

Psychophysical Vision Simulation of Diffractive Bifocal and Trifocal Intraocular Lenses

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Purpose: The visual performance of monofocal, bifocal, and trifocal intraocular lenses was evaluated by human individuals using a vision simulator device. This allowed investigation of the visual impression after cataract surgery, without the need actually to implant the lenses.

Methods: The randomized, double-masked, three-way cross-over study was conducted on 60 healthy male and female subjects aged between 18 and 35 years. Visual acuity (Early Treatment Diabetic Retinopathy Study; ETDRS) and contrast sensitivity tests (Pelli-Robson) under different lighting conditions (luminosities from 0.14–55 cd/m², mesopic to photopic) were performed at different distances.

Results: Visual acuity tests showed no difference for corrected distance visual acuity data of bi- and trifocal lens prototypes ($P = 0.851$), but better results for the trifocal than for the bifocal lenses at distance corrected intermediate ($P = 0.021$) and distance corrected near visual acuity ($P = 0.044$). Contrast sensitivity showed no differences between bifocal and trifocal lenses at the distant ($P = 0.984$) and at the near position ($P = 0.925$), but better results for the trifocal lens at the intermediate position ($P = 0.043$). Visual acuity and contrast sensitivity showed a strong dependence on luminosity ($P < 0.001$).

Conclusions: At all investigated distances and all lighting conditions, the trifocal lens prototype often performed better, but never worse than the bifocal lens prototype.

Translational Relevance: The vision simulator can fill the gap between preclinical lens development and implantation studies by providing information of the perceived vision quality after cataract surgery without implantation. This can reduce implantation risks and promotes the development of new lens concepts due to the cost effective test procedure.

Introduction

The development of good accommodative intraocular lenses (IOLs) that match their healthy natural counterpart remains the “holy grail” in cataract surgery, but it is clear that this is a long-term goal. The available accommodative IOLs are currently limited by their small accommodative power and relatively low visual acuity (VA) of approximately 0.3 to 0.5 logMAR at a defocus of 1.5 (D) diopters (intermediate) and even lower VA values at a defocus

of 3.0 D (near).¹ Although accommodative IOLs can significantly increase visual performance at intermediate positions compared with monofocal IOLs, multifocal IOLs (MIOLs) still exhibit much better performance at the near position, and provide a much higher chance of spectacle independence.^{2–4} MIOLs are divided into purely refractive designs (either rotational symmetric or sector shaped) and diffractive designs. In a meta-analysis of 35 multifocal IOLs it was found that better results were obtained with diffractive than with refractive MIOLs or accommodative IOLs, with a possible trend of fewer haloes in

diffractive MIOLs than in refractive MIOLs.⁵ Although the premium multifocal IOL market is still small in absolute sales compared with the mainstream monofocal IOL market, it is quickly expanding and corresponding commercial interest has recently increased strongly.⁶ New players with innovative multifocal IOL design concepts are likely to enter the market. Up until now, MIOLs provided only two distinct focusses, at the distant and at the near position. Recently, however, trifocal diffractive IOLs were introduced, that show superior performance not only in distant and near positions, but can also provide a third focal point at intermediate positions.^{7,8}

New IOL concepts are commonly designed with simulation software, with input and experience only coming from basic optical considerations and previously performed clinical implantation studies. Pre-clinical tests involve mainly optical bench measurements, as a proof of adherence to normative requirements (ISO 11979) and for quality control. In all these cases, physically objective parameters such as IOL power, addition power, cylinder (in case of toric IOLs), Zernike coefficients, and Modulation Transfer Function (MTF) are measured. There is, however, a huge gap between optical bench measurements and testing new IOLs in implantation studies with human beings. Currently, it is not sufficiently understood how the information gained from optical bench measurements can be translated into the actual quality of vision the patient will experience/have after cataract surgery. Furthermore, the human retina, with its uneven spatial distribution of cone and rod cells and additional important effects, such as the Stiles-Crawford effect⁹, cannot be easily compared with an optical bench's solid state camera. Beside these physical detection properties of the human retina, there are other data processing/interpretation steps in the human visual cortex that cannot currently be obtained by pure physical measurements on an optical bench.

On the other hand, direct testing of new and risky IOL concepts within an implantation study raises ethical issues and is highly cost intensive. There are also some fundamental limits with implantation studies when different IOLs are to be compared. Obviously, such studies can be performed only in parallel group design, in which patients compare vision before and after surgery. No dependent data concerning a direct comparison of different IOL types can be obtained, as one patient cannot test two or more IOL types. This limits the potential to detect

subtle differences in visual performance between different lenses.

The psychophysical setup introduced in this work can fill the gap between pure physical, preclinical optical bench measurements, and implantation studies by providing a simulation of the vision that might be achieved after cataract surgery. This is done by using a hardware model eye containing the IOL under test, and projection of the image obtained by this model eye onto the retinal plane of a subject's eye by means of a relay optic.

Beside the setup presented in this work, there are also a number of other systems and approaches to simulate vision without the need for actually implanting an IOL under test. Pujol et al. (*IOVS* 2014;55:ARVO E-Abstract 3752) used their VirtIOL system to project the image of a model eye onto the retina of a test subject. There are several groups that use adaptive optics and a vision simulator to correct for or introduce a range of optical aberration and test the visual outcome without¹⁰ and with human test subjects.^{11,12} The work of Plaza-Puche et al.¹³ is notable, because they correlated their pure optical bench measurements with postoperative visual outcomes of cataract patients. Good correlation between the image quality metric of the optical bench measurements and the clinical measurements was obtained.

In this work, the mentioned psychophysical setup was used as an efficient and cost effective way to investigate and compare bifocal and trifocal diffractive IOL prototypes as well as a monofocal IOL prototype under photopic and mesopic lighting conditions concerning visual acuity and contrast sensitivity. Results for the bi- and trifocal prototypes were compared with results of recent implantation studies investigating commercial bi- and trifocal diffractive IOLs. Note, that the vision simulator was adjusted for every test subject to correct for his/her personal refractive error, in order to obtain distance corrected distance, distance corrected intermediate, and distance corrected near values.

Methods

Study Design

In this randomized, observer, and subject masked three-way cross-over study, 60 healthy male and female subjects, aged between 18 and 35 years were tested. Recruitment took place via bulletins at the conducting institution (Department of Clinical Phar-

macology, Medical University Vienna) asking for volunteers willing to participate in this study. On the day of the study the subjects were screened for following parameters: medical history, body height and weight, blood pressure and heart rate in sitting position, visual acuity assessment, slit-lamp examination, and funduscopy. Inclusion criteria were age between 18 and 35 years, and absence of relevant abnormal findings in the medical history, normal ophthalmic findings, and refraction between -1 and $+1$ D (Note, that for the tests, the subject obtained personal correction to 0 D subjective refraction by adjusting the vision simulator optics). Exclusion criteria were greater than 0.5 D of cylinder, abuse of alcoholic beverages, participation in a clinical trial in the 3 weeks preceding the study, and symptoms of a clinically relevant illness in the 3 weeks before the study day. Topically administered medication was 1 drop cyclopentolatehydrochloride 0.5% (Thilo; Alcon, Vienna, Austria) in the right eye to initiate cycloplegia. The subjects were asked to use their right eyes during the tests with the psychophysical setup. The left eye was covered during the tests.

Before being admitted to the clinical study, the nature, scope, and possible consequences of the clinical study were explained to the study subjects in common, nonexpert language. The subjects gave written informed consent to participate in the clinical study. Prior to the study, approval by the local ethics committee was obtained. The study was carried out in accordance with the ISO-GCP guidelines and the guidelines of the Declaration of Helsinki (1964), including current revisions.

Masking of the investigator and subjects was performed by mounting the different mono-, bi-, and trifocal intraocular lenses in hermetically closed and airtight model eyes of identical shape and look, in a way that the investigators and subjects did not have direct access to the lenses. One author assigned names “A,” “B,” and “C” in a random way to the model eyes and marked them accordingly for easy discrimination during the study. The team of investigators who conducted the study, performed statistical analysis on study data, and wrote the study report had no knowledge of the actual assignment of the IOL types to the different model eyes “A,” “B,” and “C.” After finishing the statistical analysis and completing the written study report, the investigators received the demasking table for further discussion: model eye “A,” held the monofocal IOL, model eye “B,” held the bifocal IOL, and model eye “C,” held the trifocal IOL prototype.

The investigators randomly chose which model eye “A,” “B,” or “C” (and hence, IOL type) was presented first, second, and third to the test subject. This crossover design measures were necessary to track and counter possible influences of test subject exhaustion on test results.

No dropouts occurred; all 60 test subjects performed and finished the tests.

Setup

In the following paragraphs, a short overview of the setup is given as depicted in [Figure 1](#). The setup consists of four modules: (1) a mechanically stable frame/table, with mounting points for the other modules, (2) the optical system, (3) the adjustment system, and (4) the display system adjustable to arbitrary distances between near and intermediate (15–120 cm). A second display is used for assessing visual performance at the distant position. The key element of the setup is the optical system. It is designed to project the image generated behind a model eye (containing the IOL under test) directly and undisturbed onto the retina plane of a human eye. A scheme of its layout is given in [Figure 2](#). The direct projection of an image onto the retina is complicated by the fact that there are refractive structures in the test persons’ eye altering the image obtained from the model eye. This means that a test person looking through a model eye gets the refractive influence both from the model eye and the own eye. Putting a model eye with dioptric power P_{model} close to the human eye adding a power of a further P_{human} , would result approximately in a total power of $P_{model} + P_{human}$, which unrealistically changes the position of the image plane and the image magnification. In addition to the dioptric power, other parameters such as spherical aberration and chromatic aberration would change in an undesired way and would result in an unrealistically distorted and changed image in the retina plane of the test person, which then carries both the information of the model eye and the test subject’s eye. In order to correct for the influence of the test persons’ eyes, a special relay lens system was applied. If the parameters of the relay lens system are well chosen, it can cancel out the effect of a typical or average human eye, and thus ideally only the pure, undisturbed image from the model eye is retained for projection onto the human retina.

The model eye is based on the work of Liou and Brennan,¹⁴ who used population averaged biometric data of the human cornea, crystalline lens, geometric alignment between cornea and lens, and refractive

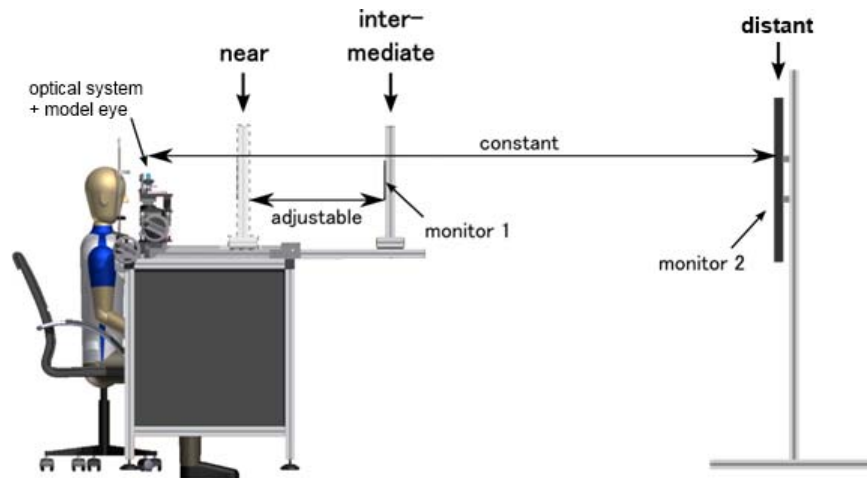


Figure 1. Overview over the psychophysical setup used in this work.

indices of all involved optical tissue structures to define their model. For the design of the discrete hardware model eye, one is limited to the available optical materials, which exhibit refractive indices different from optical tissues. Optical grade Poly(methyl methacrylate) (PMMA) was chosen as material for the discrete cornea lens, due to its high chemical stability, low water absorption, and good machining properties. The refractive indices of aqueous and vitreous humor were maintained by using NaCl_{aq} saline solution of appropriate concentration to obtain similar refractive index for both anterior and posterior chamber. Taking into account the material used for the discrete model cornea and the saline solution surrounding the IOL, the model cornea is optimized in a way that the wave-front in the retina plane of the model eye is similar to the wave-front in the retina plane of the Liou-Brennan eye. This step renders the optical effect of the original Liou-Brennan cornea and the discrete hardware cornea effectively the same.

The IOLs under test (one monofocal, one bifocal, and one trifocal prototype IOL) are mounted in three optically identical model eyes. The model eyes were inserted into self-aligning holders that allow quick replacement without a lengthy alignment step. It is a critical requirement to be able to quickly exchange the model eyes during the study, in order to allow for immediate comparison of different IOLs.

Variations of the test subject's physiology were addressed by providing various adjustment systems:

- height adjustment of the headrest for test person's body height
- adjustment of the model eye horizontal position for aligning the test person eye with the model eye
- adjustment of the relay system to the test person's refraction to allow for the best possible vision simultaneously at the selected far, intermediate, and near distances.

The letters for both the visual acuity tests charts (modified Early Treatment Diabetic Retinopathy

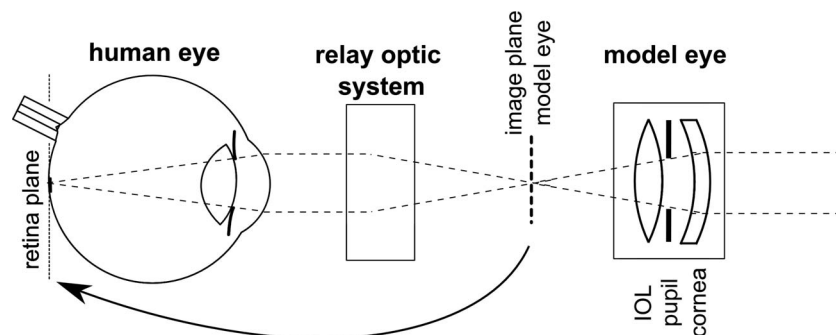


Figure 2. Scheme of the optical system. The relay optic cancels out all refractive content of the human eye, effectively moving the model eye image plane to the human eye retina plane.

Study; ETDRS charts) and contrast sensitivity (CS) test charts (Pelli-Robson) were generated with a computer and displayed via two different displays. The display at the distant position (5.5 m) remained at its position during the study, whereas an additional mobile display was used both for the intermediate and near position, which could be moved between these positions (68 and 38 cm). The letter size was adjusted semiautomatically by input of the laser-measured distance to the mobile second display into software generating the charts (letters are required to maintain their solid angle independent of the distance). Randomization of the letters was provided for both the VA as well as for the CS tests to avoid learning effects.

Setup Parameters

The luminosity of the displays was set to 55 cd/m², which was verified with the display calibration tool i1 Display Pro (X-Rite, Grand Rapids, MI).

The pupil diameter, as defined by the aperture inside the model eyes, was 3 mm at the position of the IOL. Due to cycloplegia, the test subjects' pupils were fully extended and in any case larger than the 3-mm aperture of the model eyes. The optically relevant aperture was therefore the aperture of the model eye. The 3-mm aperture diameter was kept constant at all applied illumination levels.

The positions for the intermediate and near charts were obtained with paraxial ray tracing calculations in ZEMAX (Redmond, WA) of the hardware model eye with inserted IOL. The effect of the diffractive structures on the addition value was approximated in ZEMAX via the modification of the posterior IOL surface. For the dioptric power the following relation is valid: $P_{inter} = P_{base} + (P_{add} / 2)$ and $P_{near} = P_{base} + P_{add}$, where P_{base} is the dioptric power of the refractive lens part, P_{add} is the dioptric addition value of the diffractive structures, and P_{inter} and P_{near} are the dioptric power values for the intermediate and near position. With these modified IOL dioptric power values, the object distances for the intermediate position o_{inter} and near position o_{near} can be calculated based on a distant object located at an infinite distance. Furthermore, intermediate and near positions were corrected for the finite distance of the distant chart of $o_{distant}^* = 5.5$ m. This results in corrected intermediate object distances of $o_{inter}^* = (1/o_{distant}^* + 1/o_{inter})^{-1}$ and corrected near object distances of $o_{near}^* = (1/o_{distant}^* + 1/o_{near})^{-1}$. The following corrected distances were obtained by this procedure: $o_{distant}^* = 5.5$ m, $o_{inter}^* = 68$ cm, $o_{near}^* = 38$

cm. These positions were measured from the anterior cornea apex of the model eye. All VA and CS tests were based on these positions.

Study Day

The participating volunteers performed all the tests only one time on one study day. The subjects received an introduction on the psychophysical test setup, in order to get acquainted with the necessary distance adjustments of the system. After cycloplegia of the right study eye and a resting period of 30 minutes, subjects were presented CS charts (Pelli Robson) and VA charts (ETDRS) at distant (5.5 m), intermediate (68 cm), and near positions (38 cm) on the respective screens. In order to simulate various standardized light conditions, additional neutral density filters were applied in front of the model eyes.

In order to assure masking of the investigators, one study coworker was assigned for handling and insertion of the model eyes (with IOLs mounted inside the model eyes).

The subjects were asked to read aloud the ETDRS charts at distant, intermediate, and near testing positions and ETDRS scores were recorded for each position. Reading was continued until three letters of one line were incorrect. Thereafter, subjects were presented contrast sensitivity charts and logarithm-contrast sensitivity was recorded (reading was continued until 2 of 3 letters were incorrect).

All assessments were done at the Department of Clinical Pharmacology, Medical University Vienna, Austria.

Examined IOLs

For direct comparison of IOLs it is necessary to keep constant as many IOL parameters as possible (e.g., base power, spectacle plane addition, [near] addition at the IOL plane, anterior chamber depth [ACD] inside the model eye, residual spherical aberration, material). Possible differences in the visual outcome can then be attributed to the differences in intensity distribution of the bifocal and trifocal IOL. These requirements can only insufficiently be fulfilled by comparing different commercial IOLs, because of differences in used materials, designs, and optical parameters. Therefore, we designed custom monofocal, diffractive bifocal, and diffractive trifocal IOLs. All the above mentioned parameters can be held constant with this approach. For calculation and optimization of the diffractive structures, the field tracing software

Table 1. Important Parameters for the IOL Prototypes Used in This Study

Study IOLs	Intensity Distribution			Add, D	Add _s , D	Asph, μm	ACD*, mm	Pupil	Filter
	Distant, %	Inter, %	Near, %						
Monofocal	100	0	0	n.a	n.a.	+0.1	4.27	Independent	no
Bifocal	64	0	36	3.63	2.5	+0.1	4.27	Independent	no
Trifocal	52	19	29	3.63	2.5	+0.1	4.27	Independent	no

Add, addition in IOL plane; Add_s, addition in spectacle plane; Asph, residual spherical aberration in Liou Brennan model eye at 6mm aperture at cornea; n.a, not applicable.

* Distance between posterior model cornea surface and anterior IOL surface inside the model eye.

VirtualLab (LightTrans GmbH, Jena, Germany) was used. The multifocal IOLs were designed with a near reading position of 0.4 m, if applied inside a model eye based on the work of Liou and Brennan and at a constant ACD of 4.27 mm. From the near reading distance the spectacle plane addition P_{AddS} can be calculated: $P_{AddS} = 1/(0.4\text{m}) = 2.5\text{ D}$. For the parameters of the prototype IOLs used in this study we refer to Table 1. For a summary of the properties of the IOLs used in the literature survey we refer to Table 2. A good compilation of multifocal IOL parameters can be found in the review article by de Vries et al.¹⁵ Both the monofocal as well as the multifocal prototype IOLs investigated in this study were designed with a residual spherical aberration (SA) of $+0.1\ \mu\text{m}$ at an entrance pupil of 6 mm in the Liou and Brennan eye. The monofocal IOL and multifocal IOLs differed only in the diffractive structures on top of the basic refractive design.

All prototype IOLs were made out of PMMA with a high precision lathing process. After fabrication, the IOLs were characterized for quality control.

Statistics and Analysis

Repeated measures ANOVA was performed to analyze both ETDRS data and Pelli Robson charts using planned comparisons for post-hoc analysis. The interaction between the prototype IOLs (monofocal, bifocal, and trifocal at distant position; bifocal and trifocal at intermediate and near positions) and all levels of light (ranging from 0.14–0.55 cd/m^2) was taken to calculate the significance. The trend in light levels and light level dependent data was used to calculate the significance of the lighting dependence. Assessment of the best and worst pictures was done using frequency tables and a χ^2 test. A P value less than 0.05 was considered significant.

Results

Visual Acuity

Visual acuity results under different luminosity conditions are shown in Figure 3. Analysis of the combined data for all luminosity conditions gave the following results: at the distant position, the monofocal IOL showed significantly better VA values than the bifocal ($P = 0.035$) or trifocal IOL ($P = 0.043$). No significant difference between the bifocal and trifocal IOL was obtained at the distant position ($P = 0.851$). At intermediate and near positions, the trifocal IOL delivered significantly better VA values than the bifocal IOL ($P = 0.021$, and $P = 0.044$, respectively). The better score of the trifocal IOL at intermediate position was expected, because the trifocal design intends to increase imaging quality at this position. At all positions, VA values increased with increasing light levels ($P < 0.001$). Taking into account only the lowest luminosity data (0.14 cd/m^2), qualitatively the same results were obtained. At the distant position no difference was obtained between the bifocal and the trifocal IOL ($P > 0.05$), and at the intermediate and near position the trifocal IOL was significantly better than the bifocal IOL ($P < 0.05$). In general, VA of the trifocal IOL was always better than VA of the bifocal IOL. The slope of the VA curve was smaller at the highest luminosities, which hints at possible saturation effects at higher luminosities. For all evaluated illumination intensities at both the intermediate and near positions, the trifocal IOL was always better than the bifocal prototype, with very high significance.

Contrast Sensitivity

The contrast sensitivity (Pelli-Robson) results under different luminosity conditions are shown in Figure 4. At the distant position, no significant differences between the monofocal, bifocal, and

Table 2. Commercial IOL Parameters Used for Comparison Purposes in This Work

Commercial IOLs	Intensity Distribution			Add, D	Add _s , D or mm
	Distance, %	Inter, %	Near, %		
Zeiss AT LISA 809M bifocal ^{26,27}	65	0	35	3.75	n.a.
Zeiss AT LISA tri 839MP, trifocal ^{28,29}	50	20	30	3.33	400 mm
Physiol Finevision Micro F, trifocal ^{30,31}	41	24	35	3.50	n.a.
Hanita Lens, SeelensMF ³²	65	0	35	3	2.4 D
VSY Reviol BB 611 ³³	70 at 2 mm, 60 at 6 mm	0	30 at 2 mm, 40 at 6 mm	3.75	n.a.
Alcon Restor 3 D Add SN6AD1 ³⁴	n.a.	0	n.a.	3	330 mm (310 mm)
Alcon Restor 4 D Add SN6AD3 ³⁴	n.a.	0	n.a.	4	n.a.

Add_s, addition in spectacle plane, or the reciprocal value (1/Add_s), either given in values of diopter or in millimeter; Asph, aspheric lens design.

* Targeted pseudophacic anterior chamber depth in the patient eye.

trifocal IOL were measured ($P = 0.984$). At the intermediate position, the trifocal IOL showed significantly better contrast sensitivity than the bifocal IOL ($P = 0.043$). No significant difference could be obtained at the near position ($P = 0.925$). CS values increased with increasing light levels ($P < 0.001$) at all positions. In general, the CS difference between bifocal and trifocal IOLs could only be established with smaller significance compared with the VA data. The slope of the CS seems to be reduced at the highest luminosity levels. Again, this hints at saturation effects at higher luminosities.

Discussion

This study showed that in comparison with the bifocal IOL the investigated trifocal IOL prototype had a better VA score at intermediate and near positions (both photopic and mesopic) and a better CS at intermediate position. Similar performance of the bi- and trifocal prototypes was observed in case of VA at distant position and CS at distant and near positions. Figure 5 shows a graphical comparison in order to investigate how the photopic VA results of the bi- and trifocal IOL prototypes were related to recently published photopic VA data (from defocus curves) of implanted bi- and trifocal IOLs. Table 3 shows the corresponding VA data as numbers together with the test conditions and literature references. For a consistent comparison, the specific test conditions in the current study have to be considered. The VA chart positions in the study presented in this article were chosen to be the paraxial focus of the used model eye plus inserted IOL. Other

than in the present study, typical distant corrected or uncorrected VA tests are commonly performed at a certain fixed distance (e.g., distant: 4 m, intermediate: 66 cm, near: 33 cm) independent of the used IOL. The fixed distances are more or less different from the real focal position of the respective pseudophacic eye. Besides that, different groups used different test routines with different sets of fixed distances (e.g., 6 m, 80 cm, 40 cm). Furthermore, if uncorrected VA data are used, the finite far distance and/or the non-zero refraction of the patient after surgery are not taken into account. For all these reasons, both corrected as well as uncorrected VA test data are not ideally suited for comparison with this study's data. For a proposed naming and abbreviation scheme of the different visual acuity test conditions we refer to Dupps.¹⁷ However, VA values at the correct corresponding distances can easily be obtained from defocus curves. The correct distance in this context means the distance that shows a local maximum in VA (for distance and near position; the case of the intermediate position is discussed below). Therefore, defocus curves of different multifocal IOLs found in literature were used for a comparison with the data obtained in this study. Furthermore, the results can easily be corrected for the choice of the finite distant position and the residual refraction of the patient by simply shifting the obtained defocus curve along the diopter axis until the distant VA peak is at 0 D. Therefore, VA values from published defocus curve data were used in Figure 5: the distant and near focal positions in terms of spectacle plane add values can be obtained from the x-axis (D) position of the VA maxima of the defocus curves. The

Table 2. Extended

Commercial IOLs	Asph	ACD*, mm	Pupil	Filter
Zeiss AT LISA 809M bifocal ^{26,27}	yes	4.85	Independent	no
Zeiss AT LISA tri 839MP, trifocal ^{28,29}	yes	5.32	Independent ≤ 4.5 mm	no
Physiol Finevision Micro F, trifocal ^{30,31}	yes	pACD = 5.35	Dependent	UV, blue
Hanita Lens, SeelensMF ³²	yes	n.a.	Dependent	UV, violet
VSY Reviol BB 611 ³³	yes	n.a.	Dependent	UVA, violet
Alcon Restor 3 D Add SN6AD1 ³⁴	yes	n.a.	Dependent ³⁵	UV, blue
Alcon Restor 4 D Add SN6AD3 ³⁴	yes	n.a.	Dependent ³⁵	UV, blue

maximum at negative diopters was defined as the VA value of the near position, and the maximum at approximately 0 D was defined as the VA value of the far position. The definition of the intermediate position VA is less straightforward. Bifocal IOLs show a minimum of VA at intermediate distances, due

to the lack of a focus at that distances. However, contraintuitively, all currently available trifocal IOL VA data show a minimum at intermediate, too, but with a larger minimum VA compared with the bifocal IOLs (refer to the defocus curves of, e.g., Refs. 7 and 17). Trifocal VA is therefore not associated with a

Table 3. Visual Acuity Values Taken from Photopic, Binocular Defocus Curves at the Corresponding Distance, Intermediate, and Near Positions, Together with the Applied Chart Type and Luminance Conditions

Study + Commercial IOLs	logMAR Distant VA ($\pm 2 \times$ SE)	logMAR Inter VA ($\pm 2 \times$ SE)	logMAR Near VA ($\pm 2 \times$ SE)	Chart Type	Luminance (cd/m^2)
Bifocal					
Bifocal prototype*** (this study)	0.05 (± 0.02)	0.14 (± 0.03)	0.13 (± 0.02)	ETDRS	55
AT Lisa ⁷	-0.06 (± 0.03)	0.19 (± 0.07)	0.03 (± 0.05)	ETDRS	n.a.
SeelensMF ³⁶	0.04 (± 0.04)	0.25 (± 0.11)	0.18 (± 0.13)	ETDRS	n.a.
Reviol BB 611* ²¹	-0.16 (n.a.)	0.20 (n.a.)	-0.08 (n.a.)	n.a.	n.a.
Restor 3D Add* ³⁷	-0.06 (± 0.02)	0.22 (± 0.05)	0.04 (± 0.04)	ETDRS	n.a.
Restor 3D Add ³⁸	-0.07 (± 0.01)	0.16 (± 0.02)	0 (± 0.02)	ETDRS	160
Restor 4D Add ³⁸	-0.07 (± 0.01)	0.30 (± 0.04)	0.02 (± 0.02)	ETDRS	160
Trifocal					
trifocal prototype*** (this study)	0.03 (± 0.03)	0.04 (± 0.02)	0.05 (± 0.02)	ETDRS	55
AT tri Lisa ⁷	-0.09 (± 0.03)	0.01 (± 0.03)	0.01 (± 0.04)	ETDRS	n.a.
AT tri Lisa** ³⁹	-0.10 (± 0.04)	0.04 (± 0.04)	0.09 (± 0.05)	ETDRS	85
AT tri Lisa ¹⁷	0.03 (± 0.05)	0.19 (± 0.04)	0.15 (± 0.05)	n.a.	85
Finevision ⁴⁰	-0.02 (± 0.02)	0.09 (± 0.03)	0.06 (± 0.04)	ETDRS	n.a.
Finevision ⁸	-0.06 (± 0.03)	0.08 (± 0.04)	0.02 (± 0.05)	n.a.	n.a.
Finevision ¹⁸	-0.01 (± 0.05)	0.12 (± 0.04)	0.08 (± 0.05)	n.a.	85
Finevision ⁴¹	0.05 (± 0.04)	0.23 (± 0.09)	0.19 (± 0.06)	Thomson Test Chart XPert	85

Object positions were the local extrema of the defocus curves (refer to the text). References to the literature are given at the IOL names.

* Unknown (monocular or binocular).

** Intermediate at defocus -1.5 D, near at defocus -2.5 D.

*** Monocular data corrected to the binocular case based on [21].

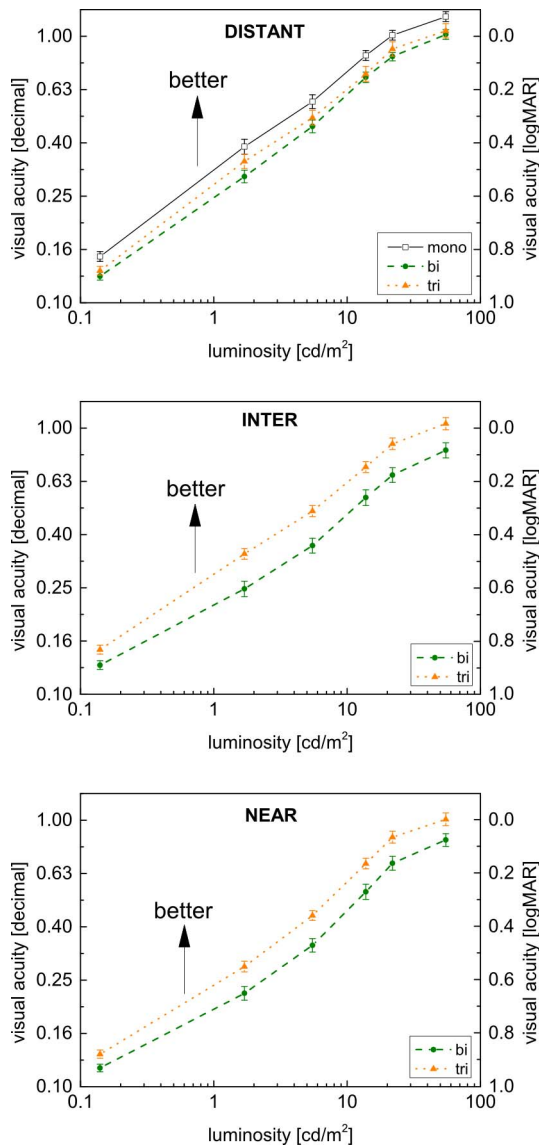


Figure 3. Arithmetic mean visual acuity values versus luminosity for the monofocal, bifocal, and trifocal prototype IOL, at distant, intermittent, and near position. Note that the x-axis is logarithmic. Error bars are 2× the SE. Monocular data are shown.

further local maximum at intermediate in between the distant and near maxima, but with a minimum just like for bifocal IOLs. For simple diffractive structures creating the different focal positions from successive diffractive orders (e.g., distant: order 0, intermediate: order 1, near: order 2) the addition value for the intermediate focus position is simply one-half of the addition value (in D) for the near position. As most diffractive IOLs seem to more or less stick to successive diffraction orders, the intermediate VA is defined in this work as the VA value at one-half of the (corrected) near addition value. In a defocus curve the

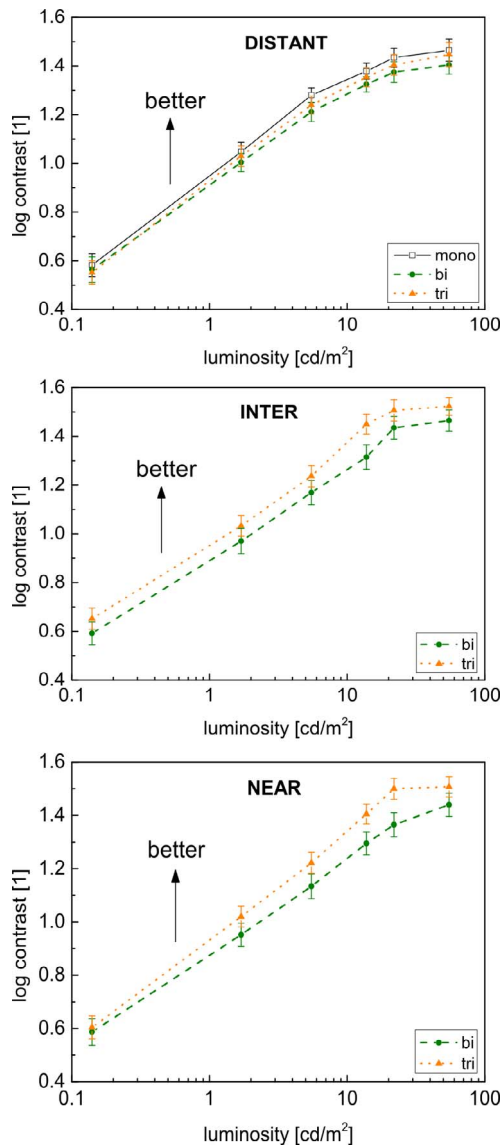


Figure 4. Arithmetic mean contrast sensitivity for the monofocal, bifocal, and trifocal prototype IOL at distant, intermediate, and near position. Note that the x-axis is logarithmic. Error bars are 2× the SE.

intermediate VA value can be found therefore exactly in the middle between the near and the distant VA maximum. Trifocal IOL VA data show a very good agreement of this one-half addition value with the dioptric position of the intermediate VA minimum. For the calculation of the confidence interval (error bars, 2× standard error of the mean [SE]), the SD, and sample size (number of eyes; N) was taken from the corresponding literature.

For a complete account of the defocus behavior of diffractive multifocal IOLs, please note that clinical defocus curves are not similar in shape and behavior

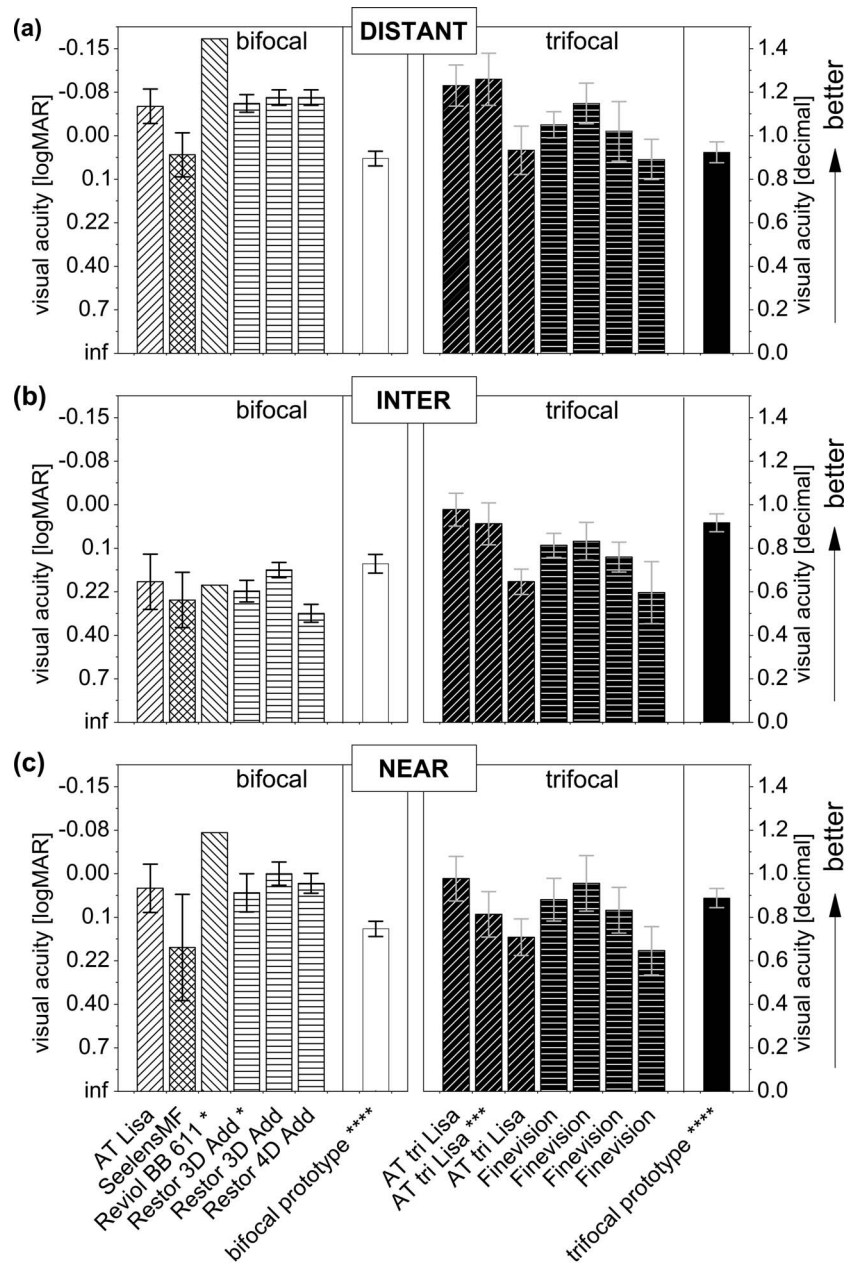


Figure 5. Comparison of photopic VA results obtained in this work with a selection of data from recently published photopic, binocular defocus curves for (a) distant, (b) intermediate, and (c) near object position. Object positions were the local extrema of the defocus curves (refer to the text). References to the VA data of the particular IOL are given in Table 3. Error bars show the 95% confidence intervals ($2 \times$ SE). *Unknown (monocular or binocular); ***intermediate at defocus -1.5 D, near at defocus -2.5 D; ****monocular data corrected to the binocular case based on Ref. 21.

to pure physical measurements of defocused modulation transfer function (through focus modulation transfer function; TFMTF) or intensity profiles in direction of the optical axis. For trifocal IOLs the TFMTF as well as the intensity profile show a local maximum at intermediate distances (Ref. 18 and response Ref. 19), in contrast to the above discussed local minimum delivered by clinical defocus curves at

intermediate distances. This supports the relevance of tests performed with human test persons if the actual visual perception delivered by a certain IOL design is required.

For the comparison of the monocular VA data of the prototype lenses recorded in this study with binocular data from the literature, the monocular data had to be corrected. According to Cagenello et

al.,²⁰ binocular vision results on average in an 11% increase of visual acuity measured in decimal VA scale. Therefore, in the following discussion, study data corrected to binocular vision based on Cagenello et al.²⁰ were used.

According to the current literature, it seems that trifocal IOLs have an approximately similar VA as bifocal IOLs at near and at far positions, but a significantly better VA at intermediate positions. Especially the randomized comparative study of Mojzis et al.,⁷ where a bifocal Zeiss AT Lisa 801 and a trifocal Zeiss AT Lisa tri 839 MP are directly compared postoperatively, show the same trend as in this study: bi- and trifocal IOLs perform the same at distance, but at intermediate and near distances the trifocal performs significantly better. There are, however, studies that were performed with bifocal IOLs that show very good and much better VA at the distant and near position than available trifocal IOLs, such as the work of Wang et al.²¹ (Reviol BB 611). The large differences between studies will be discussed in the following paragraph.

A comparison of different IOL types is tricky due to the many degrees of freedom in the design of the IOLs. In addition, the actual applied vision test chart can have a big influence on the VA or defocus data. At VA values approximately 0.25 (decimal), the VA data obtained with Snellen charts are up to 0.1 (decimal) lower than VA obtained via ETDRS charts.²² Results presented in Figure 5 are marked according to the VA charts type used to obtain the data. Furthermore, the luminosity conditions for photopic VA tests suffer from a lack of international agreement: for example, VA tests are performed at 85 cd/m² in the United States, at 300 cd/m² in Germany, and at 120 cd/m² in the United Kingdom.²³ Unfortunately, the actual applied luminosity conditions often are not documented in literature. In general, the results of Williams et al.²⁴ showed that there is a lack of a standard for VA testing and testing procedures and conditions are commonly not documented sufficiently in literature. Although the results of this study indicate there is already a certain saturation effect visible at the highest luminosities of 55 cd/m² (Fig. 3), it seems that changing the luminosity in a range 85 to 300 cd/m² will still lead to significant large differences in VA outcome. Results presented Figure 5 are marked according to the applied luminosity in candela per square meter during the tests.

In general, significant differences between different IOLs can be obtained by applying the psychophysical vision simulator introduced in this work. To give an

example, it is possible to discriminate between different IOLs with the setup. Especially the option to generate dependent data of different IOLs (different IOLs can be assessed by the same test subject) is an important feature of this setup. However, one has to keep in mind that the psychophysical setup only performs a simulation of pseudophakic vision, which is not identical to the postoperative situation of an (average) pseudophakic patient. There are some fundamental differences to pseudophakic vision. First, the setup is designed to correctly simulate vision only in a small area around the optical axis, with more peripheral parts simulated in approximation. Second, different from normal vision, the setup/the model eye does not follow the existent saccadic eye movements (e.g., the test person can look to the peripheral vision areas of the model eye, which are normally not accessible by the fovea). And third, there is some nonrealistic chromatic aberration because the model eyes were designed to be similar to the Liou-Brennan eye at only one single central wavelength of 546 nm. These three deviations most probably affect the direct quantitative comparison to implantation studies in some ways, which has to be investigated in future studies, but do not tremendously affect relative or comparative measurements of different IOLs with the setup.

A direct performance comparison between the different vision simulator devices and approaches is both beyond the scope of this work as well as somehow preliminary. Especially the lack VA testing standards and the resulting large variation of VA results in clinical studies for even the same IOL make it difficult to compare clinical results with vision simulator result. Valid clinical results, however, are necessary to calibrate vision simulator devices in order to make valid predictions of the postoperative visual functions from measured vision simulator data. Although this is also true for the work of Plaza-Puche,¹³ the good correlation between their vision simulator data and clinical data is very promising. The VirtIOL device used in the work of Pujol et al. (*IOVS* 2014;55: ARVO E-Abstract 3752) seems to overestimate VA data if compared with clinical studies. For example, for the Lentis MPlus IOL from Oculentis the VirtIOL device gave a distant VA of -0.1 logMAR, whereas clinical studies²⁵ report only $+0.1$ logMAR. The psychophysical vision simulator presented in this work, however, seems to underestimate differences in distant-, intermediate-, and near-VA test. These differences are worth being investigated in the future.

Conclusions

In summary, monofocal, diffractive bifocal, and diffractive trifocal prototype IOLs were investigated via a psychophysical vision simulator without implanting the IOLs into human patients. Test persons were asked to assess each of the three IOL prototypes in order to generate dependent data. VA and CS measurements showed significant differences between the prototype IOLs. The trifocal IOL gained higher VA ratings at intermediate and near positions than the bifocal IOL. At the distant position, the trifocal and bifocal IOL performed similar in VA tests. This matches well to an implantation study from another author, who compares the VA of population groups after bifocal and trifocal IOL. A comparison of absolute VA data of different other published studies showed a large variation of VA values even for the same IOL products. Possible reasons for the large variations of reported VA data are the usage of different VA chart types and different test conditions, especially different applied lighting conditions.

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