Correlation between Visual Acuity and Induced Optical Defocus: A New Statistical Approach

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Abstract

Purpose: To better understand the effect of induced spherical and cylindrical defocus on high contrast visual acuity (VA) and to find the range of spherocylindrical powers which produce the same reduction in VA.

Material and Methods: Observational, prospective, analytical and transversal study in which VA was measured using EDTRS (Early Treatment Diabetic Retinopathy Study) optotypes in healthy subjects under spherical and cylindrical induced defocus. Spherical lenses with powers ranging from -2.00D (diopters) to +1.00D and cylindrical lenses with powers ranging from 0.00D to 1.00-D with spherical equivalents (SER) of 0.00D, -1.00D and +0.50D were interposed. Subjects were classified in three groups depending on their amplitude of accommodation (AA). Randomized Complete Block Design (RCBD) statistical test was used to determine differences in VA among the different induced powers.

Results: VA with different induced lens defocus was evaluated in 30 subjects with a mean age of 51.20 ± 13.60 years. Differences in the reduction of VA were observed between negative (hyperopia simulation) and positive (myopia simulation) power interposed lens ranges. Induced spherical defocus of higher than +0.25D or -0.75D lead to a significant reduction of VA. VA was also reduced as the induced cylindrical defocus increased except when positive spherical equivalent was reached, mainly in the group of patients with enough accommodation capacity to compensate this induced astigmatism (AA over 1D).

Conclusions: The results of this investigation help to better understand the relationship between lens induced refractive errors and high contrast VA. The statistical block analysis presented shows correlations between different spherocylindrical powers that lead to similar reduction of VA.

Keywords: Visual Acuity; Refractive Error; Spherical Induced Power; Cylindrical Induced Power; Lens; Accommodation

Abbreviations

VA: Visual Acuity; AA: Accommodation Amplitude; D: Diopters; CEIC: Hospital Clínico San Carlos Ethics Committee's; m: Meters; SPH: Sphere; CYL: Cylinder; SER: Spherical Equivalent Refraction; ETDRS: Early Treatment Diabetic Retinopathy Study; logMAR: Logarithm of the Minimum Angle of Resolution; RCBD: Randomized Complete Block Design; lux: lx

Introduction

The knowledge of the relationship between visual acuity (VA) and refractive errors is a matter of great interest to eye care practitioners due to the importance of detecting and monitoring refractive errors and ocular pathologies and to determine the success of ocular surgeries and treatments.

Several studies have investigated the influence of refractive errors on VA. Some of them carried out retrospective research of experimental VA measurements in databases [1,2]. Despite the large amount of data presented, these classic studies were done without a well-stated protocol for measuring and reporting VA. More recent studies with a clearer protocol related VA and refractive errors doing experimental measurements with defocus produced through different methods. The induced refractive error was simulated by degradation of test quality [3-6], by degradation of vision using adaptive optics though a deformable mirror [7,8], or by using spherocylindrical lenses to induce defocus [9-11]. However, most of them evaluated VA in simulated or fictitious conditions using artificial pupils, drugs to control accommodation or by using adaptive optics to correct high order aberrations [7,8,12]. In addition, some studies investigated the influence of the astigmatism axis, and while some agree with this influence [7,8,12], others disagree [6,13]. All of these recent investigations were carried out with small samples of patients without considering the subject's accommodation [4,6-8,12,13]. Consequently, it is not possible to analyze the behavior of refractive errors in VA depending on the subject's accommodation amplitude (AA), a mechanism which plays a crucial role in this type of measurement.

Therefore, this study proposes a different experimental approach on VA measurement under lens-simulated refractive error conditions with the goal of finding correlations between different induced spherical and cylindrical defocus that lead to the same reduction of VA, while considering the subject's amplitude of accommodation for a wide age range.

Materials and Methods

Participants

This is an observational, prospective, analytic, and transversal study involving healthy patients. The acceptance criteria applied were ages ranging from 18 to 70 years, to have spherical refractive errors between + 6.00D (Diopters) and – 6.00D and/or cylindrical refractive error less than 2.50D, good general and ocular health and no medication that may affect visual function. Participants were classified in three groups according to the amplitude of accommodation: Group 1 comprised subjects with AA lower than 1.00D, Group 2 included individuals with AA between 1.00 - 2.00D and Group 3 involved subjects with AA higher than 2.00D.

The tenets of the Declaration of Helsinki were adhered to and full approval of the study was obtained from the Hospital Clínico San Carlos Ethics Committee's (CEIC) Review Board. Before consenting to participate, patients were informed of the trial protocol.

Procedure

All subjects underwent a comprehensive optometric evaluation carried out by three expert optometrists who followed a strict methodology. A subjective refraction method was used to determine the lens power that provided the best VA. Subjective refraction at 5.5m (meters) was done using a phoropter and considered the subject's previous compensation. Monocular refraction was determined when the maximum positive sphere value that provided the monocular VA taken with a pinhole was reached. For the cylinder (CYL), the cross cylinder method was used. Furthermore, amplitude of accommodation was measured using both the push-up and minus lens tests. Both methods were completed twice. Finally, amplitude of accommodation was determined as the mean of all measurements done by both techniques, following the procedure done by Momeni-Moghaddam., *et al* [14]. Furthermore, eye dominance was determined by looking through a central hole in an A4 card, held by the subject.

The best monocular high contrast VA in the dominant eye was recorded for all subjects with the interposition of different combinations of spherical and cylindrical lens powers. For spherical lens powers, VA was measured at 5.5m using ETDRS (Early Treatment Diabetic Retinopathy Study) charts via (PVVAT Software, Precision Vision, La Salle, III), with logMAR (Logarithm of the Minimum Angle of Resolution) unit notation. Black letters with a white background were displayed on a monitor (Asus screen, 21.5″) with a luminance of 160 cd/m^2 (standard recommendation, Ferris: Standardized illumination for VA testing in clinical research), that was connected to a computer. PVVAT was calibrated considering examination distance and screen luminance, in order to ensure logMAR 0.00 (20/20 Snel-

len) corresponded to letters that subtended 1 minute of arc. This test allows the use of ever renewing, random test target combinations to prevent false gains from memorization. VA was measured three times with each combination of induced refractive errors and the mean value was calculated. The size of the optotypes displayed was not corrected for the magnification/miniaturization effect of the trial lenses that were used to induce defocus because the goal was to simulate the same situation wearers would experience under overcorrected or under corrected refractive error conditions. The maximum time used for the measurements for an eye in each session was restricted to minimize the effects of fatigue. Each patient was evaluated in four sessions scheduled in different days. Each session lasted one hour with a ten-minute break midway through the session. Neither drugs nor other artificial methods to control pupil size or accommodation were used for the measurements of VA. This is because the goal of this study is to gain an understanding of monocular VA of eyes in their natural conditions, and because this is the most common clinical procedure used to measure VA by eye care professionals (Atchison, 2000). Evaluation was performed in a uniformly illuminated room under photopic conditions of 70 lx (lux).

During the evaluation, refractive errors were induced in the dominant eye with a phoropter and with the non-dominant eye covered. Each eyechart consisted of a single row of 5 optotypes (Sloan letters). The step size between successive eyecharts was 0.10 logMAR (20/25 Snellen). The subjects were asked to read the whole row of letters, starting with a letter size large enough so they were able to discern all of the optotypes in the row. New eyecharts with reduced letter size were shown until the subjects were no longer able to discern any letter. The examiner recorded the logMAR VA corresponding to the smallest chart size the subjects could fully read and added to it 0.02 logMAR for each isolated optotype correctly identified.

Different types of induced lens powers were used to simulate different levels of refractive errors. Defocus was induced by the interposition of spherical induced powers from -2.00D to +1.00D in steps of 0.25D. Astigmatism was induced by the interposition of cylindrical induced powers from 0.00 to +1.00D in steps of 0.25D, combined with sphere (SPH) powers with different spherical equivalent refraction (SER): SER = 0D that simulates a mixed astigmatism refractive error, SER = -1.00D to simulate a hyperopic astigmatism and SER = +0.50D to simulate myopic astigmatism. Each combination of spherocylindrical power was evaluated for an axis orientation of 90º and 180º.

In order to control the reliability and repeatability of the measurements, three induced lens powers were measured, each in two different visits, - 1.00D SPH (Visit 1 and 3), +0.50 SPH -1.00 CYL x 180º (Visits 2 and 4) and +0.50 SPH (Visits 1 and 2). Furthermore, interexaminer variability and measurement order influence were statistically analyzed.

Statistical analysis

Statistical analysis of data was performed with Statgraphics Centurion XVI software and included descriptive statistics of evaluated variables. Randomized Complete Block Design (RCBD) was applied to determine the differences in VA among the different induced spherical and cylindrical powers as well as axis orientation. The same test was used to determine differences in VA values due to examiner and measurement order. Statistical significance was set at a $p < 0.05$.

Results

The sample was comprised of 30 subjects, 16 men and 14 women, of mean age 51.2 ± 13.6 (from 26 to 70 years). The mean best corrected monocular VA of subjects was -0.01 logMAR (20/19.5 Snellen). The sample was divided into three groups according to amplitude of accommodation: 9 patients were included in group 1 (ages from 55 to 70), 12 subjects in group 2 (ages from 49 to 69) and 9 individuals were included in group 3 (ages from 26 to 41).

The analysis related to the reliability, repeatability, order of measurements and inter-examiner variability did not show significant statistical differences.

Influence of spherical defocus

Mean and standard error of VA was calculated for the total sample after the interposition of spherical powers from -2.00D to +1.00D in steps of 0.25D. Values obtained are presented in figure 1.
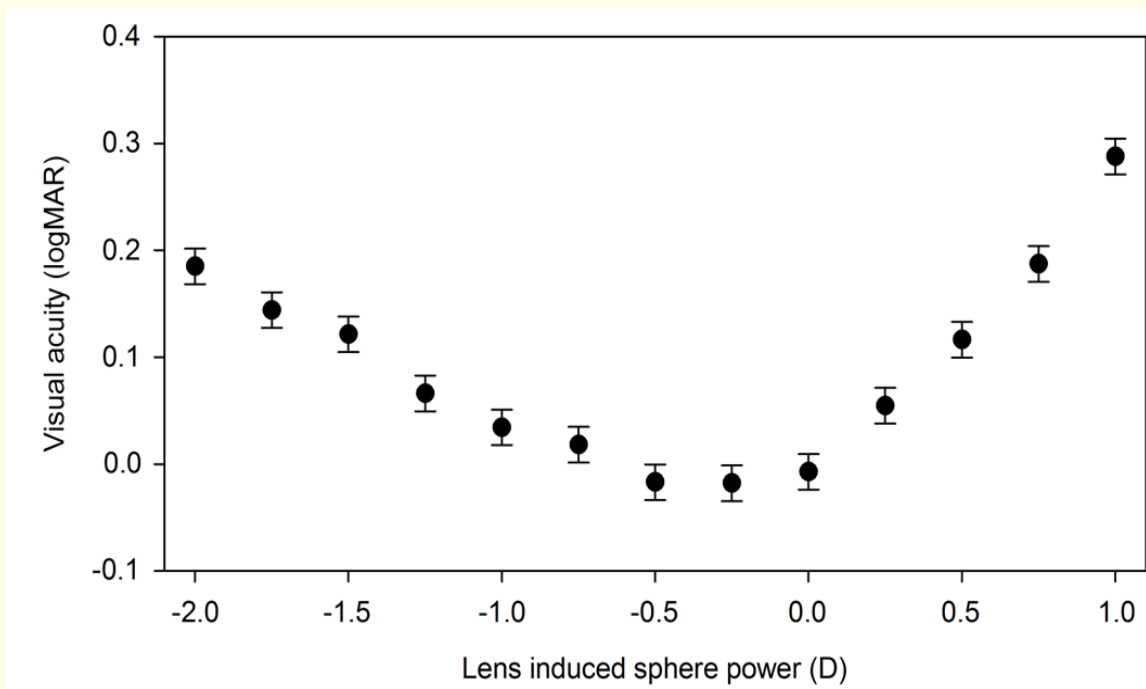
Figure 1: *VA values after the interposition of spherical powers from -2.00D to +1.00D (n = 30)*

Results show differences in the behavior of VA with positive versus negative spherical powers, mostly explained by the effect of the mechanism of accommodation. The data shows a more pronounced decrease in VA when interposing positive powers in comparison with the interposition of negative powers.

RCBD statistical test was used to determine differences in VA among the different induced SPH powers. Statistically significant differences are presented in the table 1.

	-2.00D	-1.75D	-1.50D	-1.25D	-1.00D	-0.75D	-0.50D	-0.25D	0.00D	0.25D	0.50D	0.75D	1.00D
-2.00D			*	*	*	*	*	*	*	*	*		*
-1.75D				*	*	*	*	*	*	*	*		*
-1.50D	*			*	*	*	*	*	*	*		*	*
-1.25D	*	*	*			*	*	*	*		*	*	*
-1.00D	*	*	*				*	*			*	*	*
-0.75D	*	*	*	*							*	*	*
-0.50D	*	*	*	*	*					*	*	*	*
-0.25D	*	*	*	*	*					*	*	*	*
0.00D	*	*	*	*						*	*	*	*
0.25D	*	*	*				*	*	*		*	*	*
0.50D	*			*	*	*	*	*	*	*		*	*
0.75D			*	*	*	*	*	*	*	*	*		*
1.00D	*	*	*	*	*	*	*	*	*	*	*	*	

Table 1: *Statistical differences in VA among the different induced SPH powers (n = 30). Asterisks indicate a statistically significant difference (p < 0.05) in VA between 2 different induced spherical powers. Empty cells relate spherical powers that induce similar reduction of VA.*

The results confirm the differences in behavior in VA of negative and positive spherical powers. A statistically significant reduction of VA was found from the interposition of +0.25D or higher spherical lenses in the hyperopic range and from the interposition of -0.75D or higher spherical lenses in the myopic range. Therefore, there is a range of negative spherical powers comprised between -0.25D and -0.75D in which VA remains with no statistical significant changes. In addition, it was observed that small changes in negative spherical power do not produce statistically significant differences in VA. Similar values for VA were registered with an induced spherical power of -0.75D or -1.00D, -1.00D or -1.25D, -1.50D or -1.75D and -1.75D or -2.00D.

In addition, this analysis provides information about powers that induce similar reduction of VA in subjects. For example, a power of +0.25D produced similar VA reduction that a power of -1.00D or -1.25D. Another example is a power of +0.75D which produced similar VA reduction that a power of -1.75D or -2.00D.

The statistical analysis was done individually for each of the different groups according to amplitude of accommodation. Table 2-5 show the results obtained. In group 1, induced powers ranging from +0.25D to -0.75D was found in which VA remains stable.

Group 1 - AA lower than 1.00D (n = 9)												
	-2.00D	-1.75D	-1.50D	-1.25D	-1.00D	-0.75D	-0.50D	-0.25D	0.00D	0.25D	0.50D	0.75D	1.00D
-2.00D	■			*	*	*	*	*	*	*	*	*	
-1.75D		■		*	*	*	*	*	*	*	*	*	
-1.50D			■	*	*	*	*	*	*	*	*		
-1.25D	*	*	*	■		*	*	*	*	*			*
-1.00D	*	*	*		■		*	*	*			*	*
-0.75D	*	*	*	*		■						*	*
-0.50D	*	*	*	*	*		■				*	*	*
-0.25D	*	*	*	*	*			■			*	*	*
0.00D	*	*	*	*	*				■		*	*	*
0.25D	*	*	*	*						■	*	*	*
0.50D	*	*	*				*	*	*	*	■		*
0.75D	*	*			*	*	*	*	*	*		■	
1.00D				*	*	*	*	*	*	*	*		■

Table 2: Statistical differences in VA among the different induced spherical powers for Group 1. Asterisks indicate a significant statistical difference (p < 0.05) in VA between 2 different induced spherical powers. Empty cells relate spherical powers that induce similar reduction of VA.

Group 2 - AA between 1.00 - 2.00D (n = 12)												
	-2.00D	-1.75D	-1.50D	-1.25D	-1.00D	-0.75D	-0.50D	-0.25D	0.00D	0.25D	0.50D	0.75D	1.00D
-2.00D	■	*	*	*	*	*	*	*	*	*	*		
-1.75D	*	■		*	*	*	*	*	*	*			*
-1.50D	*		■	*	*	*	*	*	*	*			*
-1.25D	*	*	*	■			*	*	*			*	*
-1.00D	*	*	*		■						*	*	*
-0.75D	*	*	*			■					*	*	*
-0.50D	*	*	*	*			■			*	*	*	*
-0.25D	*	*	*	*				■		*	*	*	*
0.00D	*	*	*	*					■	*	*	*	*
0.25D	*	*	*				*	*	*	■		*	*
0.50D	*				*	*	*	*	*		■	*	*
0.75D				*	*	*	*	*	*	*	*	■	*
1.00D		*	*	*	*	*	*	*	*	*	*	*	■

Table 3: Statistical differences in VA among the different induced spherical powers for Group 2. Asterisks indicate a significant statistical difference (p < 0.05) in VA between 2 different induced spherical powers. Empty cells relate spherical powers that induce similar reduction of VA.

Group 3 - AA higher than 2.00D (n = 9)													
	-2.00D	-1.75D	-1.50D	-1.25D	-1.00D	-0.75D	-0.50D	-0.25D	0.00D	0.25D	0.50D	0.75D	1.00D
-2.00D											*	*	*
-1.75D											*	*	*
-1.50D											*	*	*
-1.25D										*	*	*	*
-1.00D										*	*	*	*
-0.75D										*	*	*	*
-0.50D										*	*	*	*
-0.25D										*	*	*	*
0.00D										*	*	*	*
0.25D				*	*	*	*	*	*		*	*	*
0.50D	*	*	*	*	*	*	*	*	*	*		*	*
0.75D	*	*	*	*	*	*	*	*	*	*	*		*
1.00D	*	*	*	*	*	*	*	*	*	*	*	*	

Table 4: Statistical differences in VA among the different induced spherical powers for Group 3. Asterisks indicate a significant statistical difference (p < 0.05) in VA between 2 different induced spherical powers. Empty cells relate spherical powers that induce similar reduction of VA.

Spherical Power (D)	Group 1 (n = 9)		Group 2 (n = 12)		Group 3 (n = 9)	
	Mean ± SEM	95% CI	Mean ± SEM	95% CI	Mean ± SEM	95% CI
-2.00	0.31 ± 0.03	0.26 - 0.37	0.26 ± 0.02	0.22 - 0.30	-0.04 ± 0.02	-0.09 - 0.01
-1.75	0.28 ± 0.03	0.22 - 0.33	0.20 ± 0.02	0.15 - 0.24	-0.06 ± 0.02	-0.10 - -0.01
-1.50	0.24 ± 0.03	0.18 - 0.30	0.17 ± 0.02	0.13 - 0.21	-0.06 ± 0.02	-0.10 - -0.01
-1.25	0.15 ± 0.03	0.09 - 0.21	0.11 ± 0.02	0.06 - 0.15	-0.07 ± 0.02	-0.12 - -0.03
-1.00	0.09 ± 0.03	0.03 - 0.14	0.08 ± 0.02	0.04 - 0.12	-0.08 ± 0.02	-0.13 - -0.03
-0.75	0.05 ± 0.03	-0.01 - 0.10	0.06 ± 0.02	0.02 - 0.10	-0.06 ± 0.02	-0.11 - -0.02
-0.50	-0.01 ± 0.03	-0.06 - 0.05	0.04 ± 0.02	0.00 - 0.08	-0.10 ± 0.02	-0.15 - -0.05
-0.25	-0.01 ± 0.03	-0.07 - 0.04	0.03 ± 0.02	-0.02 - 0.07	-0.08 ± 0.02	-0.13 - -0.03
0.00	-0.01 ± 0.03	-0.07 - 0.04	0.04 ± 0.02	0.00 - 0.08	-0.06 ± 0.02	-0.11 - -0.02
+0.25	0.04 ± 0.03	-0.02 - 0.09	0.10 ± 0.02	0.06 - 0.15	0.00 ± 0.02	-0.04 - 0.05
+0.50	0.13 ± 0.03	0.07 - 0.18	0.14 ± 0.02	0.10 - 0.18	0.07 ± 0.02	0.02 - 0.12
+0.75	0.17 ± 0.03	0.12 - 0.23	0.21 ± 0.02	0.17 - 0.25	0.17 ± 0.02	0.12 - 0.22
+1.00	0.24 ± 0.03	0.18 - 0.30	0.31 ± 0.02	0.27 - 0.36	0.30 ± 0.02	0.25 - 0.35

Table 5: VA values (Mean ± SEM, 95%CI) after the interposition of spherical powers from -2.00D to +1.00D for the three accommodation amplitude groups.

In the group 3, a wider range of negative powers were observed that produce similar VA values (from 0.00D to -2.00D). These results agree with our expectations due to the accommodation capacity of negative powers of this group (higher than 2.00D). However, this group is highly sensitive to changes in positive induced powers; statistical differences in VA were shown with differences of positive induced powers of at least 0.25D.

As expected, results for group 2 are between the ones found for Group 1 and 3 regarding the range of spherical powers with no changes in VA (0.00D and -1.00D).

Influence of cylindrical defocus

Means and standard errors of VA were calculated for the total sample after the interposition of cylindrical powers from 0.00D to +1.00D in steps of 0.25D at axis orientations of 90º and 180º combined with SPH powers to get SER = 0.00D, -1.00D and +0.50D. Values obtained show worse VA as induced CYL lens power increases, both at 90º and 180º; except for SER = +0.50 in which VA improves for higher CYL powers oriented at 90º (Figure 2).
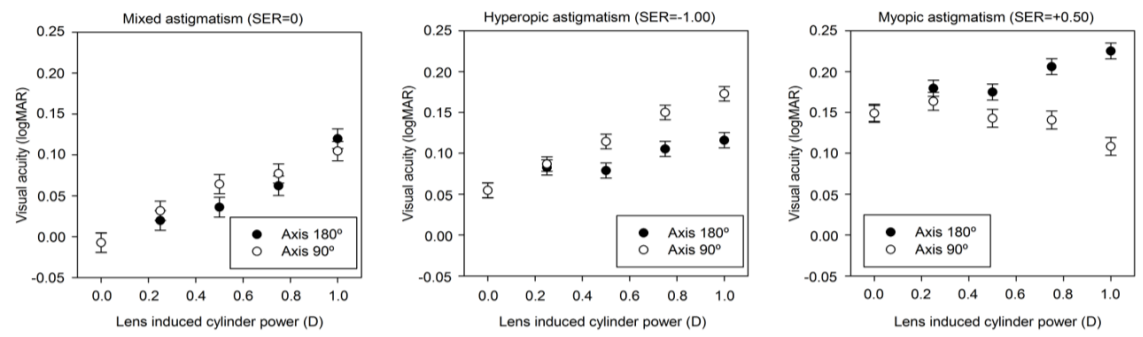

Figure 2: VA values (Mean ± SEM) after the interposition of cylindrical powers from 0.00 to +1.00D at axis orientations of 90º and 180º combined with SPH powers with SER = 0.00D, -1.00D and +0.50D (n = 30)

Means, standard errors and 95% confidence intervals of VA were calculated for each group of subjects after the interposition of cylindrical induced powers from 0.00 to +1.00D combined with SPH powers to get SER of 0.00D, -1.00D and +0.50D. Values obtained are presented in table 6. Each combination of spherocylindrical power was evaluated for an axis orientation of 90º and 180º.

Cylindrical Power (SER = 0)						
Cylindrical Power (D)	**Group 1 (n = 9)**		**Group 2 (n = 12)**		**Group 3 (n = 9)**	
	Mean ± SEM	**95% CI**	**Mean ± SEM**	**95% CI**	**Mean ± SEM**	**95% CI**
1.00 x 180	0.13 ± 0.03	0.08 - 0.18	0.14 ± 0.02	0.10 - 0.17	0.09 ± 0.02	0.05 - 0.12
0.75 x 180	0.03 ± 0.03	-0.02 - 0.08	0.07 ± 0.02	0.04 - 0.11	0.08 ± 0.02	0.05 - 0.12
0.50 x 180	0.00 ± 0.03	-0.05 - 0.06	0.07 ± 0.02	0.03 - 0.10	0.03 ± 0.02	-0.01 - 0.06
0.25 x 180	-0.02 ± 0.03	-0.07 - 0.03	0.06 ± 0.02	0.02 - 0.10	0.01 ± 0.02	-0.03 - 0.04
1.00 x 90	0.10 ± 0.02	0.05 - 0.14	0.14 ± 0.02	0.10 - 0.18	0.06 ± 0.02	0.02 - 0.10
0.75 x 90	0.07 ± 0.02	0.02 - 0.11	0.12 ± 0.02	0.08 - 0.16	0.03 ± 0.02	-0.01 - 0.07
0.50 x 90	0.08 ± 0.02	0.04 - 0.12	0.09 ± 0.02	0.05 - 0.13	0.02 ± 0.02	-0.03 - 0.06
0.25 x 90	0.03 ± 0.02	-0.01 - 0.07	0.06 ± 0.02	0.02 - 0.10	-0.01 ± 0.02	-0.05 - 0.04
Cylindrical Power (SER = -1.00)						
Cylindrical Power (D)	**Group 1 (n = 9)**		**Group 2 (n = 12)**		**Group 3 (n = 9)**	
	Mean ± SEM	**95% CI**	**Mean ± SEM**	**95% CI**	**Mean ± SEM**	**95% CI**
1.00 x 180	0.12 ± 0.02	0.09 - 0.16	0.12 ± 0.01	0.10 - 0.15	0.10 ± 0.02	0.06 - 0.14
0.75 x 180	0.13 ± 0.02	0.10 - 0.17	0.13 ± 0.01	0.11 - 0.16	0.04 ± 0.02	0.00 - 0.08
0.50 x 180	0.09 ± 0.02	0.06 - 0.13	0.10 ± 0.01	0.08 - 0.13	0.03 ± 0.02	-0.01 - 0.07
0.25 x 180	0.11 ± 0.02	0.08 - 0.15	0.11 ± 0.01	0.09 - 0.14	0.01 ± 0.02	-0.03 - 0.05
1.00 x 90	0.23 ± 0.01	0.21 - 0.26	0.22 ± 0.01	0.20 - 0.25	0.05 ± 0.02	0.01 - 0.09
0.75 x 90	0.21 ± 0.01	0.18 - 0.23	0.22 ± 0.01	0.20 - 0.25	0.00 ± 0.02	-0.04 - 0.04
0.50 x 90	0.18 ± 0.01	0.15 - 0.21	0.17 ± 0.01	0.14 - 0.19	-0.03 ± 0.02	-0.07 - 0.01
0.25 x 90	0.15 ± 0.01	0.12 - 0.18	0.14 ± 0.01	0.11 - 0.16	-0.04 ± 0.02	-0.08 - 0.00
Cylindrical Power (SER = +0.50)						
Cylindrical Power (D)	**Group 1 (n = 9)**		**Group 2 (n = 12)**		**Group 3 (n = 9)**	
	Mean ± SEM	**95% CI**	**Mean ± SEM**	**95% CI**	**Mean ± SEM**	**95% CI**
1.00 x 180	0.20 ± 0.02	0.16 - 0.23	0.21 ± 0.01	0.19 - 0.24	0.27 ± 0.02	0.23 - 0.31
0.75 x 180	0.16 ± 0.02	0.13 - 0.20	0.20 ± 0.01	0.17 - 0.23	0.26 ± 0.02	0.22 - 0.30
0.50 x 180	0.14 ± 0.02	0.11 - 0.18	0.17 ± 0.01	0.14 - 0.20	0.21 ± 0.02	0.17 - 0.25
0.25 x 180	0.13 ± 0.02	0.09 - 0.16	0.20 ± 0.01	0.17 - 0.23	0.20 ± 0.02	0.16 - 0.24
1.00 x 90	0.05 ± 0.02	0.01 - 0.09	0.15 ± 0.02	0.11 - 0.18	0.11 ± 0.02	0.07 - 0.16
0.75 x 90	0.09 ± 0.02	0.05 - 0.13	0.19 ± 0.02	0.16 - 0.23	0.13 ± 0.02	0.08 - 0.17
0.50 x 90	0.08 ± 0.02	0.04 - 0.12	0.17 ± 0.02	0.14 - 0.20	0.17 ± 0.02	0.12 - 0.21
0.25 x 90	0.10 ± 0.02	0.06 - 0.14	0.21 ± 0.02	0.18 - 0.25	0.17 ± 0.02	0.12 - 0.21

Table 6: VA values (Mean ± SEM, 95%CI) after the interposition of cylindrical powers from 0.00 to +1.00D at axis orientations of 90º and 180º combined with SPH powers with SER = 0.00D, -1.00D and +0.50D for the 3 groups.

RCBD was used to determine differences in VA among the different induced spherocylindrical powers. Statistical differences (p < 0.05) are presented in table 7.

Total sample

	-1.00D	-0.75D	-0.50D	-0.25D	0.00D
-1.00D			*	*	*
-0.75D				*	*
-0.50D	*				*
-0.25D	*	*			*
0.00D	*	*	*	*	

Group 1 - AA lower than 1.00D (n = 9)

	-1.00D	-0.75D	-0.50D	-0.25D	0.00D
-1.00D			*	*	*
-0.75D					*
-0.50D	*				
-0.25D	*				
0.00D	*	*			

Group 2 - AA between 1.00-2.00D (n = 12)

	-1.00D	-0.75D	-0.50D	-0.25D	0.00D
-1.00D			*	*	*
-0.75D					*
-0.50D	*				
-0.25D	*				*
0.00D	*	*		*	

Group 3 - AA higher than 2.00D (n = 9)

	-1.00D	-0.75D	-0.50D	-0.25D	0.00D
-1.00D			*	*	*
-0.75D					*
-0.50D	*				*
-0.25D	*				*
0.00D	*	*	*	*	

***Table 7:** Statistical differences in VA among the different induced cylindrical powers for total sample, Group 1, 2 and 3. Asterisks indicate a significant statistical difference (p < 0.05) in VA between 2 different induced cylindrical powers. Empty cell relation cylindrical powers that induce similar reduction of VA.*

SER was also included as a factor in order to determine its effect on VA. For all groups, the SER had a statistically significant influence on VA (p = 0.00). For groups 1 and 2, the best VA was obtained when the combination of SPH and CYL powers had a SER equal to 0.00D. No differences in VA were found for group 1 between SER = -1.00 or SER = +0.50. However, group 2, with the higher accommodation capacity, showed statistically significant better values of VA when interposing powers with SER = -1.00D in comparison with SER = +0.50D. For group 3, the worse VA was found with SER = +0.50. No differences were found between SER = 0.00D and SER = -1.00D for this group of subjects.

Regarding axis orientation, statistical differences were only detected for group 3 in which VA was less reduced with an astigmatism axis of 90º in comparison to 180º. For groups 1 and 2, no differences were detected.

Discussion

The results of this investigation help to determine the relationship between lens induced refractive errors and VA. In addition, thanks to a new statistical approach, this paper shows correlations between different spherocylindrical powers which lead to similar reduction of VA.

Previous studies have tried to evaluate the effect of induced refractive errors in VA from different points of view. Despite the differences in methodology in the currently published literature, in the following paragraphs, data obtained from this study is compared with data from other studies for spherical defocus and cylindrical defocus. Software xyscan.3.01 (Free Software Foundation, Inc., Boston, USA) was used to digitize data from the graphics of previous published papers.

Spherical defocus

Results of the present study show a different behavior of VA when inducing positive or negative spherical defocus. As expected, data from this study shows that small negative lens induced powers can be partially compensated in patients with enough AA.

Among all previous published studies that analyze the effects of refractive errors on VA, it should be pointed out that Peters study [1], a classical article based on an exhaustive research from many thousands of clinical records, provides a graphical representation of the relationship between refractive errors and VA. Although this study has the limitation of the lack of control in taking measurements, values obtained agree with data of the present study. Some years later, Holladay., *et al.* [15] analyzed the effects of refractive errors in a control group of patients using a variable-diameter artificial pupil. In contrast with our study, they didn't analyze the effects of cylindrical and spherical defocus separately. So, it is not possible to compare their results with data obtained in the present study. Also, the most recent study of Remón., *et al.* in 2006 [13] analyzed the effect of lens induced refractive errors on VA. However, they only provide results for a myopic range based on only 4 persons. In figure 3, a comparative graphic shows the values of VA obtained in the different studies.
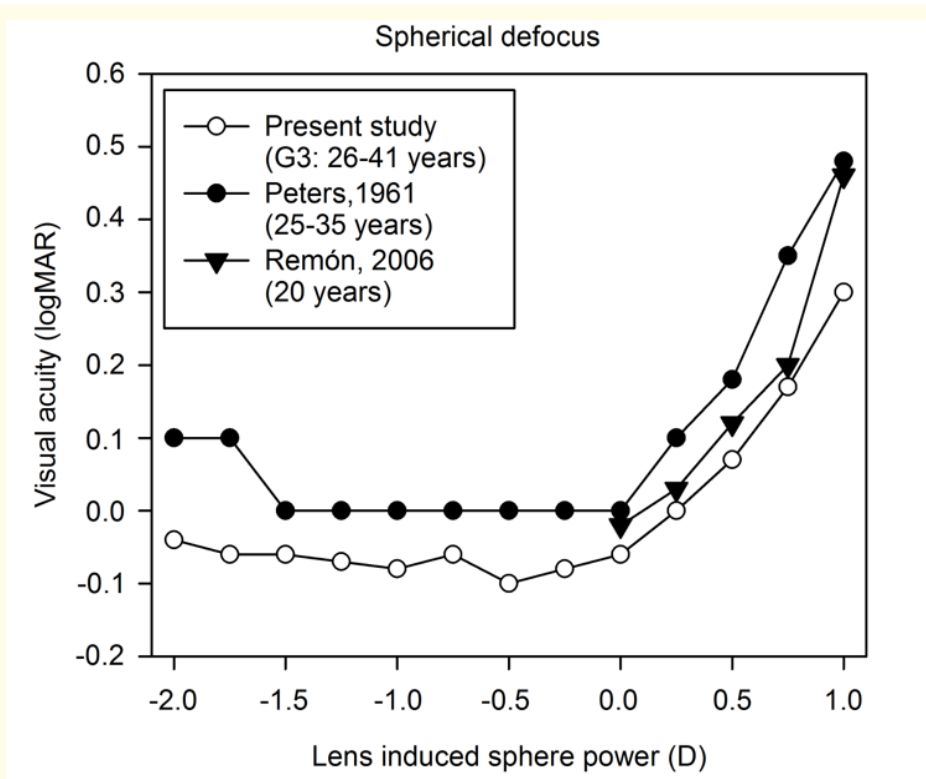

Figure 3: VA values obtained in the present study when interposing lens induced SPH power in comparison with previous published works that evaluate similar refractive errors.

On the other hand, it is relevant to compare results of this investigation with other studies that have analyzed the subjective blur limits when inducing refractive errors [6,8]. Remón., *et al.* in 2014 [6] evaluated 4 subjects (ages 24 - 26 years) in order to determine the refraction power for which the subject could not identify half of the letters for an optotype row with size 0.40 logMAR and 0.10 logMAR. For spherical defocus induced by positive lenses, their results show that a lens power of +0.93D was necessary to decrease the VA to 0.40 logMAR and +0.33D to reduce the VA to 0.10 logMAR. Their results agree with data obtained in this study for Group 3 (AA > 2.00D) that present a similar age range. In this group of patients, VA = 0.31 ± 0.17 was registered when a lens of +1.00D was interposed and VA = 0.08 ± 0.16 with a lens of +0.50D.

Guo., *et al.* [8] analyzed the subjective blur limits in a group of 10 patients. Blur was induced with a deformable, adaptive mirror and the patient had to increase the induced power by rotating a knob on a control box until different blur criteria limits were detected (first noticeable blur, just troublesome blur and objectionable blur). Their results showed that powers of about ± 0.50D induced noticeable blur when patients saw a 0.10 logMAR optotype. In comparison with our study, we found statistically significant differences in VA when a lens of +0.50D was interposed but we did not find differences when a lens of -0.50D was interposed. The use of artificial pupil and cycloplegic eye drops in Guo's study explains the differences for myopic and hyperopic ranges between the two studies.

Cylindrical defocus

Regarding cylindrical defocus, results from this study show a general reduction of VA when increasing induced cylindrical lens power. This data agrees with most of the previous published works that analyzed the effect of spherocylindrical induced powers on VA [1,11,12] (Figure 4).
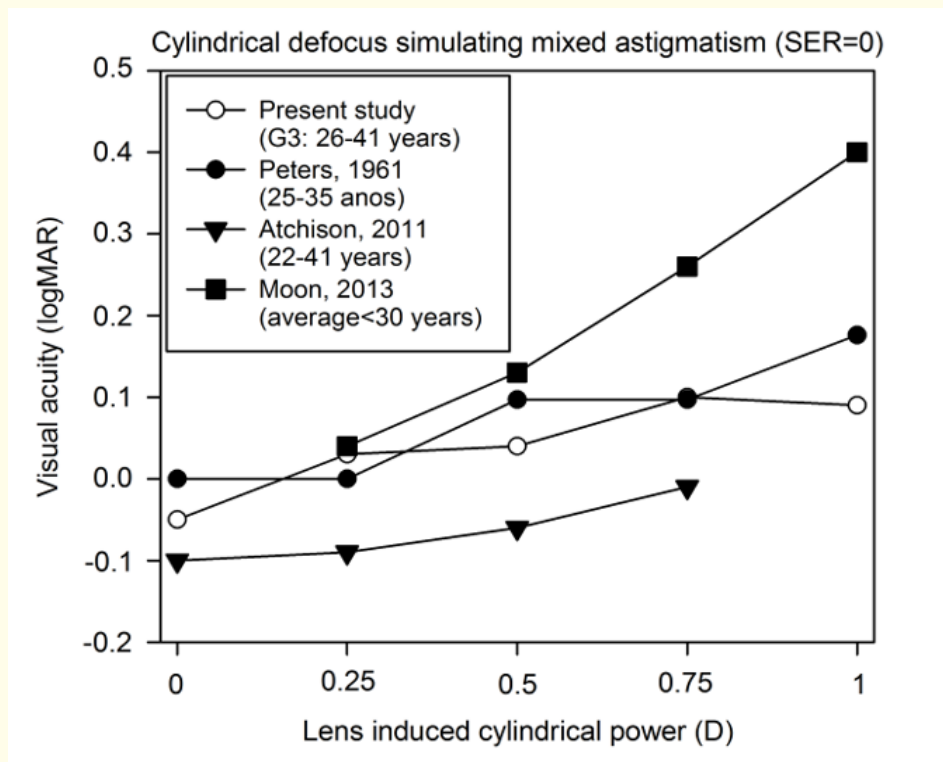

Figure 4: VA values obtained in the present study when interposing lens induced CYL powers from 0.00 to +1.00D combined with SPH powers with SER = 0 in comparison with previous published works that evaluate similar refractive errors.

It is important to note that the main limitation of these studies is the lack of analysis considering different ages or accommodation groups. In fact, most of previous studies have been done in non-presbyopic patients. For this reason, in figure 4, we compare data from previously published studies with data from our group 3 (AA > 3.00D) which has a similar age range.

It is also worth mentioning the study carried out by Wolffsohn., *et al.* [16] who analyzed the effect of uncorrected astigmatism on visual function in 21 volunteers with ages from 50 - 69 years. They found that uncorrected astigmatism caused an average loss of high contrast VA of +0.15 ± 0.03 logMAR per diopter that agrees with results obtained in the present study.

Moreover, there are several published studies analyzing the subjective perception of blur when different spherocylindrical refractive errors are induced [5,7]. Direct comparison between their results and ours is difficult, due to the different methodologies used (artificial pupils and cycloplegic to lock accommodation were used in the other studies). Atchison., *et al.* [7] asked a small group of individuals to use a tactile device that induced spherical and cylindrical powers of different magnitude. Individuals had to determine different blur limits (first noticeable blur, just troublesome blur and just objectionable blur) for different letter sizes (from 0.03 to 0.70 logMAR). Ohlendorf., *et al.* [5] also carried out a similar study to analyze the quantity of cylindrical defocus which decreased the VA to 0.00, 0.20 and 0.50 logMAR. They found that a lens of around 0.50D decreased VA to 0.00 logMAR and 1.00D decreased VA to 0.20 logMAR. In contrast with our study in which VA is highly dependent of the SER, they found similar results for myopic, hyperopic or mixed induced astigmatism.

Regarding the VA optotype used in our study, the ETDRS letter charts were used. Although Landolt C´s optotypes are recommended for measuring astigmatic defocus, Poulere., *et al.* [9] did not find statistically significant differences between letters and Landolt C using the same software that has been used in the present research.

Conclusion

The reduction of VA highly depends on the type and sign of defocus. Furthermore, the impact on VA produced by different types and magnitude of defocus differs between younger and older subjects mainly due to their accommodation capacity. This investigation provides data about the effects of different quantities of lens induced refractive errors on VA with interesting applications in the fields of Optics and Optometry. From a clinical point of view, the data allows optometrists to estimate the uncorrected VA caused by small refractive errors (myopia, hyperopia and astigmatism). Also, this data helps to explain the influence of under correction or overcorrection on VA for different age groups or understanding the effect on VA of residual error after refractive surgeries such as LASIK and/or IOLs. On the other hand, this information is very useful in the ophthalmic industry, because it can help to define how ophthalmic lenses produce a reduction of VA when looking through peripheral areas of the lens with unwanted oblique astigmatism or with unwanted spherocylindrical power caused by power progression along umbilical lines in progressive lenses. Finally, this investigation provides relevant data that is helpful to calculate defocus curves, which are used frequently in the recent years. These curves are used to optimize the performance of ophthalmic lenses, intraocular lenses and contact lenses, which are primordial in correction of refractive errors and presbyopia as in the booming phenomenon of myopia control.

Conflict of Interest

We as main authors certify that all authors have seen and approved the manuscript being submitted. We warrant that the article is the Authors' original work. We warrant that the article has not received prior publication and is not under consideration for publication elsewhere. On behalf of all Co-Authors, the corresponding Author shall bear full responsibility for the submission.

All authors agree that author list is correct in its content and order and that no modification to the author list can be made without the formal approval of the Editor-in-Chief, and all authors accept that the Editor-in-Chief's decisions over acceptance or rejection.

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