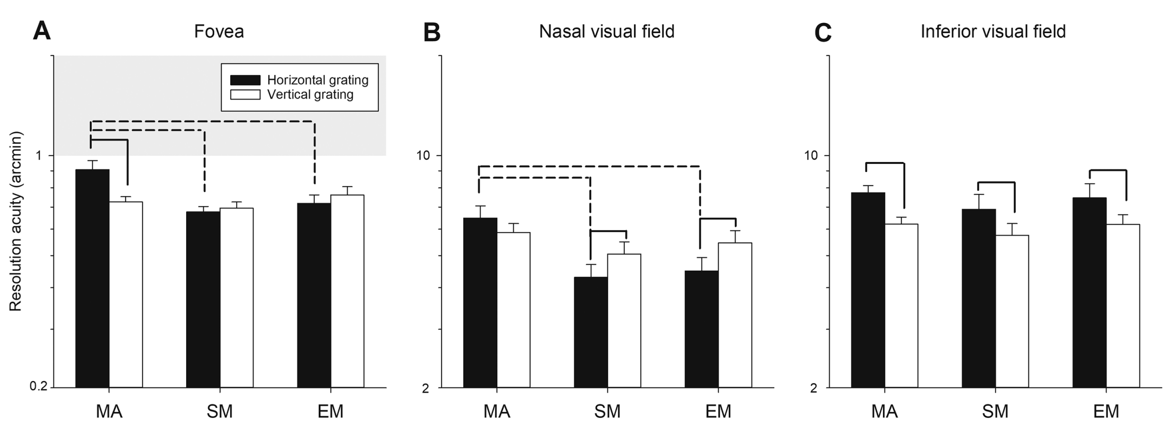

Figure 2. Mean ± SE of resolution acuity (min of arc) at the fovea (**A**), nasal (**B**), and inferior (**C**) visual fields for the horizontal (*black bar*) and vertical (*white bar*) gratings in the MA, SM, and EM groups. The *gray area* represents resolution acuity at the fovea poorer than 1 min of arc (Snellen acuity 20/20). *Dashed lines* indicate significant differences between groups; *solid lines* indicate significant within-group differences between resolution acuity for horizontal and vertical gratings.

(V: 0.76 ± 0.05 arcmin, H: 0.72 ± 0.04 arcmin; paired $t = -3.06$, $P = 0.009$).

Meridional Anisotropy in Peripheral Resolution Acuity

A radial bias in the preferred orientation was observed in the peripheral visual fields of the two nonastigmatic groups. The SM and EM participants had better resolution capacities to resolve gratings oriented radially toward the fovea than those oriented tangentially. In the nasal field, resolution acuities of the SM and EM groups for horizontal gratings (*radially* oriented) were 16% and 18% higher than those for vertical gratings (tangentially oriented), respectively (Fig. 2b, paired $t \leq -3.52$, $P \leq 0.004$). As expected, in the inferior field, resolution acuities for the SM and EM groups were 17% and 18% higher for vertical gratings (*radially* oriented) than for horizontal gratings (tangentially oriented), respectively (Fig. 2c, paired $t \geq 2.53$, $P \leq 0.02$). Data for individual participants are presented in Supplementary Figure S2b & c.

Unlike the SM and EM groups, in the nasal field, the astigmatic participants had 14% higher resolution acuity for vertical gratings (*tangentially* oriented) than for horizontal gratings (*radially* oriented; Fig. 2b, 2-way ANOVA mixed design: orientation × groups interaction: $F(2, 50) = 9.68$, $P < 0.001$). In contrast to the SM and EM groups, the mean acuity difference between the vertical and horizontal gratings did not reach statistical significance (paired $t = 1.97$, $P = 0.07$). Resolution acuity for horizontal gratings for the nasal field was significantly lower in the MA group than for the SM and EM groups (Bonferroni-Holm post hoc test, unpaired $t \geq 3.26$, $P \leq 0.004$). However, there were no significant differences in resolution acuity for vertical gratings (unpaired $t \leq 1.45$, $P \geq 0.46$) among the three groups.

In the inferior field, the astigmatic participants showed a similar tendency of meridional anisotropy as the SM and EM groups (Fig. 2c, 2-way ANOVA mixed design: orientation: $F(1, 50) = 36.25$, $P < 0.001$; groups: $F(2, 50) = 0.92$, $P = 0.41$; orientation X groups interaction: $F(2, 50) = 1.02$, $P = 0.37$). The resolution acuity for vertical gratings (*radially* oriented) was higher than that for horizontal gratings (tangentially oriented), with a 24% mean acuity difference (Fig. 2c, paired $t = 5.66$, $P < 0.001$). There were no significant differences in resolution acuity for both horizontal and vertical gratings (Bonferroni-Holm post hoc test, unpaired $t \leq 1.50$, $P \geq 0.42$) among the three groups at this location.

Discussion

This study revealed changes linked to high myopic astigmatism, in the patterns of meridional anisotropy, as inherent in spatial resolution at the fovea and more peripheral locations. The astigmatic participants exhibited lower (or worse) resolution acuity for horizontal gratings than vertical gratings in all tested retinal locations, which conformed to the orientational defocus blur caused by their WTR astigmatism (see further discussion below). Their meridional anisotropy differed from the two nonastigmatic groups in the fovea and nasal field, even though they had normal visual acuities (logMAR 0 or better).

It is evident that uncorrected astigmatism can result in meridional deficits in foveal vision.[7] Because myopic WTR astigmatism smears the horizontal component of retinal images projected from distant objects, the reduced resolution acuity for horizontal gratings may be associated with any uncorrected astigmatism or partially corrected residual astigmatism during the critical periods of visual development. While spectacle correction can effectively recover visual acuity in astigmatism-related amblyopia, meridional sensitivity loss usually persists, particularly in those with myopic astigmatism.[22]

Previous studies of astigmatism-related visual loss[9] considered only the fovea, so whether astigmatism affects peripheral vision had not been thoroughly investigated. Apart from foveal vision, apparently in the nasal field, the presence of astigmatism affected resolution acuity for the selected orientations and, hence, disturbed meridional anisotropy. In the peripheral fields, the nonastigmatic eye had finer visual resolution for gratings oriented radially: horizontal gratings in the nasal field and vertical gratings in the inferior field. Such radial bias has been thought to help maximize contextual information extraction,[23] compute optic flow,[24] and plan for saccadic eye movement.[24] Notably, in the nasal field, the astigmatic participants exhibited higher resolution acuity for *tangential* gratings (i.e., vertical gratings) rather than radial gratings, with meridional anisotropy opposite from the nonastigmatic participants.

In contrast to the nasal field, astigmatism did not affect the radial orientation bias in the inferior field of the astigmatic participants. The resolution acuity for both horizontal and vertical gratings was similar to that of the nonastigmatic participants. Note that visual inputs at peripheral field locations, even in the nonastigmatic eye, are anisotropic. In the inferior field, the retinal images contrast[15] and power spectral density for natural scenes[17,18] are lower for the horizontal (i.e., *tangential*) orientation than for the vertical orientation. While the presence of myopic WTR astigmatism may further blur the horizontal component of retinal images, it does not affect the radially biased visual input. This may explain why the astigmatic participants had the same pattern of meridional anisotropy (i.e., higher resolution acuity for vertical than horizontal gratings) in the inferior field as the nonastigmatic, although the mean difference in grating acuity between horizontal and vertical gratings in the astigmatic participants was slightly higher (MA: 24%; SM: 17%; EM: 18%).

This study intentionally recruited participants with compound myopic astigmatism. It was suspected that meridional anisotropy might be less predictable in hyperopic astigmatism, depending on the ocular accommodation status. Using compound hyperopic WTR astigmatism as an example, the two orthogonal line foci would be formed behind the retina when ocular accommodation is relaxed fully (horizontal line foci closer to the retina than the vertical). As such, vertical gratings are expected to be more blurred than horizontal gratings. However, when the eye accommodates, both of the image foci are brought closer to the retina. If the circle of least confusion falls onto the retinal plane, the retinal image quality along the principal meridians will be degraded equally. Additional ocular accommodation will further shift the image foci forward and reverse the orientation-dependent blur pattern, resulting in blurrier horizontal than vertical gratings. This unstable meridional blur may explain why meridional visual loss is usually less evident in hyperopic astigmats.[7,22] In the MA group with compound myopic astigmatism, the retinal image was far more stable and not much affected by ocular accommodation, providing an effective role model for determining how astigmatism affects meridional anisotropy. However, because this study included only myopic astigmatism, whether the results can be generalizable to hyperopic or mixed astigmatism requires further investigation.

It was not entirely clear whether myopia per se affects meridional anisotropy. It has been shown that radial orientation bias in the visual periphery originates from the radial arrangement of the retinal ganglion cells and their dendritic arborization, possibly due to the retina stretching radially as the eye grows.[25–29] Evidence from both clinical and laboratory studies has demonstrated that myopic eyes result from an overgrowth of the posterior eyeball,[30] which usually expands more for its height than its width.[31] Furthermore, recent studies have also revealed functional connectivity and morphological changes in the brains of high myopes, even though their best-corrected distance visual acuity was normal.[32–34] To remove the potential contribution of myopia to meridional anisotropy at peripheral visual fields, participants with emmetropia were recruited as a control group. However, no significant difference in the meridional anisotropy between the SM and EM groups was observed across all tested retinal locations. Thus, it is unlikely that myopia per se contributed to the difference in meridional anisotropy in the MA group.

Several measures were put in place to rule out interference of optical factors with resolution acuity measurement. First, on- and off-axis refractive errors determined respectively from subjective refraction and autorefraction were corrected by ophthalmic lenses when measuring resolution acuity. Second, high-contrast gratings were employed for the measurement of resolution acuity. While optical correction using conventional ophthalmic lenses could not fully compensate for higher-order aberrations at the peripheral visual field,[35] peripheral vision is highly resistant to optical blur. High-contrast visual acuity is largely unaffected by imposing defocus as high as 6D at 20° eccentricity.[20] The averaged high-contrast resolution acuity reported in this study (Fig. 2b & c) fell within the range for resolution acuity at or close to 15° eccentricity of peripheral visual field ranges from 2.5 to 12 arcmin reported by previous studies.[20,36,37] The wide variations in measured peripheral resolution acuity obtained by previous studies could be attributable to the differences in psychophysical methods (method of adjustment,[20] 2-up 1-down staircase,[33] and 1-up 1-down staircase[34]), tested visual field locations, and participants' refractive errors. Third, this study measured resolution acuity rather than detection acuity (i.e., identifying the presence or absence of gratings), even though the latter is also a common spatial acuity parameter. However, because detection acuity could be significantly affected by the amount of uncorrected optical blur,[20] it would be difficult to determine whether the meridional anisotropy, if any, is attributable to neural or optical factors. Lastly, the spectacle magnification difference was compensated between horizontal and vertical power meridians in the acuity measurement. Thus, it may be postulated that neural, rather than optical, factors modulate the orientation tuning in astigmatic eyes.

In conclusion, our study highlights the importance of astigmatism on meridional resolution acuity. Different meridional anisotropy patterns of the fovea and peripheral visual fields were characterized in patients with emmetropia, myopia, and astigmatism. Meridional resolution acuity can be affected by high astigmatism, even when corrected visual acuity is better than 20/20. It should be noted that only two peripheral visual fields were tested in our study. Caution should be applied before generalizing the findings to other retinal locations.

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