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ORIGINAL ARTICLE

Visual Acuity and Optical Parameters in Progressive-Power Lenses

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ABSTRACT

Purposes. The purposes of this study are to explore the effect of astigmatism and high-order aberrations of progressive-power lenses (PPLs) on visual acuity (VA) and to find a good optical metric for evaluating visual performance of PPLs.

Methods. A Hartmann-Shack (HS) wavefront sensor was used to measure PPLs and human eyes either independently or in combination. An additional channel permits the measurement of VA under the same optical conditions. Measurements were taken in six relevant locations of a PPL and in three eyes of different normal subjects. In every case, we obtained the wavefront aberration as Zernike polynomials expansions, the root mean square (RMS) error, and two metrics on point spread function (PSF): Strehl ratio and the common logarithm of the volume under the PSF normalized to one (Log_Vol_PSF).

Results. Aberration coupling of the PPL with the eye tends to equalize the retinal image quality between central and peripheral zones of the progressive lenses. In the corridor of the PPL, the combination of small amounts of coma, trefoil, and astigmatism (total RMS 0.1 μm) does not significantly affect VA. The continuous increase of astigmatism from corridor to outside zones reduces moderately the quality of vision. The highest correlations between optical metrics and VA were found for Log_Vol_PSF of the entire system eye plus PPL.

Conclusions. Ocular aberrations reduce optical quality difference between corridor and peripheral zones of PPLs. In the same way, VA through the corridor is similar to that of eyes without a lens and it decreases slowly toward peripheral locations. VA through PPLs is well predicted by the logarithm of metrics directly related with image spread (Log_Vol_PSF or equivalent) of the complete system of the eye with the lens.

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Key Words: progressive-power lenses, visual acuity, wavefront aberrations, optical metrics, correlations

In recent decades, psychophysical assessments of the performance of progressive-power lenses have been undertaken in different ways. Grating visual acuity is not significantly deteriorated when looking through low eccentricities.[1] For typical intermediate office tasks, this kind of lens provides marginally diminished performance compared with single-vision lenses.[2] Clinical surveys of patient acceptance[3–5] show a small percentage of progressive-power lenses (PPLs) wearers (around 10–15%) with adaptation problems that could be produced by different factors: distortion, the need of head movements, defocus errors, astigmatism, or perhaps high-order aberrations. Some researchers[6,7] have evaluated the amount of astigmatism that is tolerated by patients wearing PPLs. In relation to defocus tolerance, visual performance for different defocus[7–14] and depth of focus[15–18] in the eye have been widely studied.

Psychophysical estimates such as visual acuity (VA) and contrast sensitivity function (CSF) are quite useful for evaluating both visual performance and possible adaptation problems in PPLs. However, obtaining accurate visual measurements for different conditions is time-consuming and requires the cooperation of the subject. To predict visual performance, some optical parameters (for example, the radius of 84% encircled energy of the point spread function or the integral of the modulation transfer function across the frequency range of interest) have been proposed for assessing the image quality of visual instruments such as telescopes, but only for small sizes of pupil.[19] Other metrics calculated from double-pass retinal images have been relatively well correlated with VA and CSF measurements for different amounts of defocus.[14] Recently, the VA using computationally aberrated letters had been correlated with a great number of optical metrics derived from wavefront aberration (WA) assigned to the letters.[20]

The optical tests are commonly made in isolated lenses, but the image quality on the retina is the result of the entire system of the eye with lens. It is well known that in PPLs, the continuous change

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of defocus over the lens induces peripheral astigmatism that increases progressively outside the corridor.[21–25] In relation to high-order aberrations in PPLs, some previous theoretical studies[26] concluded that the shape of the image of a point through a progressive spherical power surface may be affected by coma.[23,27] In a recent study,[28] in addition to astigmatism, we found that small amounts of coma and trefoil were also present in relevant zones of PPLs. In the same work, to obtain the final optical quality of the entire system eye with PPLs, we also demonstrated the aberration coupling between both for different zones of the lens. In other work,[29] we compared three different designs of current PPLs. The results confirmed small amounts of coma and trefoil in every lens. The main difference between them was the distribution of astigmatism depending on lens design philosophy.

Following these previous works, in this article, we explore the impact of wavefront aberrations of a PPL on VA for different viewing conditions. Visual performance is evaluated with respect to three optical conditions depending on aberrations considered in WA: 1) all aberrations, 2) only astigmatism, and 3) only high-order aberrations. Optical estimates are taken both in the isolated lens and in combination with eyes. Different optical parameters calculated from WA, some based on pupil plane and others on image plane, are correlated with the VA results. In this way, we analyze the effect of aberrations of PPLs on VA and which optical parameter predicts better visual performance in this kind of ophthalmic lenses.

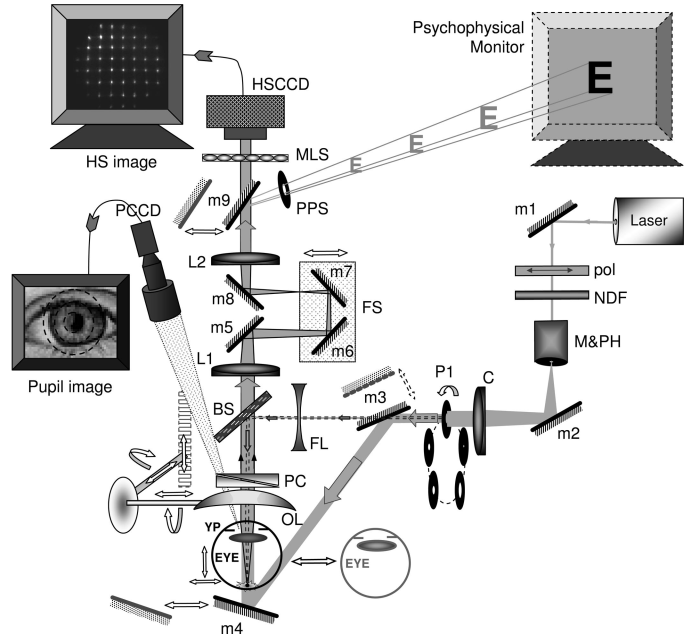

FIGURE 1.

Experimental setup. Pol, lineal polarizer; NDF, variable neutral density filters; M&PH, microscope objective and pinhole; C, collimator lens; P1, pupil-limiting studied area on the OL; YP, eye pupil; OL, ophthalmic lens; PC, prism compensator; FL, focus lens forming a point on retina; BS, beam splitter; FS, focus corrector system; PPS, pupil for psychophysical measures; MLS, microlenses; PCCD, CCD for centering control.

METHODS

A schematic view of the experimental apparatus used is shown in Figure 1. It is a Hartmann-Shack (HS) wavefront sensor system adapted to obtain measurements of ophthalmic lenses and human eyes. An additional channel allows visual testing (both with the naked eye and looking through different zones of ophthalmic lenses) under the same optical conditions. The principle of the HS sensor has been extensively described elsewhere.[30–32] In particular, our system was described in a recent work,[28] not including the channel to measure visual performance. For this reason, we only briefly describe our system emphasizing the most relevant data. So, we concentrate our explanations on the optical parameters, VA measurements, and the correlation between them.

Wavefront Measurements

The optical measurements were obtained using monochromatic green light (543 nm) from a He-Ne laser. The system can measure either the ophthalmic lens (OL) or the eye. To measure OLs, the removable mirrors (m3, m4) directed the beam to the posterior surface of the lens. The size of aperture P1 limited the maximum size of the OL on which the WA can be measured.

To measure ocular WA, a 1.5-mm aperture (P1) and a lens (FL) formed a point-like source on the retina. The level of laser exposure at the cornea was approximately 3 $\mu W/cm^2$, more than one order of magnitude below the limit set by safety standards.[33] A CCD video camera (PCCD) monitored the centration of the natural pupil with respect to the measuring beam. A removable prism compensator (PC) allowed the beam to stay aligned through our system avoiding extra aberrations by oblique incidence on the lenses. A focus corrector system (FS) was used to remove, or to change, the refractive error. The beam coming from L2 was sampled by the microlens array, MLS (square geometry, 40-mm focal length, single microlens aperture of 0.6 mm). A cooled CCD camera (HSCCD) placed at the focus location of the MLS recorded the HS images. The entrance pupil of the tested system, OL or eye, was placed at the focus of the lens L1 to be conjugated with the MLS plane. To reproduce normal viewing conditions, the OL was displaced in the three directions and tilted around horizontal and vertical axes. The displacements and the tilts were calculated taking into account a pantoscopic tilt of 12° and a distance from the back vertex of the lens to the center of rotation of the eye of 27 mm. In primary position, the back vertex of the PPL was placed 14 mm in front the cornea, and the changes of this distance with the sight directions were considered in the displacement of the lens. Subjects were fixed using a bite-bar attached to a three-axis micropositioner to minimize head movements.

Wavefront aberrations were fitted to Zernike polynomials up to the fifth order. The measurements in the different zones of the PPL were processed for 4.5- and 3.0-mm pupil diameters. We assumed that the remaining accommodation in the subjects would compensate for small amounts of defocus induced by the difference between refraction of the lens zone and the object distance. For this reason, the value of Zernike coefficient for defocus was set to zero for all the results. From the HS images, we computed the Zernike coefficients (represented using the OSA standards[34]) and the root mean square (RMS) of the WA. The point spread function (PSF) was also calculated from the WA. In addition to the RMS, two other optical parameters were computed from PSFs: 1) the Strehl ratio and 2) the logarithm of the volume under the PSF when the

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maximum was normalized to one (Log_Vol_PSF). The Strehl ratio was strictly computed as the quotient between the intensity peak in the system's PSF and the diffraction-limited PSF. The volume of the PSF was calculated by adding the intensity of each pixel of the image when all intensity values were normalized between zero and one. This parameter is similar to that one used with double-pass images.[14]

Although all metrics were obtained from WA, the RMS was calculated from coefficients of the wave aberration in the pupil plane, whereas the parameters from PSF (Strehl ratio and Log_Vol_PSF) give direct information on retinal image quality.

Visual Acuity Measurements

By means of a removable mirror (Fig. 1, m9), the monitor used to measure psychophysical performance was seen through the same optical path as that used for HS measurements. An artificial aperture (PPS) set the pupil diameter size in the eye pupil plane. The "tumbling E" with four possible orientations (right, left, up, and down) was presented for measuring the VA expressed by decimal units (1/minimum angle of resolution). A computer program built from the VSG2/5 (visual stimulus generator from Cambridge Research System, U.K.) produced the video signal input to a Sony GDM-F520 monitor. To compare optical and psychophysical parameters in visible green light, the green gun of this monitor was used. The luminance of the screen was 80 cd/m^2 and the visual field subtended 7.5°. First, the letter size was reduced by steps of 0.2 arc-min up to the smallest letter that the subject saw in the best focus. In addition to this reference size, four sizes more (two up and two down) around it were measured in this way: the computer program randomly presented a letter for 1 second, repeating this 80 times (16 times for each size). By counting the number of letter orientations correctly identified by the subject for each size, a four-parameter sigmoidal fit (constraining correct responses to 25% and 100% when minimum angle of resolution was zero and infinity, respectively) was used to obtain the value of VA. We chose the value of decimal VA for the 75% of correct responses.

The VA measurements were taken with two different artificial pupil diameters (Fig. 1, PPS): 4.5 and 3 mm. Two different contrast values, 100% and 15%, were also measured.

Experimental Procedures

HS measurements were taken in three naked eyes and in six locations of an isolated PPL. Standard deviations of ocular WA and VA were calculated from three experimental measurements. VA was measured for the naked eyes and when looking through the different zones of the PPL. All results were obtained for 3- and 4.5-mm pupil diameter, because larger pupils are uncommon in presbyopic eyes.[35]

Subjects. The left eyes of three normal male subjects were measured. From HS measurements, their refractions were estimated: MA (29 years old): -2.50 to 0.25 × 50 JO (26 years old): +0.60 to 0.60 × 20 EL (29 years old): −1.50 to 0.20 × 100

These low amounts of ocular astigmatism were not compensated to study the coupling with the astigmatism of the PPL and its influence in the visual performance. As we show in the "Discussion" section, the largest value of astigmatism of our subjects (0.60 D) is inside the tolerable interval of astigmatism proposed in many previous studies. All subjects had a spherical-corrected decimal VA better than 1. Accommodation was paralyzed and the pupil was dilated with two drops of tropicamide (1%) for each hour. The study followed the tenets of the Declaration of Helsinki, and signed informed consent was obtained from the subjects after the nature and all possible consequences of the study had been explained.

Progressive-Power Lens. We measured the WA and VA at six relevant locations across a PPL (Varilux Comfort; Essilor International, France) with plano distance power, 2-D power addition, 18-mm corridor length (vertical measurement from the fitting cross to the center of the near circle), and 2.5-mm inset of the near portion. The far and near zones of PPLs are nearly free of aberrations. However, in the zones for intermediate vision, the power progression along the corridor produces coma, trefoil, and a progressive increase of peripheral astigmatism. Usually the horizontal width of the lens zone used for foveal vision is <15° from the central position (around 7 mm on ophthalmic lenses). Thus, the most interesting locations for optical and visual testing are placed between far and near zones with a width up to 7 mm on both sides from the corridor. Figure 2 shows the selected locations, six representative locations of the PPLs: two in the corridor, c1 and c2; three in nearby zones at 3-mm outside, n1 in the nasal side, and t1 and t2 in the temporal side; and another one 5.5 mm away from the corridor, t3.

Aberrations of the Progressive-Power Lens-Plus-Eye System. The estimation of the WA of the entire system eye with lens was obtained as the addition of the WAs of the eye and the zone of the PPL measured independently. The coupling of aberrations of the eyes and the PPL for different locations was tested in a recent work.[28]

Correlations Between Optical Metrics and Visual Acuity

VA measurements for different viewing conditions (3- and 4.5-mm pupil diameters, 100% and 15% contrast values) were linearly correlated with optical parameters (processed for the cor-

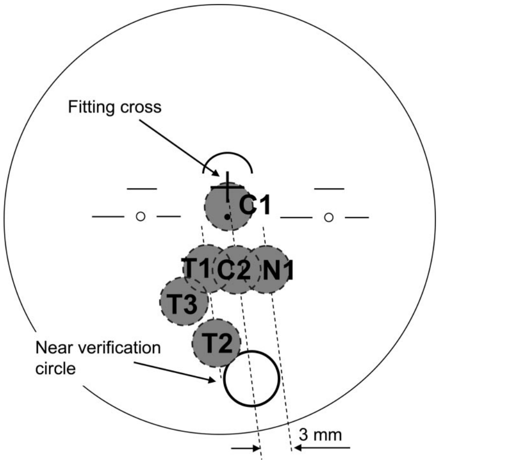

FIGURE 2.
Progressive-power lens with the locations of the measured zones, which are 4.5-mm in diameter.

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responding pupil size) taking into account two optical systems: isolated PPL and entire system eye plus lens. Optical metrics considering the whole WA, only astigmatism, and only high-order aberrations were related with visual measurements. R-squared coefficient of the linear correlation and p values were used to compare the results and to obtain the best optical metric for predicting visual performance in PPLs.

RESULTS
Wavefront Aberrations

Figure 3 shows the WA and PSF maps for the six tested zones of the PPL, the naked eyes, and the sum of the zones of the lens plus eyes. PSF maps were calculated on the image plane where defocus was zero. In the locations of the corridor, C1 and C2, the ocular aberrations degrade the image quality significantly more than those of the lens. In zones of the PPL outside the corridor, astigmatism increases and becomes the dominant aberration. However, the small amount of coma produces a higher intensity at the bottom of the PSFs. For all locations, the different shapes of the WAs and PSFs depend on the aberrations coupling between eyes and PPL zones. For example, for eye JO at N1, the WA map shows a very aberrated system, but the PSF intensity is mainly concentrated in a small area. Figure 4 shows the Zernike values for the zones of the lens. We only show up to fourth order because for fifth order, the values of the coefficients were negligible. Small amounts of astigmatism (Zernike coefficients 3 and 5), coma (coefficients 7 and 8), and trefoil (coefficients 6 and 9), around 0.05 μm, each one for 4.5-mm pupil diameter, were found in areas of the corridor of the PPL. In the other peripheral locations, astigmatism increases, whereas coma and trefoil remained within the same small values as in the corridor. The other higher aberrations of the isolated PPL are negligible for every location. Zernike coefficients of the three eyes are presented in the same figure to be compared with those of the lens. The magnitude of coma and trefoil in the eyes is similar to those in the different zones of the lens. The higher aberrations are also nearly negligible, except the spherical aberration (coefficient 12) of subject JO. The ocular values of astigmatism are similar to those of the corridor and nearby zones of the PPL.

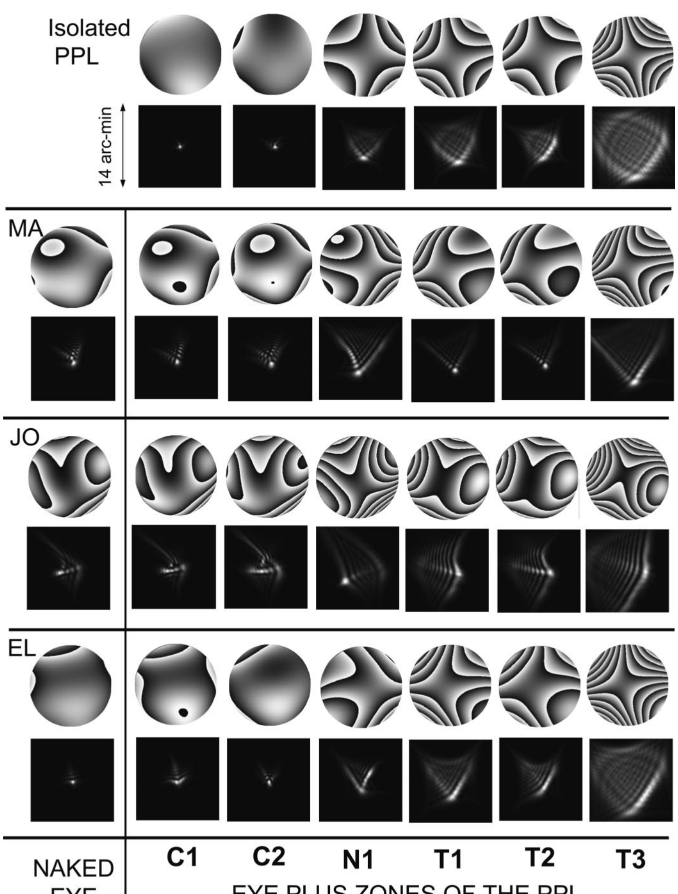

FIGURE 3.

A modulus 2π representation of the wavefront aberration (WA) and the associated point spread functions of the naked eyes and the six tested zones of the progressive-power lens measured independently and in combination by adding WAs. Defocus Zernike coefficient set to zero. A 4.5-mm pupil diameter.

Optical Parameters

Figure 5 presents the optical metrics (RMS, Strehl ratio, and Log_Vol_PSF) of the three eyes without lenses and in combination with the six zones of the PPL for a 4.5-mm pupil diameter. For the small pupil, 3.0-mm diameter, the optical quality is better but the relative performance is similar to that shown for the 4.5-mm pupil. The optical parameters have been calculated taking into account all aberrations (up to the fifth order) except defocus (coefficient 4). Although all metrics show that the optical quality is worse in peripheral locations of the lens mainly as a result of the increase of astigmatism, there are significant differences between the three metrics. For example, the optical quality of eye JO expressed by Log_Vol_PSF or by Strehl ratio progressively decreases from naked eye to zone T3, whereas RMS shows an abrupt change in zone N1.

In the section on correlations, we show that the Log_Vol_PSF is the optical parameter that gives the highest correlation coefficient for the entire system eye plus lens and in particular for 4.5-mm pupil size and 100% contrast VA (see Fig. 11). For this reason, we

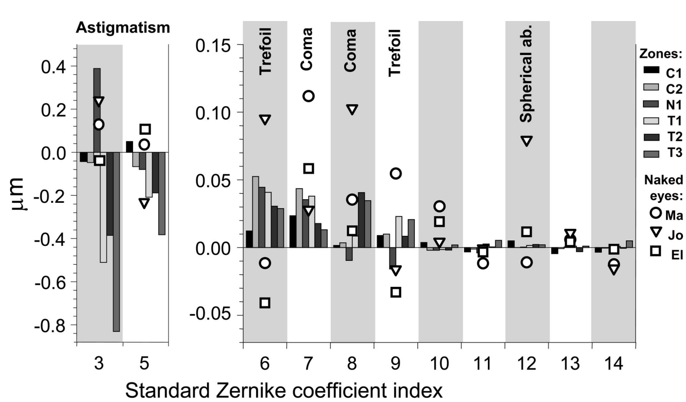

FIGURE 4.

Zernikes coefficients of the naked eyes and the six zones of the isolated progressive-power lens to be compared between them. A 4.5-mm pupil diameter. The Seidel aberrations corresponding to Zernike coefficients are shown on top of the graph. The scale of astigmatism in microns can be transformed in diopters by multiplying by 1.94.

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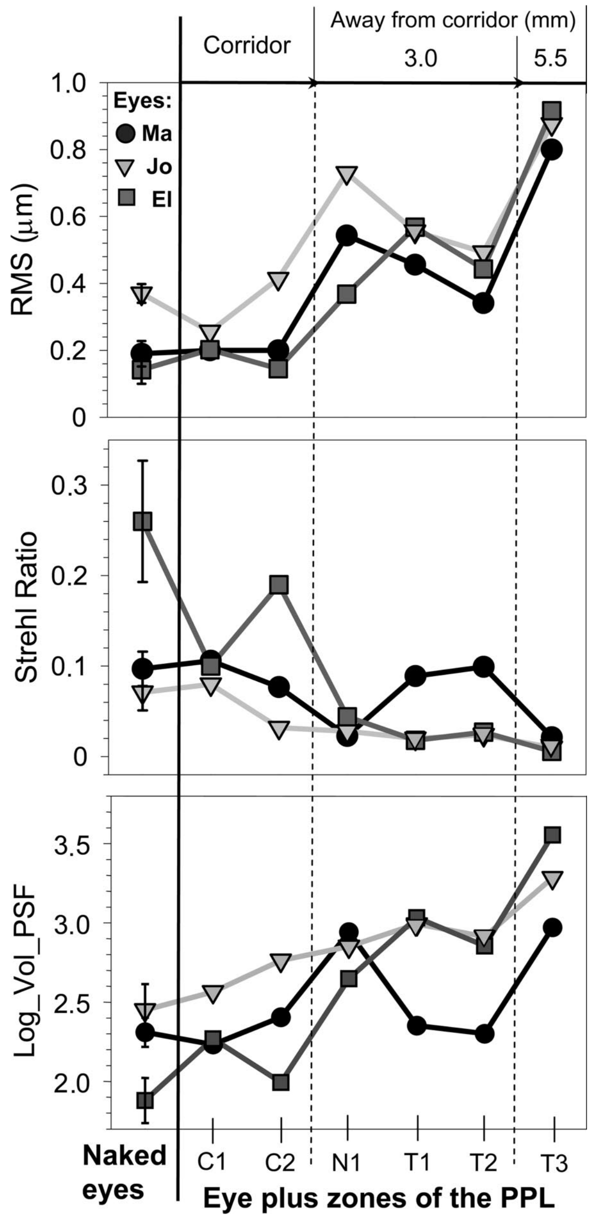

FIGURE 5.

Optical parameters (root mean square, Strehl ratio, Log_Vol_PSF) in the naked eyes and in combination with the six zones of the progressive-power lens. A 4.5-mm pupil diameter.

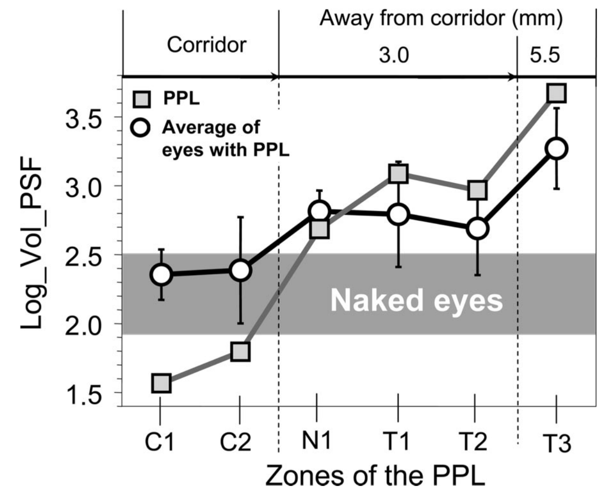

FIGURE 6.

Optical quality expressed by Log_Vol_PSF of isolated progressive-power lens (PPL) and average of the eyes with the PPL in comparison with the range of intersubject variability (standard deviation) of the eyes without lens. A 4.5-mm pupil diameter.

Visual Acuity

VA results, expressed in decimal units (1/minimum angle of resolution), are shown in Figure 7, for the three tested eyes and

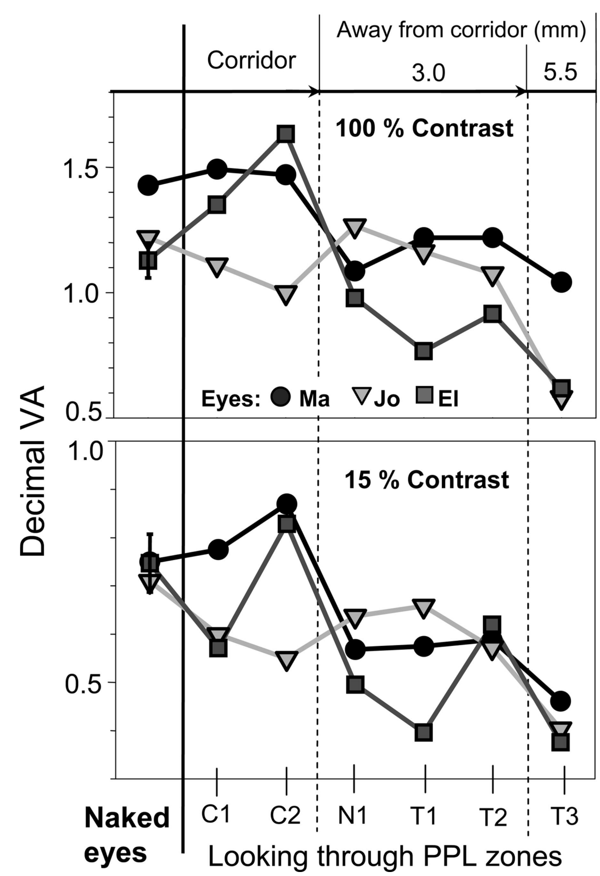

FIGURE 7.

Decimal visual acuity of the eyes, both isolated and when looking across the six zones of the progressive-power lens. Experimental errors are equal or lower than the bars presented in the naked eye of the subject EL. A 4.5-mm pupil diameter.

chose the metric Log_Vol_PSF for comparing the average optical quality of the eyes plus PPL with the lens alone and with the range of intersubject variability (standard deviation) of the naked eyes (see Fig. 6). The optical quality of the isolated PPL decreases very fast from corridor to peripheral zones. However, the combination of the aberrations of the eye and the progressive lens reduces the relative differences of optical quality between central and eccentric zones. The aberration coupling reduces the optical quality in the corridor, whereas the peripheral areas remain the same or even improve with respect the PPL alone. The optical quality of the eyes through the zones of the corridor is in the range of variability of the eyes without lenses. The corridor zones of the isolated PPL produce better optical quality than the naked eyes.

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4.5-mm pupil diameter. As expected, the VA for 100% contrast value is better than for 15%, but the behavior in the different locations of the lens is similar for both contrast values. The visual quality when the eyes are looking through the corridor areas of the PPL is similar to those of the naked eye, even in some cases better. In these zones, high- and low-contrast VA ranges between 1.00 to 1.65 and 0.55 to 0.85, respectively, whereas in the naked eyes, these ranges are 1.15 to 1.45 and 0.70 to 0.80. In general, the visual degradation is not so important in the zones nearer to the corridor (locations N1, T1, and T2), although the behavior is subject-dependent. For subject JO, VA is only decreased by the high astigmatism in zone T3. The high-contrast VA of subject MA remains very stable in all zones. The larger changes from corridor to peripheral zones are present in the low-contrast VA of subject MA and in both contrast values of subject EL. All results of high-contrast VA at locations 3 mm (N1, T1, and T2) and 5.5 mm (T3) away from the corridor ranges between 0.75 to 1.25 and 0.55 to 1.10, respectively. The values for low-contrast VA ranges between 0.40 to 0.65 and 0.35 to 0.45. In every case, the experimental error, expressed by standard deviation, is equal or lower than 0.07. In Figure 7, this maximum error bar is presented in the naked eye of subject EL.

Figure 8 shows the average results of VA for every tested condition compared with the range of intersubject variability (standard deviation) of the eyes without a lens. The VA decreases moderately from corridor to peripheral zones in a way similar to the optical quality expressed by Log_Vol_ PSF (see Fig. 6) of the eye with a lens. VA through the corridor and in nearby zones is similar or slightly lower than that found in eyes without lenses. The abrupt change is observed from 3 to 5.5 mm outside locations. No important differences are found between high- and low-contrast VA. In the case of a 3-mm pupil size, VA remains more stable for all zones.

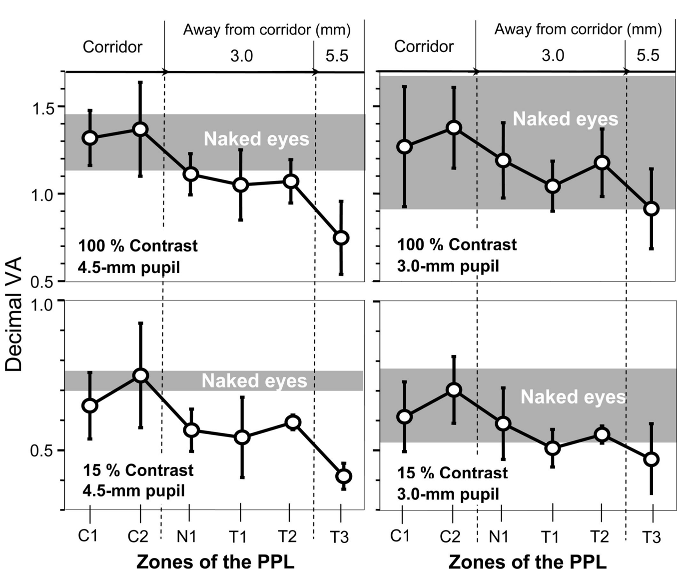

FIGURE 8.

Average visual acuity of the eyes with the progressive-power lens in comparison with range of intersubject variability (standard deviation) of the eyes without lenses for every pupil diameter (4.5- and 3-mm diameter) and contrast value (100% and 15%).

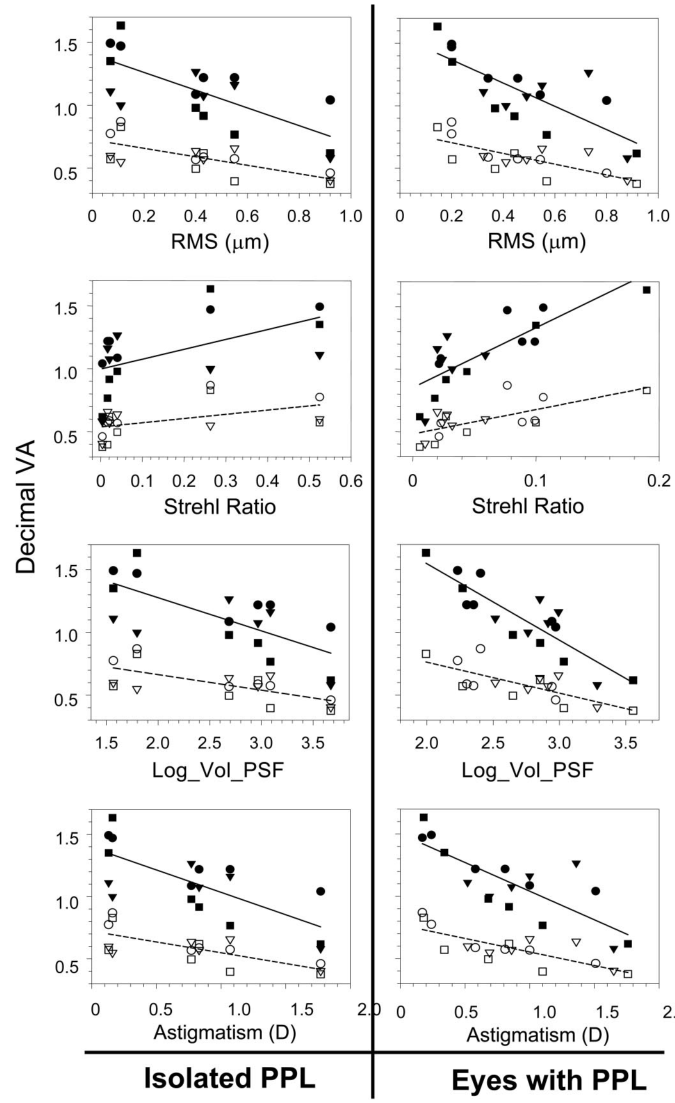

FIGURE 9.

Correlation between optical parameters (root mean square, Strehl ratio, Log_Vol_PSF, and astigmatism) and all visual acuity (VA) data of the subjects, eye MA (circles), eye JO (triangles), and eye EL (squares), taking into account only the wavefront aberration (WA) of the progressive-power lens (PPL) (isolated PPL) and adding the WAs of the eyes and the lens (eyes with PPL). VA and linear regression for both values of contrast: 100% (black symbols and solid lines) and 15% (white symbols and dashed lines). A 4.5-mm pupil diameter.

Correlations of Optical Parameters and Visual Acuity

Figures 9 and 10 show correlations of optical parameters and VA for 4.5-mm pupil diameter. Figure 9 presents the relationship between VA and optical parameters (RMS, Strehl ratio, Log_Vol_PSF, and astigmatism) of the isolated PPL and in situ (PPL plus eye), taking into account all results of the three subjects. The solid lines are the linear fitting for 100% contrast VA and the dashed lines are the linear fitting for 15% contrast VA. The parameters RMS, Strehl ratio, and Log_Vol_PSF have been estimated from whole WA (except defocus). Figure 10 presents the relationship of VA and Log_Vol_PSF taking into account only high-order aberrations (astigmatism and defocus

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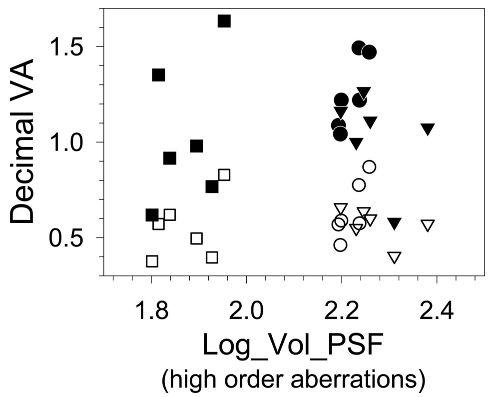

FIGURE 10.
Correlation between values of Log_Vol_PSF from wavefront aberrations of the progressive-power lens plus eyes without defocus or astigmatism (i.e., only high-order aberrations) and all visual acuity data of the subjects, eye MA (circles), eye JO (triangles), and eye EL (squares) for both values of contrast: 100% (black symbols) and 15% (white symbols). A 4.5-mm pupil diameter.

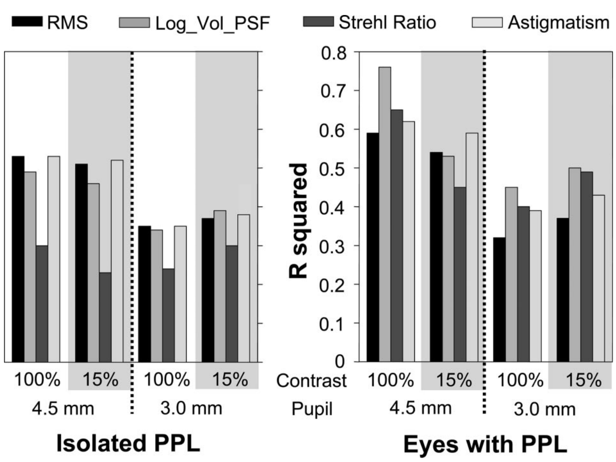

FIGURE 11.
R-squared coefficients of the linear correlations between visual acuity data of the three subjects and optical metrics, considering only progressive-power lens (PPL) and the complete system eyes plus PPL.

set to zero) for the entire system eye with the lens. In the statistical analysis, we calculated linear R-squared coefficients and p values for all combinations of optical parameters and VA. All optical metrics obtained from complete WA (with astigmatism and high-order aberrations) are significantly correlated with VA ($p < 0.05$). However, as we show in Figure 11, there are important differences in the R-squared values. The parameters calculated from whole WA of the system eye plus lens correlate better than those of the lens alone. In general, when comparing results of both pupil diameters, better correlations are found for the larger pupil size. Considering only the PPL, Strehl ratio presents the lowest correlation values (R-squared equal or lower than 0.3, $p > 0.02$). VA is relatively well correlated with RMS, Log_Vol_PSF, and astigmatism of the isolated PPL (R-squared values around 0.5 for 4.5-mm pupil, $p < 0.002$). As expected, the majority of correlation values are higher when considering the entire system lens plus eye. In the cases of a 4.5-mm pupil and 100% contrast VA, all optical metrics give high values of correlation around 0.6 or higher ($p < 0.0002$), and, in particular, the best correlation is produced by the parameter Log_Vol_PSF (R-squared equal to 0.76, $p < 0.0001$). As shown in Figure 10, we have not found linear correlation between visual performance and optical parameters calculated from WA with only high-order aberrations (R-squared < 0.2 for all cases, $p > 0.1$).

DISCUSSION

Impact of Progressive-Power Lens' Aberrations on Visual Acuity

In the corridor, the small amounts of astigmatism, coma, and trefoil (around 0.05-μm RMS each one for a 4.5-mm pupil diameter) do not have a significant effect on VA. This confirms the assumption made from recent calculations on an analytical model describing optical aberrations of the corridor.[36] The progressive increase of astigmatism in outside zones (around 0.75 and 2.00 D 3- and 5.5-mm away from corridor, respectively) moderately degrades visual performance. This progressive and not abrupt change from corridor to eccentric zones is also produced in the optical quality (expressed by Log_Vol_PSF) of the entire system eye plus PPL in contrast to more rapid changes in the isolated lens. The aberrations of the young eyes of our study tend to equalize the retinal image quality between central and peripheral areas of the progressive lens. This effect could be even larger in the presbyopic eyes as a result of the increase of high-order aberrations with age.[37,38] Moreover, the intraocular light scattering is an additional phenomenon that also reduces the quality of vision through life.[39] In this way, the difference between the visual performance of the presbyopic eyes without lenses and when looking through PPLs should be even lower than that shown for young eyes.

Visual Tolerance to Optical Aberrations

The effect of different wavefront aberrations on visual performance and the tolerance thresholds in visual ocular system is an important issue for researchers on visual optics. In particular, the tolerance limits of astigmatism and defocus have been widely studied for evaluating the visual quality and the acceptance of PPLs. However, the tolerance to other aberrations present in PPLs has still not been considered. Maitenaz[7] regarded 0.3 D to be the tolerable limit of astigmatism, Davis assumed 0.5 D, and Shinohara and Okazaki proposed values up to 1 D to be acceptable. In recent experiments done in our laboratory,[40] in most subjects, visual acuity did not improve with correction of small amounts of astigmatism (lower than 0.5 D). Sullivan and Fowler[1] measured the grating VA eccentrically from a midpoint on the umbilical line of three PPLs (2.00 D near addition) in a single subject. For all lenses, in eccentricities <10° in which the maximum astigmatism was around 1.5 D, decimal VA was better than 1. Our results show a VA equal or better to 1 as long as total astigmatism (lens in combination with eye) is lower than 0.90 D (0.46-μm RMS). This value corresponds approximately to that in zones N1 and T1 (around 6° of eccentricity).

In the works of Atchison et al.[17] and Marcos et al.,[18] the values of tolerance to defocus (expressed as the half of whole range for which the target appears unchanged) were similar, around 0.50,

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0.30, and 0.25 for 2-, 4-, and 6-mm pupil diameters, respectively. Campbell[15] regarded 0.215 D to be the limit of defocus for a 3-mm pupil. In recent studies, Atchison et al.[41] reported a noticeable blur limit of 0.3 D for 4-mm pupil size and letter size of 1 arc-min. Ciuffreda et al.[42] also included presbyopes in their work, and they obtained a detectable blur threshold around 0.5 D for a 5-mm pupil diameter and letter size of 2.5 arc-min. In our experiments, we estimated the defocus error as the difference between spherical refraction predicted from adding ocular refraction plus lens power and that measured directly by the focus corrector system with the eye looking through the lens. Although there was a large variability in results (from 0.05 to 0.60 D), the average defocus error of 0.20 D (for a 4.5-mm pupil diameter and smallest letter size that the subject was able to read) is in concordance with previous outcomes.

Coma and trefoil are the other aberrations also present in PPLs. In a recent work, Applegate et al.[43] showed that values of Zernike coefficient 6 (trefoil) lower than 0.2 μm did not decrease the high-contrast VA. In our study, the combination of the similar amounts of coma, trefoil, and astigmatism (total RMS around 0.1 μm) of the corridor of the PPL have a very small effect on visual performance independently of pupil size and letters contrast.

Prediction of Visual Performance From Optical Parameters

In the process of designing a PPL, it is very advantageous to be able to predict the visual performance from the optical parameters. Thus, the designers can a priori know what will be the level of acceptance and satisfaction of the future users of the PPL. Many theoretical and empiric previous works have studied the optical quality and visual performance of PPLs. However, as far as we know, we have not found results on optical parameters that correlate better with psychophysical measurements in this kind of lens for presbyopes. In addition, to estimate the impact of PPL's aberrations on visual performance, the other main goal of our study was to find the optical parameter that better predicts the visual quality.

We have studied four optical parameters calculated from WA, two directly from WA (RMS and astigmatism) and two from associated PSF (Strehl ratio and Log_Vol_PSF) for two pupil sizes, 4.5- and 3.0-mm diameters. In general, for the smaller pupil, the correlation values are worse as a result of the reduction of the effect of aberrations on VA. When considering the PPL alone, except Strehl ratio, all optical parameters give similar values of correlation. It is well known that Strehl ratio is not a convenient image quality descriptor for high values of aberrations.[14] Our results show good correlation values for the Strehl ratio of the complete system eye plus lens, because the aberrations are not too high. However, as shown in Figure 11, for the entire system (PPL with the eye), the parameter Log_Vol_PSF seems more adequate. In addition to Log_Vol_PSF, we also calculated the natural logarithm of the Strehl ratio (Ln_Strehl_R.). In the image plane, the intensity peak is inversely proportional to the image spread. This means an inverse linear relationship between Strehl ratio and the volume of the PSF normalized to one, which results in a perfect linear correlation of Ln_Strehl_R and Log_Vol_PSF values.

In summary, VA is predicted slightly better by metrics of image spread (Log_Vol_PSF or equivalent) than by RMS. This is in accordance with previous results[14] that show a good linear correlation of the logarithm of the volume under the double-pass image normalized to one and VA measurements in the presence of defocus. However, in addition to image spread, the shape of the image possibly also influences the quality of vision.[43,44] For instance, when eye JO is looking through the PPL, the Log_Vol_PSF is very similar in all zones, but in the zone N1, the PSF is very concentrated in a small circle (see Fig. 3). In this particular case, these optical conditions produce a high VA, 1.25 for high-contrast and 4.5-mm pupil diameter.

On the other hand, previous work[45] demonstrated that the visual system compensates for the eye's aberrations. This effect could influence the temporal adaptation process to PPLs. However, in recent experiments,[46] we have not found a neural adaptation to the aberrations of PPLs over time.

The Effect of Focus Errors on Our Results

In our experiments, the VA measurements were taken with the best subjective spherical focus, and the optical measurements were processed for Zernike defocus coefficient set to zero. Thus, we supposed a perfect response of the accommodation to changes in target vergence. In natural conditions, the high-order aberrations, and in particular spherical aberration, may influence the stimulus/response relationship.[47,48] Furthermore, accommodation can produce small changes in the ocular aberrations, especially in the spherical aberration.[47–51] The error in focus and the changes of high-order aberrations increase progressively with the amount of accommodation. However, in the case of presbyopes, the residual accommodation (usually lower than 2.5 D) may only produce very small changes in defocus and in other aberrations.

On the other hand, it is commonly assumed that the optimum defocus that maximizes the optical quality should yield the best subjective focus.[52] In our computing process, we also calculated the correlations of VA and the optical parameters on the image plane (Strehl ratio and Log_Vol_PSF) where Zernike defocus coefficient maximized these parameters. The values of linear correlation coefficients were lower (0.44 for Strehl ratio, 0.51 for Log_Vol_PSF, with high-contrast VA and 4.5-mm pupil diameter) than those obtained for defocus coefficient set to zero (0.65 and 0.76, respectively). This may be explained by, in some images, the maximum values were found in the plane of one of both Sturm foci or in nearby axial positions, far from the best subjective focus, which was in or around the circle of least confusion.

CONCLUSIONS

In isolated PPLs, the optical quality decreases very fast from corridor to peripheral zones. However, the aberration coupling with the eye tends to equalize the retinal image quality between central and outside zones of the progressive lenses.

The small amounts of astigmatism and higher-order aberrations, coma and trefoil, that are present in the central areas (corri-

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dor) of progressive lenses appear to have a limited impact on VA. In these and nearby locations, aberration coupling between eye and PPL can even yield slightly better VA than in the naked eye. At peripheral areas of the lens, larger amounts of astigmatism moderately reduce VA.

The logarithm of metrics on retinal image spread, Log_Vol_PSF or equivalent, of the entire system eye plus PPL are the parameters that best predict high-contrast visual performance.

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