

# Effects of Lens-Induced Astigmatism at Near and Far Distances

Silvia Tavazzi<sup>1,2</sup>, Natalia Vlasak<sup>3</sup>, Fabrizio Zeri<sup>1,2,4</sup>

<sup>1</sup>Materials Science Department, University of Milano-Bicocca, Milan, I-20125, Italy; <sup>2</sup>University of Milano-Bicocca, COMiB Research Centre in Optics and Optometry, Milan, I-20125, Italy; <sup>3</sup>Hoya Vision Care, Amsterdam, 1043 NX, the Netherlands; <sup>4</sup>College of Health and Life Sciences, Aston University, Birmingham, B4 7ET, UK

Correspondence: Silvia Tavazzi, Department of Materials Science, University of Milano-Bicocca, Via Roberto Cozzi 55, Milan, I-20125, Italy, Tel +39 02 6448 5035, Email [silvia.tavazzi@unimib.it](mailto:silvia.tavazzi@unimib.it)

**Purpose:** To investigate and compare the degradation of visual acuity (VA) in myopic presbyopes due to lens-induced astigmatism at near and at far distance.

**Patients and Methods:** Fourteen corrected myopic presbyopes were recruited. VA (logarithm of the minimum angle of resolution) was measured binocularly for different conditions of lens-induced astigmatism: cylindrical powers of  $-0.25$ ,  $-0.50$ ,  $-0.75$ ,  $-1.00$ ,  $-1.50$ , and  $-2.00$  diopters (and positive spherical power of half the cylindrical power) with two axis orientations (with-the-rule WTR and against-the-rule ATR) were added to their optical correction. Measurements were carried out at far and near distance both in photopic and mesopic conditions, and for high and low contrast (HC/LC) stimuli. The paired Wilcoxon signed-rank statistics test was used to evaluate difference between conditions.

**Results:** The measured VA as a function of the lens-induced astigmatism was described by regression lines in all investigated experimental conditions. The angular coefficients (slopes) of these lines represent the VA degradation, ie, the variation in logMAR corresponding to the addition of 1.00 diopters of cylindrical power. In photopic HC conditions, the VA degradation is significantly more pronounced at far distance than at near distance ( $0.22 \pm 0.06$  diopters<sup>-1</sup> vs  $0.15 \pm 0.05$  diopters<sup>-1</sup>,  $p = 0.0061$  in WTR conditions;  $0.18 \pm 0.06$  diopters<sup>-1</sup> vs  $0.12 \pm 0.05$  diopters<sup>-1</sup>,  $p = 0.0017$  in ATR conditions), although VAs at near and at far with zero cylinder were similar ( $-0.14 \pm 0.10$  vs  $-0.14 \pm 0.08$ ,  $p = 0.824$ ).

**Conclusion:** The better tolerance to lens-induced astigmatism blur at near than at far distance in photopic conditions with HC stimuli is tentatively attributed to a possible experience-mediated neural compensation associated to the tendency of the eye toward an inherent astigmatism at near.

**Keywords:** cylindrical power, blur, visual acuity, myopic presbyopes

## Introduction

In the eye, astigmatism produces an alteration of the retinal image. This optical effect may be accompanied by blur, the visual sense of lack of sharpness. Some authors discussed that something may be special about the visual performances in cases of astigmatism.<sup>1</sup> Indeed, they compared the effects of “simulated” and “real” spherical defocus on visual acuity (VA) and found that there were only minor differences, while real astigmatism reduced VA by only half compared to simulated astigmatism. In general, a quantification of the astigmatism-induced blur is of interest for those cases of surgically-induced astigmatism (keratoplasty, cataract surgery),<sup>2,3</sup> keratoconus,<sup>4</sup> and for the optimisation of the design of multifocal and progressive addition lenses (PALs).<sup>5</sup> For these reasons, the relationship between astigmatism and VA degradation has been studied by different authors. Some studies concerned the depth of focus (DoF), which is the variation in image distance from the retina which can be tolerated without incurring a lack of sharpness.<sup>6-12</sup> Astigmatism typically causes an increase in the DoF extension,<sup>8</sup> such as in studies concerning pseudophakic eyes and intraocular lenses.<sup>13-21</sup> Other studies took into consideration the drop in visual performances for increasing astigmatism beyond the DoF extension.<sup>22-29</sup> In the case of lens-induced astigmatism, the reduction in vision is typically reported to be lower with lens-induced with-the-rule (WTR) compared to against-the-rule

(ATR) astigmatism,<sup>22–26</sup> but there are also conflicting opinions.<sup>27–29</sup> In astigmatic subjects, more than one study found that the visual impact of lens-induced astigmatism is linked to habitual axis due to an effect of adaptation of the astigmatic subjects, which is interpreted as an experience-mediated neural compensation.<sup>23,24,30,31</sup> Myopic refractive error must also be taken into consideration. Indeed, many studies report better tolerance to blur of myopes than emmetropes. This is typically interpreted as a consequence of adaptation to the greater ocular aberrations and to an uncorrected level of blur in myopes.<sup>32–42</sup> A further comment concerns the age-dependence of the astigmatism-induced blur. It is well known that aging disrupts compensation between corneal and internal astigmatism and there is a trend towards ATR astigmatism with ageing due to the change in corneal curvature.<sup>8,43–46</sup> This could result in less astigmatism-blur sensitivity in elderly people.<sup>43,47</sup> Some studies concerned the increase of tolerance to spherical defocus blur as a consequence of the increase of the DoF with age (DoF increase was estimated to be about 0.03 diopters per year between about 20 and 50 years<sup>48</sup>), together with an increased pupillary miosis, and an increase of ocular aberrations.<sup>8,48–51</sup> Besides defocus blur, a better understanding of the astigmatism blur in elderly people in different conditions is expected to improve the maintenance of vision quality and the development of PAL designs.

This study aimed to provide additional experimental evidence on this theme by measuring and comparing the VA degradation both at far and at near distance as a function of the lens-induced astigmatism in a group of corrected myopic presbyopes. More specifically, the study aimed to study the effect of different cylindrical powers along two possible orthogonal axes, assessing VA both at far distance and at near distance, at high and at low contrast, in photopic and mesopic environmental conditions.

## Materials and Methods

### Preliminary Examination

The study was approved by the Ethics Committee of the University of Milano-Bicocca (prot. Int. 0055048/19, classif. II.18, C. IPA unimib C.AOO:AMMU06, C. reg. prot.: RP01). The research followed the tenets of the Declaration of Helsinki. Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study.

An initial eye and visual examination was performed. Ophthalmoscopy and slit-lamp examinations were carried out. Anomalies in ocular motility were investigated by the H pattern test, dissociated heterophorias through an alternating cover test and a prism bar, fusional reserves at far distance with a prism bar. A possible suppression was evaluated by the Worth 4-Dot test at far distance. Stereoscopic acuity was measured by the circles subtest (Wirt rings) of the Stereo Fly Test (Stereo Optical Co.) at 40 cm with the near optical correction arranged in a trial frame.

Non-cycloplegic subjective refraction at far distance was carried out by a phoropter procedure (monocular refraction by maximum plus to maximum VA and binocular balance by prism dissociated blur balance of accommodation).<sup>52</sup> The spherical equivalent (SE) was calculated. The mean value (MSE) of the SEs of the two eyes measured at far distance was calculated. The addition for near (40 cm) was firstly determined according to the age expected procedure<sup>53</sup> and then adjusted subjectively to obtain the final near addition by fused cross cylindrical procedure.<sup>52</sup> Monocular amplitude of accommodation was evaluated by the push-up test.

The preliminary assessment also included the measurements of the best corrected visual acuity (BCVA) in logarithm of the minimum angle of resolution (logMAR) in different conditions as described in the paragraph 2.2.

Inclusion criteria were: being a presbyope (addition at near  $\geq 2.00$  diopters), having no known ocular or systemic pathology, not undergoing any medical therapy, being near-sighted in both eyes with a difference (absolute value) of the spherical equivalents in the two eyes  $\leq 3.00$  diopters, having a natural astigmatism  $< 2.00$  diopters in both eyes with a difference (absolute value) of the cylindrical power in the two eyes  $\leq 1.00$  diopters, having a binocular photopic high-contrast (HC) BCVA at far distance  $\leq 0.1$  logMAR with a difference (absolute value) between the BCVA of the two eyes  $\leq 0.1$  logMAR, the difference (absolute value) between binocular photopic HC BCVA (logMAR) at far and at near being  $< 0.1$ , and having good binocular vision (no anomalies in ocular motility, heterophorias at far and near and fusional reserves at far distance within the limit of the expected values,<sup>54</sup> and a stereoscopic acuity of at least 60 arcsec). Fourteen participants were part of the sample under consideration having met the inclusion criteria.

## BCVA

HC and low-contrast (LC) BCVAs were measured in photopic and mesopic conditions with the optical correction at far (4 m) arranged in a trial frame using Sloan letters displayed on a liquid crystal display (LCD) optotype system described in paragraph 2.3. A row of five Sloan letters was presented in descending logarithmic progression of 0.10 logMAR. Every single 5-letter row was randomly generated among twenty-eight different sets of balanced readability and presented in isolation.<sup>55</sup>

BCVA was also measured at near (40 cm) using a set of thirteen paper charts containing twelve lines of five Sloan-font letters. The row of five letters was reduced in size with a progression of 0.1 logMAR according the ETDRS set up between 0.8 (1.0) and -0.3 (0.1) logMAR at HC (LC). Each single five-letter line was chosen among twenty-eight different sets of five letters balanced for readability.<sup>55</sup> The same set of five letters was used only once in the same chart and the sequence of the set of five letters in the different charts was always different.

A forced choice procedure<sup>56</sup> and a letter-by-letter (0.02 logMAR) scoring criterion were used to assess the threshold.

## Luminance

The illumination in the room was measured by a luxmeter HT307, HT Italia (450±50 lux and 8±2 lux in photopic and mesopic conditions, respectively).

As described in paragraph 2.2, HC and LC BCVA were measured at far using Sloan letters displayed on a LCD optotype system (Vision Chart CSO, Florence, Italy). At near, HC and LC BCVAs were measured using Sloan letters on paper charts, as described in paragraph 2.2. Luminance was measured (photometer Chroma Meter CS-100A, Minolta, Japan) to test the difference between actual (Table 1) versus nominal (100% at HC and 10% at LC) contrast.

## Lens-Induced Astigmatism

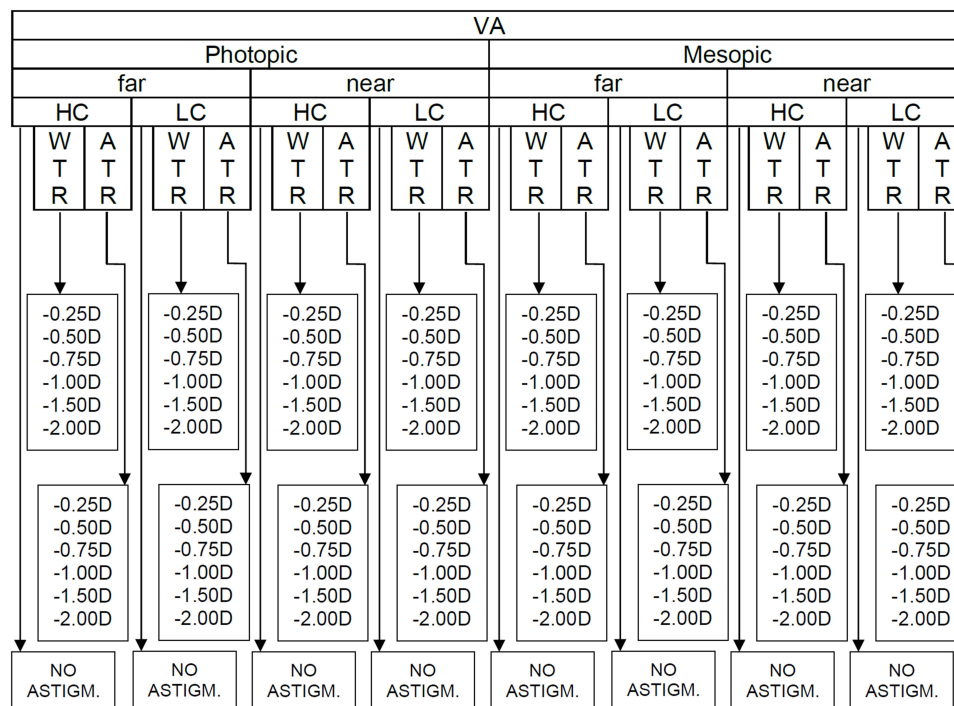
The experimental phase consisted of VA measurements carried out in photopic and mesopic conditions, at far and at near, with HC and LC stimuli, and for different levels and axis orientation of the added lens-induced cylindrical power. VA was evaluated by adding, in the trial frame, different cylindrical lenses to the best subjective correction evaluated for each subject during the preliminary examination. For VA assessment at near, the addition in both eyes was also added. Two axis orientations were tested, ie, 90° (negative cylindrical power inducing WTR astigmatism) and 180° (negative cylindrical power inducing ATR astigmatism). For each axis orientation, six levels of cylindrical power were tested (-0.25 diopters, -0.50 diopters, -0.75 diopters, -1.00 diopters, -1.50 diopters, -2.00 diopters). The negative cylindrical power was inserted together with a positive spherical power equal to half the cylindrical power to keep the Sturm's conoid centred on the retina. Measurement was also taken without any cylindrical power (plano).

**Table 1** Measured Contrast

			Measured Contrast (%)
Far	Photopic	HC	97.8±0.2
		LC	10.4±0.1
	Mesopic	HC	92.0±0.2
		LC	10.6±0.1
Near	Photopic	HC	96.1±0.1
		LC	10.0±0.1
	Mesopic	HC	96.2±0.1
		LC	9.4± 0.1

**Notes:** Contrast (mean ± standard deviation) measured as described in paragraph 2.3 in the different experimental conditions.

**Abbreviations:** HC, high contrast; LC, low contrast.



**Figure 1** Scheme of the study design showing the conditions under which VA was measured, ie at far and at near distance, in photopic and mesopic conditions, at high contrast and low contrast, and for six different level of power and two different axis orientations of the added cylindrical lens.

**Abbreviations:** VA, visual acuity; D, diopters; WTR, astigmatism with-the-rule; ATR, astigmatism against-the-rule; HC, high contrast; LC, low contrast.

The number of conditions under which VA was measured (Figure 1) was one hundred and four for each participant. Different conditions were selected in random order. A single masked crossover study was performed. Participants were masked to the randomisation scheme, but investigators were not. Each participant had to sit six times to be assessed during the two phases of the study. During the first visit, the preliminary examination was carried out. The experimental phase of the study was divided in the second, third, fourth, fifth, and sixth visits lasting about 45 minutes each.

Scatterplots were plotted to evaluate the relationship between VA (logMAR) and the level of the lens-induced astigmatism for each participant and for each condition. For this purpose, the actual cylindrical power affecting the ocular system was determined taking into account the optical correction arranged in a trial frame and the distance between the ocular apex and the frame. Linear regressions were worked out to find the corresponding equations describing the dependence of the VA on the lens-induced cylindric power. The slope of the line was considered as an indicator of the extent of the VA degradation. Indeed, the slope represents the variation in logMAR corresponding to the addition of 1.00 diopters of cylindrical power. Instead, one-tenth of the reciprocal of the angular coefficient can be used as a definition of the DoF because it represents the cylindrical power which produces a 0.1 logMAR worsening of the VA.<sup>22</sup>

## Statistical Analyses

Non-parametric statistics were used to analyse the data. To describe how well the relationship between two variables is described using a monotonic function, the Spearman's rank correlation coefficient was calculated. For paired comparison, the Wilcoxon signed-rank test was used to evaluate difference between conditions. Statistical significance was set at the overall level ( $p_s$ ) of 0.05. In case of multiple comparisons, the Bonferroni correction was adopted and the significance level was set at  $p_s/n$ , where  $n$  is the number of hypotheses. All statistical analyses were performed using IBM SPSS Statistics 26.

## Results

The main outcomes of the preliminary visual assessment are reported in Table 2. The paired comparison between the BCVA at far and at near without any additional cylindrical power showed that no statistical difference was found with HC stimuli. Statistically significant difference was found between far and near BCVA in case of LC stimuli.

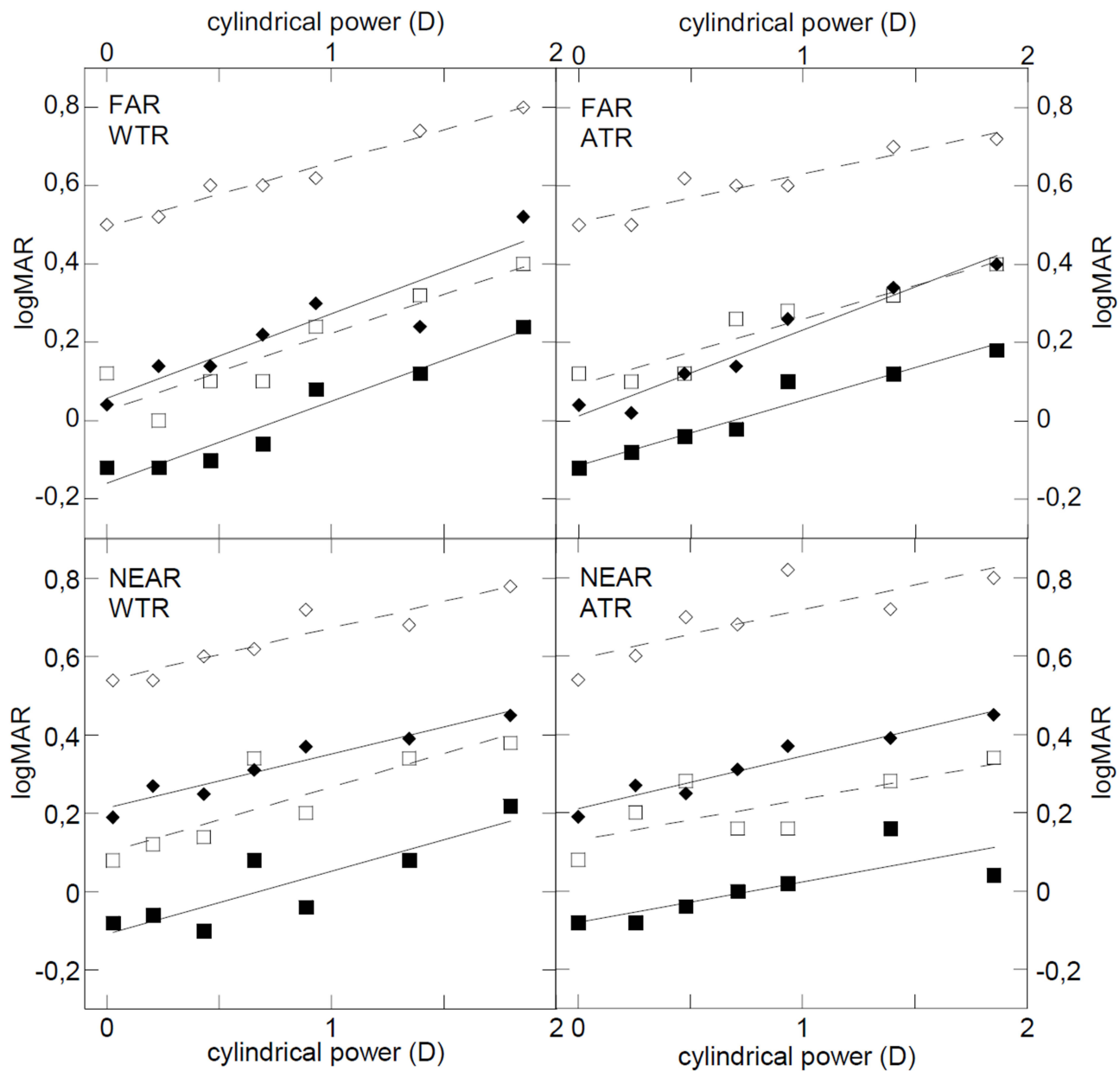
An example of the effect of the lens-induced astigmatism on VA is reported in Figure 2 as obtained on a participant in the different experimental conditions. A positive slope of the regression line indicates a worsening of the VA. For each subject and for each experimental condition, a linear regression of the data was performed, similarly as performed in Figure 2. The fitting made it possible to obtain the slopes of the lines and the DoF as defined above.

**Table 2** Preliminary Assessment

	Far	Near	p-value
N of enrolled subjects who met the inclusion criteria (of which women) Age (years)	14 (5) Mean: 57.0 Std Dev: 5.1 Min: 51 Max: 69		
Mean spherical equivalent (MSE) of the two eyes (diopters)	Mean: -2.75 Std Dev: 2.11 Min: -6.38 Max: -0.25		
Mean natural astigmatism (cyl value) of the two eyes (diopters)	Mean: -0.72 Std Dev: 0.42 Min: -1.50 Max: -0.25		
Addition for near (diopters)		Mean: 2.36 Std Dev: 0.21 Min: 2.0 Max: 2.5	
Binocular HC BCVA (logMAR) in photopic condition	Mean: -0.14 Std Dev: 0.10 Min: -0.30 Max: 0.04	Mean: -0.14 Std Dev: 0.08 Min: -0.25 Max: 0.02	0.824
Binocular HC BCVA (logMAR) in mesopic condition	Mean: 0.09 Std Dev: 0.09 Min: 0.00 Max: 0.30	Mean: 0.05 Std Dev: 0.13 Min: -0.10 Max: 0.32	0.123
Binocular LC BCVA (logMAR) in photopic condition	Mean: 0.10 Std Dev: 0.10 Min: 0.00 Max: 0.34	Mean: 0.27 Std Dev: 0.09 Min: 0.14 Max: 0.46	<b>0.001</b>
Binocular LC BCVA (logMAR) in mesopic condition	Mean: 0.55 Std Dev: 0.16 Min: 0.36 Max: 0.94	Mean: 0.62 Std Dev: 0.08 Min: 0.50 Max: 0.72	<b>0.027</b>

**Notes:** Preliminary visual assessment outcomes and p-values of the paired comparison between far and near distance data (Wilcoxon signed-rank test). Bold characters indicate that the difference is statistically significant within the significance level of 0.05.

**Abbreviations:** BCVA, best corrected visual acuity; logMAR, logarithm of minimum angle of resolution; HC, high contrast; LC, low contrast.



**Figure 2** Visual acuity (logMAR) of one participant measured at far and at near distance, in photopic (full markers) and mesopic (empty markers) conditions, for HC (squares) and LC (diamonds) stimuli at different levels of induced WTR and ATR astigmatism. The continuous lines show the results of the linear regressions of the data. **Abbreviations:** D, diopters; logMAR, logarithm of minimum angle of resolution; WTR, with-the-rule; ATR, against-the-rule.

To study the dependence of the VA degradation on the level of myopia of the subject, the Spearman's rank correlation coefficient was calculated for the VA slopes with respect to the MSE of each subject (Table 3). No significant correlations were found with p-values all well above the significance threshold.

Figure 3a shows the mean slope (mean of the angular coefficients of the fourteen subjects) in each experimental condition. The same figure (panel b) also shows the mean of the DoFs calculated as one-tenth of the reciprocal of the slopes.

Using the slopes as parameters, various statistical comparisons were made. Table 4 shows the results focused on the comparison between the drop of VA at far and at near distance. The difference between far vision and near vision is clear in photopic conditions. The statistical comparison on which Table 5 focuses is between WTR and ATR astigmatism and no statistically significant differences are found. Table 6 and Table 7 allow the comparison between mesopic and photopic conditions and between the two contrast levels, respectively. Two out of eight differences are significant when comparing photopic and mesopic conditions. In particular, the VA degradation is worse in photopic conditions (for LC stimuli at far). A similar scenario is

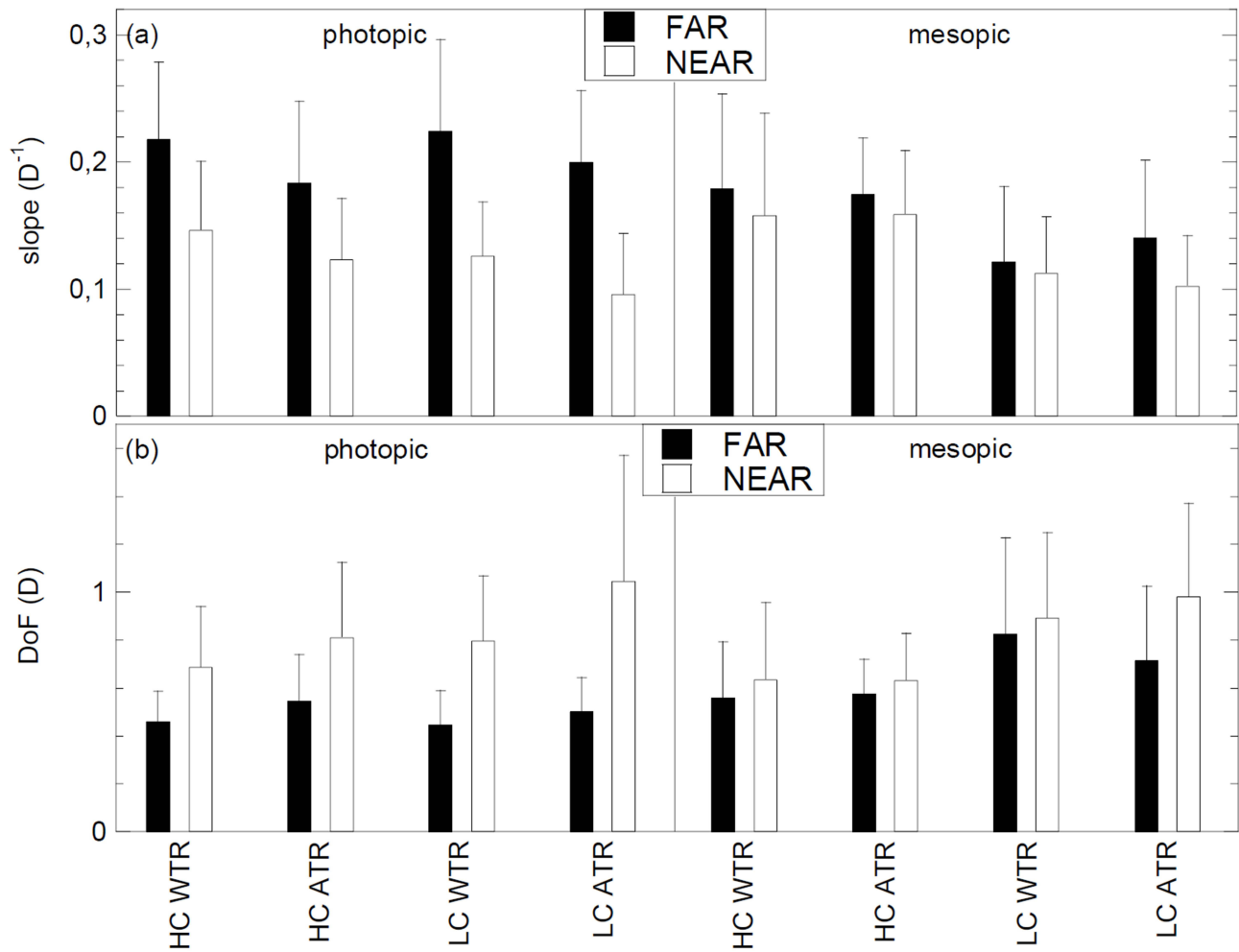
**Table 3** VA Degradation vs Myopia Level

	WTR				ATR			
	Photopic		Mesopic		Photopic		Mesopic	
	HC	LC	HC	LC	HC	LC	HC	LC
Far	0.158 (0.589)	-0.246 (0.396)	0.099 (0.736)	0.224 (0.441)	-0.123 (0.675)	0.101 (0.731)	0.308 (0.284)	-0.062 (0.834)
Near	-0.018 (0.952)	-0.066 (0.823)	0.317 (0.270)	0.029 (0.923)	-0.059 (0.840)	0.400 (0.156)	0.451 (0.106)	-0.261 (0.388)

**Notes:** Rank correlation coefficients of Spearman (first value in each cell) and p-value (second value in brackets) showing the correlation between the myopia level (mean spherical equivalent (MSE) of the two eyes) and the VA degradation due to the lens-induced astigmatism (slopes of the regression lines as those in Figure 2).

**Abbreviations:** HC, high contrast; LC, low contrast; WTR, with-the-rule; ATR, against-the-rule.

observed in Table 7 although with no statistical relevance. Indeed, in two conditions out of eight (corresponding both to the mesopic condition), the p-value is about 0.008, ie, very close to the threshold 0.05/8. In these cases, the VA degradation with HC stimuli is worse compared with LC ones. For each comparison, each (Tables 4–7) shows the mean values and the standard deviations of the slopes for the two groups, the p-values obtained by Wilcoxon test, the difference ( $\Delta$ ) between the means of the measured data, and the threshold value ( $\Delta_{\text{threshold}}$ ) for the difference between the means that can be proved statistically with



**Figure 3** (a) Mean slopes indicating the visual acuity (A) drop induced by astigmatism (WTR and ATR) at far and at near distance, for HC and LC stimuli, in photopic and mesopic conditions. (b) Mean DoF calculated as one tenth of the reciprocal of the slopes, thus representing the cylindrical power which produces a 0.1 logMAR worsening of the visual acuity. The bars indicate the standard deviations of the data.

**Abbreviations:** DoF, depth of focus; D, diopters; D<sup>-1</sup>, diopters<sup>-1</sup>; WTR, astigmatism with-the-rule; ATR, astigmatism against-the-rule; HC, high contrast; LC, low contrast.

**Table 4** Far vs Near Comparison

	WTR				ATR			
	Photopic		Mesopic		Photopic		Mesopic	
	HC	LC	HC	LC	HC	LC	HC	LC
Far	<b>0.22 (0.06)</b>	<b>0.22 (0.07)</b>	0.18 (0.07)	0.12 (0.06)	<b>0.18 (0.06)</b>	<b>0.20 (0.06)</b>	0.17 (0.04)	0.14 (0.06)
Near	<b>0.15 (0.05)</b>	<b>0.13 (0.04)</b>	0.16 (0.08)	0.11 (0.04)	<b>0.12 (0.05)</b>	<b>0.10 (0.05)</b>	0.16 (0.05)	0.10 (0.04)
P-value Far vs Near	<b>0.0061</b>	<b>0.0001</b>	0.4263	0.2676	<b>0.0017</b>	<b>0.0001</b>	0.2676	0.0266
$\Delta$	<b>0.07</b>	<b>0.09</b>	0.02	0.01	<b>0.06</b>	<b>0.10</b>	0.01	0.04
$\Delta_{\text{threshold}}$	<b>0.054</b>	<b>0.049</b>	0.069	0.050	<b>0.052</b>	<b>0.052</b>	0.044	0.049

**Notes:** Mean slopes in diopters<sup>-1</sup> (and standard deviations in diopters<sup>-1</sup> units in parentheses) indicating the VA worsening due to lens-induced astigmatism (WTR and ATR), at far and at near distance, for HC and LC stimuli, in photopic and mesopic conditions. The p-values obtained by Wilcoxon test are reported for the paired comparison between the data measured at far and those measured at near in corresponding experimental conditions, together with  $\Delta$  and  $\Delta_{\text{threshold}}$  (both in diopters<sup>-1</sup>). Bold values indicate that the difference is statistically significant within the significance level of 0.05/8 (Bonferroni correction where 8 is the number of comparisons) ie significance is reached only for a p-value lower than 0.0063.  $\Delta$ , difference between the means of the measured data;  $\Delta_{\text{threshold}}$ , threshold value for the difference between the means that can be proved statistically with significance at 0.05 based on the number of recruited subjects and the standard deviations of the two groups.

**Abbreviations:** HC, high contrast; LC, low contrast; WTR, with-the-rule; ATR, against-the-rule.

**Table 5** WTR vs ATR Comparison

	FAR				NEAR			
	Photopic		Mesopic		Photopic		Mesopic	
	HC	LC	HC	LC	HC	LC	HC	LC
WTR	0.22 (0.06)	0.22 (0.07)	0.18 (0.07)	0.12 (0.06)	0.15 (0.05)	0.13 (0.04)	0.16 (0.08)	0.11 (0.04)
ATR	0.18 (0.06)	0.20 (0.06)	0.17 (0.04)	0.14 (0.06)	0.12 (0.05)	0.10 (0.05)	0.16 (0.05)	0.10 (0.04)
P-value WTR vs ATR	0.0785	0.1726	0.6257	0.2412	0.0580	0.0504	0.2958	0.5049
$\Delta$	0.04	0.02	0.01	0.02	0.03	0.03	0.00	0.01
$\Delta_{\text{threshold}}$	0.057	0.062	0.054	0.058	0.049	0.044	0.063	0.039

**Notes:** Mean slopes in diopters<sup>-1</sup> (and standard deviations in diopters<sup>-1</sup> in parentheses) indicating the va worsening due to lens-induced astigmatism (WTR and ATR) at far and at near distance, at HC and at LC, in photopic and mesopic conditions. The p-values obtained by Wilcoxon test are reported for the paired comparison between the data measured by inducing WTR astigmatism and those measured inducing ATR astigmatism in corresponding experimental conditions, together with  $\Delta$  and  $\Delta_{\text{threshold}}$  (in diopters<sup>-1</sup>).  $\Delta$ , difference between the means of the measured data;  $\Delta_{\text{threshold}}$ , threshold value for the difference between the means that can be proved statistically with significance at 0.05 based on the number of recruited subjects and the standard deviations of the two groups.

**Abbreviations:** HC, high contrast; LC, low contrast; WTR, with-the-rule; ATR, against-the-rule.

significance at 0.05. This threshold was calculated by a power analysis based on the number of available data (fourteen) and on the standard deviations of the two groups. As can be seen in Tables 4–7,  $\Delta_{\text{threshold}}$  varies between about 0.040 diopters<sup>-1</sup> and 0.070 diopters<sup>-1</sup>, both for comparisons in which the difference turned out to be statistically significant (bold in the tables) and for comparisons which, on the contrary, did not show a significant difference. It can be concluded that, in general, the sample size of this experiment did not allow to demonstrate any possible difference lower than 0.055±0.015 diopters<sup>-1</sup> between the slopes of two investigated subgroups. In other words, the sample size did not allow to demonstrate any possible difference below 2.7±0.8 letters in one row of the logMAR chart. Some differences between the means of two subgroups proved to be higher than the detectable threshold and reached values of 0.10 diopters<sup>-1</sup> (corresponding to one complete row in the chart).



**Table 6** Photopic vs Mesopic Comparison

	FAR				NEAR			
	WTR		ATR		WTR		ATR	
	HC	LC	HC	LC	HC	LC	HC	LC
Photopic	0.22 (0.06)	<b>0.22 (0.07)</b>	0.18 (0.06)	<b>0.20 (0.06)</b>	0.15 (0.05)	0.13 (0.04)	0.12 (0.05)	0.10 (0.05)
Mesopic	0.18 (0.07)	<b>0.12 (0.06)</b>	0.17 (0.04)	<b>0.14 (0.06)</b>	0.16 (0.08)	0.11 (0.04)	0.16 (0.05)	0.10 (0.04)
P-value Photopic vs Mesopic	0.1189	<b>0.0006</b>	0.6750	<b>0.0023</b>	0.4420	0.3636	0.0353	0.9687
$\Delta$	0.04	<b>0.10</b>	0.01	<b>0.06</b>	0.01	0.02	0.04	0.00
$\Delta_{\text{threshold}}$	0.062	<b>0.062</b>	0.050	<b>0.058</b>	0.063	0.039	0.049	0.044

**Notes:** Mean slopes in diopters<sup>-1</sup> (and standard deviations in diopters<sup>-1</sup> in parentheses) indicating the VA worsening due to lens-induced astigmatism (WTR and ATR) at far and at near distance, for HC and LC stimuli, in photopic and mesopic conditions. The p-values obtained by Wilcoxon test are reported for the paired comparison between the data measured in photopic and mesopic conditions in corresponding experimental conditions, together with  $\Delta$  and  $\Delta_{\text{threshold}}$  (both in diopters<sup>-1</sup>). Bold values indicate that the difference is statistically significant within the significance level of 0.05/8 (Bonferroni correction where 8 is the number of comparisons) ie significance is reached only for a p-value lower than 0.0063.  $\Delta$ : difference between the means of the measured data;  $\Delta_{\text{threshold}}$ : threshold value for the difference between the means that can be proved statistically with significance at 0.05 based on the number of recruited subjects and the standard deviations of the two groups.

**Abbreviations:** HC, high contrast; LC, low contrast; WTR, with-the-rule; ATR, against-the-rule.

**Table 7** HC vs LC Comparison

	FAR				NEAR			
	WTR		ATR		WTR		ATR	
	Photopic	Mesopic	Photopic	Mesopic	Photopic	Mesopic	Photopic	Mesopic
HC	0.22 (0.06)	0.18 (0.07)	0.18 (0.06)	0.17 (0.04)	0.15 (0.05)	0.16 (0.08)	0.12 (0.05)	0.16 (0.05)
LC	0.22 (0.07)	0.12 (0.06)	0.20 (0.06)	0.14 (0.06)	0.13 (0.04)	0.11 (0.04)	0.10 (0.05)	0.10 (0.04)
P-value HC vs LC	0.6698	0.0085	0.3910	0.0353	0.1242	0.04187	0.0830	0.0081
$\Delta$	0.00	0.06	0.02	0.03	0.02	0.05	0.02	0.06
$\Delta_{\text{threshold}}$	0.062	0.062	0.058	0.050	0.044	0.060	0.049	0.044

**Notes:** Mean slopes in diopters<sup>-1</sup> (and standard deviations in diopters<sup>-1</sup> in parentheses) indicating the VA worsening due to lens-induced astigmatism (WTR and ATR) at far and at near, for HC and LC stimuli, in photopic and mesopic conditions. The p-values obtained by Wilcoxon test are reported for the paired comparison between the data acquired at HC and at LC in corresponding experimental conditions, together with  $\Delta$  and  $\Delta_{\text{threshold}}$  (both in diopters<sup>-1</sup>).  $\Delta$ , difference between the means of the measured data;  $\Delta_{\text{threshold}}$ , threshold value for the difference between the means that can be proved statistically with significance at 0.05 based on the number of recruited subjects and the standard deviations of the two groups.

**Abbreviations:** HC, high contrast; LC, low contrast; WTR, with-the-rule; ATR, against-the-rule.

## Discussion

The measured VA (logMAR) of myopic presbyopes as a function of the lens-induced astigmatism was described by regression lines in all investigated experimental conditions. The slopes of the linear regression (or the corresponding DoFs) can be compared with some values reported in the literature. Leube et al, after blocking the accommodation, evaluated the DoF of young subjects by measuring binocular defocus curves in the spherical range of  $\pm 1.5$  diopters.<sup>22</sup> They defined the DoF as the horizontal dioptric range at the threshold level of +0.1 logMAR compared to the best VA. They found  $0.89 \pm 0.32$  diopters for far vision and  $0.94 \pm 0.40$  diopters for near vision. For a comparison with the DoFs of the present work, the values of Leube et al<sup>22</sup> must be divided by two because their definition of DoF includes both a positive and a negative defocus. However, it must also be said that 1.00 diopters of cylindrical power applied in this

work should be compared to a spherical defocus of 0.50 diopters since a positive spherical power equal to half the cylindrical power was here added. These two opposite aspects make it possible to directly compare the values of Leube et al<sup>22</sup> with those in Figure 3b. At far, the mean values in Figure 3b ( $0.46\pm 0.14$  diopters and  $0.56\pm 0.20$  diopters for the two axis orientations) are slightly lower than the corresponding value of Leube et al<sup>22</sup> ( $0.89\pm 0.32$  diopters) although the order of magnitude is similar considering the distribution of the results around the means. Similarly, the values in Figure 3b at near ( $0.68\pm 0.26$  diopters and  $0.82\pm 0.32$  diopters for the two axis orientations) are slightly lower than the value in Leube et al ( $0.94\pm 0.40$  diopters), but compatible when considering the distribution of the results around the means. A difference is the age of the participants since Leube et al<sup>22</sup> analysed young subjects, while this work concerns presbyopic eyes. One might expect less astigmatism-blur sensitivity (higher DoF) in elderly people,<sup>8,43–47</sup> but the comparison between the data of Leube et al<sup>22</sup> on young subjects and the results of this paper on older subjects appears to be the opposite. One might expect less astigmatism-blur sensitivity because aging produces a trend towards eye astigmatism<sup>43,47</sup> and an increase of the DoF with age was also reported for spherical defocus blur,<sup>48</sup> together with the increased pupillary miosis and ocular aberrations.<sup>8,48–51</sup> It must be said that, the work of Leube et al<sup>22</sup> concerns the reduction of VA as a function of defocus while this work concerns astigmatism blur.

The slightly lower DoF compared to the work of Leube et al<sup>22</sup> can also be described as a slightly greater VA slope as a function of the additional cylindrical power. A recent work in which the VA worsening is directly reported is that of Hughes et al.<sup>23</sup> They considered far vision and reported a worsening of logMAR due to 1.00 diopters of cylindrical power varying from  $0.26\pm 0.09$  to  $0.45\pm 0.12$  logMAR, depending on the axis of the induced astigmatism and on the natural astigmatism of the subjects, if present. Due to the added positive spherical power of half the cylindrical power, the VA drop due to 1.00 diopters of cylindrical power in this work should be compared with the 0.50 diopters drop in Hughes et al<sup>23</sup>. Therefore the values shown in Figure 3a at far ( $0.22\pm 0.06$  diopters<sup>-1</sup> and  $0.18\pm 0.06$  diopters<sup>-1</sup> for the two axis orientations) are in very good agreement with the results of Hughes et al (from  $0.26\pm 0.09$  to  $0.45\pm 0.12$ ).<sup>23</sup> On the contrary, a lower slope was found by Serra et al,<sup>26</sup> who studied the influence of 2.00 diopters lens-induced astigmatism on VA at far and found a VA worsening ranging from 0.19 to 0.28 logMAR. Since no spherical compensation was added,<sup>26</sup> the slopes in Figure 3a ( $0.22\pm 0.06$  diopters<sup>-1</sup> and  $0.18\pm 0.06$  diopters<sup>-1</sup> for the two axis orientations) should be compared with  $\frac{1}{4}$  of the drop reported by Serra et al ( $\frac{1}{4}$  of  $0.19–0.28$ ).<sup>26</sup> The agreement is relatively poor, the slopes in Figure 3a being three to four times greater. Also, Casagrande et al<sup>29</sup> investigated the effect of astigmatism on VA. They evaluated near vision performances. Participants were fogged with cylindrical lenses. These authors evaluated the effect of WTR astigmatism ( $-1.50$  diopters), which resulted in 0.09 logMAR worsening of near VA compared with no cylinder power added. Since no spherical compensation was added,<sup>29</sup>  $\frac{1}{3}$  of 0.09 should be compared with  $0.15\pm 0.05$  and  $0.12\pm 0.05$  diopters<sup>-1</sup> (Figure 3a).

From the measurements conducted in the present study, it emerges that the most marked VA worsening induced by astigmatism clearly occurred at far with HC stimuli in photopic conditions, showing a significant difference compared to the steepness of the VA drop at near (Figure 3 and Table 4). It must be said that, although the assessments were conducted on the same subjects in the same environment, some methodological differences between far and near measurements were inevitable. The near test was on paper, while at far the measurements were carried out with an LCD system. VA at far distance was measured using an isolated line of letters, while all lines of the chart were simultaneously visible during near measurements. Changes of the interpupillary distance were not taken into consideration between far and near conditions. The likely decrease in pupil size at near due to convergence was not compensated. Nevertheless, without any added cylinder, the data acquired at near in photopic conditions and HC stimuli provided similar results as the corresponding analyses performed at far (Table 2). Conversely, in the same experimental condition the slopes of the VA drop in the presence of astigmatism were significantly different (Figure 3a and Table 4). The tendency of the eye toward an inherent astigmatism at near depending on the accommodative demand could be a possible explanation for the greater tolerance to astigmatism blur.<sup>57–59</sup> This tolerance could be due to an experience-mediated neural compensation, similarly as found in case of spherical defocus blur for subjects with relatively high myopia, but further investigations are required.<sup>34,37–39,41,57–60</sup> This compensation is expected to be a long-term neural adaptation that takes place at the brain level of the visual pathway to compensate a reduction in optical quality of the retinal image.

Concerning the axis orientation, Tsukamoto et al found a greater accommodative response at near in the vertical meridian than in the horizontal meridian in binocular condition in emmetropes (WTR accommodative astigmatism).<sup>58</sup>

Lee et al found that WTR astigmatism and oblique astigmatism were increased on near vision.<sup>59</sup> Overall, a tendency toward WTR astigmatism at near is reported,<sup>58,59,61</sup> so that a greater WTR blur tolerance might be expected. On the contrary, age is expected to lead to an ATR astigmatism which could make presbyopes less sensitive to ATR blur.<sup>43,47</sup> In this study, no significant differences were found between the VA worsening for WTR and ATR orientations (Table 5). In the sample examined in this work, there are subjects with natural astigmatism whose axis could influence the difference between WTR and ATR, as discussed in the literature.<sup>23,24,30</sup> The interference between all these aspects (WTR accommodative astigmatism, ATR age astigmatism, natural astigmatism) may have influenced the possibility of observing clear dependencies on the axis of the lens-induced astigmatism.

Unlike the measurements in the photopic environment, the clear difference between VA worsening at near and at far due to lens-induced astigmatism was not observed in mesopic conditions.

## Conclusion

The VA degradation due to lens-induced astigmatism (with a positive spherical power equal to half the negative cylindrical power in order to keep the Sturm's conoid centred on the retina) has been investigated in myopic eyes with presbyopia. A linear trend was found for the measured VA (logMAR) as a function of the lens-induced astigmatism in all investigated experimental conditions.

In photopic conditions with HC stimuli, the tolerance to astigmatism blur was found better at near than at far distance. This is here tentatively attributed to a possible long-term experience-mediated neural compensation associated to the tendency of the eye toward an inherent astigmatism at near, similarly as found in the literature in case of spherical defocus blur for subjects with relatively high myopia.

## Disclosure

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