Uncorrected Refractive Error and Distance Visual Acuity in Children Aged 6 to 14 Years

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SIGNIFICANCE: This study presents the relationship between distance visual acuity and a range of uncorrected refractive errors, a complex association that is fundamental to clinical eye care and the identification of children needing refractive correction.

PURPOSE: This study aimed to analyze data from the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study to describe the relationship between distance uncorrected refractive error and visual acuity in children.

METHODS: Subjects were 2212 children (51.2% female) 6 to 14 years of age (mean ± standard deviation, 10.2 ± 2.1 years) participating in the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study between 2000 and 2010. Uncorrected distance visual acuity was measured using a high-contrast projected logMAR chart. Cycloplegic refractive error was measured using the Grand Seiko WR-5100K autorefractor. The ability of logMAR acuity to detect various categories of refractive error was examined using receiver operating characteristic curves.

RESULTS: Isoacuity curves show that increasing myopic spherical refractive errors, increasing astigmatic refractive errors, or a combination of both reduces distance visual acuity. Visual acuity was reduced by approximately 0.5 minutes of MAR per 0.30 to 0.40 D of spherical refractive error and by approximately 0.5 minutes of MAR per 0.60 to 0.90 D of astigmatism. Higher uncorrected hyperopic refractive error had little effect on distance visual acuity. Receiver operating characteristic curve analysis suggests that a logMAR distance acuity of 0.20 to 0.32 provides the best balance between sensitivity and specificity for detecting refractive errors other than hyperopia. Distance acuity alone was ineffective for detecting hyperopic refractive errors.

CONCLUSIONS: Higher myopic and/or astigmatic refractive errors were associated with predictable reductions in uncorrected distance visual acuity. The reduction in acuity per diopter of cylindrical error was about half that for spherical myopic error. Although distance acuity may be a useful adjunct to the detection of myopic spherocylindrical refractive errors, accommodation presumably prevents acuity from assisting in the detection of hyperopia. Alternate procedures need to be used to detect hyperopia.

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Optom Vis Sci 2021;98:3–12. doi:10.1097/OPX.0000000000001630
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Refractive errors are recognized as a disabling vision disorder among children.[1–3] Undetected refractive error can interfere with development, can impede effective learning, and is associated with developmental disability among children.[3] Reduced vision from uncorrected refractive error can be improved if diagnosed and optically corrected in a timely manner.[3,4] Both federal and state government organizations recognize the importance of vision in children. Healthy People 2010 and the upcoming Healthy People 2020 have national vision objectives including "reduce blindness and visual impairment in children and adolescents aged 17 years and under."[5–7] In the United States, Medicaid (a U.S. government program for low-income families) considers children's vision to be an essential component of their Early Periodic Screening Diagnostic and Treatment program and mandates the inclusion of the diagnosis and treatment of defects in vision.[8,9] Other reviews support the importance of correction of refractive errors to improve vision in children.[10,11]

Distance visual acuity is an important clinical measure when evaluating refractive error. Uncorrected distance visual acuity often guides the experienced clinician in estimating the degree of refractive error. Maximizing visual acuity indicates a successful refraction, whereas acuity deficits aid in the detection of amblyopia or ocular pathology. Distance visual acuity obviously worsens with greater uncorrected myopic spherocylindrical refractive error but without consensus of whether the pattern is linear or nonlinear. This likely results from study design limitations that include the following: evaluating either spherical or astigmatic errors but not both, expressing spherocylindrical errors in nonclinical vector terminology, small sample sizes, or including adult subjects only and no children with hyperopia.[12–16]

One of the more useful depictions of the relationship between visual acuity and a wide range of uncorrected spherocylindrical refractive errors in children was provided by Peters.[17] The Orinda Study plotted "iso-oxyopia" (isoacuity) curves to display how a range

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of uncorrected refractive errors was associated with various levels of uncorrected distance visual acuity.[18] These classic curves are often taught to optometry students because they provide a graphical representation of what eventually develops through clinical experience, namely, what level of acuity corresponds to different levels of spherical and astigmatic refractive errors. These curves have not been revised in 60 years. The Orinda Study isoacuity curves were also developed before the widespread use of computers and were therefore drawn manually.[18] Using a large and diverse cohort of children from the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study, we developed similar curves but derived them using well-defined statistical methods based on data from acuity charts using more rigorous design principles. We present these curves using clinical variables of sphere and cylinder in addition to the more modern notation of spherical equivalent and J_0.[19] An additional analysis examined the ability of visual acuity to detect various categories of cycloplegic spherocylindrical refractive error.

TABLE 1. Frequency and percent for subject sex and race/ethnicity

	n (%)
Sex	
Male	1080 (48.8)
Female	1132 (51.2)
Race/ethnicity	
Native American	546 (24.7)
Asian	211 (9.5)
African American	481 (21.7)
Hispanic	742 (33.5)
White	215 (9.7)
Other	17 (0.8)

METHODS

Subjects

Subjects were 2212 children (51.2% female) 6 to 14 years of age (mean ± standard deviation, 10.2 ± 2.1 years) participating in the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study between 2000 and 2010 (detailed study methods described previously).[20,21] The years 2000 to 2010 were chosen because the Grand Seiko WR-5100K (Grand Seiko Co., Hiroshima, Japan) used for cycloplegic autorefraction during this period provided more consistent and valid measures of astigmatism compared with the Canon R-1 (Canon, Lake Success, NY) used in previous years.[22,23] The Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study was a multicenter cohort study of ocular component development and risk factors for the onset of myopia. Each of the clinic sites was charged with recruiting the majority of its subjects from one of the major racial/ethnic groups in the United States. Each affiliated university's institutional review board (University of Alabama at Birmingham; University of California, Berkeley; University of Houston; The Ohio State University; Southern California College of Optometry; University of Arizona) approved informed consent documents according to the tenets of the Declaration of Helsinki. Parents provided consent and children assent before the children were examined. Parents designated the child's racial/ethnic group using one of six designations (corresponding to the categories used by the National Institutes of Health as of 1997 when ethnic data were first gathered): American Indian or Alaskan Native; Asian or Pacific Islander; Black, not of Hispanic origin; Hispanic; White, not of Hispanic origin; other; or unknown. Table 1 provides the distribution of sex and race/ethnicity for the subjects.

Measurements

Monocular uncorrected distance acuity was measured by trained and certified study personnel using a high-contrast projected slide of a logMAR chart consisting of letters patterned after those described by Bailey and Lovie-Kitchin.[24] The projected letter size was calibrated weekly and each time the screen or projector was moved between schools, so that 20-ft Snellen size letters subtended 5 minutes of arc. The test distances were 10 to 19 ft, depending on the examination space provided by the schools. The letters on the chart ranged from 0.8 logMAR (20/126) to 0.0 logMAR (20/20), with five letters on each line. The full chart was presented, and the examiner was allowed to point to a specific line or letter when testing younger children with limited attention. The right eye was tested first followed by the left eye, with the untested eye covered with an occluder. Study personnel monitored the adequacy of occlusion and test distance. Children were asked to read the smallest line of letters they could see without squinting and to guess when the letters became difficult for them to see. Testing stopped when all five letters on a line were missed or when the child read the 20/20 line (or 20/25 line if in first grade). Visual acuity was recorded in logMAR notation, beginning with the last line where all letters were correctly identified, with 0.02 subtracted for each letter correctly identified on any subsequent lines. The acuity for children unable to read any letters on the largest line on the chart (20/126) was recorded as missing data. Visual acuity was measured more for its clinical value than as a primary study outcome. This range did not allow for the determination of maximum best visual acuity or the acuity for very high and uncommon refractive errors. Acuity data are reported for the right eye because only the right eye was measured with cycloplegic autorefraction.

Cycloplegic refractive error measurements for the right eye were made by certified study personnel using the Grand Seiko WR-5100K autorefractor (Grand Seiko Co.). At least 10 autorefractor readings were taken with the eye in primary gaze. Readings were eliminated if they exceeded the mode for cylinder by ±0.75 D or the mode for sphere by ±1.00 D. Refractions were then converted to their vector form using the matrix method described by Harris,[25] averaged, and converted back to a spherocylinder notation. Testing was done 30 minutes after one drop of proparacaine 0.5% and two drops of tropicamide 1% when subjects had an iris color of grade 1 or 2, or 30 minutes after one drop of proparacaine 0.5% and one drop each of tropicamide 1% and cyclopentolate 1% when subjects had an iris color darker than grade 2.[26,27] Previous studies found average differences of 0.20 D or less when comparing refractive errors in the same subjects using tropicamide compared with cyclopentolate.[28–30] Subjects fixated a reduced Snellen chart through a +4.00 D Badal lens in primary gaze. The Badal system allows subjects to fixate on an in-focus target at the far point of either hyperopic or myopic errors without stimulating accommodation while keeping the retinal image size of the target constant.

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TABLE 2. Descriptive statistics for 7722 study observations

	Average ± SD	Median	Range
Age (y)	11.4 ± 2.0	11.5	5.3 to 17.5
Spherical equivalent (D)	0.07 ± 1.23	0.17	–9.70 to +10.08
J_0 (D)	0.24 ± 0.54	0.09	–1.22 to +3.41
Sphere (D)	0.46 ± 1.35	0.45	–8.13 to +10.86
Minus cylinder (D)	–0.78 ± 0.97	–0.47	0.00 to –7.37
Uncorrected logMAR distance acuity	0.19 ± 0.23	0.08	0.00 to 0.88

SD = standard deviation.

Statistical Methods

Isoacuity Contour Plots

The data set for analysis of isoacuity contours contained 7722 observations from 2212 subjects. All analyses were performed using SAS 9.4 for Windows (SAS Institute Inc., Cary, NC). The SAS procedure locally estimated scatterplot smoothing was used to estimate the functional relationship between visual acuity as the dependent variable and two independent variables: the spherical equivalent and the horizontal/vertical component of astigmatism (J_0). The oblique astigmatic component J_{45} was far smaller and was not included in this analysis. The analysis was also done using the more conventional clinical notation of sphere and minus cylinder. Locally estimated scatterplot smoothing performs localized regression using weighted least squares to fit an outcome in neighborhoods of the independent variables. Observations in a neighborhood were weighted by a smooth decreasing function of their distance from the neighborhood's center. The neighborhood radius was selected to minimize the bias-corrected Akaike information criteria, a criterion that balances tightness of fit and model complexity.[31] For the localized regression, the dependent variable was assumed to be well approximated by a quadratic function of the independent variables. The results were summarized as contour plots.

Visual Acuity and Detection of Uncorrected Refractive Error

The purpose of this analysis was to determine the sensitivity (the true-positive rate) and specificity (the true-negative rate) of visual acuity to detect seven categories of clinically significant refractive error. Only 1724 (22.3%) of the 7722 study observations had refractive errors within these classifications. Most of the excluded observations either were emmetropic or had clinically insignificant refractive errors. These categories of refractive error were assessed over the range of logMAR cut-point values using receiver operating characteristic curves. Optimal logMAR values to detect each refractive error group were identified according to the Youden Index.[32] The Youden Index is the logMAR value that is associated with the maximum value of ([sensitivity + specificity] – 1) over the range of logMAR cut points. It is the value that is farthest along a vertical drawn up from the 1:1 line on a receiver operating characteristic curve. The area under the receiver operating characteristic curve estimates the proportion of randomly drawn pairs of children where the one who has clinically significant refractive error also has a worse acuity.

Seven categories of clinically significant refractive error were analyzed: (1) myopic (not astigmatic but myopic in both meridians), (2) simple myopic astigmatism (astigmatic with one meridian emmetropic and one meridian myopic), (3) compound myopic astigmatism (astigmatic with both meridians myopic), (4) hyperopic (not astigmatic but hyperopic in both meridians), (5) simple hyperopic astigmatism (astigmatic with one meridian emmetropic and one meridian hyperopic), (6) compound hyperopic astigmatism (astigmatic with both meridians hyperopic), and (7) mixed astigmatism (astigmatic with one meridian myopic and one meridian hyperopic). For the refractive error to be classified as astigmatic, the cylinder value had to be at least 0.75 D. A myopic meridian was defined as having –0.75 D or more myopia. A hyperopic meridian was defined as having +1.00 D or more hyperopia. An emmetropic meridian was between –0.25 and +1.00 D (exclusive). Cycloplegic refractive errors between –0.25 and –0.75 D were not included in this analysis, as they were considered to be of marginal clinical significance and within the measurement error of cycloplegic autorefraction.[33] An additional condition was imposed in order to make the categories more clinically meaningful. The power vector length for the refractive error had to be 1.00 D or greater for all myopic categories but had to be 2.00 D or greater for hyperopia, simple hyperopic astigmatism, and compound hyperopic astigmatism.[14,19] Power vector length was defined as follows:

$$\text{Power vector length} = \sqrt{(\text{sphere})^2 + (\text{sphere}^*\text{cylinder}) + \left(\frac{\text{cylinder}^2}{2}\right)}$$

RESULTS

As seen in Table 1, the 2212 subjects (51.2% female) included more Hispanic, Native American, and African American children than Asian or White. As shown in Table 2, the average spherical

TABLE 3. Distribution of 1724 observations of refractive error by ethnic group

	Native American (n = 677)	Asian American (n = 149)	African American (n = 270)	Hispanic American (n = 522)	White American (n = 90)	Other (n = 16)
Simple myopia	102 (15.1)	108 (72.5)	154 (57.0)	308 (59.0)	40 (44.4)	4 (25.0)
Simple hyperopia	12 (1.8)	6 (4.0)	23 (8.5)	22 (4.2)	20 (22.2)	None
Compound myopic astigmatism	96 (14.2)	27 (18.1)	51 (18.9)	77 (14.8)	10 (11.1)	2 (12.5)
Compound hyperopic astigmatism	83 (12.3)	None	36 (13.3)	33 (6.3)	12 (13.3)	6 (37.5)
Simple myopic astigmatism	117 (17.3)	3 (2.0)	4 (1.5)	39 (7.5)	5 (5.6)	4 (25.0)
Simple hyperopic astigmatism	70 (10.3)	None	2 (0.7)	14 (2.7)	None	None
Mixed astigmatism	197 (29.1)	5 (3.4)	None	29 (5.6)	3 (3.3)	None

n (%) of observations in each ethnic group.

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equivalent for the 7722 observations was nearly emmetropic, but the overall distribution had a wide range of both myopic and hyperopic refractive errors. The average amount of J_0 or minus cylinder was also low, but the sample as a whole had a wide range of against-the-rule (negative sign for J_0) and particularly with-the-rule astigmatism (positive sign for J_0). Uncorrected acuity ranged from all letters correct (0.0 logMAR) to one letter correct on the largest line (0.88 logMAR). The average level of uncorrected acuity was a two-line reduction in acuity from 0.0 logMAR. As shown in Table 3, most subjects with refractive error were myopic, followed

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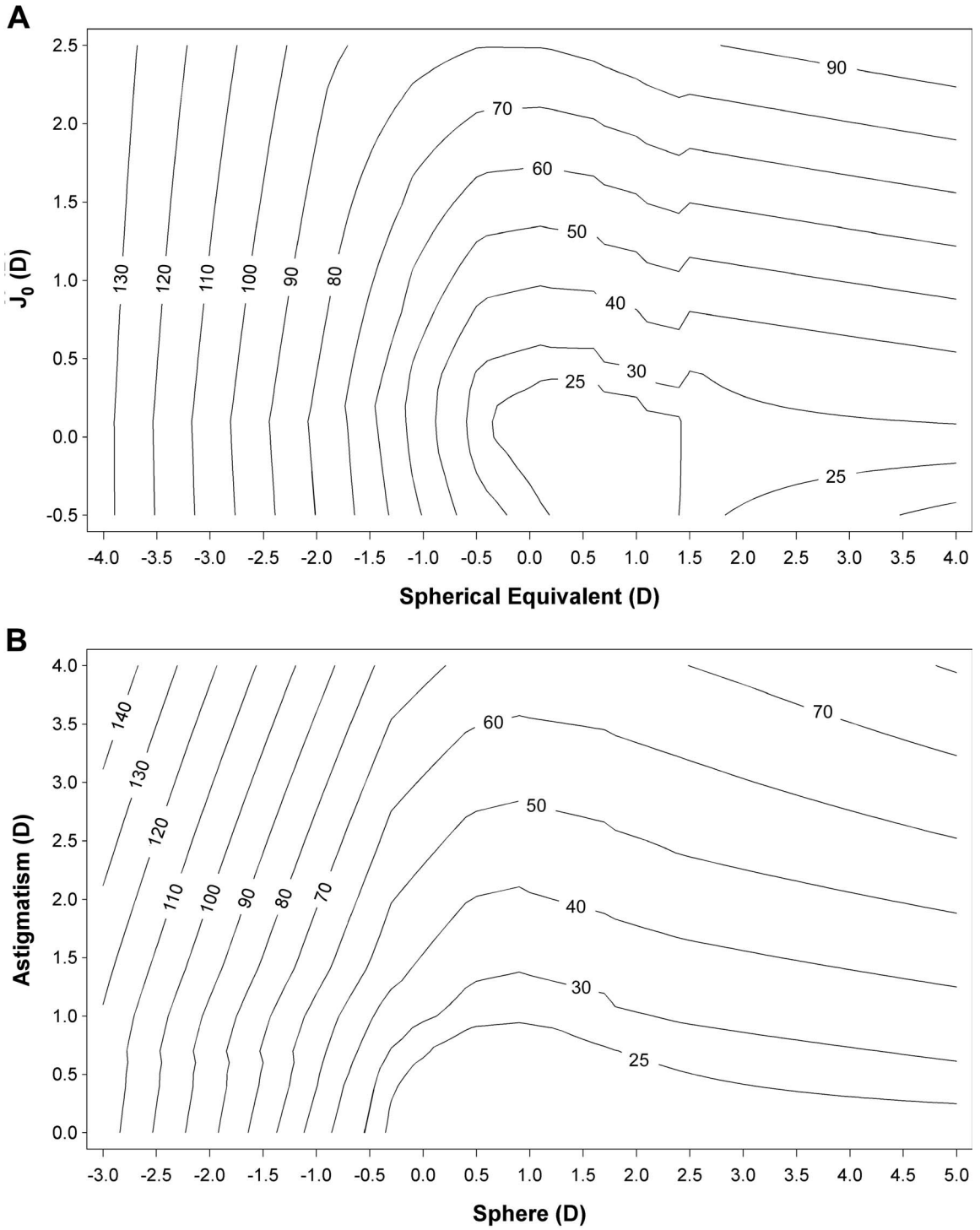

FIGURE 1. (A) Contours of visual acuity as a function of J_0 and spherical equivalent refractive error (in diopters). Positive values of J_0 are with the rule in orientation, and negative values are against the rule. (B) Contours of visual acuity as a function of astigmatism (minus cylinder; in diopters) and the spherical component of refractive error (in diopters).

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by compound myopic astigmatism and mixed astigmatism. Refractive error groups varied considerably by ethnicity. Mixed astigmatism was the most common refractive error in Native Americans, and hyperopia was the rarest, with fairly even distribution across the other categories. Myopia was the most common finding in Asian American and Hispanic American children, followed by compound myopic astigmatism. Myopia was also the most common refractive error among African American children, followed by both compound myopic and compound hyperopic astigmatism. Although myopia was the most common refractive error among children overall, hyperopia was also seen frequently, followed by both compound myopic and compound hyperopic astigmatism.

Isoacuity Contour Plots

Isoacuity contour plots are shown in Fig. 1. Contours were plotted in two ways: visual acuity as a function of J_0 and spherical equivalent refractive error in diopters (Fig. 1A) and visual acuity as a function of astigmatism expressed as minus cylinder in diopters and the spherical component of refractive error in diopters (Fig. 1B). The isoacuity contour lines show the levels of visual acuity associated with different combinations of refractive error. In Fig. 1A, for example, the acuity in the zone where the spherical equivalent and J_0 are both 0.00 D corresponds to 20/20. As expected, acuity was worse with higher magnitudes of myopic spherical equivalent refractive error. The change in acuity was an increase in MAR by approximately 0.5 minutes of arc per 0.30 to 0.40 D in myopic spherical equivalent. Interestingly, there was little difference in acuity for a given myopic spherical equivalent with a higher value of J_0, particularly for values of spherical equivalent more myopic than –2.00 D. The effects of spherical equivalent and J_0 were quite different for hyperopic refractive errors. There was little difference in acuity with more hyperopic spherical equivalent, an expected result if the subjects were compensating by accommodating. In contrast to the lack of effect of difference in J_0 for myopic spherical equivalents, MAR was worse by approximately 0.5 minutes per 0.30 to 0.40 D difference in J_0 when the spherical equivalent was hyperopic.

Increases in the value of astigmatism had similar effects on acuity across the range of refractive errors when the data were represented as sphere and cylinder. Given that J_0 represents half the value of cylinder in a prescription, the effect of cylinder on acuity was about double that for J_0, namely, approximately 0.5 minutes of arc worse in MAR per 0.6 to 0.9 D greater astigmatism for both hyperopic and myopic values for sphere. As with spherical equivalent, the difference in acuity was a higher value of MAR by approximately 0.5 minutes of arc per 0.30 to 0.40 D in myopic spherical defocus. Isoacuity contours were again mostly horizontal for hyperopic sphere values.

The isoacuity plots in Fig. 1 are useful descriptions of the average relationship between refractive error and distance visual acuity, but they do not have error bars or some other indication of variability. The variability in this relationship is depicted in Fig. 2A, box and whisker plots of the 10th, 25th, 50th, 75th, and 90th percentiles for distance visual acuity as a function of refractive error and the same percentiles for refractive error as a function of distance visual acuity in Fig. 2B. Figs. 1 and 2A both show that increasing amounts of myopia worsened distance visual acuity more rapidly than increasing amounts of hyperopia. There was considerable variability, however, with interquartile ranges of 0.20 to 0.28 logMAR for myopic refractive errors and as high as 0.42 logMAR for hyperopic refractive errors. Fig. 2B indicates that a given distance visual acuity does not always correspond to a specific refractive error. Distance visual acuities of 0.22 logMAR or better generally indicated emmetropia, but a plano spherical equivalent was also within an interquartile range for distance visual acuity as poor as 0.7 logMAR. Interquartile ranges for refractive errors at various levels of distance visual acuity worse than 0.22 logMAR were from 1.3 D to as high as 2.9 D. A distance visual acuity of 0.66 to 0.70 logMAR covered a range between the 10th and the 90th percentiles between –2.5 and +2.5 D.

Receiver Operating Characteristic Curves

The receiver operating characteristic curves for the seven different refractive error categories show the effect of changing sensitivity (true positive rate) against 1 – specificity (false-positive rate) across the range of logMAR cut points (Figs. 3A to H). Fig. 3H shows this relationship if a child had refractive error in any one of the seven categories. The general shape of the receiver operating characteristic curves is similar across refractive errors, suggesting similar levels of sensitivity and specificity regardless of category when using visual acuity to detect refractive error. The exception was the flat, diagonal pattern of the receiver operating characteristic curve for hyperopia (Fig. 3D). Consistent with the lack of change in distance visual acuity with increasing hyperopia displayed in Figs. 1A and B, the similarity between the receiver operating characteristic curve and the 1:1 line in Fig. 3D reinforces the finding that use of uncorrected logMAR acuity to detect simple hyperopia is comparable to random guessing. Ethnicity did not affect the ability of distance visual acuity to detect the presence of refractive error. The combined false-positive and false-negative rate varied by only ±5% across ethnic groups. These receiver operating characteristic curves also identify a visual acuity criterion that maximizes sensitivity and specificity, that is, the value that is farthest along a vertical drawn up from the 1:1 line. As can be seen in Table 4, these optimal uncorrected logMAR acuity criteria showed some minor variation by refractive error. For myopia and simple hyperopic astigmatism, the optimal logMAR criterion was approximately 0.3 (roughly Snellen 20/40). For simple myopic astigmatism, compound myopic astigmatism, compound hyperopic astigmatism, mixed astigmatism, and any refractive error, the optimal logMAR criterion was approximately 0.2 (roughly Snellen 20/32). For hyperopia, the distance visual acuity criterion was 0.02, resulting in a respectable sensitivity of 0.86 but a poor specificity of 0.23, misclassifying as hyperopic 77% of those who did not have hyperopia. Sensitivity for detecting categories of refractive error other than hyperopia by visual acuity was also good, 0.85 to 0.97 (Table 4). Specificity for detecting other categories of refractive error was much higher than for hyperopia, between 0.68 and 0.85. Areas under the receiver operating characteristic curves were consistently between 0.79 and 0.93, with performance significantly better than chance for all refractive error categories except hyperopia.

DISCUSSION

This study analyzed distance visual acuity and refractive error data measured by trained and certified examiners from the large and diverse cohort enrolled in the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study to characterize the relationship between uncorrected refractive error and distance visual acuity. The analysis used the same approach as the original Orinda Study, presenting isoacuity contour plots.[17,18] Improvements over the original Orinda Study included determining contour

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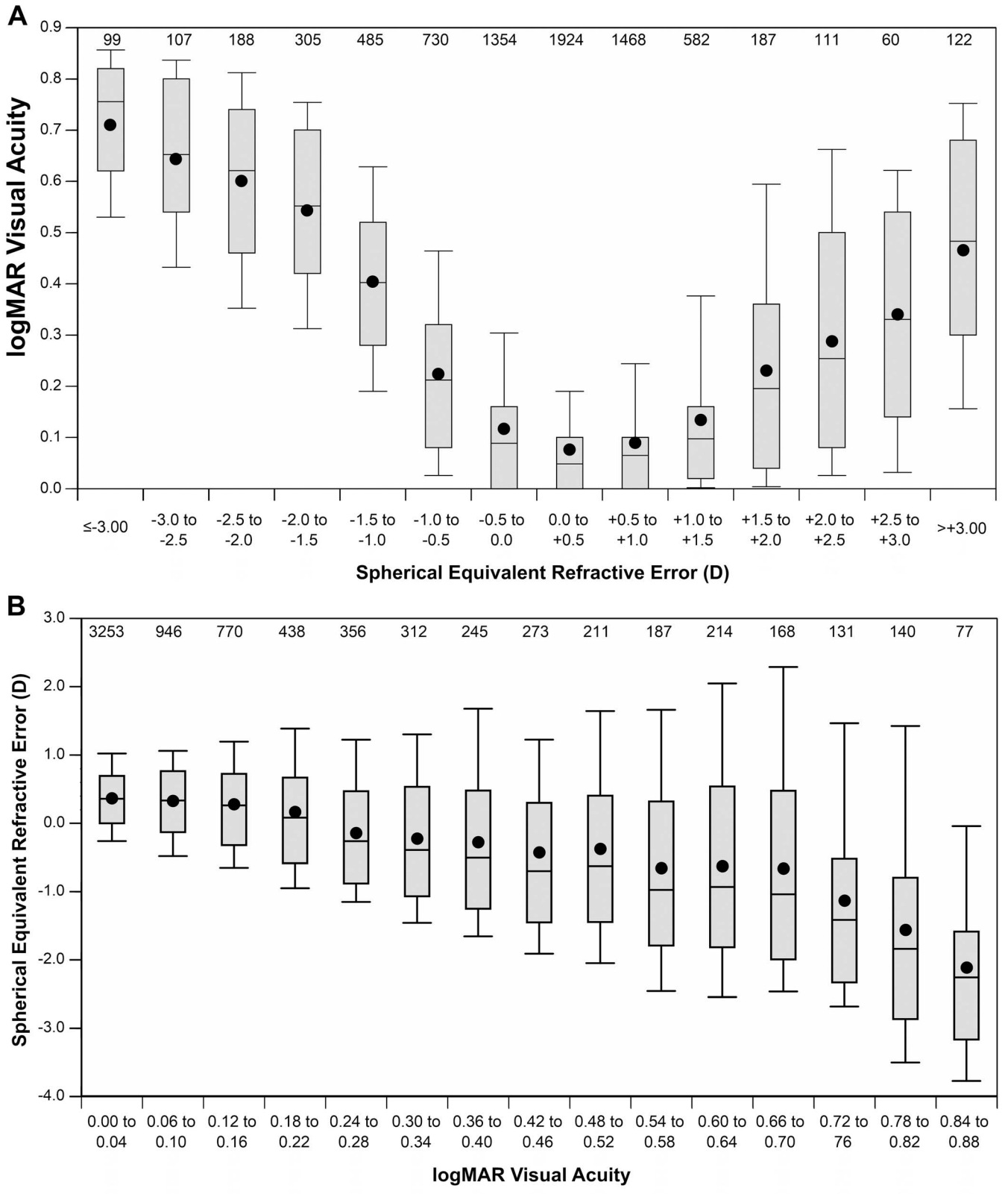

FIGURE 2. (A) Box and whisker plots of the 10th, 25th, 50th, 75th, and 90th percentiles for distance visual acuity as a function of refractive error. (B) Box and whisker plots of the 10th, 25th, 50th, 75th, and 90th percentiles for refractive error as a function of distance visual acuity. The number of subjects appears above each bar. The filled circle represents the mean.

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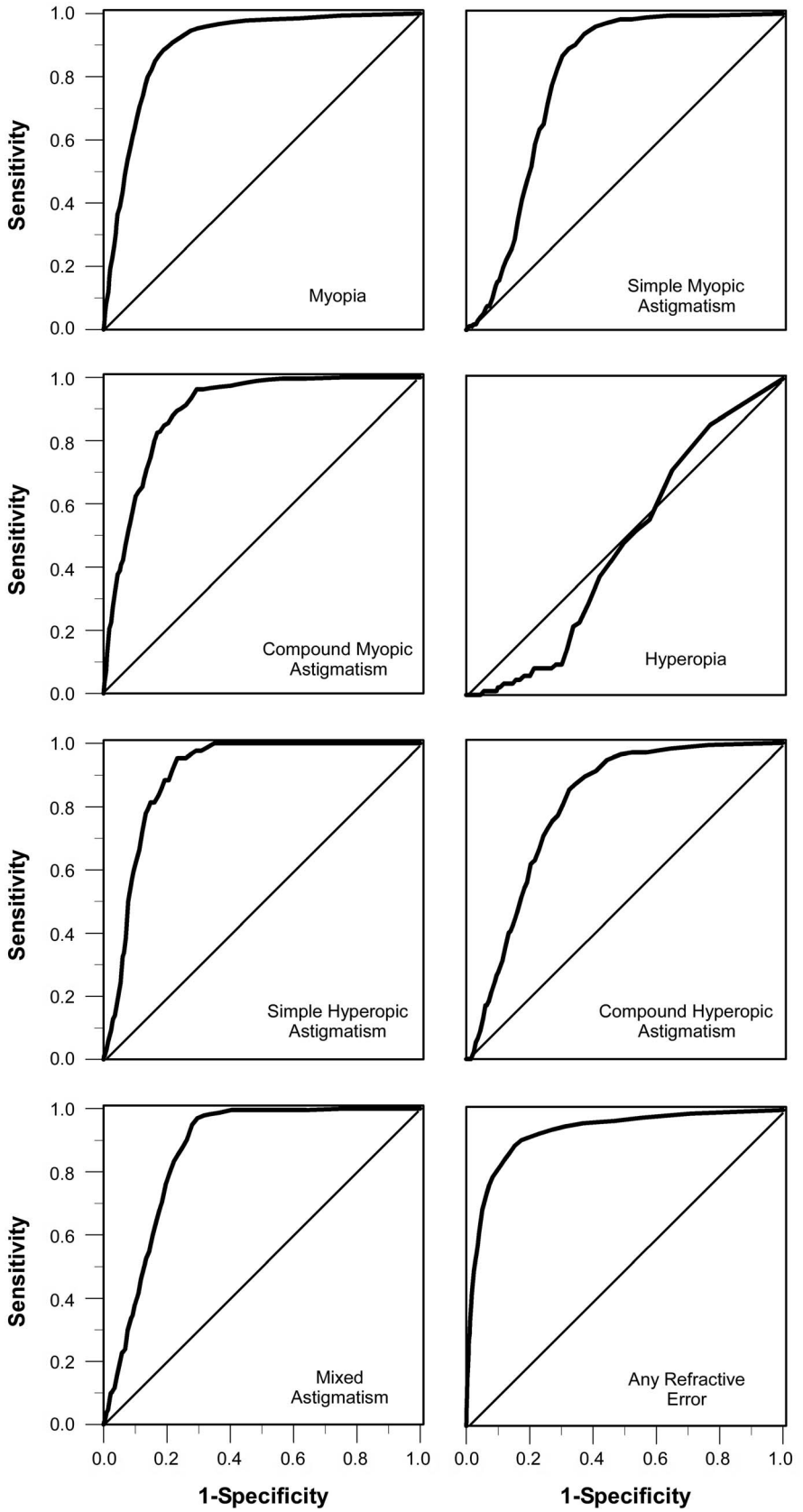

FIGURE 3. Receiver operating characteristic curves for uncorrected refractive errors: myopia, simple myopic astigmatism, compound myopic astigmatism, hyperopia, simple hyperopic automatism, compound hyperopic astigmatism, mixed astigmatism, and any clinically significant refractive error.

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TABLE 4. The optimal logMAR visual acuity criteria for detecting specific refractive error categories based on the sum of sensitivity and specificity, the corresponding Snellen equivalent acuity, sensitivity and specificity at that acuity criterion, and the area under the receiver operating characteristic curve

	LogMAR cut point	Snellen fraction cut point (20/)	Sensitivity	Specificity	Area under the curve (95% CI)
Myopia	0.30	39.9	0.88	0.81	0.90 (0.89–0.91)
Simple myopic astigmatism	0.20	31.7	0.89	0.68	0.79 (0.77–0.81)
Compound myopic astigmatism	0.22	33.2	0.96	0.71	0.90 (0.88–0.91)
Hyperopia	0.02	20.9	0.86	0.23	0.47 (0.42–0.52)
Simple hyperopic astigmatism	0.32	41.8	0.95	0.77	0.90 (0.88–0.92)
Compound hyperopic astigmatism	0.20	31.7	0.85	0.67	0.80 (0.78–0.82)
Mixed astigmatism	0.22	33.2	0.97	0.70	0.86 (0.85–0.88)
Any refractive error	0.22	33.2	0.89	0.85	0.93 (0.92–0.93)

CI = confidence interval.

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plots using statistical methods rather than by hand and using a more contemporary acuity chart, with letters of equal legibility arranged in a logarithmic progression in size and spacing, rather than a conventional Snellen chart. Fig. 4 shows the original Orinda Study isoacuity contour plot of visual acuity and spherocylindrical refractive error to facilitate comparison.[17] Comparing Figs. 1B and 4, uncorrected sphere and cylinder adversely affected distance visual acuity in a similar qualitative pattern. Acuity was worse with more myopic sphere, with isoacuity lines in an arc toward a much flatter profile for hyperopic errors, most likely because of the effects of compensating accommodation in children with uncorrected hyperopia.

There are several important differences between the two studies. The current results predict better distance visual acuity for a given level of myopic and astigmatic refractive error than what was reported in the original Orinda Study. For example, –1.00 DS translates to 20/60 in the original Orinda Study (Fig. 4) compared with 20/40 in the current data set (Fig. 1B). A refractive error of –2.00 DS signifies 20/100 in the original Orinda Study but was associated with a visual acuity of 20/80 in the current data set. A refractive error of plano –3.00 × 180 signifies 20/100 in the original Orinda Study but was associated with 20/60 in the current data set. The reasons for the differences are difficult to pinpoint, but the use of Snellen acuity in the original Orinda Study and the use of the Bailey–Lovie-Kitchin optotypes with logarithmic-sized progression of letter size in the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study may be an important factor. There were also differences when refractive error was hyperopic.

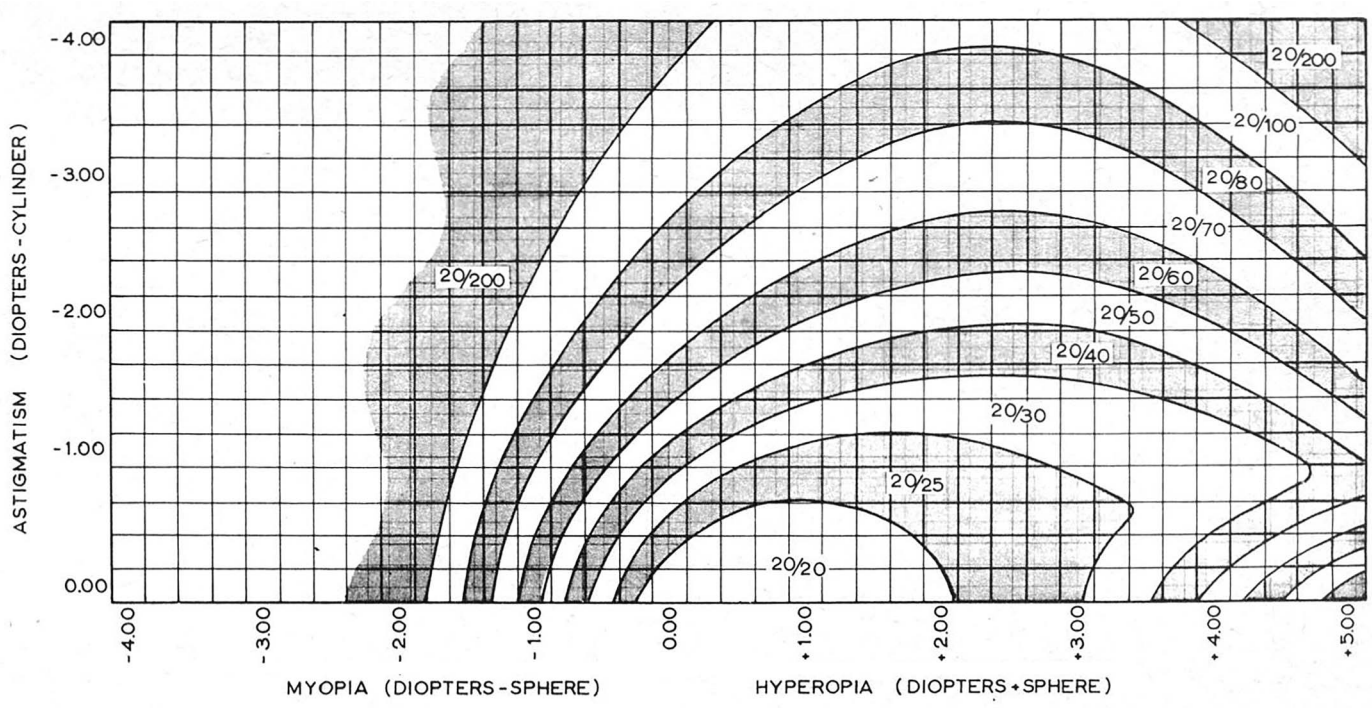

FIGURE 4. Relationship between visual acuity and refractive error in children aged 5 to 15 years. Reproduced with permission from Peters.[17]

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The isoacuity arcs corresponding to worse acuity with more minus cylinder tended to have their peak at a sphere of +1.00 D in the current study (Fig. 1B). This shape implies what most would assume that a child who is +1.00 – 2.50 × 180 would have better acuity (20/40) than a child who is +3.00 – 2.50 × 180 (20/50). In the original Orinda Study, the peaks tended to shift to the right (Fig. 4) toward more hyperopic values of sphere, suggesting the opposite to be true (20/70 and 20/60, respectively). A second difference is that the isoacuity lines in Fig. 1B for higher levels of astigmatism trended downward slowly but in a monotonic fashion, with more hyperopic values of sphere. In the original Orinda Study (Fig. 4), some of the contour lines reflect backward at sphere values greater than +3.50 D. This pattern in the original Orinda Study data implies that for a sphere of +4.50 D, for example, acuity would at first improve with increasing astigmatism up to approximately −1.00 DC and then start to worsen at higher amounts of astigmatism. The current data suggest that higher levels of astigmatism will reduce visual acuity at any given level of hyperopic sphere.

The isoacuity contours describe the average relationship between uncorrected refractive error and distance visual acuity, but they do not convey any information on variability. The lack of error bars or some other indication of variability may lead some readers to mistakenly assume that the relationship is more definitive than it actually is and misuse these results to assume that a given level of distance acuity equates to a specific refractive error and vice versa. The box and whisker plots in Fig. 2 show the range of distance visual acuity for a particular refractive error and the range of refractive error for a given visual acuity. Refractive errors estimated from distance visual acuity may differ from the actual values by several diopters. As can be seen from the isoacuity curves in Fig. 1, estimating refractive error from distance visual acuity is not likely to be valid for low myopia and for all forms of hyperopia.

Distance visual acuity seems to have little to no ability to detect significant hyperopic refractive errors in school-aged children. Sensitivity for detecting hyperopia using 0.2 or 0.3 logMAR was the lowest of any type of refractive error. For hyperopia, acuity criteria that provided adequate sensitivity were associated with unacceptably poor specificity. The receiver operating characteristic curve indicated that the ability of distance visual acuity to detect hyperopia was no better than chance alone. We chose +2.00 D in power vector length as clinically significant hyperopia, but the amount of hyperopia that warrants referral and correction is unclear, varies between eye care professionals, and warrants more specific study.[34–37]

The current results are comparable to those obtained in the Sydney Myopia Study, described by the authors as a population-based examination of 2353 Australian high school students 11 to 14 years of age.[38] Both studies used logMAR charts and cycloplegic autorefraction. Clinically significant myopia was defined as a spherical equivalent of at least −1.00 D, hyperopia as at least +2.00 D, and astigmatism as at least 1.00 D of cylinder. Sensitivity and specificity for detecting myopia in these older Australian children by visual acuity were higher than in the current study, 97.8 and 97.1% compared with 88 and 81%, respectively. Importantly, neither study found visual acuity to be useful in detecting hyperopia. There were two interesting differences between the studies. The Sydney Myopia Study found nearly normal acuities of $6/6^{-2}$ and 6/6 to be the optimal cut points for detecting any significant refractive error and astigmatism, respectively.[38] The current study values seem more reasonable at 0.22 logMAR (20/33) for any significant refractive error and between 0.20 and 0.32 logMAR (20/32 and 20/42) for the various categories of astigmatism.

This study also analyzed data from the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error Study to determine the optimal distance visual acuity criteria for detecting various categories of refractive errors in children. The criteria of logMAR 0.20 (20/32) to 0.32 (20/42) maximized the sensitivity and specificity for detecting most refractive error categories, with the exception of hyperopia, whereas logMAR 0.22 (20/33) seemed best for refractive error in general. These cut points are close to those used in many state vision screening programs as well as the consensus standard of the American Association for Pediatric Ophthalmology and Strabismus.[39]

One study limitation is that the sample was not population based; however, the sample included children from different geographic locations, was large in size, and included diverse racial/ethnic groups. Although the ethnic distribution of this study differed from that of the United States, this did not likely affect the results, as the misclassification errors by ethnic group were within ±5%. The range of refractive errors that could be represented on the isoacuity contour plots was also limited in that the smallest line corresponded to 20/20 and the largest line on the acuity chart corresponded to 20/126. The current study used a longitudinal design that may have led to some improvement in the children's ability to read the visual acuity chart in subsequent years. Familiarity with the task, however, is not the same thing as familiarity with the letters, as the examinations were 1 year apart with little to no opportunity for memorization. This study also used experienced and trained optometrists for the data collection who always encouraged the children to guess the letters on the chart. The use of less experienced personnel, different acuity charts, and different testing environments would likely increase the variability inherent in using visual acuity for screening for refractive error.

This study measured both cycloplegic refractive error and uncorrected distance visual acuity. Vision screenings that only measure noncycloplegic refractive error and then estimate uncorrected visual acuity or that use visual acuity to estimate refractive error are at high risk of making errors. As can be seen from the isoacuity curves in Fig. 1, estimating refractive error from distance visual acuity is not likely to be valid for low myopia and for all forms of hyperopia.

CONCLUSIONS

The updated isoacuity contour plots in this study depict a reliable relationship between uncorrected myopic refractive error and distance visual acuity in children. These plots may strengthen the delivery of eye care and the teaching of examination techniques and help determine the best practices for distance vision screening using visual acuity. The variability in the relationship between refractive error and visual acuity shows that specific refractive errors cannot be used to predict visual acuity. This statistical analysis with a diverse group of children using cycloplegic autorefraction provides a significant update to the classic figure produced 60 years ago by the original Orinda Study. The data from this study provide an evidence-based approach in a diverse group of children that supports the use of distance visual acuity of logMAR 0.22 or Snellen 20/33 to detect uncorrected, nonhyperopic refractive errors. It also shows that distance visual acuity alone does not equate to a specific refractive error. No criterion was found for hyperopia that was better than chance. When the presence of hyperopia is suspected, alternate procedures such as a cycloplegic refraction should be considered.

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ARTICLE INFORMATION

Submitted: March 27, 2020

Accepted: September 20, 2020

Funding/Support: National Eye Institute and the Office of Minority Research (EY08893, EY12273; to KZ); Ohio Lions Eye Research Foundation (to KZ); and E F Wildermuth Foundation (to KZ).

Conflict of Interest Disclosure: None of the authors have reported a conflict of interest (RNK, LTS, LAJ-J, SAC, JDT). DOM receives an honorarium for services on the Welch Allyn Vision Care Advisory Board. KZ is a consultant for Nevakar, LLC.

Donald F. Everett, MA, of the National Eye Institute was involved in the design and conduct of the study.

The other funding sources had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Study Registration Information: ClinicalTrials.gov Identifier: NCT00000169 (Observational Study).

Author Contributions: Conceptualization: RNK, DOM, KZ; Data Curation: LTS, LAJ-J; Formal Analysis: LTS; Funding Acquisition: RNK, SAC, REM, JDT, KZ; Investigation: RNK, DOM, SAC, REM, JDT, KZ; Methodology: RNK, DOM, KZ; Writing – Original Draft: RNK, DOM, LTS; Writing – Review & Editing: RNK, DOM, LTS, LAJ-J, SAC, REM, JDT, KZ.

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