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Do diffractive intraocular lenses break the beneficial interaction between chromatic and monochromatic aberrations in the eye?

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Abstract: This study investigates whether a diffractive presbyopia-correcting multifocal intraocular lens disrupts the favorable interaction between chromatic and monochromatic aberrations in the eye. This is analyzed not only for distant objects but also for closer viewing distances, where the lens utilizes different diffraction orders depending on its design. We consider diffractive designs based on the zero-diffraction order for far vision and the first diffraction order for near vision (i.e., 0F/+1N design). Within the limitations of clinical visual acuity examination in various groups of subjects, our results prove that diffractive presbyopia-correcting lenses with 0F/+1N design preserve the beneficial interaction between chromatic and monochromatic aberrations at both far and near vision. The results are obtained for lenses with varying energy efficiency distributions between the far and near focal points, ranging from balanced (bifocal contact lens) to far-dominant (50% far, 30% near in a trifocal intraocular lens) configurations. These findings are specific to the 0F/+1N design and cannot be extrapolated to other diffractive lens types.

1. Introduction

Human vision operates in white light. Although optical aberrations typically degrade the retinal image quality, the existence of positive interactions between chromatic and monochromatic aberrations has proved to benefit visual acuity (VA) [1–3]. After the pioneering work conducted by Liang et al. [4] achieving measurement and full correction of ocular high-order-aberrations (HOAs), the manipulation of ocular aberrations with adaptive optics (AO) has largely boosted visual science, with a wealth of research exploring its impact on vision (the interested reader can be addressed, for instance, to a tutorial [5] some reviews [6–8] and the references therein). Concerning the interaction between chromatic and monochromatic aberrations, while sophisticated AO techniques have provided valuable insights [2,9–11], the field remains far from fully understood. Importantly, the influence of aberrations extends beyond pure optics; the subject's neural adaptation to their inherent aberrations also plays a key role [12–14]. Suchkov et al. [10] suggested a possible visual system adaptation to explain the VA robust response against modified conditions of the natural chromatic difference of refraction. Research in this area not only contributes to the fundamental understanding of human vision, but also holds significant implications for the design and personalized selection of ophthalmic lenses, including intraocular lenses, contact lenses, and free-form spectacle lenses.

The wavelength-dependent nature of the human eye's optical imaging system results in a difference in power, known as longitudinal chromatic aberration (LCA) [15], and an angular displacement of focus, affecting image magnification, referred to as transverse chromatic aberration (TCA) [16]. LCA exhibits relatively consistent variation across individuals, explaining the development of effective LCA correctors for the general population (e.g., [17]. In contrast, monochromatic wave aberrations and TCA demonstrate significant individual variability [18].

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Eyes with larger amounts of monochromatic aberrations, particularly of the cornea, tend to exhibit higher TCA [19]. The human visual system's remarkable ability to adapt to significant amounts of longitudinal chromatic aberration, around 2 diopters (D) across the visible spectrum (400-700 nm), may explain the limited interest on clinically assessing and compensating for this aberration. This is despite the fact that the protocols and instrumentation involved would not be inherently complex or time-consuming [20,21]. Furthermore, correcting both spherical aberration (SA) and LCA bilaterally has the potential to improve binocular spatial VA [9,22].

Marcos et al. [11] investigated the impact of LCA in pseudophakic patients implanted with monofocal aspheric intraocular lenses (IOLs) that compensated, fully or partially, corneal SA during cataract surgery. The study employed wavefront aberration measurements and both objective and psychophysical assessments of LCA. Their findings revealed that the influence of LCA on the response to blue illumination (480 nm, corresponding to the peak sensitivity of S-cones) was strongly dependent on the magnitude of the patient's monochromatic aberrations. Interestingly, the least aberrated eyes exhibited a significant decrease in optical quality for blue light, while conversely, there was practically no difference observed for the blue, green and red lights (555 nm and 564 nm correspond to the peak sensitivities of M-cones and L-cones, respectively) in the most aberrated eyes.

New questions about the interaction of monochromatic and chromatic aberrations in the eye raise with the use of diffractive profiles in the design of presbyopia-correcting lenses, particularly with the possibility of compensating for LCA at certain distances. These diffractive profiles are commonly used in various multifocal IOL designs to provide additional focusing power (add power) on top of the base power of the lens. The specific diffraction orders employed determine both the add power and the light distribution (energy efficiency) for far, intermediate (in trifocal lenses), and near vision. These two key features – add power and energy efficiency – are highly dependent on the wavelength of light (except for the zeroth diffraction order, which has no add power independently of wavelength).

We recently investigated the impact of this wavelength dependence on vision in pseudophakic patients with diffractive multifocal IOLs [23] and diffractive contact lens wearers [24]. We employed optometric tests adapted for clinical assessment and observed asymmetric variations in VA depending on the object distance and the illumination spectral band (blue or red). These variations were attributed to the diffractive properties of the lens design, specifically the wavelength dependence of add power and energy efficiency. The lens design we studied utilized the zeroth and +1st diffraction orders for far and near vision, respectively (hereafter referred to as the "0F/+1N" design for brevity). Our findings were consistent with previous observations reported by Labuz et al. [25] in pseudophakic patients implanted with a multiorder diffractive IOL (+1F/+2N design) [26].

The influence of chromatic changes in vision with diffractive presbyopia-correcting lenses remains largely unexplored. This study investigates whether a diffractive multifocal IOL disrupts the favorable interaction between chromatic and monochromatic aberrations in the eye. We will examine this not only for distant objects but also for closer viewing distances, where the lens utilizes different diffraction orders depending on its design. Furthermore, we aim to determine if a clinically feasible examination protocol, adapted with readily available materials, can yield meaningful results. To achieve this, monocular VA of pseudophakic subjects will be assessed under white and green light conditions using standard methods, procedures, and materials employed in routine clinical examinations. Our study will be complemented by monocular VA measurements obtained from presbyopic phakic subjects wearing a diffractive bifocal contact lens (CL) with a 0F/+1N design. Although several difficulties limited uptake of the concept in the marketplace and diffractive contact lenses are no longer available, they remain suitable for the purposes of this investigation.

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2. Method

High-contrast VAs at far and near distances were assessed monocularly in pseudophakic subjects with diffractive presbyopia-correcting IOL and two illuminations:

- Broadband white light (W), for which spatio-chromatic alterations caused by the diffractive nature of IOL multifocality may have an influence on the interaction between monochromatic and chromatic aberrations.

- Narrow band green light (G), close to the design wavelength of the lens, for which spatio-chromatic alterations and chromatic aberrations have limited impact. Monochromatic aberrations do contribute.

We measured also VA for distant objects in monofocal pseudophakic subjects for reference. In addition to inter-class VA measures with pseudophakic subjects, we further include intra-class VA measures with phakic presbyopic subjects with and without a diffractive bifocal CL.

2.1. Diffractive presbyopia-correcting lenses

Two different diffractive presbyopia-correcting trifocal IOLs were included in the study: FineVision Micro F12 (PhysIOL SA, Liège, Belgium) and AT LISA tri 839MP (Carl Zeiss Meditec AG, Jena, Germany). A monofocal IOL, Y601075 (AJL Ophthalmic, Álava, Spain), was included for comparison. Table 1 contains the specifications of these lenses.

We used bifocal Pilkington Diffrax, which is made of rigid gas permeable material, for diffractive presbyopia-correcting CL (Table 1). The set of Diffrax CLs consisted of nine positive (+3.25 D) and nine negative (−3.25 D) spherical power, with a back radius of curvature ranging from 7.3 to 8.1 mm, in steps of 0.1 mm. The diffractive profile provided a nominal add power of +2.00 diopters.

The design wavelength of these lenses is about 550 nm.

2.2. Subjects

The clinical data were obtained from three groups of pseudophakic subjects: a first one implanted with the diffractive trifocal FineVision, a second one with the diffractive trifocal AT LISA tri, and a third one, for reference, with a monofocal lens Y601076. FineVision subjects were recruited from Presbit (Sabadell) (12) and Creu Groga (Calella) (8). AT LISA subjects were recruited from Presbit (Sabadell) (10), Creu Groga (Calella) (3), Eurolaser (Mataró) (1), and Hospital de Mataró (Mataró) (6). Monofocal Y601075 subjects were recruited from Hospital de Mataró (30). All centers are located in the province of Barcelona, Spain.

Eligible patients presented bilateral cataracts and no comorbidities. They underwent bilateral cataract surgery with implantation of the same type of IOL in both eyes, using similar technique (phacoemulsification and implantation into the capsular bag). Inclusion criteria were preoperative refraction error (spherical equivalent) less than ±5.0 D, postoperative best distance corrected VA better than 0.1 logMAR. Key exclusion criteria were complications during or post-surgery, abnormalities in color vision (as assessed by the Ishihara test), prior ocular pathology or ocular surgery, including refractive procedures. The examination was done between one and six months after surgery.

An additional group of presbyopic phakic subjects was recruited in the Faculty of Optics and Optometry (Terrassa) for the group of diffractive bifocal CL. Key inclusion criteria were refraction error (spherical equivalent) less than ±5.0 D, best distance corrected VA better than 0.1 logMAR, and absence of ocular pathologies, prior refractive surgery, media opacities, or abnormal color vision (as assessed by the Ishihara test). They were examined in the clinical setting of the center.

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Table 1. Specifications of the ophthalmic lenses.

	Intraocular lens			Contact lens
	Monofocal	Trifocal	Trifocal	Bifocal
	AJL Y601075	AT LISA tri	FineVision	Diffrax
Material	Hydrophilic acrylic	Acrylic with hydrophobic surface	Hydrophilic acrylic	Rigid gas permeable
Refractive index	1.46	1.46	1.46	NA
Abbe number	47	58	58	NA
Optical diameter (mm)	6.0	6.0	6.15	11 rings cover 5.0 mm central region[a]
Spheric aberr. (μm) (6.0 mm pupil)	Spheric design	−0.18[b]	−0.11	NA
Diffractive profile	Not applicable	Central 4.34 mm zone: trifocal. Peripheral zone (>4.34 mm): bifocal	Full aperture, Apodized double profile: 1st Profile 2nd Profile	Single profile
Orders of diffraction	Not applicable	Far: 0 order Interm:1st order of 1st profile Near: 1st order of 2nd profile[c]	Far: 0 order Interm:1st order of 1st profile Near: 1st order of 2nd profile[c]	0 order (Far) + 1order (Near)[d]
Near (interm) powers (D)	Not applicable	3.33 (1.66) at the IOL plane	3.5 (1.75) at the IOL plane	2.0 at the corneal plane
Energy efficiency distribution (nominal)	≲ 100% (Far)	50% (Far) 30% (Near)[b]	43% (far) 28% (near)[e]	41% (Far) 41% (Near)

NA, not available.
[a][24],
[b][27],
[c][28],
[d][29],
[e][30].

This cross-sectional study followed the tenets of the declaration of Helsinki. Subjects were fully informed about the study and provided written consent. Table 2 contains the distribution and sociodemographic data of the subjects recruited for all the groups, including age [mean ± standard deviation (SD)].

2.3. Charts and lighting

We used a series of C Landolt optotype charts designed on purpose and printed for measuring VA in this study. The angular size of the stimulus was calculated for the testing distances of 3.5 m or 4.0 m (adaptable to the dimensions of the optometric examination room). We chose the 8-position test to minimize the possibility of obtaining false positives and avoid cognitive issues. Three C Landolt charts were printed and used for the tested distance to prevent memorization during the VA assessment. The optotype chart and the procedure for VA assessment is further described elsewhere [31]. A near vision chart specifically designed for a 50 cm testing distance was positioned approximately 45 to 50 cm away from the observer when testing near VA in presbyopic phakic subjects.

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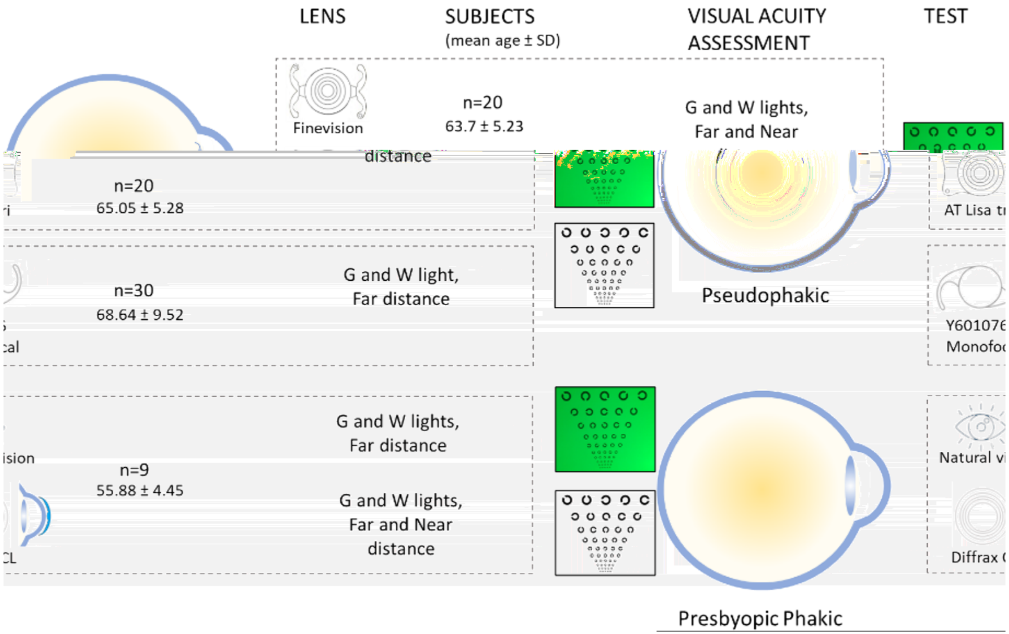
Table 2. Scheme of the examination procedure. Data of subjects and groups.



To evaluate VA under W and G light conditions, the chart was sequentially illuminated with separate light sources: a white light-emitting diode (LED) and a green LED. The white LED (model MCWHL5, Thorlabs GmbH, Munich, Germany) had a correlated color temperature of 6500 K and CIE 1931 chromatic coordinates of $(x,y)_W = (0.3128, 0.3292)$. The green LED emitted light with a nominal wavelength of 530 nm, a full width at half maximum (FWHM) of 33 nm, and CIE 1931 chromatic coordinates of $(x,y)_G = (0.1224, 0.7478)$. The intensities of both light sources were adjusted to maintain a constant luminance of 25.3 ± 0.10 cd/m^2 for all charts throughout the evaluation. Luminance was measured using a Mavolux 5032 C photometer (GOSSEN GmbH, Nuremberg, Germany). To prevent interference with the experiment, the examination room was maintained under mesopic light conditions.

2.4. *Clinical VA examination and data acquisition*

Subjective refraction and distance correction using W light were performed on all patients and applied throughout the testing. To account for the viewing distance of 3.5 to 4.0 m during VA assessment, a −0.25 D vergence offset was incorporated into the manifest refraction, effectively adjusting the measurements to infinity. All VA measurements were conducted monocularly, using the eye with better VA under W light and with the pupil size in its natural state. An IOLMaster (Carl Zeiss Meditec, Jena, Germany) was employed for optical biometry measurements, including pupil size. All subject examinations were consistently performed by the same experienced optometrist (LC).

The refractive correction determined for far VA assessment under W light illumination was also used for the far VA examination with G light.

Pseudophakic subjects implanted with a diffractive trifocal IOL were tested for both far and near vision under W and G light conditions (Table 2). To simulate near object distances, a negative power spectacle lens was added to a trial frame during near VA testing. The specific power of the negative lens depended on the characteristics of the diffractive IOL itself. For the FineVision group, assessed first, a −3.0 D trial lens was used for both W and G light conditions. The AT LISA tri group, evaluated at a later time than the FineVision group, each subject received

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individual near vision correction under W light to achieve their optimal VA, resulting in an average correction of −2.53 D (± 0.11 D). This same correction was then used for near vision assessment under G light. Notably, during both far and near vision assessments under G light, AT LISA tri subjects were offered the option to adjust the focus (using an additional spectacle lens, with precision of ± 0.25 D), to compensate for any perceived difference compared to W light. For the monofocal IOL group, VA was only measured for far vision under both W and G light conditions.

The VA assessment for presbyopic phakic subjects with a diffractive CL followed a distinct procedure. A diffractive CL was fitted according to the manufacturer's instructions. These instructions recommend selecting a lens with a back central optic radius 0.1 mm steeper than the flattest corneal radius of curvature [29]. We chose the power that most closely corresponded to the subject's refraction. After the CL stabilized on the observer's eye, an over-refraction was conducted to determine the distance corrected VA under W light. This refractive correction was then maintained for the far VA assessment under G light. Near VA was tested under both W and G lights without any additional spectacle lens correction. Instead, the observer relied solely on the add power provided by the first diffractive order of the Diffrax CL's diffractive profile. In this case, a near vision chart specifically designed for a 50 cm testing distance was positioned approximately 45 to 50 cm away from the subject. Presbyopic phakic subjects also underwent far VA assessment under natural vision conditions for reference. This refers to their distance vision without any correction, or with their usual distance spectacle correction if they required one.

The examination session duration ranged from 15 minutes for subjects in the monofocal pseudophakic group to 30 minutes for subjects in the presbyopic phakic group (with and without CL) (Table 2).

VA outcomes in decimal scale were converted into logMAR scale. Descriptive statistics (mean ± SD) characterized the sample. The Kolmogorov–Smirnov test did not confirm the normal distribution of data, possibly due to the sample size. The Wilcoxon test was applied to paired data to assess the VA differences.

3. Results

Figure 1 shows the mean clinical VA outcomes for subjects in each group, tested at far and near distances under W and G illumination. Table 3 provides the numerical values.

Table 3. Clinical VA (logMAR) values (mean ± SD) for far and near vision under W and G lights.

			Visual Acuity (logMAR)			
Group	**Pupil** (mm)	**Sph. Eq.** (D)	**Far vision**		**Near vision**	
			W	**G**	**W**	**G**
Monofocal Y601075 IOL	3.77 ± 0.40	−0.09 ±0.59	−0.012 ±0.07	−0.009 ±0.08		
Diffractive FineVision IOL	3.74 ± 0.60	0.21 ±0.49	0.06 ±0.04	0.08 ±0.04	0.24 ±0.07	0.28 ±0.09
Diffractive AT LISA tri IOL	3.51 ± 0.39	−0.12 ±0.41	0.03 ±0.05	0.07 ±0.05	0.15 ±0.06	0.17 ±0.06
Diffractive Diffrax Contact lens	Not available	−0.32 ±2.07	0.10 ±0.11	0.16 ±0.08	0.11 ±0.10	0.16 ±0.12
Presbyopic phakic natural vision	Not available	−0.32 ±2.07	−0.07 ±0.04	−0.02 ±0.05		

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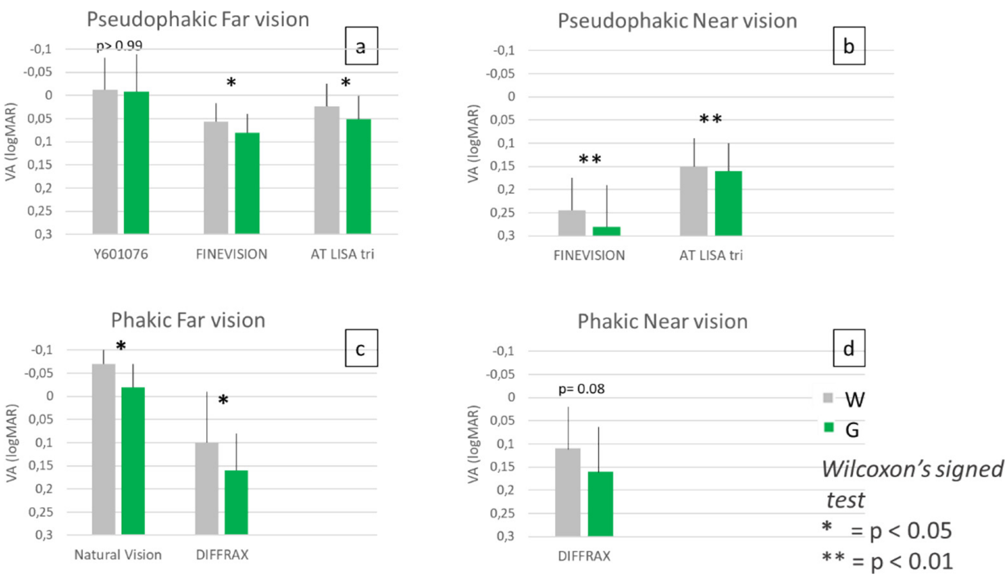

Fig. 1. (a) VA at far distance (mean ± SD) with W and G lights for the three groups of pseudophakic patients, implanted with the monofocal IOL (Y601075), the diffractive trifocal lenses (FineVision and AT LISA); (b) VA at near distance (mean ± SD) with W and G lights for the two groups of patients implanted with the diffractive trifocal IOLs. (c) VA at far distance (mean ± SD) with W and G lights for the group of presbyopic phakic patients with natural vision (spectacle lens if needed) and wearing the Diffrax CL. (d) VA at near distance (mean ± SD) with W and G lights for the presbyopic phakic group with the Diffrax CL. * $p < 0.05$, ** $p < 0.01$. P values under 0.05 show statistical difference between G and W VA values. (Wilcoxon test).

From Fig. 1, far vision VA is generally superior to near vision across all groups. Monofocal and presbyopic phakic subjects with natural vision were not tested for near vision due to the large defocus experienced at that distance. Within the subjects with diffractive presbyopia-correction, the disparity between far and near VA is most pronounced for subjects with diffractive multifocal IOLs. These lenses were designed to prioritize far vision, directing a greater proportion of light energy towards the far focus at the expense of near vision. Conversely, subjects with a diffractive bifocal CL exhibit a negligible difference between far and near VA. This is because the bifocal lenses were designed to distribute light energy more evenly between the far and near focal points.

Despite being close to the lens design wavelength and the maximum efficiency of human vision in photopic conditions, G light consistently resulted in lower mean VA compared to W light across all groups and for both far and near distances. For presbyopic phakic subjects with natural vision, far VA outcomes with G light were worse on average than with W light ($p < 0.05$). This decrease in VA with G light was minimal for the monofocal pseudophakic subjects, who achieved a practical level of visual performance ($p > 0.99$). These subjects, implanted with a standard refractive lens, are affected by common ocular dispersion and the inherent dispersion of the IOL material, which also contributes to chromatic aberration. Unlike the other groups with diffractive IOLs, monofocal pseudophakic subjects avoid the combined effects of wavelength dependence of both the add power and the energy efficiency distribution, characteristics inherent to diffractive IOLs. For subjects implanted with diffractive trifocal IOLs, the decrease in VA with G light was subtle in far vision but became relatively more pronounced in near vision.

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4. Discussion

The results consistently demonstrated superior mean VA under W light compared to G light across all groups and distance conditions (Fig. 1, Table 3). In subjects with diffractive presbyopia-correcting lenses featuring a 0F/+1N design, the advantageous VA with W light suggests that these lenses preserve the beneficial interaction between chromatic and monochromatic aberrations, a phenomenon previously described in the natural eye [1–3] and in pseudophakic eyes with aspheric monofocal IOLs [11].

Statistically significant differences in VA were observed between W and G light conditions for most groups, with G light leading to slightly poorer performance. Exceptions included the monofocal pseudophakic group ($p > 0.99$) and the presbyopic phakic group wearing a diffractive CL at near distance ($p = 0.08$), where differences were not statistically significant. These findings diverge from those reported by Aissati et al. [2]. In a comprehensive and meticulous work supported by optical and visual quality measurements and computer simulations, Aissati et al. proved the lack of favorable interactions between the monochromatic and chromatic aberrations when a stimulus convolved with the point spread function derived from the subject's monochromatic aberrations is seen through AO-corrected optics and polychromatic illumination. In one of the experiments, two conditions for monocular VA were tested in seven young subjects, under cycloplegia to minimize the effects of accommodation and 6-mm pupil: natural HOAs with a high-contrast stimulus illuminated in (a) monochromatic light (555 nm) and (b) white light. The average VA under natural HOAs was slightly better under 555 nm light than under white light (difference of -0.05 ± 0.01 logMAR). In our work, we observed also little difference, but with opposite sign. It is worth remarking that the magnitude of such VA differences between G and W light conditions was subtle (limited to two or three letters of the same line in a clinical chart) and almost negligible in the clinical practice. The consistent observation of poorer VA under G light compared to W light across all groups and observation distances suggests the influence of defocus effects arising from residual refractive errors. A potential explanation lies in our methodology: unlike Assiati et al.'s study, we optimized distance-corrected VA under W light, a standard clinical practice, and subsequently applied the same correction for G light (nominal 530 nm) evaluation. In consequence, some defocus could have affected our VA results, in particular those obtained from the multifocal groups for which, both the efficiency and add power of the diffractive lenses (features fairly dependent on the wavelength) were offset from the manufacturing specification, typically reported for 550nm [26]. However, although the AT LISA tri group was given the opportunity to further refine their VA under G light using trial spectacle lenses (of optical power not smaller than 0.25 D in absolute value), no significant improvements were observed for any subject within the group, meaning that our clinical testing procedures were not precise enough. Phakic presbyopic subjects in natural far vision would be also affected by a residual refractive error with 530 nm light because, despite the large individual variability in the wavelength in focus, a general consensus considers that a mid-long wavelength is usually in focus for distance objects (596 nm, with a range of 73 nm for 6 m viewing distance in Jenkins [32]; 589 nm in Thibos et al [33], among others). Interestingly, Cooper and Pease [34] reported a mean of 518 nm with a range of 136 nm (457 to 593 nm) at 3 m viewing distance, that is, 0.33 D object vergence. These data allow us to speculate that a residual myopic refractive error of about 0.25 D defocus might have affected the phakic presbyopic subjects in natural far vision.

A more detailed analysis reveals consistency with the underlying optical characteristics of a diffractive 0F/+1N lens design. In the far focus (zero-diffraction order), only the material dispersion of the diffractive lens contributes to ocular LCA. In far vision, the diffractive lens behaves like a conventional refractive monofocal lens in terms of LCA. Previous studies have measured LCA in eyes with monofocal IOLs using various techniques [11,20,21,35,36]. These independent investigations consistently demonstrate that LCA in monofocal pseudophakic eyes is generally lower than in phakic eyes, aligning with the refractive index and Abbe number of the

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IOL material. For presbyopic phakic eyes wearing a diffractive 0F/+1N CL, the lens's material dispersion slightly increases its contribution to ocular LCA in far vision, similar to the effect of other ophthalmic corrections like spectacle lenses. However, given the human eye's remarkable tolerance to chromatic aberration [10], the impact of these LCA variations induced by the CL material is likely negligible.

In the near focus (+1diffraction order), the diffractive 0F/+1N lens contributes to LCA with a compensating term that depends on the wavelength and the add power [26]. This term is much larger than the term caused by the lens material dispersion and typically compensates for the ocular LCA in part [23,24] (Table 4).

Table 4. LCA of the diffractive 0F/+1N lenses of this study in both the far and near foci.

	Near focus (D)	Far Focus (D)
FineVision[a]	-1.13 ± 0.10	0.08 ± 0.10
AT LISA Tri[a]	-1.20 ± 0.10	0.00 ± 0.10
Diffrax CL[b]	-0.62	0.00

LCA in the spectral range from 455 to 625 nm:
[a][23]
[b][24].

So far, the variations in LCA introduced by diffractive 0F/+1N presbyopia-correcting lenses do not appear to disrupt the beneficial interaction between chromatic and monochromatic aberrations at either far or near distances. Furthermore, pseudophakic eyes implanted with aspheric IOLs, such as the diffractive trifocal lenses examined in this study, gain an additional advantage through SA compensation [37]. This compensation mimics the SA balance found in the young human eye; a property known to diminish with age [38]. In contrast, pseudophakic eyes with spherical monofocal IOLs do not benefit from SA compensation. Instead, these eyes experience an increase in SA that compounds their natural positive corneal SA. The impact of such increased positive SA (with 3.77 ± 0.40 mm average pupil) is speculated to mask the impact of switching from W to G light on visual performance ($p > 0.99$) [9]. Despite the differences in SA compensation (Table 1), the VA results for both W and G lights (Fig. 1) do not demonstrate conclusive variations in the impact of SA on visual performance across the different IOL groups.

The subjects wearing diffractive CLs presented distinct characteristics. The Diffrax CL set was manufactured using lathe technology available approximately three decades ago. In addition to thorough disinfection and hydration, we examined each lens in the set with a microscope to confirm its integrity and suitability for testing before inclusion in our study. While we lacked additional data on CL quality, the presence of imperfections, lens displacement during blinking, or irregularities in the central region could potentially contribute to an increase in monochromatic aberrations and TCA of the eye with the CL, consequently affecting the overall image quality [19].

The distribution of energy efficiency between the far and near focal points is another critical optical characteristic of a diffractive 0F/+1N design, influenced by wavelength. Table 1 shows the nominal energy distribution at the design wavelength (550 nm): a far-dominant pattern for diffractive trifocal IOLs (43% far, 28% near for FineVision; 50% far, 30% near for AT LISA tri) and a balanced distribution for the diffractive CL (41% far, 41% near). Approximately 20% of incident energy does not contribute effectively to image formation in either the zero or first diffraction order. This energy distribution significantly impacts VA at both far and near distances. For subjects with far-dominant IOLs, the in-focus image receives more energy than the superimposed out-of-focus image when viewing distant objects, leading to improved far VA. Conversely, for near viewing, the in-focus image receives less energy, resulting in reduced near VA. This explains the substantial difference in VA between far and near vision for subjects with

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diffractive trifocal IOLs under both illumination conditions. In contrast, the balanced energy distribution of the diffractive bifocal contact lens contributes to a more consistent VA at both distances.

The energy efficiency distribution between the far and near focal points varies significantly with wavelength, exhibiting a red dominance in the far focus for all three diffractive lenses studied, and a blue dominance in the near focus for the AT LISA tri IOL and the Diffrax CL. This red-blue asymmetry could potentially impact VA as demonstrated in studies employing red or blue chart illumination and clinical VA assessment [23,24]. However, our VA results with W and G light do not seem to be affected. Despite the spectral shifts in image formation at both far and near focal points, W light consistently yielded better VA than G light (Fig. 1, Table 3).

Considering both LCA and energy efficiency in these diffractive lenses, a stronger far focus dominance generally correlates with a performance closer to that of a refractive lens, enhancing the eye's protection against chromatic blur.

Within the limitations of clinical examination, our results agree with the fact that diffractive 0F/+1N presbyopia-correcting lenses preserve the beneficial interaction between chromatic and monochromatic aberrations at both far and near vision. This result has been proved for lenses with varying energy efficiency distributions between the far and near focal points, ranging from balanced (bifocal CL) to far-dominant (50% far, 30% near) configurations. However, it is important to note that these conclusions are specific to the 0F/+1N design and cannot be extrapolated to other diffractive lens types. Further research is required to evaluate the impact of different diffractive designs on chromatic and monochromatic aberration interactions in human vision.

Abbreviations

0F/+1N, 0^{th} diffraction order for Far focus and $+1^{st}$ diffraction order for Near focus

D, diopter

IOL, intraocular lens

CL, contact lens

FWHM, full width at half maximum

G, green

LCA, longitudinal chromatic aberration

LED, light emitting diode

SA, spherical aberration

SD, standard deviation

VA, visual acuity

W, white

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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