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ORIGINAL ARTICLE

Visual Acuity in Simple Myopic Astigmatism: Influence of Cylinder Axis

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ABSTRACT

Purpose. The relationship between astigmatic refractive errors and their associated visual acuity has been studied in recent years in the context of refractive power space. The influence of the axis of astigmatism remains a matter of controversy. Our goal in this study is to provide additional experimental evidence to clarify this subject. The influence of the simulated axis orientation was compared with other factors that affect visual acuity such as the particular design of the test and the differences between eyes.

Methods. Simple myopic astigmatism from 0 to −3.00 D, in steps of −0.25 D, and with five different axes between 0° and 90°, were simulated on four healthy eyes of young observers. In each case, visual acuity was recorded for three different tests. Refractions were expressed in the form of vectors and visual acuity was represented as a function of strength.

Results. No significant differences in visual acuity were found for astigmatism of the same power but different axes. In fact, our results show these differences are even less important than those recorded for the same astigmatism induced in different eyes. The highest discrepancies in visual acuity were found when different charts were used to test the same astigmatic error.

Conclusions. The strength of the vector representing the astigmatic refractive state describes very accurately the performance of visual acuity across simple myopic astigmatic errors. In these cases, visual acuity can be associated with a single refractive parameter. This fact could be useful, especially in statistical studies involving visual performance.
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Key Words: visual acuity, refractive state, subjective refraction, multivariate statistics, power vector, astigmatism

Visual acuity (VA) is the standard parameter by which the outcome of most clinical trials are judged. In particular, the relation between VA and refractive state is a matter of great interest to optometrists and ophthalmologists and especially clinical researchers.[1,2] Several studies have described the effects on VA of spherocylindrical refractive errors.[3–7] In 1961, Peters[3] investigated the relation between VA and uncompensated ocular defocus. He developed charts of iso-oxyopia (lines of equal acuity) that gave expected VA in eyes of different uncompensated refractive states. In other studies relating VA and defocus,[4–6] lenses were used to blur compensated eyes and VA tests of various types were used. In most of these analyses, the traditional representation of astigmatic power in terms of sphere, cylinder, and axis was used and transformed to nearest equivalent sphere, ignoring the multivariate nature of refractive state. A three-dimensional power space for the representation of astigmatic powers as vectors and its relationship with VA gives interesting results. This space is uniform in the sense that an equal amount of defocus or a Jackson crosscylinder (JCC) lens produces blur circles of equal diameter.[7–9] Using the empiric VA data compiled by Pincus, Raasch[10] demonstrated that the single parameter that better correlates refractive errors with its associated VA is the strength (norm) of the vector that represents the refractive error in the three-dimensional power space. This theoretical model proposed by Thibos[8] predicts that the cylinder axis has no influence on the expected VA. This result was later supported by Oechsner and Kusel using numeric simulations.[11] More recently, Rubin and Harris[12] also explored the relation between VA and defocused refractive state in the context of a symmetric dioptric power space. For a single stimulus size (20/60 computer-generated letter O), they obtained the associated refractions simulated in healthy eyes by means of spheres and Jackson's crosscylinders. They found that the experimental data represented in the dioptric power space can be fitted to *surfaces of constant VA.* These surfaces are in general ovoids, but it seems that when the effect of accommodation is minimized (elderly subjects), they become ellipsoids or spheres centered at the refractive compensation. They claimed that the elliptical cross-sections of these three-dimensional surfaces reveal the dependence of VA on cylinder axis. This assertion creates a discrepancy with previous results.[10,11]

The purpose of this work is to analyze additional empiric results to elucidate whether the simulated cylindrical axis changes influence the expected VA and, if so, to what extent. To this end, astigmatism of several degrees with variable axis orientations were simulated on compensated eyes and the maximum VA achieved in each case recorded. The relative influence of the test was considered using three different VA charts. To isolate the effect of the axis orientation, and to control for accommodation, only simple myopic astigmatism (SMA) was considered.

METHODS

Monocular distance VA was measured in healthy young (20-year-old) subjects. This research followed the tenets of the Declaration of Helsinki and consent was obtained from the subjects after explanation of the nature and possible consequences of the study. Four eyes of different subjects were included in this study with the following refractions: E1: −0.50/−0.50 × 180°; E2: −0.75/−0.50 × 10°; E3: −0.50/0.00; and E4: 0.00/−0.50 × 90° for which compensated VA was 20/20 or better. SMA of powers ranging from 0.00 D to −3.00 D, in steps of −0.25 D, were induced on the refractive correction in each eye using in each case a positive sphere and a minus cylinder of the same magnitude. Table 1 summarizes the combination of lenses used to simulate each astigmatic power. In each case, five axes were considered: 0°, 30°, 45°, 60°, and 90°. For each induced astigmatism, the corresponding conventional script notation (S;CxA) were converted to power vector coordinates and the norm of the power vector, or blurring strength, was computed using the following equations.

$$M = S + \frac{C}{2} \tag{1}$$

$$J_0 = -\frac{C}{2}\cos 2\alpha \tag{2}$$

$$J_{45} = -\frac{C}{2}\sin 2\alpha \tag{3}$$

$$|u| = \sqrt{M^2 + J_0^2 + J_{45}^2} \tag{4}$$

TABLE 1.
Combination of sphere (S) and cylinder (C) used to simulate different simple myopic astigmatism[a]

S	C	|u|
+0.25	−0.25	0.18
+0.50	−0.50	0.35
+0.75	−0.75	0.53
+1.00	−1.00	0.71
+1.25	−1.25	0.88
+1.50	−1.50	1.06
+1.75	−1.75	1.24
+2.00	−2.00	1.41
+2.25	−2.25	1.59
+2.50	−2.50	1.77
+2.75	−2.75	1.94
+3.00	−3.00	2.12

[a]|u| is the modulus of the corresponding power vector.

The values of power and axis were randomized in each session of measurements. Additionally, for comparison purposes, spherical defocus was induced with positive spheres ranging from 0.00 D to +2.25 D in steps of 0.25 D. All these refractions were induced with a NIDEK-RT 600 phoropter (NIDEK Co., Ltd., Aichi, Japan). For each induced refractive error, the corresponding VA was recorded leaving a short interval of time between measurements. The time involved in measuring the VA for an eye in each session was restricted to 45 minutes to minimize the effects of fatigue (many days elapsed between sessions). Pupil size and accommodation were not controlled artificially because this study attempted to gain understanding of the nature of VA in eyes in their natural states. However, the measurements were performed in a quiet environment exclusively used for research activities with constant ambient lighting conditions.

Three high-contrast VA tests were used. We used letter charts (L-chart) from Shin-Nippon CP-10 chart projector (Ajineomoto Trading, Inc., Tokyo, Japan) projected onto an aluminum screen. To avoid learning effects, we used two tests available from the Internet, both presented in a CRT computer monitor following the instructions of the providers. The first one was developed by the Pediatric Ophthalmology Unit at The Children's Hospital of Buffalo (I-Chart)[13] consisting of Snellen letters, and the other was the "Freiburg Visual Acuity & Contrast Test" (FrACT) developed by Bach[14] consisting of Landolt-C's (C-Chart). The main features of these VA tests are summarized in Table 2.

The mean luminance of the tests were approximately 40 cd/m^2 for the projected tests and 60 cd/m^2 for the monitor. Working with L-Chart and I-Chart, the subject was asked to identify the optotypes on each line from left to right and the VA was computed when three or more of the five optotypes were identified. The chart type was changed after 20 measurements.

RESULTS

Our first goal was to compare the influence of the axis on VA using different tests. In Figure 1, we show the results obtained for eye E4 (similar results were obtained for the other eyes). In each plot, the results of the VA for five different orientations of the axis in the range 0° to 90° are included. As expected, the plot of the log minimum angle of resolution against the norm of the refractive power vector, *u*, shows a linear reduction in monocular VA with increasing astigmatic blur. Note that, globally, increments of 0.25 D produce an approximated loss of VA of 0.1 as the usual clinical convention. For each value of $|u|$, the mean value of the VA for the five axis orientations was computed for each one of the three tests. These mean data points were fitted to the following equations:

$$\begin{aligned} &\mathrm{I-Chart:\ LogMar} = 0.2775\,|u| - 0.0775 \\ &\mathrm{C-Chart: LogMar} = 0.2723\,|u| - 0.1693 \\ &\mathrm{L-Chart: LogMar} = 0.3706\,|u| - 0.1656 \end{aligned} \tag{5}$$

On the other hand, for each one of the five axes, the regression line was obtained and both the correlation coefficient, R, and the slope (or regression coefficient), b, were computed. For the I-Chart, the five correlation coefficients were within the range from 0.96 to 0.98 and the range of slopes was from 0.36 to 0.40. For the

TABLE 2.
Main features of the different tests used in the study

	L-Chart Shinn-Nippon CP-10	I-Chart (IVAC)	C-Chart (FrACT)
Types of symbol	Non-serif letters (fixed)	Non-serif letters (random)	Landolt C Eight random orientations
Progression of letter sizes	Variable 1.20×–2.05×	Variable 1.25×–2.00×	Not specified
Spacing between symbols in a row	Variable	Variable	Single symbol presented without surrounding
Number of symbols per row	Variable (1–4)	Variable (1–5)	1
Spacing between rows	Almost equal to the height of the letters in the smaller row	Single line	
Number of letters	17/26 Not used: G, H, I, J, M, Q, U, W, X, Y	25/26 Not used: Q	1
Observation distances	6 m	5 m	5 m

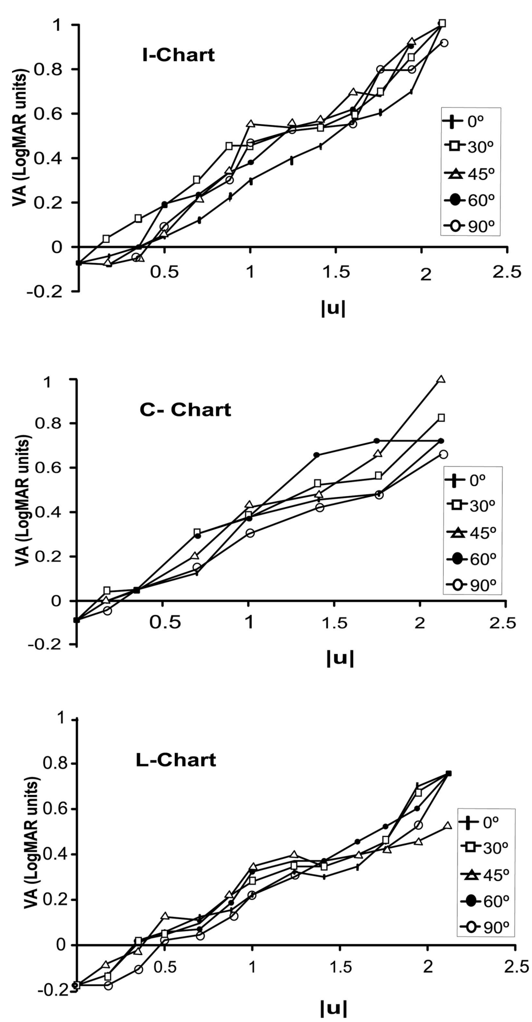

FIGURE 1.
LogMar as a function of $|u|$ in simple myopic astigmatism. Results for different axes and different charts. I-Chart: LogMar = 0.2775 $|u|$ − 0.0775 C-Chart: LogMar = 0.2723 $|u|$ − 0.1693(5) L-Chart: LogMar = 0.3706 $|u|$ − 0.1656

C-Chart, the range of correlation coefficients was from 0.93 to 0.99 and the range slopes from 0.24 to 0.34. For the L-Chart, the range of correlation coefficients was from 0.93 to 0.98 and the range slopes from 0.20 to 0.29. The results for the three tests show small variations in VA for the different orientations of the astigmatic axis. In fact, for the same value of $|u|$ in each plot, the mean standard deviation of data corresponding to the five axis orientations were 0.054, 0.069, and 0.049 for the I-, C-, and L-Charts, respectively. C-Chart gives the higher variability (this was a common feature of four eyes). For C- and L-Charts, there is a little improvement of the VA at 90°, but only for low degree of blurring. It can be seen that better VA was reached with the projected L-Chart, suggesting a learning effect of the optotypes. In the measurements performed with the other two tests, this effect was not observed.

From Figure 1 it can be deduced that, in general, the highest variation of the VA is attained when different tests are used rather than when different axes are simulated. To confirm this effect, in Figure 2, the VA records of the same eye obtained with the I-Chart

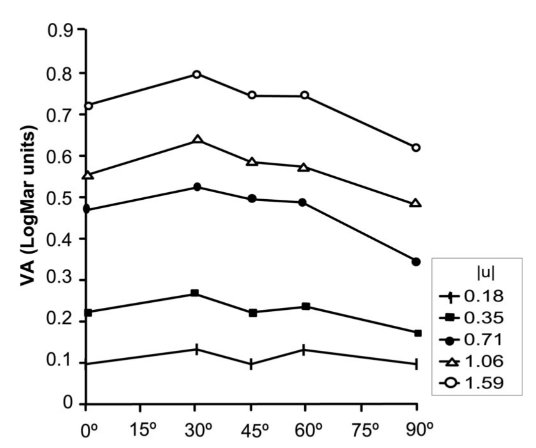

FIGURE 2.
LogMar as a function of axis for different values of $|u|$.

are presented as a function of the astigmatism axis. It can be seen that for each value of $|u|$ VA presents minor differences with axes, the highest VA corresponds to 90°. Presumably, this is because letters in the chart have a greater number of vertical strokes than oblique strokes, making them more legible.

In Figure 3, we compare the VA of the different subjects using the two charts from the Internet (the projected L-Chart was not considered here because of the learning effect already mentioned). For the comparison, we show the results for the axis that gives more variability between eyes, i.e., 45°. Here the I-Chart correlation coefficients for the four lines, corresponding to the different eyes, were within the range from 0.94 to 0.99 and the range of the corresponding slopes from 0.34 to 0.42. For the C-Chart, the range of correlation coefficients was from 0.93 to 0.99 and the range slopes from 0.34 to 0.45. The mean values of the standard deviation for data corresponding to the four eyes were 0.01 and 0.16 for the I-Chart and C-Chart, respectively. From the comparison between the data corresponding to the same chart in Figures 1 and 3 and the corresponding statistical values, it is evident that the differences of the VA attained at a given value of $|u|$ are higher for different eyes (Fig. 3) than the differences for different axes in the same eye (Fig. 1). In Figure 4, we have represented the VA attained with spherical defocus equivalent to the values in Figure 3 (note that in this case, the value of $|u|$ is equal to the value of the spherical defocus). Here the I-Chart range of correlation coefficients was from 0.93 to 0.98 and the slopes range from 0.47 to 0.54. For the C-Chart, the range of correlation coefficients was from 0.92 to 0.97 and the slopes range from 0.42 to 0.43. The mean values of the standard deviation were 0.07 and 0.10 for the I-Chart and C-Chart, respectively.

The comparison between Figures 3 and 4 and the corresponding statistics show that the spherical and astigmatic defocus corresponding to the same values of $|u|$ give similar results. Therefore, results in Figures 1, 2, and 3 show that the VA is primarily affected by the selected test followed by the anatomic and/or psychophysical characteristics of the observers and, finally, by the axis of the astigmatism. In summary, the results for SMA confirm the prediction of Raasch[10] in the sense that the norm of the power vector representing the refractive error, which is independent of the astigmatic axis, is the better predictor of its associated VA.

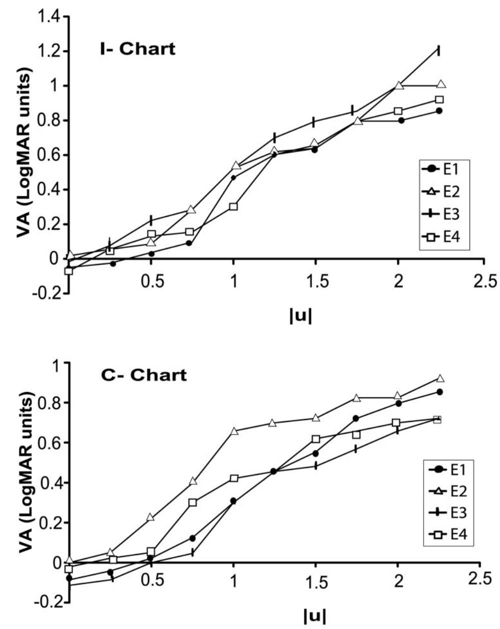

FIGURE 4.
LogMar as a function of $|u|$ in myopia. Results for different eyes.

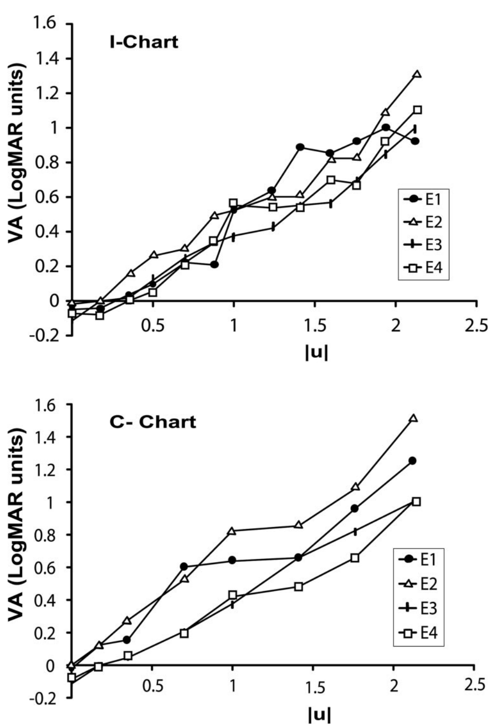

FIGURE 3.
LogMar as a function of $|u|$ in simple myopic astigmatism. Results for 45° axis and different eyes.

Discussion and Conclusions

Thibos[8] and Raasch[10] relate VA to a single parameter: the magnitude of the dioptric power vector u. In this approach, surfaces of constant VA in the three-dimensional power space are spheres of radius $|u|$. In this article, we confirmed this hypothesis for SMA. We found that astigmatic vectors corresponding to refractive states with the same magnitude of astigmatism, but different axis orientations have all nearly the same associated VA.

Only monocular measurements of VA have been included in this article. We designed an experimental protocol with 180 measurements of VA for each eye. To prevent the learning effect, two Internet-based VA test with random letter presentation were used. In fact, for this reason, the results for the projected letter chart (L-Chart) are omitted from Figures 2, 3, and 4. To prevent fatigue, the sessions for each eye were limited to 45 minutes per day.

It was found that when accommodation is not active, the influence of the cylinder axis is of less importance than other clinical variables such as the selected VA chart. Moreover, the same astigmatic error (same power and axis) induced in different eyes provides VA variations of higher amount than those provided by astigmatism of the same power and different axes induced in the same eye.

On the other hand, our results agree with those of Rubin and Harris[12] to some extent. As they claimed, when there is a loss of ocular accommodation, surfaces of constant visual acuity take a nearly spheroidal form. Thus, the departure from the spherical surface in their study can be mainly attributed to accommodation, whose effect has been minimized in our study. It is interesting to note that although the experimental data of Rubin and Harris[12] has been fitted to ellipses, many of the experimental data points lie in a circle (see Fig. 1A in Rubin and Harris[12]); the authors did not comment on this particular result.

The fact that VA for an ametropic eye can be associated with a single refractive parameter could be very useful, especially in studies involving visual performance. However, additional research is needed to quantify the influence of accommodation on other types of astigmatism.

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