Original Investigation

Development of a Reading Accessibility Index Using the MNREAD Acuity Chart

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IMPORTANCE We define a Reading Accessibility Index for evaluating reading in individuals with normal and low vision.

OBJECTIVE To compare the Reading Accessibility Index with data from the Impact of Cataracts on Mobility (ICOM) study.

DESIGN, SETTING, AND PARTICIPANTS This investigation was a secondary data analysis from the ICOM study performed between July 1, 2014, and September 20, 2015, at 12 eye clinics in Alabama from October 1, 1994, through March 31, 1996. Participants were 321 adults with cataract (n = 92), pseudophakia (n = 131), or natural crystalline lenses without cataract (n = 98).

MAIN OUTCOMES AND MEASURES The Reading Accessibility Index (hereafter referred to using the abbreviation ACC for the first 3 letters of *Accessibility*) is defined as an individual's mean reading speed measured across the 10 largest print sizes on the MNREAD Acuity Chart (Precision Vision) (0.4-1.3 logarithm of the minimum angle of resolution at 40 cm), normalized by 200 words per minute, which was the mean value for a group of 365 normally sighted young adults. The ACC is a single-value measure that captures an individual's range of accessible print sizes and reading fluency within this range.

RESULTS The study cohort comprised 321 participants. Their age range was 55 to 85 years, and 157 (48.9%) were female. The ACCs for the ICOM study participants ranged from 0.19 to 1.33, where 1.00 is the mean value for normally sighted young adults. The ACC for the cataract group (mean [SD], 0.65 [0.18]) was significantly lower than that for the pseudophakia group (mean [SD], 0.77 [0.16]) and the control group (mean [SD], 0.76 [0.19]) ($P < .001$ for both). The correlation between the ACC and Early Treatment Diabetic Retinopathy Study visual acuity ($r = -0.22$) and Pelli-Robson contrast sensitivity ($r = 0.20$) was weaker than that with a reading-related measure of instrumental activities of daily living ($r = -0.60$) ($P < .001$ for both).

CONCLUSIONS AND RELEVANCE The ACC represents an individual's access to text across the range of print sizes found in everyday life. Its calculation does not rely on curve fitting and provides a direct comparison with the performance of normally sighted individuals. Changes in an individual's ACC might be used to evaluate the effect of ophthalmic treatment, rehabilitation programs, or assistive technology on reading accessibility. Data from the ICOM study show that the ACC reflects characteristics of reading performance in everyday life and is sensitive to improved reading accessibility for pseudophakic eyes.

JAMA Ophthalmol. 2016;134(4):398-405. doi:10.1001/jamaophthalmol.2015.6097
Published online February 11, 2016.

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Improved outcome measures are needed to evaluate new therapies for the prevention of visual impairment. Because reading difficulty continues to be a primary concern,[1,2] there is a need for better tools to evaluate reading deficits.

The MNREAD Acuity Chart (Precision Vision) measures reading speed as a function of print size in persons with normal and low vision.[3-5] The test consists of short sentences with print size decreasing by 0.1 log unit steps from a maximum of 1.3 logMAR (equivalent to 20/400 or 6/120 when viewed at 40 cm) to −0.5 logMAR (equivalent to 20/6 or 6/2). An MNREAD Acuity Chart curve of reading speed vs print size has a typical shape for normally sighted persons and many low-vision individuals (**Figure 1**). This curve is characterized by 3 summary values. At large print sizes, reading speed remains fairly constant, forming a plateau that represents the maximum reading speed (MRS). As the print size decreases, a critical print size (CPS) is reached at which reading speed begins to decline rapidly. Finally, the smallest print size that can be read is defined as the reading acuity (RA). These 3 parameters of the MNREAD Acuity Chart curve have been used to summarize visual reading function. They have been shown to have high test-retest reliability in normally sighted persons.[6] Their repeatability is not as high for low-vision individuals,[7,8] for whom the parameters may be difficult to extract if the number of tested print sizes is truncated or if the curve does not have the typical form. In such cases, it would be useful to summarize the MNREAD Acuity Chart data in a single value, without the need for curve fitting. This summary value could be used to measure outcomes in clinical trials, to evaluate the effectiveness of reading devices or reading rehabilitation programs, and to study the effect of viewing conditions, such as light level. It could also be useful in other applications, such as a comparison with an individual's self-reported judgment of reading ability or performance on related activities of daily living, as well as the association with nonvisual variables, such as general health status or depression. In this article, we introduce a fourth MNREAD Acuity Chart parameter, a Reading Accessibility Index (hereafter referred to using the shorthand abbreviation ACC for the first 3 letters of *Accessibility*). This shorthand was chosen in lieu of RAI to distinguish it from the RA and from the Activity Inventory (AI) described by Goldstein et al.[9]

The ACC is defined as the mean reading speed in words per minute (wpm) across the 10 largest physical print sizes on the MNREAD Acuity Chart, normalized by the value for a group of normally sighted young adults (Figure 1). For a viewing distance of 40 cm, this range of print sizes corresponds to 0.4 to 1.3 logMAR.

This range of print sizes was chosen for 2 reasons. First, it sustains the MRS in normally sighted persons.[10] Second, it covers most contemporary printed text found in everyday life.[11] By using a normalizing factor estimated from normally sighted young adults, we obtained an ACC of 1.00 for normal performance. For a given individual, a value of 0.00 means that he or she could not read any of the sentences in the designated range. Values greater than 1.00 indicate persons who exceed the mean of the normally sighted young adults.

According to the standard MNREAD Acuity Chart scoring procedure, a reading speed is computed for each of the 10 print sizes using the measured reading time and the number of errors. Occasionally, some print sizes will not be tested, especially with low-vision individuals. Figure 1 shows the rules for handling missing data in the specified range of physical print sizes and for extrapolating their values for use in the calculation of the ACC.

> **Key Points**
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> **Question:** How does an individual's measure of reading across the 10 largest print sizes on the MNREAD Acuity Chart (Precision Vision), called the Reading Accessibility Index (ACC, shorthand for the first 3 letters of *Accessibility*), capture his or her access to printed material?
>
> **Findings:** Among 321 participants in the multicenter Impact of Cataracts on Mobility study, the ACC ranged from 0.19 to 1.33, where 1.00 is the mean normal value.
>
> **Meaning:** These data suggest that the ACC reflects characteristics of reading performance in everyday life and is sensitive to improved reading accessibility for pseudophakic eyes.

Demonstration of the ACC in individuals with cataract is based on data from the Impact of Cataracts on Mobility (ICOM) study.[12] In developed countries, cataract is routinely treated with surgery by removing the opaque lens and replacing it with an artificial intraocular lens (IOL). An eye with an IOL is usually referred to as pseudophakic. Extensive literature is available on the effect of IOL types on visual function[13,14] and reading.[15-17] However, only a few studies[18-21] have investigated the difference in reading performance across individuals with cataract, pseudophakia, and normal vision. Elliott et al[19,20] reported no difference in optimal reading speed measured at large print sizes for groups of cataract, pseudophakic, and control participants. They found a postsurgical improvement in reading speed measured for small print (0.4 logMAR). These results illustrate the need for a measure that takes into account both the range of legible print sizes and the reading performance within that range.

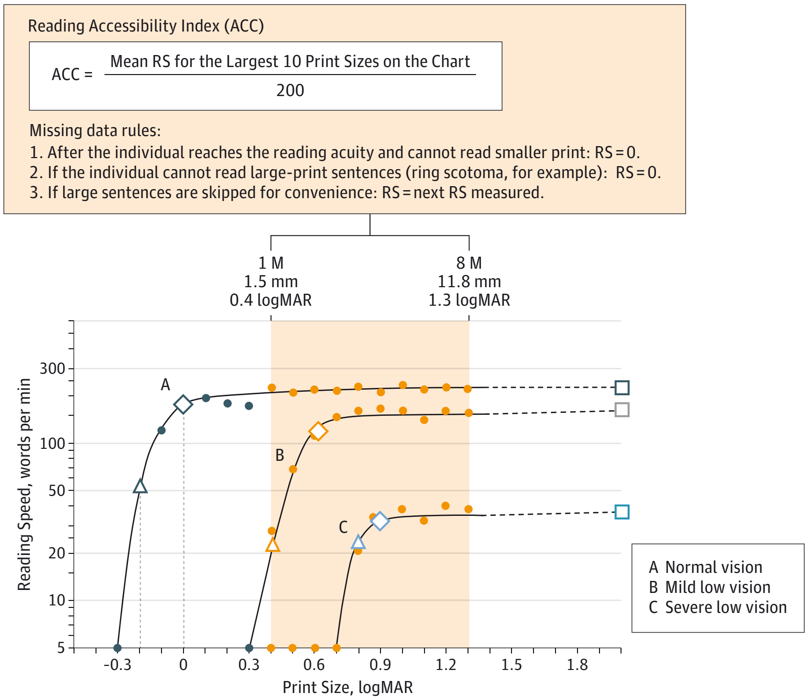
In this article, we apply the ACC measure to the MNREAD Acuity Chart data collected in older adults who participated in the ICOM study by Owsley and colleagues[12] at The University of Alabama at Birmingham. The primary objective of the ICOM study was to evaluate whether vision improvement after cataract surgery expands driving habits and improves safety.[22] The University of Alabama at Birmingham Institutional Review Board for Human Use approved the ICOM study. All participants provided written informed consent after the nature and purpose of the study were described.

Methods

Derivation of a Normalizing Factor for the ACC

The MNREAD Acuity Chart data from 365 normally sighted young adults (mean age, 22 years; age range, 18-39 years) were analyzed to derive a mean nonnormalized value for the ACC. The data were obtained from several studies at the Minnesota Laboratory for Low-Vision Research under the direction of one of us (G.E.L.). All data were obtained with written informed consent, and the investigations were approved by the Institutional Review Board at the University of Minnesota.

Figure 1. Typical MNREAD Acuity Chart (Precision Vision) Curves for Normal and Low Vision



Squares show the maximum reading speed; diamonds, the critical print size; and triangles, the reading acuity. logMAR indicates logarithm of the minimum angle of resolution; M, M-unit (1 M-unit subtends a visual angle of 5 minutes of arc at 1 m); and RS, reading speed. Print sizes included in the calculation of the Reading Accessibility Index (shorthand abbreviation ACC) are highlighted in orange. The upper box gives a full definition of the ACC.

Table. Measures Obtained for the Impact of Cataracts on Mobility Study Participants by Lens Status

Variable	Cataract Group (n = 92)	Pseudophakia Group (n = 131)	Control Group (n = 98)
Age, mean (SD), y	72 (5)	72 (7)	68 (6)
Sex, No.			
Male	60	56	48
Female	32	75	50
Clinical vision tests, including monocular measurements of both eyes for each participant			
ETDRS visual acuity, logMAR	0.27 (0.19)	0.18 (0.19)	0.06 (0.16)
Pelli-Robson contrast sensitivity, logMAR	1.35 (0.14)	1.43 (0.15)	1.51 (0.13)
MNREAD Acuity Chart (Precision Vision) measures, including monocular measurements of both eyes for each participant			
Reading Accessibility Index[a]	0.65 (0.18)	0.77 (0.16)	0.76 (0.19)
Maximum reading speed, words per minute	146 (26)	158 (24)	153 (24)
Critical print size, logMAR	0.62 (0.25)	0.46 (0.24)	0.35 (0.16)
Reading acuity, logMAR	0.24 (0.16)	0.12 (0.14)	0.04 (0.11)
Reading-related daily visual function, including binocular measurement for each participant			
TIADL-R measure	0.44 (1.06)	−0.12 (0.55)	−0.22 (0.50)

Abbreviations: ETDRS, Early Treatment Diabetic Retinopathy Study; TIADL-R, reading-related timed instrumental activities of daily living.

[a] Shorthand abbreviation ACC.

All individuals had normal or corrected-to-normal distance visual acuity (mean [SD], −0.12 [0.08] logMAR) and no history of reading, visual, or cognitive impairment. Participants were native or fluent English speakers. All data were collected with the standard MNREAD Acuity Chart testing procedure. Reading speed (in words per minute) was computed for each sentence by multiplying 10 minus the number of errors times 60, divided by the reading time.

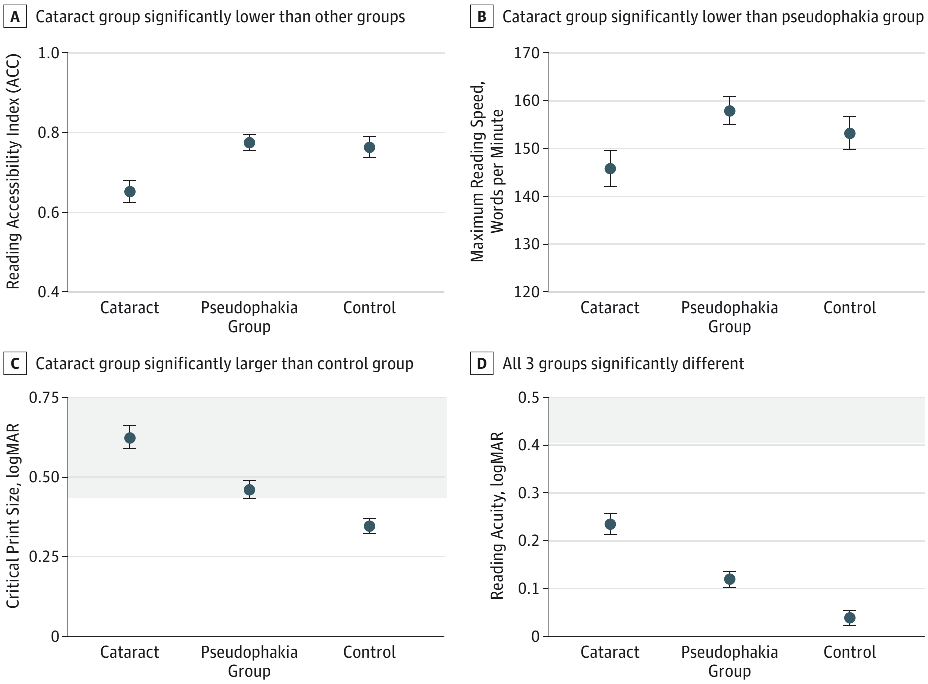
For each individual, a nonnormalized value of reading accessibility was calculated by averaging the 10 values of reading speed across the print size range of 1.3 to 0.4 logMAR. The mean (SD) value across the entire sample was 200.70 (29.06) wpm. A value of 200 was used as a normalizing factor for the calculation of the ACC.

Data From the ICOM Study

Participants

A secondary analysis performed between July 1, 2014, and September 20, 2015, and approved by The University of Alabama at Birmingham Institutional Review Board was conducted on measurements previously collected in the ICOM study from October 1, 1994, through March 31, 1996. Only participants for whom we had MNREAD Acuity Chart data for at least 4 different print sizes in both eyes were included. Data from 336 participants were divided into 3 groups depending on lens status. For reasons discussed in the MNREAD Acuity Chart Data Fitting subsection, data from only 321 participants (age range, 55-85 years) were maintained in the analysis (**Table**).

Figure 2. Mean Values for the MNREAD Acuity Chart (Precision Vision) Parameters by Lens Status



Bars shows group values with 95% CIs. The print size range included in the calculation of the Reading Accessibility Index (shorthand abbreviation ACC) is highlighted in gray.

Participants in the cataract group (n = 92) were diagnosed as having cataract in both eyes[23] with a best-corrected distance acuity of 20/40 or worse. Individuals in the pseudophakia group (n = 131) had cataract surgery in both eyes. Persons in the control group had natural crystalline lenses without clinically significant cataract in both eyes (n = 98) and had no identifiable eye disease and no previous cataract surgery and demonstrated a best-corrected distance acuity in each eye of 20/25 or better.[22] All MNREAD Acuity Chart tests were administered with the participants wearing their typical near-viewing lens correction prescribed within 6 months of enrollment. Inclusion criteria were monocular measures of distance visual acuity (using the Early Treatment Diabetic Retinopathy Study [ETDRS] letter chart[24]) and contrast sensitivity (using the Pelli-Robson contrast sensitivity chart[25]).

Measures of Performance in Daily Visual Tasks

Performance was measured for timed instrumental activities of daily living (TIADL) tasks.[26] Five of the 17 tasks that were most directly related to reading were included in the present analysis. These tasks were reading ingredients on a can of food, reading directions on a prescription medicine bottle, finding a name and number in a telephone book, reading a newspaper article, and dialing a number on a touch-tone telephone. For each individual, an overall *z* score was calculated.[27] This reading-related TIADL measure is referred to as the TIADL-R, for which a large value represents poor reading performance.

Measures of Reading

The MNREAD Acuity Chart was used to measure monocular reading performance. Participants were tested one eye at a time at 40 cm on the regular black-on-white version of the chart. All tests were administered in the same windowless room with constant illumination. For convenience, all individuals were tested starting at 1.0 logMAR. Reading speed was measured as a function of the print size and corrected for the number of errors.

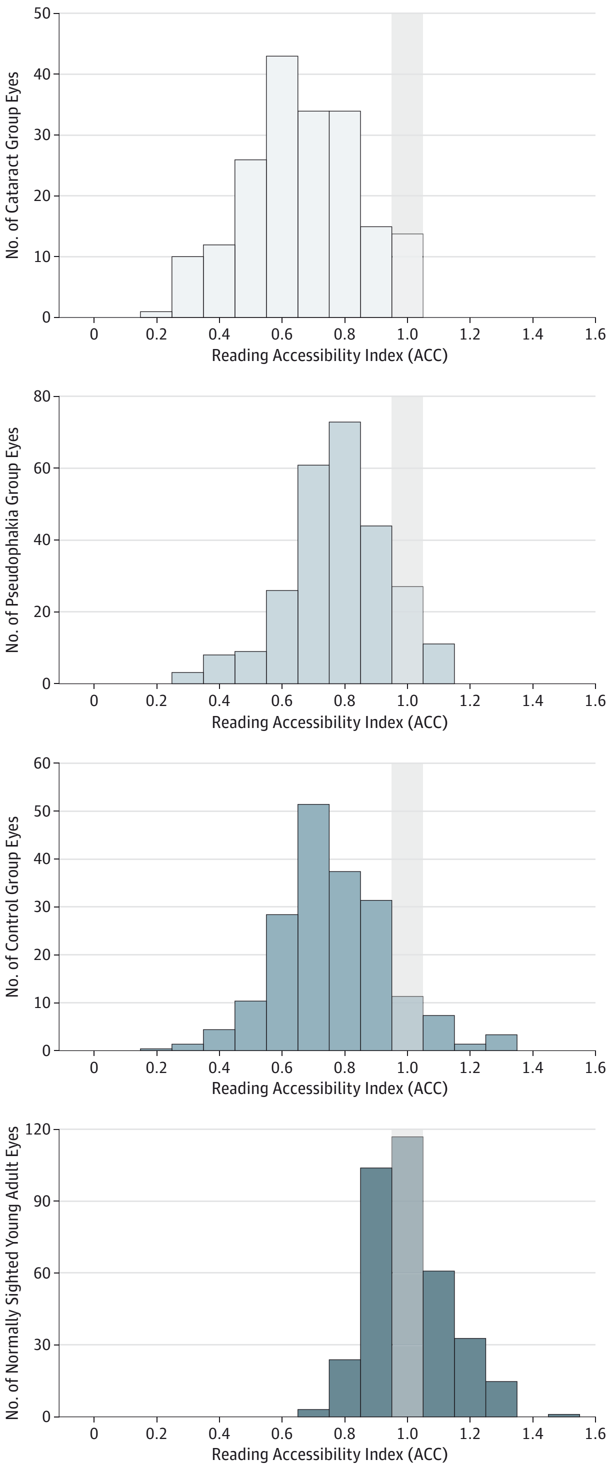
Reading Accessibility Index (ACC)

The ACC was calculated for each eye using the formula in Figure 1. For the 3 largest print sizes, which were not tested, reading speed was set to the value for the largest print size tested (1.0 logMAR) according to the rules for missing data in Figure 1.

MNREAD Acuity Chart Data Fitting

To extract the other reading parameters, the MNREAD Acuity Chart curves (log reading speed in words per minute vs logMAR print size) were fitted with an exponential decay function using a nonlinear mixed-effects model.[28] For each individual, we estimated separate curves for each eye. Values of the exponential decay function estimates were modeled by a nonlinear mixed-effects model to the data sets of all 336 participants simultaneously. Effects of lens status (cataract, pseudophakia, and control) on the 3 MNRead Acuity Chart parameters were modeled as fixed effects. Variations across individuals and between the 2 eyes were modeled as random effects with eye nested within individual. The 3 parameters were extracted as follows: (1) MRS (in words per minute) was obtained from the nonlinear mixed-effects model estimation, (2) CPS (in logMAR) was defined as the smallest print size that yielded 90% of the MRS, and (3) RA (in logMAR) was calculated by adding 0.01 logMAR to the smallest tested print size for each error made in the test. For each eye, the MRS and CPS

Figure 3. Distribution of the Reading Accessibility Index (Shorthand Abbreviation ACC) by Lens Status



For the purpose of age comparison, the distribution for a group of normally sighted young adults is given.

were used in a multivariate outlier detection procedure.[29] Fifteen participants had one or both eyes identified as outliers and were excluded from the study. The subsequent analysis included data from the remaining 321 individuals.

Statistical Analysis

We investigated the effect of lens status on each of the 4 MNREAD Acuity Chart parameters (ACC, MRS, CPS, and RA). Linear mixed-effects models were used to compare the 3 groups of participants using data from each eye of each participant. Four models (one for each MNREAD Acuity Chart parameter) were created with lens status set as a fixed effect. Participants and eyes were modeled as random effects with eyes nested within individuals. In the Results section, the reported findings are from the linear mixed-effects models unless otherwise specified. We report the mean values estimated by the models for each group. Pairwise differences between the groups and their *P* values (95% CIs) were adjusted for multiple comparisons using the Tukey test.

Pearson product moment correlation coefficients were calculated for the association between the ACC and measures of visual function, including a reading-related measure of instrumental activities of daily living in the better eye of each participant. That eye was chosen as the one with the better visual acuity. When both eyes had the same ETDRS score, the better eye was chosen as the one with greater contrast sensitivity.

Results

Effect of Lens Status on the 4 MNREAD Acuity Chart Parameters

The Table lists the group mean (SD) values for demographic, clinical vision test, and reading variables. Values are given by lens status.

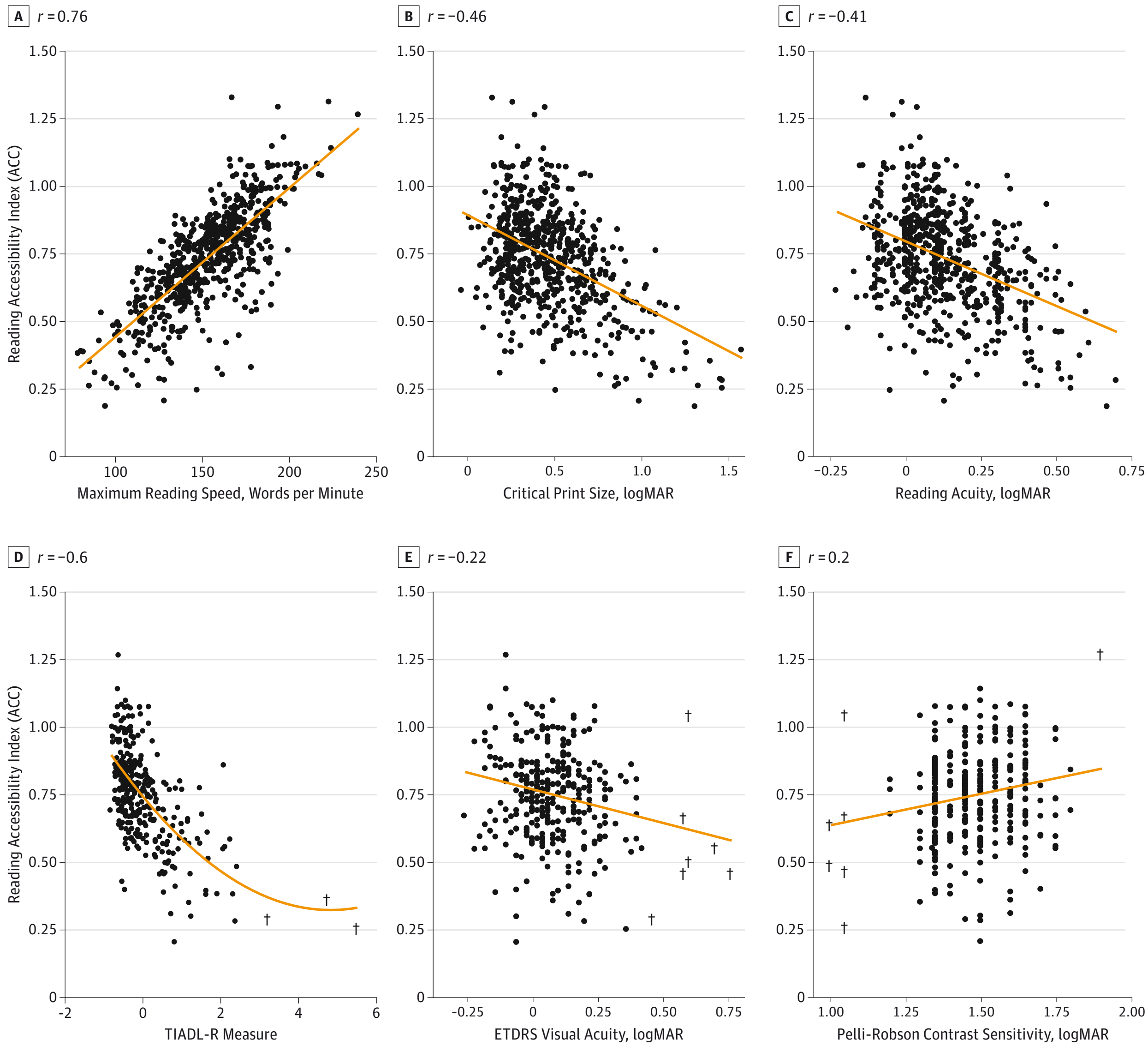
The ACCs ranged from 0.19 to 1.33. A value of 0.00 indicates no reading within the accessible range, and 1.00 is the mean value for normally sighted young adults. The ACC for the cataract group (mean, 0.65) was significantly lower than that for the control group (mean, 0.76) by 0.11 (95% CI, 0.06-0.15; $P < .001$) and the pseudophakia group (mean, 0.77) by 0.12 (95% CI, 0.08-0.16; $P < .001$) (**Figure 2**A).

The group mean values for the MRS were 146 wpm for the cataract group, 158 wpm for the pseudophakia group, and 153 wpm for the control group (Figure 2B). The MRS for the cataract group was significantly lower than that for the pseudophakia group by 12 wpm (95% CI, 6-19 wpm; $P < .001$). No significant difference was found between the pseudophakia and control groups or between the cataract and control groups.

The CPS for the cataract group (0.62 logMAR) was significantly larger than that for the control group (0.35 logMAR) by 0.27 logMAR (95% CI, 0.22-0.33 logMAR; $P < .001$) (Figure 2C). The CPS for the cataract group (0.62 logMAR) lies within the range of print sizes included in the calculation of the ACC (0.4-1.3 logMAR, highlighted in gray in Figure 2C), whereas the CPS for the control group (0.35 logMAR) is outside of this range.

The RA differed significantly across all 3 groups ($P < .001$). Figure 2D shows that all 3 mean values were less than 0.4 logMAR. Therefore, they fell outside of the print size range included in the calculation of the ACC.

Figure 4. Correlations Between the Reading Accessibility Index (Shorthand Abbreviation ACC) and Visual Measures



Distributions are fitted by linear regressions of the form *y* as a function of *x* (A, B, C, E, and F) and *y* as a function of $x + x^2$ (D). Pearson product moment correlation coefficients are given, and extreme data points are shown as crosses. ETDRS indicates Early Treatment Diabetic Retinopathy Study; logMAR, logarithm of the minimum angle of resolution; and TIADL-R, reading-related timed instrumental activities of daily living.

The mean (SD) ACC for the control group was 0.76 (0.19). That is 24% less than the value of 1.00 that represents the reading accessibility of our group of normally sighted young adults (**Figure 3**).

Correlation Between the ACC and Measures of Vision

The ACC was significantly correlated with the MRS ($r = 0.76$, $P < .001$), CPS ($r = -0.46$, $P < .001$), and RA ($r = -0.41$, $P < .001$) (**Figure 4**). The ACC was also significantly correlated with the TIADL-R measure ($r = -0.60$, $P < .001$).

The correlation between the ACC and ETDRS visual acuity ($r = -0.22$, $P < .001$) and Pelli-Robson contrast sensitivity ($r = 0.20$, $P < .001$) was low. Inspection of extreme values revealed no influence on the correlation results.

Discussion

Because a person's reading access depends on both the range of print sizes that can be recognized visually and the reading speeds for those print sizes, we defined a composite variable, the ACC. For some readers with mild low vision (Figure 1), the MRS will be close to the normal value, but reading accessibility will be reduced because of a restricted range of accessible print. A person with more severe low vision will have reduced reading accessibility because of both a restricted range of print sizes and reduced reading fluency. This situation is often encountered in age-related macular degeneration.[30] Access to small print can often be addressed with suitable magnification.[31] However, the motor demands of operating an optical or electronic magnifier can sometimes reduce reading speed.[32] The combined effects on reading performance could be assessed by measuring the ACC with and without the magnifier.

A strength of the ACC is that it can be assessed from the MNREAD Acuity Chart data without the need for curve fitting or parameter estimation. Its calculation remains simple, even when only a few sentences can be read and the data are not well fit by a standard curve, which often happens with severe low vision.

It is important to remember that the ACC is defined in terms of physical print sizes rather than angular (logMAR) print sizes. Because angular print size is based on a viewing distance, it is likely that an individual's ACC will depend on the viewing distance. For example, a person with low vision is likely to have a higher ACC for a shorter viewing distance. A higher ACC indicates that the individual has greater functional access to the important range of physical print sizes at the nearer distance.

Our definition of the ACC differs from the widely used concept of reading ability.[33] The latter is a latent trait measure representing the intrinsic visual reading ability of an individual and is derived from visual function questionnaires using Raasch analysis.[9,34] So defined, a person's reading ability is an individual characteristic independent of the text properties or viewing conditions. By comparison, our concept of reading accessibility is intended to quantify the capability of a person to read across an ecologically valid range of print sizes given the viewing conditions at hand, including the use of magnifiers or other assistive technology. In general, we would expect the ACC to depend on both a person's reading ability and the environmental conditions in which reading is performed.

The mean ACC of 0.76 for the normally sighted controls in the ICOM study data set is notably below the value of 1.00 for our group of normally sighted young adults. This difference might be related to age. In the ICOM study, the mean age was 68 years for the control group compared with 22 years for our group of normally sighted young adults. Another possible difference is the educational level. However, this variable does not appear to be a major factor. After screening the ICOM study participants to match the educational level (high school completion) of our normally sighted young adults, the ACC for the older control group was still significantly lower.

The ACC for the cataract group was significantly lower than that for the control group, indicating reduced reading accessibility. Consistent with previous findings,[35] the MRS of the 2 groups did not differ. However, the CPS for the cataract group was significantly larger than that for the control group. The ACC combines these 2 potential sources of reading difficulty into a single measure.

Conclusions

Overall, the ACC was found to be a better predictor of the TIADL-R measure ($r = -0.60$) than ETDRS visual acuity ($r = 0.24$, $P < .001$) or Pelli-Robson contrast sensitivity ($r = -0.27$, $P < .001$). This result suggests that the ACC reflects reading performance in everyday life. However, the conclusion is limited by the small spectrum of visual impairment tested in this study. Further investigation in a low-vision population with more severely reduced visual acuity and contrast sensitivity would be beneficial to confirm this conclusion.

Measuring the standard 3 MNREAD Acuity Chart parameters in low-vision individuals is useful because each can give informative insight on reading performance. In this article, we introduce an additional MNREAD Acuity Chart parameter, the Reading Accessibility Index (ACC). This single-value measure of reading performance allows a direct comparison with other visual measures. Future research is needed to measure its test-retest reliability in patients with low vision as well as its sensitivity in detecting changes in visual function.

ARTICLE INFORMATION

Submitted for Publication: August 31, 2015; final revision received November 3, 2015; accepted December 2, 2015.

Published Online: February 11, 2016. doi:10.1001/jamaophthalmol.2015.6097.

Author Contributions: Dr Calabrèse had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.
Study concept and design: Calabrèse, Owsley, Legge.
Acquisition, analysis, or interpretation of data: All authors.
Drafting of the manuscript: All authors.
Critical revision of the manuscript for important intellectual content: Calabrèse, McGwin, Legge.
Statistical analysis: All authors.
Obtained funding: Owsley, Legge.
Administrative, technical, or material support: Owsley.
Study supervision: Legge.

Conflict of Interest Disclosures: All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest. Dr Calabrèse reported receiving grants from the National Eye Institute to support the analysis and interpretation of the data and the preparation and review of the manuscript. Dr Owsley reported receiving grants from the National Institute on Aging, EyeSight Foundation of Alabama, Research to Prevent Blindness, and National Eye Institute to support the design and conduct of the study. Dr McGwin reported receiving grants from the National Institute on Aging, EyeSight Foundation of Alabama, Research to Prevent Blindness, and National Eye Institute to support the collection, management, and analysis of the data and reported receiving personal fees from Lupus Clinical Trials Consortium, Tesla Motors, The Henry M. Jackson Foundation for the Advancement of Military Medicine, and an additional confidential source outside of the present work. Dr Legge reported receiving grants from the National Eye Institute during the conduct of the study, reported being one of the developers of the MNREAD Acuity Chart (Precision Vision), and reported receiving royalties for sales of the MNREAD Acuity Chart through a licensing agreement between the University of Minnesota and Precision Vision outside of the present work.

Funding/Support: The design and conduct of the study and the collection, management, analysis, and interpretation of the data were supported by grants EY002934NIH, P50AG11684, P30AG22838, R21EY14071, and R21EY16801 from the National Institutes of Health, by the EyeSight Foundation of Alabama, and by Research to Prevent Blindness.

Role of the Funder/Sponsor: The preparation and review of the manuscript and the decision to submit the manuscript for publication were supported by grant EY002934NIH from the National Institutes of Health.

Additional Contributions: Yihan Yang, MS (School of Statistics, University of Minnesota), and Yangfan Qin, MS (School of Statistics and School of Engineering, University of Minnesota), assisted with implementing the MNREAD Acuity Chart (Precision Vision) data fitting in R (R Foundation). Allen Cheong, PhD (School of Optometry, The Hong Kong Polytechnic University), discussed and analyzed measures of reading ability. No compensation was provided.

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