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Perceptual impact of astigmatism induction in presbyopes

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ABSTRACT

We investigated the effect of induced astigmatism on subjective best focus and on visual acuity in 28 subjects of different ages (pre-presbyopic and presbyopic) and with different refractive profiles (emmetropes and astigmats). Measurements were performed using a custom-developed Adaptive Optics system, which allowed correction of high order aberrations and induction of astigmatism (0.5, 1, 1.5 and 2.0 D; axis: 180°, 45° and 22.5°). Upon induction of astigmatism, best focus shifted towards negative values in pre-presbyopic emmetropic eyes (by −0.14 D for 0.5 D and by −0.33 D for 2.0 D), while it shifted towards positive values in presbyopes, both in emmetropic presbyopes (by +0.04 D for 0.50 D and by +0.16 D for 2.0 D) and in astigmatic presbyopes (by +0.23 D for 0.50 D and by +0.40 D for 2.0 D). Also, visual acuity was most sensitive to astigmatism induction in pre-presbyopic emmetropes and least sensitive in presbyopes, particularly when high order aberrations were corrected: visual acuity ratio with/without astigmatism was: 0.74/0.85/0.98 (for astigmatism induced at 180°) and 0.68/0.73/0.86 at 45°, for pre-presbyopic emmetropes/presbyopic emmetropes/presbyopic astigmats. These findings may be connected to long term exposure to astigmatism in astigmats and corrected presbyopes.

1. Introduction

With age, the capability of the crystalline lens to dynamically focus near and far is lost, thus optical solutions are needed to produce functional vision at different distances. Solutions for presbyopia include multifocal contact lenses (which work on the principle of simultaneous vision) and progressive ophthalmic lenses (which work on the principle of alternating vision) (Mancil et al., 2011). Multifocal contact lenses impose blur on the retinal image as they superimpose on the retina images focused at different distances. In progressive lenses, the upper part of the lens compensates for the optical refraction at far, and progressively increases the optical power to provide a near add in the lower part of the lens, with an optical corridor for intermediate distances in the center of the lens. This change of optical power results in aberrations in the peripheral regions of the lens, in particular in astigmatism (Guilino, 1993; Villegas & Artal, 2004). In general, presbyopes wearing presbyopic corrections appear to adapt to the new visual experiences, to both blur in simultaneous vision images (Radhakrishnan, Dorronsoro, Sawides, & Marcos, 2014) as well as to distortions and to the presence of asymmetric aberrations produced by progressive lenses (Alvarez, Kim, & Granger-Donetti, 2017), in consistency with reported mechanisms of spatial neural adaptation (Sawides, de Gracia, Dorronsoro, Webster, & Marcos, 2011)

In general, understanding how presbyopic lens designs can be improved, and even customized to the patient's refractive profile, requires understanding focus perception in presbyopic patients and to what extent visual perception with a new correction is affected by prior visual experience. Previous studies have shown adaptation to astigmatism (Hughes, Mallen, & Elliott, 2016; Marcos et al., 2015; Vinas et al., 2013), reflected by a strong bias in the perception of blur orientation.

There are several reports of changes in perceived best focus setting following changes in visual experience. In particular, we found that subjects shift their neutral best perceived focus following brief periods of adaptation to simulated astigmatic images (Sawides, Marcos et al., 2010). Furthermore, naturally astigmatic subjects perceive as isotropic images that are blurred along their axis of astigmatism. Following correction of their natural astigmatism, the neutral best focus shifts towards isotropy (Vinas, Sawides, de Gracia, & Marcos, 2012). In addition, young astigmatic subjects appear to be more sensitive to the reduction of visual acuity upon induction of astigmatism than non-astigmats (de Gracia, Dorronsoro, Marin, Hernández, & Marcos, 2011), particularly when astigmatism is induced along the axis of their natural

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astigmatism (Vinas et al., 2013). Other studies have shown that subjects are not only adapted to their native astigmatism, but also to the magnitude (Sawides et al., 2011) and orientation (Artal, 2004; Sawides, Marcos et al., 2010; Hughes et al., 2016) of their own aberrations, and that the best perceived focus shifts following adaptation to high order aberrations (Marcos et al., 2015). Achieving optimal best focus is key to providing best optical quality with a correction. Defocus, astigmatism and high order aberrations interact optically, as demonstrated from optical simulations (Applegate, Ballentine, Gross, Sarver, & Sarver, 2003), and experimentally using Adaptive Optics (Marcos, Sawides, Gambra, & Dorronsoro, 2008). These interactive effects across aberrations and their impact on subjective spherical error need to be considered when the correcting alternatives simultaneously induce astigmatism and high order aberrations, as it is the case with progressive lenses. Also, it has been observed that prior adaptation to astigmatism also plays a major role in the way certain optical corrections work, as well as in the selection of best focus. In a previous study we found that certain combinations of astigmatism and coma increase optical quality through focus (compared to astigmatism alone) (de Gracia et al., 2010). However, the benefit of the interactive effects of coma and astigmatism appears to be much lower in habitually non-corrected astigmats (de Gracia et al., 2011.). On the other hand, the best focus setting is shifted in the presence of astigmatism, and the actual shift depends on the refractive profile of the patient (Marcos et al., 2015). The fact that the same best focus shift trends were found when aberrations were corrected with adaptive optics indicates that this shift is primarily a result of prior adaptation. Those previous studies investigated adaptational effects to astigmatism, and the impact of astigmatism on visual function and on best focus setting in young subjects of different refractive profiles (emmetropes, myopes and hyperopes, non- astigmats or habitually/non-habitually corrected astigmats) (Marcos et al., 2015). However, to our knowledge, these effects have not been investigated in presbyopic subjects (i.e. subjects that do not or minimally accommodate, and need presbyopic correction).

In this study, we investigated shifts in subjective best focus upon induction of astigmatism, and the effect of astigmatism induction on visual function in presbyopes, in comparison to a pre-presbyopic emmetropic group, to assess the effect the presence of astigmatism (measurements were done on emmetropic and astigmatic presbyopes) and of presbyopic correction wear (progressive addition lenses) on subjective best focus when astigmatism is induced.

2. Methods

Best focus and Visual Acuity (VA) were measured in three groups of subjects with different refractive profiles (pre-presbyopic emmetropic and emmetropic presbyopic and astigmatic presbyopes), under natural aberrations and under corrected aberrations with Adaptive Optics, upon induction of astigmatism (different amounts and orientation). Differences in the best focus setting and VA across subjects and conditions were evaluated.

2.1. Subjects

A total of 28 caucasian subjects participated in the study. Subjects followed an optometric and ophthalmological evaluation at School of Optometry Clinic of the Universidad Complutense de Madrid (UCM). Subjects were classified in three groups, according to their age (pre-presbyopic subjects and corrected presbyopic subjects) and refractive profile (emmetropes or astigmats). Table 1 shows the patients' profile of the subjects in the three groups (G1): pre-presbyopic emmetropic group ($n = 10$), spherical error -0.5 to $+0.5$ (0.1 ± 0.36 D on average); cylindrical error ≤ 0.25D; age: 29.3 ± 6.5 years. (G2): emmetropic presbyopic group; ($n = 8$); spherical error: -0.5 D to $+1.5$ (0.47 ± 0.7 D on average); cylindrical error ≤ 0.25D; addition: 2.4 ± 0.35 D; age: 62.6 ± 6.3 years. (G3): astigmatic presbyopic group ($n = 10$); spherical equivalent: -0.8 ± 1.84 D; cylinder -1.52 ± 0.4 D (S1, S9 & S10 against the rule, and the rest with the rule); addition: $+2.28 \pm 0.28$ D; age: 56 ± 4 years. Presbyopic subjects used progressive ophthalmic lenses (PALs) to correct their presbyopia (having worn them between 6 months to 3 years by the time of participation in the study), and therefore exposed long-term to astigmatism induced by PALs.

The experiment was performed on one eye (in bold in Table 1), with its refraction meeting the inclusion criteria. If both eyes were eligible, measurements were performed on the dominant eye. Protocols met the tenets of the Declaration of Helsinki and were approved by the Institutional Review Board. Subjects signed an informed consent following explanation of the nature of the study.

2.2. Experimental set-up

Measurements were performed with a custom-developed Adaptive Optics (AO) system, described in detail previously (Sawides, Gambra, Pascual, Dorronsoro, & Marcos, 2010). The system is provided with a Hartmann-Shack wavefront sensor (32x32 microlenses; HASO 32 OEM, Imagine Eyes, France), a superluminescent diode ($\lambda = 827$ mm) for illumination, an electromagnetic deformable mirror (52 actuators and 50 mm stroke; MIRAO, Imagine Eyes, France), a motorized Badal system, a subject's pupil continuously monitoring channel (LED ring illuminator and a CCD camera), and a psychophysical channel (CRT monitor, Mitsubishi Diamond Pro2070, with an angular subtend of 2 deg). All optoelectronic elements are controlled by a C++ software and Matlab program. Visual stimuli were seen through a maximum of 5 mm pupil diameter, limited by an artificial pupil placed in a conjugate pupil plane.

2.3. Best-focus search method

Best focus was systematically searched using a staircase algorithm, based on four interleaved staircases with random initial position (Marcos et al., 2015). Focus shifts were achieved using a motorized Badal optometer, which allows adding positive or negative sphere power (in 0.125 D steps) until the optimal appearance of a natural gray-scale image (consisting of a face) is reached, according to the subject's responses. The algorithm is based on a randomized-step efficient method, where the subject reports (using two buttons in a keyboard) whether the image presented in the display appears more blurred or sharper than the precedent image. The maximum number of trials in each staircase was 40 and best focus was selected after a maximum number of 20 reversals. The four interleaved staircases start in different initial values (-0.75, -0.50, $+0.50$ and $+0.75$ D) from an initial focus setting manually searched by the subject while looking at the Maltese cross stimulus. The best focus was defined as the average of the last 8 reversals.

2.4. Visual acuity measurement method

A tumbling E-letter test was used to measure Visual Acuity (VA). Snellen E letters of varying size (white E-letters on a black background) were presented at 8 random orientations. The subject's task was to identify the orientation of the E letter. The size of the E-letter in the subsequent presentation was changed depending on the subject's response using a quaternion estimation algorithm. A run consisted of 50 trials and 20 reversals, and the visual acuity was measured as the mean of the last 10 reversals.

2.5. Experimental protocol

Measurements were performed under cycloplegia with tropicamide 1%, one drop instilled at the beginning of the session and then every 60 min (3 drops instilled per session). After dilation, the subject's pupil

Table 1
Participating subject's profile: age, days between sessions and refraction of both eyes (measured eye in bold).

		Age	Days between sessions	OD			OS			Add
				Sph	Cyl	Axis	Sph	Cyl	Axis	
G1	**S#1**	23	2	**−0.50**	**–**	**–**	−0.50	−0.50	180°	–
	S#2	31	71	**0.00**	**–**	**–**	0.00	–	–	–
	S#3	24	57	**0.50**	**–**	**–**	0.50	–	–	–
	S#4	38	1	−0.25	–	–	**0.25**	**–**	**–**	–
	S#5	37	3	**0.25**	**–**	**–**	0.25	–	–	–
	S#6	24	14	**0.25**	**–**	**–**	0.25	–	–	–
	S#7	23	49	**0.50**	**–**	**–**	0.50	–	–	–
	S#8	36	81	**−0.50**	**−0.25**	**2°**	0.00	−0.75	13°	–
	S#9	34	96	–	–	–	**0.00**	**–**	**–**	–
	S#10	23	22	2.50	–	–	**0.25**	**–**	**–**	–
	Mean	**29.3**		**0.10**	**−0.03**					
	std	**6.5**		**0.36**	**0.08**					
G2	**S#1**	55	1	**0.00**	**−0.50**	**80°**	1.00	–	–	2.5
	S#2	67	9		–	–	**1.50**	**−0.50**	**105°**	2
	S#3	75	2	1.00	–	–	**0.00**	–	–	2.5
	S#4	61	3	1.25	−0.50	10°	**0.75**	–	–	2.5
	S#5	61	5	−1	−0.25	43°	**−0.25**	–	–	2.75
	S#6	65	30	**0.00**	–	–	0.00	0.75	90°	2.75
	S#7	60	32	**1.50**	–	–	1.50	–	–	2.5
	S#8	57	12	**0.25**	**−0.50**	**120[a]**	0.50	−1.00	80°	1.75
	Mean	**62.6**		**0.47**	**−0.19**					**2.40**
	st	**6.32**		**0.7**	**0.25**					**0.35**
G3	**S#1**	58	10	**0.25**	**−1.25**	**95°**	1.00	−1.25	85°	2.75
	S#2	56	3	**0.25**	**−1.50**	**180°**	−0.25	−1.00	169°	2.5
	S#3	54	2	**−1.25**	**−2.00**	**5°**	−1.50	−2.00	15°	2
	S#4	56	4	**0.00**	**−1.00**	**180°**	0.25	−0.50	180°	2
	S#5	51	2	**1.25**	**−1.50**	**18°**	1.00	−0.50	0°	2.25
	S#6	55	5	−2.50	−2.50	175°	**−2.75**	**−2.00**	**180°**	2.5
	S#7	62	5	0.50	−2.00	10°	**0.00**	**−2.00**	**170°**	2
	S#8	50	9	**1.25**	**−1.75**	**5°**	1.75	−2.50	170°	2.25
	S#9	56	18	−3.75	−0.50	90°	**−3.75**	**−1.00**	**80°**	2
	S#10	62	2	**−3.25**	**−1.25**	**95°**	−3.50	−0.75	100°	2.5
	Mean	**56**		**−0.80**	**−1.53**					**2.28**
	std	**4.0**		**1.84**	**0.40**					**0.28**

eye was aligned to the optical axis of the instrument, with the subject stabilized using a dental impression on a bite bar. The subject's spherical error was corrected with the Badal system. The optical aberrations were measured. The following states of the mirror were searched in a closed-loop operation and saved in the computer to be used when applicable: (1) correction of subject's high order aberrations; (2) correction of the subject's astigmatism alone; (3) induction of astigmatism (0.5, 1, 1.5 and 2 D, at 180, 45 and 22.5°).

Measurements (best focus search and visual acuity) were performed in two different sessions (Table 2), conducted in two different days. Table 1 shows the difference between sessions for each subject. In the first session, the best focus was searched using the staircase procedure, for different amounts of induced astigmatism (0, 0.50, 1.5, 2.00 D at 180°); with natural high order aberrations (correcting astigmatism) and with all high order aberrations corrected using Adaptive Optics. Measurements were also performed for 1.00 D of induced astigmatism at 180° in the AO-correction condition (this condition was repeated in the second session).

In a second session, best focus was search for 1-D astigmatism induced at 180°, 22° and 45°, and Visual Acuity was measured for 1-D astigmatism induced at 180° and 45°, with natural aberrations and AO-correction. Best focus and visual acuity were also measured without induction of astigmatism (with and without aberration correction). Under induced astigmatism, Visual Acuity was measured with both the initial search focus and with the staircase-searched best focus.

Table 2
Conditions tested in each session.

Session A Magnitude of induced astigmatism		Session B Angle of induced astigmatism	
Nat	AO	Nat	AO
0.5D 180° BF 1.50D 180° BF 2.00D 180° BF	0.5D 180° BF 1.00D 180° BF 1.50D 180° BF 2.00D 180° BF	1.00D 180° BF + VA 1.00D 45° BF + VA 1.00D 22.5° BF	1.00D 180° BF + VA 1.00D 45° BF + VA 1.00D 22.5° BF
Duration: 120 min		Duration: 120 min	

2.6. Data analysis

Optical aberrations were described using a Zernike polynomial expansion following the OSA Standards for the report of ocular aberrations (ANSI Z80, 2004). Root-Mean-Square of High Order Aberrations (RMS HOA) was used as optical quality metric.

A Mixed Model Analysis with two fixed factors (group and induced astigmatism (0.5, 1, 1.5 and 2.00 D; axis: 180°, 45° and 22.5°) and subject as a random factor in Repeated Measures was used to evaluate the differences between groups in the change of best perceived focus and Visual Acuity with induced astigmatism. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Measured, induced and corrected aberrations

Optical aberrations were measured before correction (Fig. 1, natural

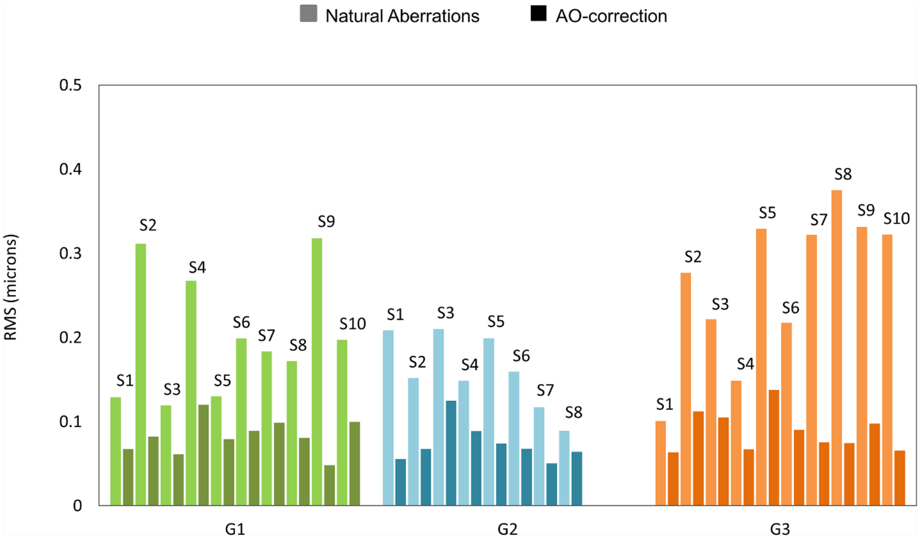

Fig. 1. Root-Mean-Square (RMS) wavefront error of astigmatism and HOAs for all subjects of the study for natural aberrations (light bars) and AO-corrected aberrations (dark bars). Data are for 4.08-mm pupil diameters. G1: Pre-presbyopic emmetropic group; G2: Presbyopic emmetropic group; G3: Presbyopic astigmatic group.

aberrations), after closed-loop correction of HOA (Fig. 1, AO-correction) and after induction of astigmatism. Maximum pupil diameters ranged from 5.17 to 4.08 mm. Data were re-scaled to the smallest pupil for averaging across subjects. On average, residual RMS following AO-correction was 0.11 ± 0.13 µm (for 4.08-mm pupil). There were no statistically significant differences across groups in the natural RMS wavefront error for high order aberrations ($p = 0.23$), nor in the RMS of the residual aberrations after AO-correction ($p = 0.19$). Natural spherical aberration was 0.027 (G1), 0.032 (G2) and 0.040 (G3) µm for 4.08-mm pupils. As expected (Calver, Cox, & Elliot, 1999), the presbyopic groups (G2 and G3) showed higher spherical aberration, although differences were not statistically different across groups (p-value = 0.51).

The attempted astigmatism magnitude was induced with an accuracy of 3% (on average across subjects and the four induced magnitudes) and the attempted angle was induced within 10% (on average across subjects and the three induced orientations). Fig. 2 shows the difference in the best focus when HOAs are corrected in comparison with the best focus found with Natural aberrations.

3.2. Best focus shift with induced astigmatism magnitude and angle

In the majority of subjects, there was a shift in the best focus position upon correction of high order aberrations, and also upon induction of astigmatism. When astigmatism and HOA aberrations were corrected with AO, best focus shifted by 0.05 D (G1), −0.19 D (G2) and −0.08 D (G3). Shifts in best focus for different amounts of induced astigmatism were measured with natural aberrations and AO-correction, relative to the respective best foci without induced astigmatism. Fig. 3 A-F shows the shift in best focus for all subjects in each group: G1 (A, B); G2 (C, D) and G3 (E, F) as a function of the magnitude of induced astigmatism, with natural aberrations (A, C, E) and AO-correction (B, D, F). Each symbol represents the average of four repeated focus settings for each individual subject. The average standard deviation across repeated measurements across all subjects was 0.28 D (natural aberrations) and 0.26 D (AO-correction).

In pre-presbyopic emmetropic subjects (G1), there was a consistent shift towards negative defocus, which tended to be higher, the higher the magnitude of induced astigmatism. Best focus values shifted towards less negative defocus (emmetropic presbyopes, G2) or towards predominantly positive defocus (astigmatic presbyopes, G3). The shift in best focus produced by astigmatism in G1 was statistically different from G2 when aberrations were corrected, for all magnitudes of induced astigmatism ($p < 0.04$ for 0.50D of astigmatism induced; $p < 0.015$ for 1.00D, 1.50D and 2.00D). S7 of emmetropic presbyopes group (G2), presents a slightly higher best focus shift in the condition of

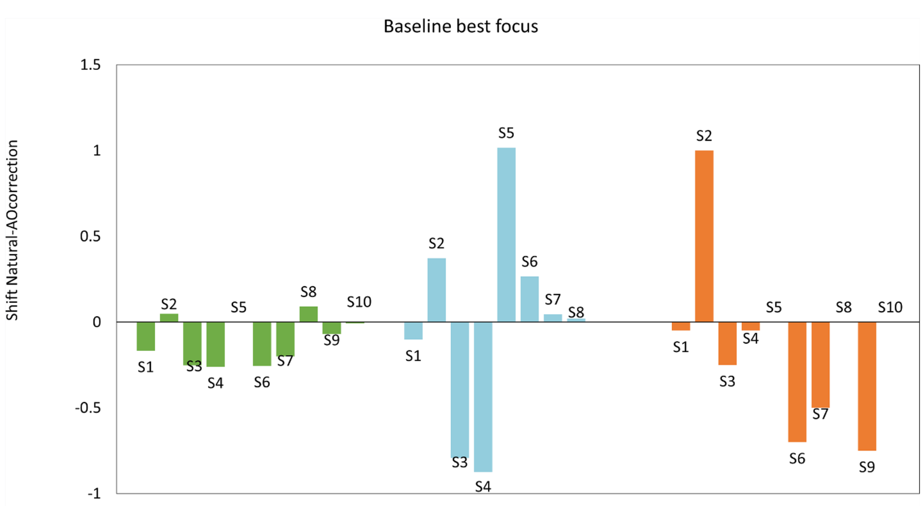

Fig. 2. Baseline (no astigmatism) best focus point for all subjects, relative to the best focus point in the presence of natural aberrations. The values shown in graph represent the focus shift when HOA are corrected.

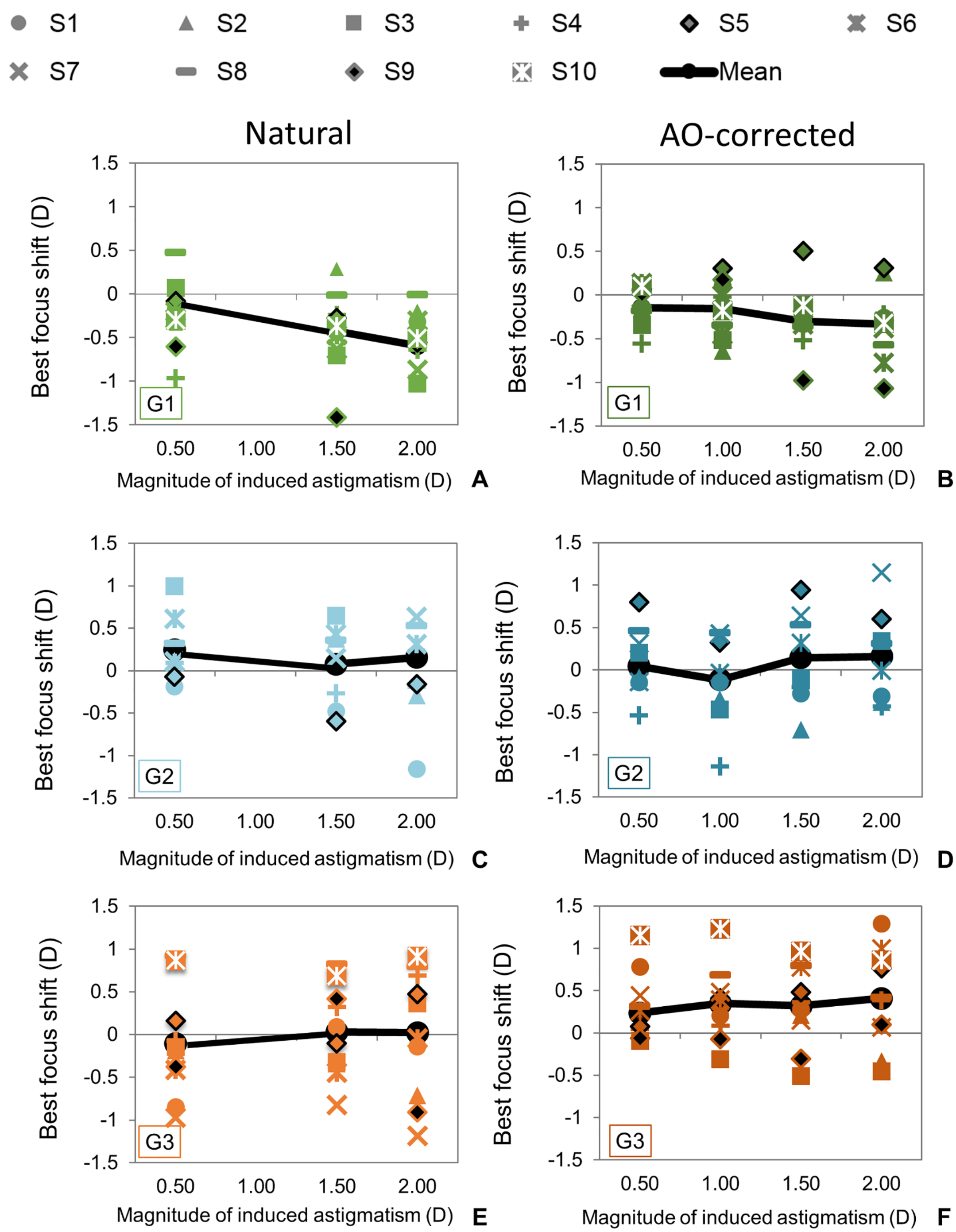

Fig. 3. Shift of best focus setting as a function of induced astigmatism (with respect to the not-induced astigmatism condition), for all subjects in G1 (A, B), G2 (C, D) and G3 (E, F). Left: Natural correction; Right: AO-correction. A positive shift indicates a focus shift towards horizontally oriented blur in the retina, and a negative shift towards vertically oriented blur in the retina.

2.00 D of astigmatism induction with HOA correction, that may be caused by furthest from strict emmetropia in this group.

One condition (1.00D 180° AO-corrected) was repeated in both sessions. An inter-session variability analysis showed no statistical differences between these repeated measurements in any group. However, we found statistical differences in the best focus setting across groups upon induction of astigmatism: best focus in general significantly shifted towards more negative values in G1 (both under natural and AO-corrected aberrations), towards less negative values (under natural aberrations) or even positive values (under AO-corrected aberrations) in G2, and towards more positive values (under AO corrected aberrations) in G3. Statistical significance values are shown in Fig. 4.

In general, the best focus shift was independent of the angle at which astigmatism was induced for measurements performed both under natural aberrations or under AO-correction (Fig. 5). Only astigmatism induced at 180° resulted in slightly higher shift in G1. The best focus shift was more positive in the presbyopic groups than in the pre-presbyopic group at all angles, with the astigmatic presbyopes (G3) exhibiting the more positive shifts. The shift in best focus produced by astigmatism in G1 was statistically different from G2 at all angles ($p < 0.015$, $p < 0.02$, for astigmatism induced at 180° and 22.5°, and 45° respectively).

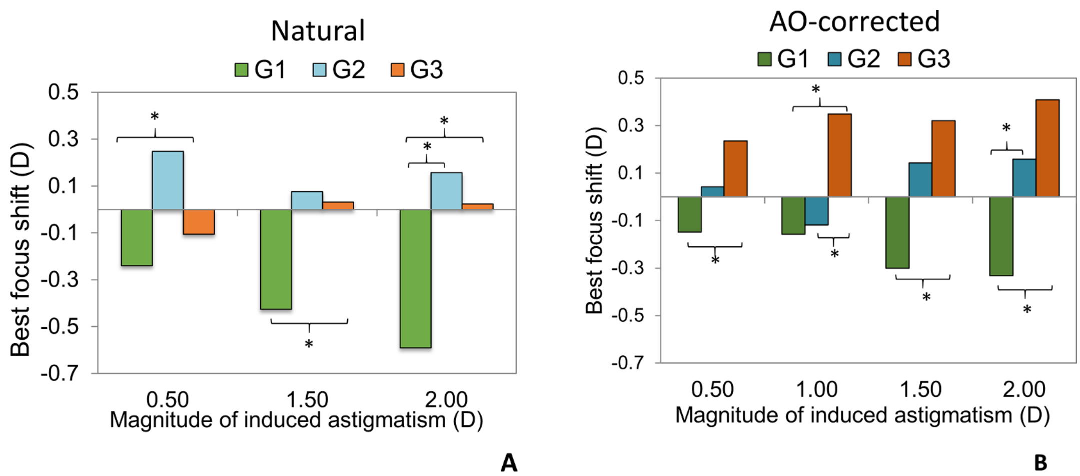

Fig. 4. Average best focus shift across subjects in each group upon induction of astigmatism. Left: Natural aberrations; Right: AO–corrected aberrations. *p- ≤ 0.05. A positive shift indicates a focus shift towards horizontally oriented blur in the retina, and a negative shift towards vertically oriented blur in the retina.

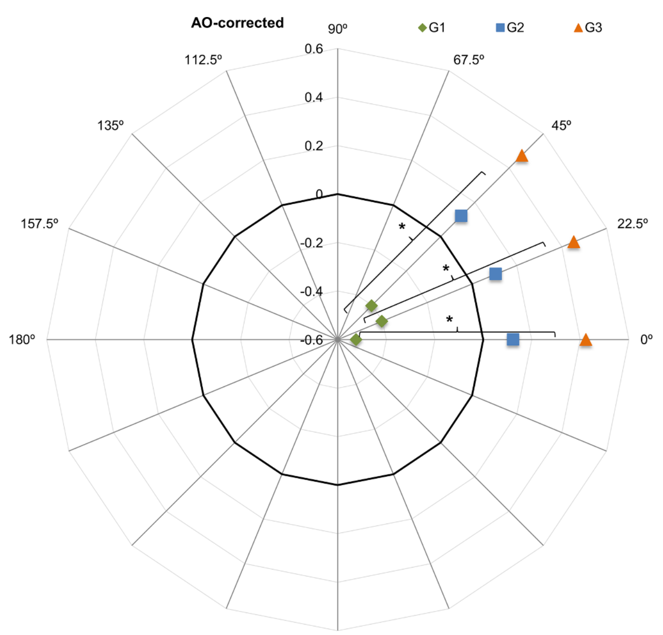

Fig. 5. Average mean best focus shift across subjects in each group upon induction of 1.00D of astigmatism at different angles, for AO–corrected aberrations. *p-values ≤ 0.05.

3.3. Decimal visual acuity

Pre-presbyopic emmetropic subjects (G1) showed the highest VA, and the astigmatic presbyopic group (G3) the lowest VA, and the differences were statistically significantly different under AO-correction ($p < 0.01$). VA improved significantly ($p < 0.01$) in pre-presbyopic emmetropic subjects (G1) and in emmetropic presbyopes (G2) when astigmatism and HOA were corrected, but not in astigmatic presbyopes (G3). Induction of astigmatism produced the largest degradation of VA for G1, particularly when astigmatism was induced at 45°, and the lowest degradation of VA for G3, which appeared rather insensitive to induction of astigmatism, particularly at 180°.

Fig. 6 shows decimal VA under natural aberrations (left columns) and AO-correction (right columns) without astigmatism and with astigmatism induced at 180° and 45°, for G1 (A), G2 (B) and G3 (C). Measurements were performed at the initial focus setting without astigmatism (Ini), which was different for the Natural and AO-corrected conditions, and the focus setting obtained following the staircase procedure (SC).

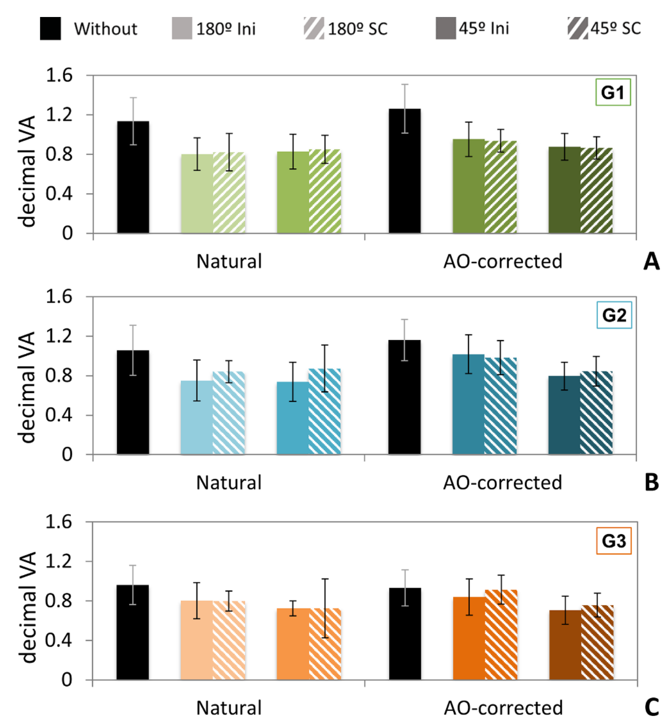

Fig. 6. Decimal Visual Acuity without astigmatism induction (black bar) and for 1.00D of induced astigmatism (measured at the initial best focus setting, Ini, –prior to astigmatism induction, solid colored bars- and at the best focus setting following the staircase procedure, SC –upon astigmatism induction, dashed bars-). Lighter bars in each panel stand for 1D of astigmatism induced at 180° and darker bars for astigmatism induced at 45°. Data are for Natural Condition (left panels) and AO-correction (right panels for the three groups (A, G1, pre-presbyopic emmetropes; B, G2, emmetropic presbyopes; C, G3, astigmatic presbyopes). Error bars are SDs.

Fig. 7 shows the decrease in Decimal VA in terms of ratios of VA with induced astigmatism (at best focus)/VA without astigmatism, for all groups and conditions. The VA Ratio with/without induced astigmatism was higher in G2 and G3, indicating that presbyopes are less sensitive to the induction of 1D of astigmatism, both at 180° and 45°, especially when natural aberrations were corrected. All groups experienced a larger decrease in visual acuity when astigmatism was induced at 45° than at 180°, more remarkable under AO-correction.

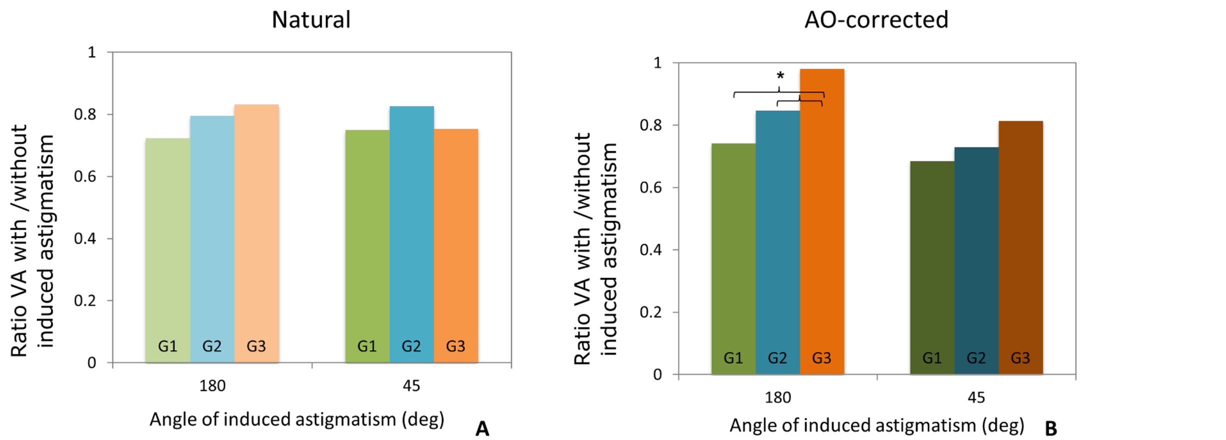

Fig. 7. Ratio VA with astigmatism/VA without astigmatism Ratios, for 1.00D of astigmatism induced at 180° or 45°, under natural aberrations (A, left panel) and AO-correction of aberrations (B, right), for the three groups (G1, in green; G2 in blue; G3 in orange). *p-values ≤ 0.05. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

We measured the impact of inducing astigmatism in pre-presbyopic emmetropes and two groups of presbyopic patients, non-astigmats and astigmats. All patients in both presbyopic groups were PAL wearers, therefore exposed to a visual experience consistent with the presence of astigmatism produced by progressive power changes in their spectacle correction. The best focus setting in the presence of astigmatism as well as the Visual Acuity with induced astigmatism was compared to a control group of pre-presbyopic emmetropes. We found that presbyopes, most prominently those that were natural astigmats, showed significant differences in the impact of astigmatism induction on best focus setting and on Visual Acuity, compared to pre-presbyopic emmetropes. Since it was not possible to include an age-matched presbyopic group not wearing any presbyopic correction, given that the majority of the population of this age wears some sort of correction aid for their presbyopia, we cannot rule out that the predominant factor in the effect is age or the correction, and it is likely a combination of the two. Despite the relatively small number of subjects in each group, the groups are equality distributed and their variance is homogenous and follow a normal distribution, resulting in a statistical power of ~70%.

Our results in emmetropes are in good agreement with a prior study on young subjects where we compared best focus settings upon 1-D induced astigmatism in young emmetropes (myopes, and hyperopes), as well as in young myopic astigmats (Marcos et al., 2015). For the same age group and refractive profile (Fig. 8, red triangle and blue triangle, emmetropic subjects, EM) we found a similar shift in best focus towards negative values (around −0.35 D) upon induction of 1.00 D of astigmatism. Fig. 8 also compares findings of best focus shift in young emmetropes and young astigmats of a prior study (Marcos et al., 2015) with presbyopic emmetropic subjects (G2) and presbyopic astigmats (G3) of the current study, now divided in astigmats with the rule (WTR) and astigmats against the rule (ATR). Similarly to our earlier reported on young astigmats (Marcos et al., 2015), we found that presbyopes also shift their perceived best focus toward less negative defocus values (or positive) in the presence of astigmatism, with largest shifts occurring in the presbyopic astigmats. A positive shift is consistent with horizontally oriented blur in the retina, and a negative shift is consistent with vertically oriented blur in the retina. It should be noted that the aberrations were corrected in monochromatic light, allowing for potential natural interactions between chromatic and monochromatic aberration to occur (McLellan, Marcos, Prieto, & Burns, 2002). In any case, that the wavelength that is best focused when polychromatic targets are focused is close to 555 nm (Coe, Bradley, & Thibos, 2014), suggesting that at least, in general best focus settings should not be biased by chromatic effects, although may be the cause behind some intersubject variation).

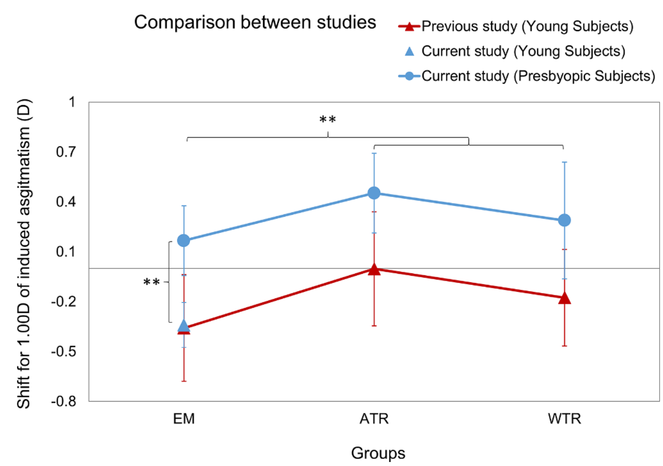

Fig. 8. Shift in best focus upon induction of 1.00D of astigmatism at 180°, in presbyopes (blue circles, current study) and young subjects (triangles, from the current study -blue- and Marcos et al., 2015 -red-).). EM stands for Emmetropes, ATR for Against the Rule Astigmats and WTR for With the Rule Astigmats. Shifts in best focus with induced astigmatism parallel in young and presbyopic subjects, but in presbyopes they are significantly more positive in all refractive groups (**p-≪0.01). Shifts in the young emmetropic subjects of the two studies are not statistically different. Error bars are SDs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The reasons for the consistent negative shift found in young emmetropes in all studies are not clear, but may be connected to a lower reduction in visual acuity with vertical blur (as opposed to other orientations) found in emmetropes (Vinas et al., 2013) and also reported in this study (Fig. 6). Interestingly, in the current study, which examined induction of astigmatism at various orientations, the largest shift in emmetropes occurred at 180° (when high order aberrations are corrected). On the other hand, while in the prior study the consistent positive shift in best focus upon induction of astigmatism at 180° was only found in ATR astigmats (explained by the fact ATR myopic astigmats would be naturally adapted to horizontal blur in the retina), in the current study a more positive blur is found regardless the axis of native astigmatism (i.e. both in ATR and WTR astigmats). These findings may be explained by the fact that older subjects have higher amounts of aberrations (although differences did not reach statistical significance in our cohort) or by adaptation effects produced by their habitual presbyopia correction, as progressive ophthalmic lenses may induce horizontal, vertical and oblique astigmatism (even for the non-natural astigmats of G2). Intersubject variabilities in this effect could not be associated to a particular characteristic (refraction or aberration magnitude), particularly as the range of spherical error was slightly higher in G3 than in the other groups. While the PAL induced astigmatism is mostly peripheral (intermediate corridor), and prior work has shown little effect of peripheral blur adaptation to central vision perception (Venkataraman, Radhakrishnan, Dorronsoro, Lundström, & Marcos, 2017), the integrated vision at all distances in PAL wearers is likely more affected by astigmatism than in non-PAL wearers. Aberrations are expected to affect also foveal vision, as the eye looks through different parts of the lens (Villegas & Artal, 2003). Longer-term exposure to astigmatism in native astigmats may explain the larger best focus shifts differences in this group. Under corrected aberrations, the best focus shift was consistently positive for all magnitudes of induced astigmatism in all subjects of G3, except in two subjects (S3, a WTR astigmat, and S9, an ATR astigmat), for astigmatism induced at all different orientations. The clear difference on the axis-dependency of the best focus shift upon induced astigmatism between pre-presbyopic and presbyopic astigmats may be associated to age, presbyopia (accommodation not being able to scan through the Sturm interval in neither myopic nor hyperopic presbyopes) or potential differences between the astigmatic correction wear in non-presbyopic subjects and that of the habitual presbyopic correction in presbyopic subjects. It is also likely that the observation made in young astigmats (Yehezkel, Dov Sagi, Sterkin, Belkin, & Polat, 2010) that adaptation can be actually transferred to a long-term storage that can be instantly engaged when blur is reapplied, can also hold in older subjects wearing PALs. Measurements were made for a fixed pupil diameter. We can only speculate on the effects of the natural pupil size (and their influence on retinal bur) on adaptation, as to the best of our knowledge, this has not been systematically evaluated. The magnitude of the blur level and (to a lesser extent) the blur orientation depend on the pupil diameter. Yehezkel et al. (2010) also pointed out to the potential learned ability of storing multiple transformations of the visual world, allowing observers to switch between different states of adaptation, which, regarding the pupil may correspond to different pupil diameters.

Potential adaptation to astigmatism in presbyopic correction wearers and indications of a prior adaptation to astigmatism in native-astigmat presbyopes is also evidenced by the different impact of astigmatism induction on Visual Acuity, found in the current study. As reported in recent studies, we found that emmetropes experienced the largest degradation (lower VA with astigmatism/without astigmatism Ratios) when astigmatism was induced. Astigmatism induced at 180° imposed less degradation than when it was induced at 45°, also as previously found (Vinas et al., 2013). On the other hand, astigmatic presbyopes were the least sensitive to the induction of astigmatism, with minimal degradation (Ratio with astigmatism/without = 0.98 in G3) for astigmatism induced at 180° (with aberrations corrected).

Differences between the native astigmatism angle and induced astigmatism (at 180°) ranged between 0–20 deg (7 subjects) and 80–90 deg (3 subjects). We did not find a systematic difference neither in the defocus shift or decrease in VA with induced astigmatism, as a function of angle difference. We only found higher variability in the measured best focus shift value in patients with native against the rule than in patients with the rule astigmats (1.80 D vs 0.63 D), but not a difference in the shift sign. Our results suggest then that it is rather the presence of astigmatism, rather than the sign (horizontal or vertical), the main contributor to the effect. In fact, the higher insensitivity of astigmats to the induction of astigmatism, regardless the angle of native and induced astigmatism, parallels findings by de Gracia et al. This paper reported that inducing 0.5 D of astigmatism at 45° in a young cohort of subjects produced a decrease in VA by 23% and in habitually corrected astigmatic subjects by 21%, whereas in habitually non-corrected astigmatic subjects (with astigmatism angles ranging from 30 to 180) the decrease was only 5%. In that study, the finding was attributed to accommodation possibly sweeping the retinal image in the Sturm interval, therefore allowing exposure and adaptation to retinal images blurred in range of orientations. We can speculate here that prior exposure to different retinal oriented blur in now a presbyopic group, in combination with the effects of the current presbyopic correction (which produces a similar, yet reduced bias in non-astigmats) could result in similar effects.

The general effects of astigmatism on visual performance occurred both in the presence or absence of natural aberrations, although differences (and statistical significance) were more marked when the native aberrations of the subject were corrected, as previously found in young subjects (Marcos et al., 2015). The overall effect of correcting aberrations on visual performance appears to be significantly higher in the pre-presbyopic group (G1) than in the presbyopic groups (G2, G3). While for G1 VA improved from 1.14 to 1.30 when aberrations were corrected, the other two groups either experienced a minor improvement of VA (1.06 to 1.16, G2) or did not significantly improve VA when aberrations were corrected (0.96 to 0.93, G3). A comparison of ocular aberrations across groups showed only a small HOA RMS increase and spherical aberration positive-shift in the older groups (particularly G3), likely insufficient to explain the lower VA in the older group. The lack of benefit of aberration correction in the older groups suggests that the lower VA is in fact additionally affected by other optical effects (i.e. intraocular scattering) and neural effects. Interestingly, shifting focus to the best focus as identified in the presence of astigmatism did not improve VA, indicating that improved perceptual image quality is not necessarily associated to improved performance, although may result in higher visual comfort to the patient.

In summary, presbyopes experience shifts in the best focus upon induced astigmatism and higher insensitivity to astigmatic induction, which is consistent to habitual exposure to higher aberrations and astigmatism. The effect was found in presbyopic patients wearing progressive lenses, whether they are native astigmats (where the effect is higher) or emmetropes. Our study shows that the best focus correction in the presence of astigmatism is dependent on the refractive profile of the patient, and can be optimized to the patient's preference, even if this only have a minimal impact on visual performance.

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