Differences in visual quality with orientation of a rotationally asymmetric bifocal IOL design

Aiswaryah Radhakrishnan, M.Phil¹, Carlos Dorronsoro, Ph.D¹, Susana Marcos, Ph.D¹

¹Laboratory of Visual Optics and Biophotonics, Instituto de Óptica “Daza de Valdés”, Consejo Superior de Investigaciones Científicas, Madrid, Spain

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Corresponding Author

Aiswaryah Radhakrishnan

Visual Optics and Biophotonics Laboratory,

Instituto de Optica, CSIC,

Serrano, 121, Madrid-28006, Spain.

Ph: +34-915616800 (301)

e-mail: aishu@io.cfmac.csic.es

Abstract

Purpose: To evaluate visual and perceptual performance for different orientations of a rotationally asymmetric bifocal IOL simulated optically using a laboratory simultaneous vision simulator.

Setting: Instituto de Optica, CSIC, Madrid, Spain.

Design: Prospective observational study.

Methods: Perceptual quality and High Contrast Decimal Visual Acuity (HCVA) was measured, in 20 cycloplegic subjects (21 – 62 yrs), for 8 orientations of asymmetric bifocal IOL phase pattern at far, intermediate and near distances simulated with simultaneous vision simulator using face images and tumbling E targets. The preferred (centroid) orientation at each distance was calculated for the polygon encompassing the data for eight orientations. Visual-Strehl (VS) was calculated using subjects' ocular aberrations and multifocal pattern at each orientation and optical predictions were obtained implementing an ideal observer model based on differential VS values.

Results: Horizontal orientation (near segment between $0/180\pm45^\circ$) was preferred by 14 and 13 subjects at far and near; 8 subjects showed strong preferences in orientation. Significant differences (Bernoulli cdf $p<0.05$) in the perceptual quality with orientation were observed across distances. Mean difference in preferred orientation between far and near was $27^\circ\pm22^\circ$. No significant differences in HCVA was observed. Optical predictions correlated strongly and significantly with measurements ($r_{\text{far}}=0.71$, $r_{\text{near}}=0.62$, $p<0.0001$). The mean difference between measurement and simulation in the preferred orientation was $28^\circ\pm29^\circ$ at far and $36^\circ\pm28^\circ$ at near.

Conclusion: Perception varied for different orientations of an asymmetric bifocal IOL design tested using the simultaneous vision simulator. Optimal orientation is driven by interactions of the design with the optical aberrations of the eye.

Introduction

Multifocal corrections are popular solutions for the treatment of presbyopia¹. Clinical studies on patients implanted with multifocal IOLs show improvement of near vision generally at the expense of degradation of distance vision, in comparison with monofocal corrections². Refractive multifocal patterns devote discrete zones of the pupil for far vision, and others for near (and sometimes also intermediate) vision. Computational³ and experimental studies using adaptive optics⁴ show that multifocal designs with non-rotationally (angular) distribution of zones outperform designs with lower number of far/near zones generally outperform designs with higher number of zones and with a radial zone distribution. Also, a recent experimental study simulating angularly-segmented bifocal corrections with a simultaneous vision simulator demonstrated visual benefits for 2-zone angularly segmented designs in comparison with concentric or hybrid distributions^A. However, the rotationally asymmetric nature of the angular design and the orientation in which they are implanted may potentially impact visual performance.

The M-Plus lens by Oculentis is an angular design IOL with 60% of the total lens area dedicated for far vision and 40% dedicated for near vision. Eyes implanted with the M-Plus lens have demonstrated functional vision similar or better than other multifocal or accommodative IOLs⁵⁻⁸. Typically M-Plus lenses are implanted with the near vision zone placed inferiorly. A case report showed that placing the lens in a different orientation could actually be beneficial⁹. Conversely, a recent report found that, on average across a group of patients, the orientation of the IOL does not influence visual performance¹⁰. Computational studies show that the ocular aberrometric profile¹¹ and the corneal comatic axis¹² of each patient may play a role in optical and visual

outcomes with the M-Plus lens at that this interaction changes with the lens orientation. Comparisons of visual perception and visual performance across IOL orientations in the same patients are hard to evaluate clinically, since for any given patient, the lenses are implanted at a single orientation.

Adaptive optics visual simulators, are capable of simulating a multifocal correction, enabling the systematic evaluation of multifocal designs on the same patient, non-invasively. Piers et al.,¹³ demonstrated expansion of the subjective depth-of-focus with spherical aberration, and, de Gracia et al.¹⁴ with certain combinations of astigmatism and coma, induced with adaptive optics visual simulators. Vinas et al.⁴. demonstrated differences in visual perception in normal subjects with simulated angular and radial segmented multifocal designs, using a deformable mirror and Spatial Light Modulator based adaptive optics system. Using a simultaneous vision simulator Dorronsoro et al.,^A showed that bifocal rotationally asymmetric designs tended to outperform other bifocal designs, although this differed across subjects. This simulator can be programmed for automatic simulation of different orientations of a multifocal IOL allowing for evaluating both optical and neural interactions between the eye and the multifocal IOL design.

In this study we used the custom-developed simultaneous vision simulator provided with a spatial light modulator to test the influence of lens orientation of a rotationally asymmetric IOL design, on perceived visual quality and visual acuity at different distances in patients with paralyzed accommodation.

Methods

Subjects

Twenty subjects (aged 21-62 years) participated in the study, with refractive errors ranging from +2.50 D to -5.50 D, astigmatism < 1 D. Eight of the subjects did not have

prior experience in performing psychophysical experiments. All measurements were performed with paralyzed accommodation and therefore under simulated presbyopia. Cycloplegia was pharmacologically induced with 1% tropicamide (3 drops at 5 minutes interval 15 minutes prior to beginning of measurements and maintained by instilling one drop of every hour). The measurement protocols met the tenets of declaration of Helsinki and were approved by the review board of Consejo Superior de Investigaciones Cientificas. All subjects provided a written informed consent.

Simultaneous Vision Setup

A custom simultaneous vision simulator (Fig. 1) was used to simulate angular bifocal corrections and to perform psychophysical evaluations at three distances. The system has been described in detail in prior publications^{15,A-C}. In brief, two channels provided with two Badal systems separated by two beam splitters recombine at a pupil plane, therefore allowing to change defocus independently. One channel is focused at far, while the other introduces a near addition that can be changed continuously. A Digital Light Projector (DLP; Texas Instruments; resolution of 800 x 600 pixels) projects visual stimuli that are viewed simultaneously through both channels. In a modified version of the instrument^C a transmission spatial light modulator (SLM) is placed in a pupil conjugate plane with a linear polarizer. These are found to be efficient to simulate phase patterns, as shown by the good correspondence between visual perception with physical multifocal pattern lenses and reflection SLM simulations of those patterns^{16,A,C,D}. Two orthogonally oriented linear polarizers placed in the Badal channels projects near or far focused images, following the black and white pupillary masks displayed in the SLM. The current configuration of the system is showed in figure 1. The

effective luminance of the test stimulus was 39 cd/m². Test stimulus and pupillary mask presentation were synchronized in Matlab using the Psychtoolbox¹⁷.

In this study, the focus difference between the two channels was set to + 3 D. Far vision was simulated by placing the far channel (Badal 2) at best focus (BF) and the near channel (Badal 1) at BF+3 D. Near vision was simulated by placing Badal 2 at BF-3 D and Badal 1 at BF. Intermediate vision was simulated by placing Badal 2 at BF-1.5 D and Badal 1 at BF+1.50 D. All measurements were done for 5 mm pupil diameters, addressed by the SLM.

Simulation of the rotationally asymmetric IOL

The M-Plus (Oculentis Inc^E), an angular profile lens with a small radial zone at the center for far vision, was simulated. The far/near energy ratio was 60/40. Masks were created using Matlab consisting on white and black portions of a circular image (5 mm diameter) representing far and near vision zones respectively. Figure 2a shows an example of the mask and its optical representation at the pupil plane. These patterns are programmed in the SLM and presented at eight orientations of the mask. The angular notation (Fig. 2b) represents the orientation of the near zone. For convention, the right eye data are flipped horizontally¹⁸, so that 0 deg represents nasal orientation both in right and left eyes.

Perceptual Scoring

Subjects viewed 2 deg visual field face images (Figure 3, top) displayed by the DLP through the 8 orientations of the bifocal design presented in random order interspersed with a gray field (Figure 3, middle). For each presentation, the subject graded the image in a six-score grading scale from very blurred (-10), blurred (-5), not so blurred (-1), not

so sharp (1), sharp (5), and very sharp (10), using keyboard inputs. Figure 3 provides an example of the scoring given by one subject on a particular series of presentations. The measurement was repeated ten times and the average score for each orientation was calculated and taken as the Perceptual score^{4,33}. Presentation of test image and pupil mask, and acquisition of response were synchronized using Matlab.

Orientation preference

For testing the orientation preference (Figure 4), subjects viewed subsequently, a face image (2 deg field) through two pairs of random orientation bifocal patterns. Each image was viewed for 1.5 s, with a gray screen presented in between each image pair presentation. The subject's task was to choose the better focused image (first or second) of the pair and indicate the confidence of choice on a 3 confidence level scale. Each session consisted of presentation of 36 random pairs and the measurements were repeated 10 times.

Decimal Visual acuity measurements

Decimal visual acuity ($\log\text{MAR} = -\log_{10} [\text{decimal acuity}]$)¹⁹ was measured using white E letters on a black background that was presented in eight random orientations of varying sizes (Fig. 5). At the beginning of the trial, an E target is presented of supra-threshold size and a random orientation. The task of the subject was to identify the orientation of the E-letter and respond using a keyboard (8AFC). The size of E in the subsequent presentation is decreased or increased depending on the subject's response using a QUEST algorithm²⁰. The presentation orientation is randomized. A run consisted of 50 trials and 20 reversals and the visual acuity was measured as the

average of last ten reversals. The measurements were repeated for all the eight orientations of the bifocal pattern and for far, intermediate and near distances.

Aberrometric measurements

The ocular aberrations were measured using a Shack-Hartmann aberrometer (HASO32, Imagine Eyes), part of a custom-developed adaptive optics system²¹. Measurements were performed under cycloplegia. Defocus was corrected using a Badal optometer while the subject fixated a 2 deg white Maltese-cross in a black background. Pupil diameter was limited to 5 mm using an artificial pupil placed at a pupil conjugate plane.

Optical simulations

Pattern orientation preference was simulated using an “ideal observer model” whose responses to an orientation preference task (similar to the subjective task) are based on Visual Strehl (VS) metric²². For each subject, the through-focus VS was computed for wavefront aberration resulting from the combination of the measured subject’s ocular aberrations (astigmatism + HOA) and the bifocal patterns at each orientation. In all patients and for all distances (best focus, at +1.5 D and at +3 D), differential VS for each orientation was compared with that for all the other orientations. Scores of 10, 5 and 1 were assigned when the differences above 75%, 50% and 25% thresholds, corresponding to the monofocal VS at that distance, respectively

Data analysis

Both perceptual and optical preference measurements were analyzed similarly. Weights were assigned to the positive (images selected as better of the pair) and negative

responses (images not selected) according to the confidence of the response (from +10 to +1 / -10 to -1). The scores assigned to each pattern orientation were summed and a sum weighted preference score was obtained. A polar plot was generated from the scores at each orientation and the centroid of the corresponding polar curve was calculated for each distance. The orientation of the centroid indicates the preferred orientation and the radius indicates the strength of the preference. For identifying significant preferences, a Bernoulli statistics was used. A score greater than +15 for a given orientation is considered significant, indicating that that orientation produced significantly better optical or visual performance.

Results

Changes in Perceptual Score with pattern orientation

Figure 6 shows the Perceptual Score for different orientations across different distances as a polar plot. The center of the plot corresponds to a score of -10 and the outer line to +10 symmetrically in all orientations. Data for far are indicated in red, intermediate in green and near in blue. The average perceptual score across subjects did not vary across orientations or distances (Fig. 6 A), although the curves tended to elongate for 0 and 180 deg. However, there were high intersubject variabilities in this performance. Fig. 6 B-D show perceptual score plots for three individual subjects. For example, for S2, perceptual score is highest for 180 deg at far, and for 270 deg at intermediate and near. For the other two subjects shown (S11 and S18), the score is highest at 0 deg for both far and near, and 0 and 90 for far and near, respectively.

The overall perceived image quality across orientations at any distance was calculated as the area of the circle formed by the perceptual scores at the given distance. The

mean score was 5.6 (SD: 1.2) at far, 2.1 (SD: 1.07) at intermediate, and 4.1 (SD: 1.05) at near. The mean difference in perceived image quality (score) between far and near was 2.5 (SD: 1.4) and was not significant ($p=0.37$).

Orientation preference

Figure 7 shows the weighted preference with the respective centroids for all subjects. The center of the plot corresponds to a preference score of -100 and extends symmetrically across all orientations to a score of +100. The arrows indicate the orientation of the centroid (preferred orientation) and the length of the vector indicates the strength of preference. The weighted perceptual preferences (Experiment 2) correlated significantly with the perceptual score (Experiment 1) across all subjects and distances ($r=0.48$, $p=0.004$). At far, 6 subjects preferred nasal quadrant orientations (0 ± 44.5 deg), 4 subjects preferred superior quadrant orientations (90 ± 44.5 deg), 8 subjects preferred temporal quadrant orientations (180 ± 44.5 deg) and only 2 subjects preferred inferior quadrant orientations (270 ± 44.5 deg). At near, 8 subjects preferred nasal quadrant, 5 temporal quadrant, 6 inferior quadrant and one the superior quadrant orientations.

Figure 8 shows the centroid locations for far (filled) and near (open). Values outside the inner circle (radius of 15) are significant. Eight subjects had strong orientation preference at far and 9 subjects had strong orientation preference at near. The mean angular difference in the centroid orientation between far and near was 27 ± 22 degrees and correlated significantly ($r=0.32$, $p<0.05$), indicating that in most subjects the orientation preference was retained across distances.

Changes in Decimal Visual acuity

Mean decimal visual acuity, across subjects and orientations was 0.63 at far (SD: 0.02) and 0.556 at near (SD: 0.021). This corresponds to one line difference in visual acuity with conventional charts¹⁹. As shown in Figure 9, the visual acuity did not vary much across orientations at any distance. The maximum difference in average visual acuity across any two orientations at far, intermediate and near was 0.06, 0.11 and 0.05, respectively.

Ideal observer model

Responses of an “ideal observer model” were based on the Visual Strehl values at the measured distances. In a diffraction-limited eye through-focus VS curves are the same for all orientations (Fig.10 A). In real eyes, the amplitude and overall shape of the through-focus curves may vary across orientations (an example for patient S2 is shown in Figure 10 B). Figure 11 shows the orientations preferences obtained for each subject using the ideal observer model, which responds based on VS values. As in the perceptual orientation preference plots (Figure 7), the center of the plot corresponds to the optical preference score of -100 and extends symmetrically across all orientations to a score of +100. The arrows indicate the orientation of the centroid (preferred orientation) and the length of the vector indicates the strength of preference. The simulated optical preference plots and the perceptual preference plots correlated significantly with the measured data at far and near distances ($r_f=0.71$, $r_n=0.62$, $p<0.0001$), although not for intermediate distances ($r=-0.021$, $p=0.87$). A Bland-Altman analysis revealed good agreement (better for far distance) between measurements and simulations at all distances ($p_f=0.46$, $p_i=0.19$ and $p_n=0.24$).

Figure 12 A-C shows the centroid locations of the perceptual preference (filled symbols) and optical simulated (open symbols) preference polar plots, for far, intermediate and near distances. There is in general a high correspondence between perceptual and optical centroid locations for far (28 deg, SD: 29) and for near (36 deg, SD: 28) distances, both data falling in the same quadrant, but not for intermediate distances (80 deg, SD: 63). Correspondingly, there was a strong significant correlation (Fig. 13) between the perceptual and optical centroids at far and near distances ($r_f=0.89$, $r_n=0.94$, $p<0.0001$). Even at intermediate distance a weak correlation was observed ($r_i=0.47$, $p<0.05$). The radius of the centroid estimated from optical simulations was higher than from perceptual measurements in about 65% of the subjects across distances, probably resulting from discrepancies in perceptual weighting by the subject and the ideal observer. On average across distances and subjects, the difference in radius between simulations and measurements was 1.8 (SD: 7.8) and did not correlate significantly at any distance.

Discussion

We evaluated systematically the perceptual and visual performance differences with orientation of a rotationally asymmetric bifocal pattern (mimicking the Oculentis M-Plus design) simulated in a simultaneous vision simulator. While visual acuity did not change significantly, the perceptual score showed a clear bias towards specific orientations. Perceptual orientation preferences varied across subjects, and in some cases across distances. Interestingly, these preferences were determined mostly by the optical interactions of the eye's optical aberrations and the bifocal pattern.

Visual performance

Multifocal IOL implantation is aimed at providing patients with good uncorrected visual acuity for both distance and near visual tasks. The bifocal design we tested provided high contrast visual acuity at far and near distances in the near normal visual acuity range. The bifocal design was distance dominant and, concurrent to the bifocal design, the visual acuity at near was >1 lines lower than the distance visual acuity. The visual acuity reported in our study was within the range of visual acuities reported in previous studies². Despite the absence of a correction at the intermediate region, the visual acuity was relatively well preserved at intermediate distance.

Decimal visual acuity measured at high contrast was unaffected by the orientation of the angular bifocal design. It is likely that the differences across orientations are not apparent with high contrast stimuli, although these differences may have been present in a low contrast visual acuity^{23,24}. In other words, conventional tests for visual acuity appear to be insensitive to changes introduced by blur orientation and might not be a useful indicator of preferred orientation of the IOL.

Perceptual differences across orientations

Changes in perceived image quality at different orientations from both perceptual measurements (perceptual scoring and perceptual preference) were concurrent in most subjects. Twelve of the 20 subjects had a significant correlation between perceptual scores and weighted perceptual scores for far distance across all orientations, and only in two subjects, these were uncorrelated or negatively correlated. Similar to visual acuity results, the overall perceptual quality was better at far than at near and was worse for intermediate acuity. It is, however, to be taken into account that the intraocular lens design simulated was a bifocal (60F/40N) and had no energy dedicated

at in-intermediate. The residual optical quality at intermediate is likely to have resulted from the interaction between the ocular aberrations of each subject and the peak foci. Also, measurements were performed for a fixed pupil diameter of 5 mm. The angular nature of the design makes performance less dependent from pupil diameter^E. A 5 mm pupil diameter was chosen, corresponding to the typical average pupil diameter, for a luminance of 44cd/m², in presbyopic population(40yrs – 60 years)²⁵, and as the pupil diameter for which optical performance of the M-Plus IOL has been characterized on-bench^E. The angular nature of the design makes performance less dependent from pupil diameter^E. While modifying the pupil diameter will modify the amount of aberrations and the interactions of the aberrations with the lens, we do not anticipate these differences to affect the general trends.

On an average, the orientation preferences showed a trend to the horizontal axis (Fig. 8 A), although the orientation bias differed across subjects. The conventional orientation of IOL implantation in the clinic is with the near zone at 270 degrees, however only one subject showed consistent preferences at all distances to this orientation. Many subjects showed a preference along the horizontal axis for far and near distances, in both perceptual score and orientation preference measurements, although the vertical orientation was favored more often at near distance. This bias could have an optical or neural origin.

Orientation tuning in the visual system^{26,27} especially to horizontally oriented targets^{28,29} have been reported by previous researchers. Ohlendorf²⁸ et al., showed that subjects could tolerate horizontally oriented astigmatism better than vertically oriented astigmatism. Also, Vinas²⁹ found lower visual degradation to induced horizontal astigmatism than to astigmatism induced vertically or obliquely. Long term bias to

oriented blur was shown to persist even after long term wear of corrective astigmatic lenses³⁰. While, it has been shown that subjects are adapted to their own aberration orientation³¹, it has also been shown that subjects can adapt to a new aberration pattern/blur orientation³² and even to pure simultaneous vision blur³³. Whether subjects can adapt to new oriented blur produced by a rotationally asymmetric lens remains to be investigated.

Perceptual differences across subjects

The perceptual preference to orientation showed distinct trends among groups of subjects. While some subjects showed consistent and strong orientation preference across distances, few subjects showed strong preferences that varied across distance and few subjects did not show any significant orientation preferences. On an average across all subjects, even though the preferred orientation was along the horizontal axis, the strength of preference was reduced, indicating that these preferences are highly subjective and should be treated on an individual-basis. This finding explains why a bias was not be apparent as a group trend by de Wit et al¹⁰ in patients where the M-Plus IOL had been implanted in different orientations.

Simulations vs Measurements

Orientation preferences were simulated using an ideal observer model generated from the through focus VS calculated from the ocular aberration measurements at best-focus. A good agreement was found between optical simulations and the perceptual measurements ($r_f=0.89$, $r_n=0.94$, $p<0.0001$). In fact at far, the preferred orientation estimated from perceptual measurements were within 45 degrees (smallest step of rotation measured in the study) of the preferred orientation obtained from simulations in

90% of the subjects. On the other hand, 40% of the subjects still had a difference of less than 20 degrees (clinically relevant) between simulated and measured preferred orientation. These results suggest that the orientation bias is strongly influenced by the ocular optics. Most of the subjects in this study had coma-like aberrations oriented along the oblique axis, which reflected in the orientation preferences¹².

The optical simulations were performed using Visual Strehl as a metric, which represents exclusively optical contrast differences across orientations. It is conceivable that a metric that also considered the orientation of the retinal blur (produced by each combination of ocular aberration and bifocal pattern orientation) instead of overall contrast only may even improve the predictions. Given the good prediction of the orientation bias on optical grounds it is conceivable that the best selection of the lens orientation can be planned based on the optical aberrations. In any case, a full account of both the optics and neural aspects can be achieved by using a simultaneous vision simulator or adaptive optics visual simulators.

Implications

This study shows that choosing the optimal orientation of a rotationally asymmetric IOL may have an impact in improving the visual performance with these lenses. Several subjects showed clear preferences to a particular orientation which was the same at far, intermediate and near distances and few other subjects showed no typical tendencies with orientation at any distance. These are probably the most ideal subjects for the implantation of angularly segmented multifocal IOLs. On the other hand, over a third of the subjects showed a different preferred orientation for far and near distances. The orientation of implantation might, in these cases depend on the subject's visual needs

or might be based on the preferences at far. Since some of these subjects have strong preferences to orientation, this further stresses the importance of orientation preference assessment prior to the surgical intervention.

A natural follow-up to the study can entail potential changes in the orientation preference after adaptation to a non-preferred orientation. In previous studies we found short-term adaptation effects after exposure to pure simultaneous vision, to other aberration patterns, and to oriented blur, suggesting that adaptation to an initially non-preferred orientation may happen.

In this study, the rotation accuracy needed for this optimization can only be speculated, as our perceptual measurements were done in 45 deg increments, and the average difference between the predicted best orientation and that estimated from perceptual measurements (centroids from polar plots in each case) was around 20 deg. These accuracies can be easily achieved manually by surgeons. In brief, similarly to the selection of optimal orientations of toric IOLs^{34,35}, it is conceivable to develop algorithms based on the aberrations of the eyes that guide clinicians to choose the optimal orientation of the lens, similarly to the “ideal observer model” approach described here. These should preferably use the topography-based corneal aberrations, as the crystalline lens is removed in the procedure. Alternatively, adaptive optics or simultaneous vision systems can be used to base the decision on perceptual measurement in patients, provided that the lens is not fully opacified by cataract.

Conclusion

In this study, we measured visual and perceptual performance to different orientations of a commercial bifocal design at far, intermediate and near. The high contrast visual

acuity did not differ much across orientations and distances. The perceptual performance and preferences were different across orientations and distances in most subjects. We show that these preferences are closely associated with the optical quality of the eye defined by the lower and higher order aberrations. In absence of modalities to customize the entire IOL design, small changes in the orientation of IOL implantation could result in improved perceptual quality. These preferences should be assessed prior to surgery, considering the visual needs of the patients and more importantly, taking into consideration, their own optical quality.

WHAT WAS KNOWN

- Computer and experimental visual simulations show that rotationally asymmetric IOL designs tend to provide better visual quality compared to concentric lens designs
- The predicted optical quality with angular designs varies with orientation and is affected by the subject's aberrations, particularly coma.
- Clinical studies on averaged groups do not suggest an impact on lens orientation (0 vs 180 deg), but visual simulations show differences across orientations at an individual level.

WHAT THIS PAPER ADDS

- Visual simulations of a rotationally asymmetric IOL at different orientations on the same patient show consistent differences in perceived visual quality across orientations.
- Implanting a rotationally asymmetric IOL along the identified preferred orientation can optimize perceptual quality and visual performance.

- The preferred orientation is influenced by ocular optics and ocular/corneal aberrations, which can be used to predict the orientations in which the IOL should be implanted.

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Figure legends

Figure 1: Schematic diagram of the modified Simultaneous Vision Simulator

Figure 2: Gray-scale patterns programmed in the SLM, representing the Oculentis M-Plus Lens. A. Programmed gray-scale image (left) and pupillary plane image captured on a CCD placed at the eye's pupil plane. B. Gray-scale patterns programmed at different orientations. White segments correspond to the far vision zone, black segment corresponds to near vision zones and the gray region corresponds to the transition zones.

Figure 3: Illustration of a perceptual scoring setting for one subject on one face image (top) viewed through 8 different rotated patterns (middle). Scores ranged from -10 (very blurred) to + 10 (very sharp) (bottom)

Figure 4: Illustration of the pattern preference psychophysical paradigm

Figure 5: Decimal visual acuity measurement using E optotypes in 8 orientations

Figure 6: Perceptual score across orientations at far (in red), intermediate (in green) and near distances (in blue) (A) Average Perceptual Score (B)-(D) Examples of subjects

Figure 7: Weighted orientation preference for all subjects at far (red), intermediate (green) and near (blue) distances. At any orientation, the axes extend from +100 to -100 in the center with black line representing zero. Arrows indicate the preferred orientation

at the respective distances with the length of the arrow indicating significant preferences.

Figure 8: Centroid locations of the weighted orientation preference plots for all subjects. Filled symbols represent centroid locations for far and open symbols centroid locations for near. The inner circle represents the limit for statistical significance (i.e. values outside the circle are significant).

Figure 9: Average Decimal visual acuity at different orientations across subjects at far (red), intermediate (green) and near distances (blue)

Figure 10: Wave aberrations and Through-focus VS for 8 orientations for (A) a diffraction-limited eye. (B) a patient's eye with real aberrations (S2)

Figure 11: Simulated weighted orientation preference for far (red), intermediate (green) and near (blue) distances for all subjects. The axes extend from +100 to -100 in the center with black line representing the zero. Dashed arrows indicate the preferred orientation at the respective distances with the length of the arrow indicating significant preferences.

Figure 12: Centroid locations from perceptual measurements (filled symbols) and optical simulations (open symbols) data at (A) far, (B) Intermediate and (C) Near distances for all subjects. Inner circle represents significant radius of centroids.

Figure 13: Correlations of the weighted orientation preference plot centroid angular coordinates (optimal orientation) from perceptual measurements and optical simulations for (A) far, (B), intermediate and (C) near distances.