

Reading Acuity as a Predictor of Low-Vision Reading Performance

Ying-Zi Xiong,¹ Aurélie Calabrèse,^{1,2} Allen M. Y. Cheong,^{1,3} and Gordon E. Legge¹

¹Department of Psychology, University of Minnesota, Minneapolis, Minnesota, United States

²Laboratoire de Psychologie Cognitive, Aix-Marseille University, Marseille, France

³School of Optometry, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China

Correspondence: Ying-Zi Xiong, Department of Psychology, University of Minnesota, No. 79 East River Road S219, Minneapolis 55455, MN, USA; yingzi@umn.edu.

Submitted: May 3, 2018

Accepted: August 30, 2018

Citation: Xiong YZ, Calabrèse A, Cheong AMY, Legge GE. Reading acuity as a predictor of low-vision reading performance. *Invest Ophthalmol Vis Sci.* 2018;59:4798–4803. <https://doi.org/10.1167/iovs.18-24716>

PURPOSE. Most people with low vision experience difficulty with reading. Reading assessment can provide guidance for prescription of reading aids and strategies for reading rehabilitation. Here we investigate the effectiveness of letter acuity (LA) and reading acuity (RA) as predictors of low-vision reading performance.

METHODS. Low-vision subjects ($n = 58$), young control subjects ($n = 52$), and older control subjects ($n = 14$) participated in this study. The low-vision subjects were separated into a Macular group ($n = 30$) and a Nonmacular group ($n = 28$) based on whether the diagnoses primarily affected the macular area. LA was measured with the Lighthouse Distance Visual Acuity Chart and RA with the MNREAD Acuity Chart. Reading speeds were obtained across a range of print sizes from the MNREAD test. The MNREAD data were used to estimate required print sizes for three functionally important types of reading for each subject: spot reading (40 words/min [wpm]), fluent reading (80 wpm), and critical print size (required to achieve maximum reading speed).

RESULTS. For equal values of LA, the Macular group had significantly worse RA than the Nonmacular group. The differences between vision groups, as well as individual variations within groups, were largely explained by the differences in RA. RA is a better predictor than LA for spot reading size, fluent reading size, and critical print size.

CONCLUSIONS. RA may provide more accurate assessment of reading performance than LA for purposes of low-vision reading rehabilitation.

Keywords: low vision, reading, reading acuity, letter acuity

Difficulty in reading is a common reason for low-vision individuals to seek rehabilitation services.^{1,2} Reading is typically accomplished with high-acuity central vision and thus becomes especially difficult for individuals with central vision loss.^{3–5} Reading assessment can provide guidance for prescription of reading aids.^{6–8} Detailed reading assessment can be achieved with specialized reading tests.⁹ Typically, these tests require reading of multiple passages, often across a range of print sizes, with documentation of reading accuracy, reading time, reading errors, or reading comprehension. When detailed assessment is not practical, it would be useful to use simpler clinical measures to predict reading performance. Here we focus on two easy-to-obtain clinical measures: letter acuity (LA) and reading acuity (RA).

LA is the threshold print size for single letter recognition. With modern logMAR charts, it is measured as the smallest print size for which letters can be recognized, corrected for the number of errors made throughout the test. Because letters are the basic units of reading, we would expect LA to impose a bottleneck on reading ability.¹⁰ RA is the threshold print size for word recognition. RA can usually be obtained with standard clinical reading tests.^{9,11} By analogy to LA, RA is scored as the smallest size of printed text attempted, corrected for the number of misread words.

Some reading tests are composed of continuous text, which require a dynamic process of reading (e.g., MNREAD Charts¹²

and RADNER Reading Charts¹³), whereas others use unrelated words avoiding semantic and syntactic context (e.g., Bailey-Lovie Word Reading Chart¹⁴ and SKread Test¹⁵). Here we focus on RA measured by continuous text, which is more representative of real-world reading.

Although RA and LA differ in various aspects,¹⁰ they have been found to be highly correlated.^{5,16} RA has been reported to be better than LA (smaller logMAR values) in normal vision,¹⁷ with dioptric blur¹⁸ and in low-vision with intact central vision.¹⁹ However, for low vision with central vision loss due to macular deficit, there is evidence that RA is similar or even worse than LA, both when RA was measured by charts with continuous text^{16,19} and charts with unrelated words.^{6,20} These differences raised the possibility that RA provides a better indicator of the impact of central vision status on reading.

Although LA and RA determine the smallest print for letter and word recognition, larger print sizes are needed to achieve “spot reading” (40 wpm) for short text such as price labels, “fluent reading” (80 wpm) for long text such as newspapers, and maximum reading speed, which varies across individuals.²¹

The print size for maximum reading speed is termed “critical print size.”^{12,14} It is an important reading index and has been extensively studied. RA has been found to be better than LA as a predictor for critical print size in low-vision reading.⁵ However, whether this advantage of RA holds for spot



reading and fluent reading is unknown. Moreover, it remains unclear whether this advantage of RA over LA is dependent on central vision status.

The current study aimed at evaluating the significance of RA assessment by answering three questions. (1) Do RA and LA show different relationships for people with macular-related diagnoses versus other diagnoses? (2) Is RA a better predictor than LA for spot reading size and fluent reading size? (3) Does an advantage of RA in predicting reading performance hold for both patients with macular-related diagnoses and other diagnoses?

METHODS

Subjects

The data from 124 subjects were assembled from four studies conducted at the Minnesota Laboratory for Low-vision Research directed by Gordon E. Legge, including two published studies^{22,23} and two unpublished studies (unpublished data, 2016, 2017). All subjects were native English speakers with no known nonvisual reading disabilities.

The low-vision subjects ($n = 58$; 64.8 ± 18 years) were recruited from our laboratory's roster of low-vision participants and from Vision Loss Resources (Minneapolis, MN, USA). Subjects were separated into two groups based on whether their diagnoses primarily affected the macular area. The Macular group consisted of 30 subjects with the main diagnosis being macular degeneration ($n = 28$), plus two subjects diagnosed with macular hole and choroidal sclerosis. The Nonmacular group was more heterogeneous with main diagnoses, being retinitis pigmentosa ($n = 8$) and optic neuropathy ($n = 8$) (see Supplementary Figs. S1 and S2 for individual diagnoses). Fifty-two subjects were normally sighted young adults (21.2 ± 3.1 years) recruited from the University of Minnesota (young control group). Fourteen older adults (68.3 ± 5.6 years) were recruited from the Retirees Volunteer Center at the University of Minnesota (old control group).

All subjects were tested with their most up-to-date reading glasses, if any. This study was approved by the University of Minnesota Institutional Review Board and followed the Declaration of Helsinki. Consent forms were acquired from all subjects prior to their participation.

Procedure

LA was measured binocularly with a Lighthouse Distance Visual Acuity Chart²⁴ at the viewing distance of 1 m using the standard test protocol. LA was scored on a letter-by-letter basis with the following formula: LA = smallest print size attempted (logMAR) + (total letter errors \times 0.02).

RA was measured binocularly using the MNREAD test following the standard test protocol.¹² Viewing distance was 40 cm, with the exception that some low-vision subjects were tested at shorter viewing distances so that they could read at least four sentences on the chart. The logMAR print sizes were corrected for viewing distance. RA was calculated with the following formula: RA = smallest print size attempted + (total word errors \times 0.01). Note that this scoring rule for RA was initially determined by the chart designers to be consistent with the scoring of LA with letter charts.¹²

Data Analysis

Analyses in the current study mainly focused on the two low-vision groups. Data from the two control groups were included in some of the analyses for comparisons.

TABLE 1. LA and RA (Mean and SD) of the Four Vision Groups: Young Control, Old Control, Nonmacular and Macular

Groups	Letter Acuity Mean \pm SD (logMAR)	Reading Acuity Mean \pm SD (logMAR)
Young control ($n = 52$)	-0.07 ± 0.09	-0.15 ± 0.07
Old control ($n = 14$)	0.05 ± 0.07	-0.04 ± 0.12
Nonmacular ($n = 28$)	0.82 ± 0.40	0.71 ± 0.41
Macular ($n = 30$)	0.64 ± 0.31	0.73 ± 0.43

Group Reading Curves. Group reading curves were estimated for the two low-vision groups (Nonmacular and Macular). For each of these groups, subjects' data were pooled together, and an average group reading curve was obtained by a local weighting least-squares method (loess).²⁵ The local weighting was performed based on 75% of neighborhood data. R^2 was calculated to represent how much variance within-group data was explained by the group average. Such analysis helps determine how accurately a group summary represents the behavior of individuals within the group.

Individual Reading Curves. Individual reading data (reading speed versus print size) were fitted with a nonlinear mixed-effects (NLME) model using the "mnreadR" package in R.²⁶ Specifically, reading curves were fitted with an exponential function, and variations between subjects were modeled as random effects.²⁷ Three threshold print sizes were then derived from each fitted curve (see Supplementary Figs. S1 and S2 for individual reading curves).

- Spot reading size: estimated as the print size that allowed a reading speed of 40 wpm (1.60 log wpm). One subject from the Macular group was not able to reach a reading speed of 40 wpm and was excluded from analysis of spot reading size.
- Fluent reading size: estimated as the print size that allowed a reading speed of 80 wpm (1.90 log wpm). Five subjects from the Macular group and seven subjects from the Nonmacular group were not able to reach a reading speed of 80 wpm and were excluded from analysis of fluent reading size.
- Critical print size: maximum reading speed was obtained as the plateau of the fitted curve, and critical print size was estimated as the print size yielding a reading speed of 90% of the maximum reading speed. All subjects' data were included.

RESULTS

Comparing LA and RA

Group averages and SDs of LA and RA in the four vision groups are listed in Table 1. The mean difference scores (LA – RA) are shown in Figure 1A; a corresponding scatterplot with individual data for the Macular and Nonmacular groups is shown in Figure 1B.

For the young control and old control groups, LA was significantly worse (larger logMAR values) than RA by an average of 0.08 logMAR ($P < 0.001$, 95% confidence interval [CI] = 0.06, 0.11) and 0.09 logMAR ($P = 0.003$, 95% CI = 0.04, 0.14), respectively. For the Nonmacular group, LA was also significantly worse than RA, with a mean difference of 0.11 logMAR ($P = 0.001$, 95% CI = 0.05, 0.17). However, for the Macular group, LA was significantly smaller than RA by an average of 0.09 logMAR ($P = 0.017$, 95% CI = -0.17 , -0.02).

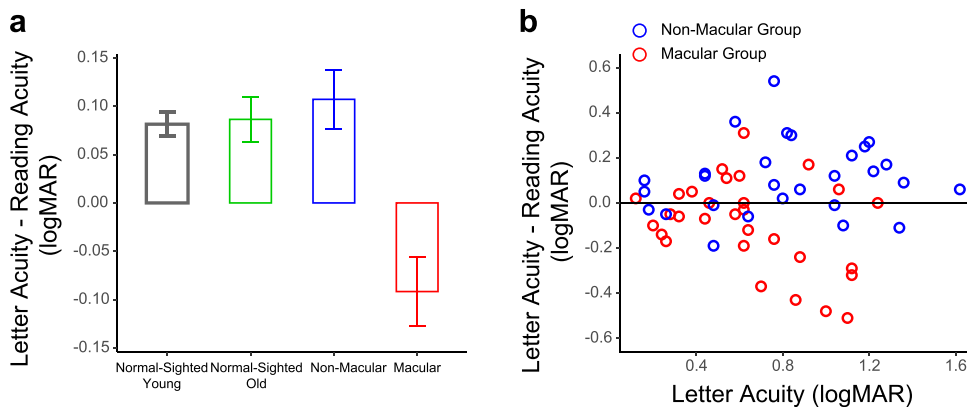


FIGURE 1. Difference between LA and RA. (a) Mean LA – RA difference in four groups: young control (gray), old control (green), Nonmacular (blue), and Macular (red). (b) Scatterplot of the LA – RA difference in the Nonmacular (blue) and Macular (red) groups.

To ensure that the difference between the two low-vision groups was not due to an overall difference in the range of acuities, ANCOVA analysis was performed on RA with group as the variate and LA as the covariate. The main effect of group was significant ($F_{(1,54)} = 19.61, P < 0.001$), indicating that the difference between RA in the two groups was not due to the overall difference in acuity range. Moreover, the difference between RA in the two groups was larger when LA was poorer (larger logMAR values), as shown by the significant interaction between group and LA ($F_{(1,54)} = 4.88, P = 0.031$).

Using LA and RA to Account for Reading Performance Differences

Reading speeds at original logMAR print sizes are plotted in a scatter plot for the two low-vision groups (Fig. 2A). Both groups showed wide distributions of data. Average group reading curves (see Methods) had inverted-U shapes instead of the typical reading curve shape. The reading curve in the Nonmacular group lay above the Macular group. Group average explained only 5.7% of the total variance in the Nonmacular group and 4.0% in the Macular group.

Next, we investigated whether the within-group variations and between-group differences could be accounted for by differences in LA. Original logMAR print sizes were adjusted by subtracting individual LA, and reading speeds were plotted against the adjusted print sizes (Fig. 2B). The adjusted print sizes represent the logMAR difference between the tested print size and the subject’s LA. Again, average group reading curves were obtained. The new average reading curves showed typical reading curve shapes, but the group difference persisted. The group average explained 31.9% and 24.6% of the total variance in the Nonmacular and Macular groups, respectively. This means that adjusting print size for LA resulted in greater convergence of reading speeds across subjects for both groups.

A similar analysis was then performed by adjusting the original print sizes by subtracting individual values of RA (Fig. 2C). With this normalization, the difference between the two groups almost disappeared. The group average explained 64.0% and 61.7% of the total variance in the Nonmacular and Macular groups, respectively, showing considerably reduced within-group divergence.

Taken together, the plots in Figure 2 demonstrate that group and individual differences in low-vision reading performance are greatly reduced when RA is taken into account. Adjusting (normalizing) by RA leads to greater uniformity across subjects and between low-vision groups than adjusting by LA.

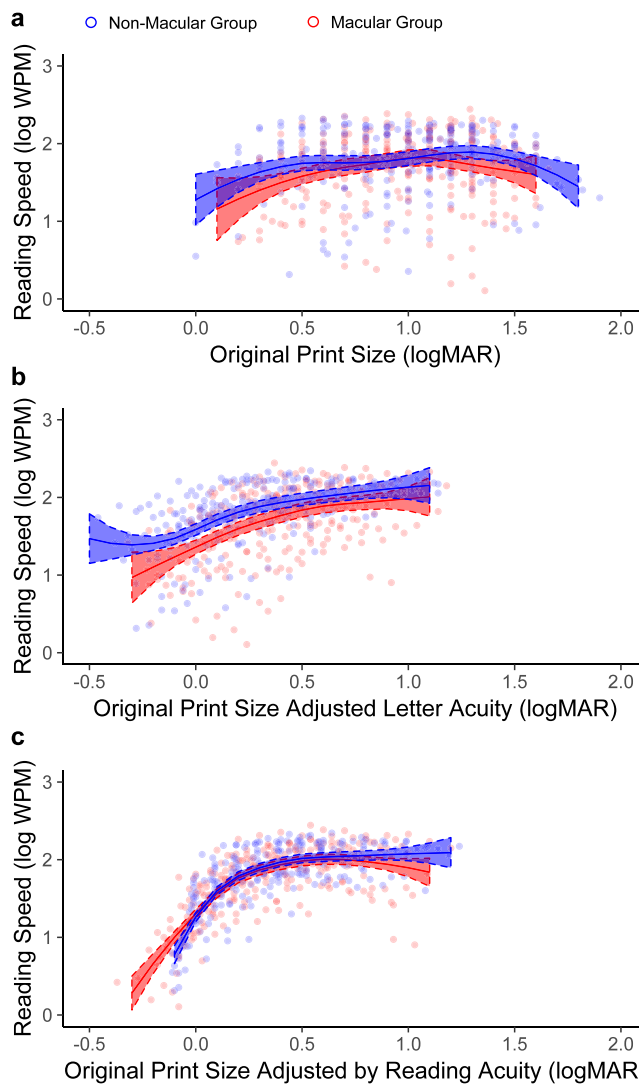


FIGURE 2. For each sentence read on the MNREAD chart, reading speed is plotted against original print size (a), print size normalized by LA (b), and print size normalized by RA (c). Low-vision status is color coded, with the Nonmacular group in blue and the Macular group in red. Average group reading curves and corresponding 95% confidence intervals bands are also presented.

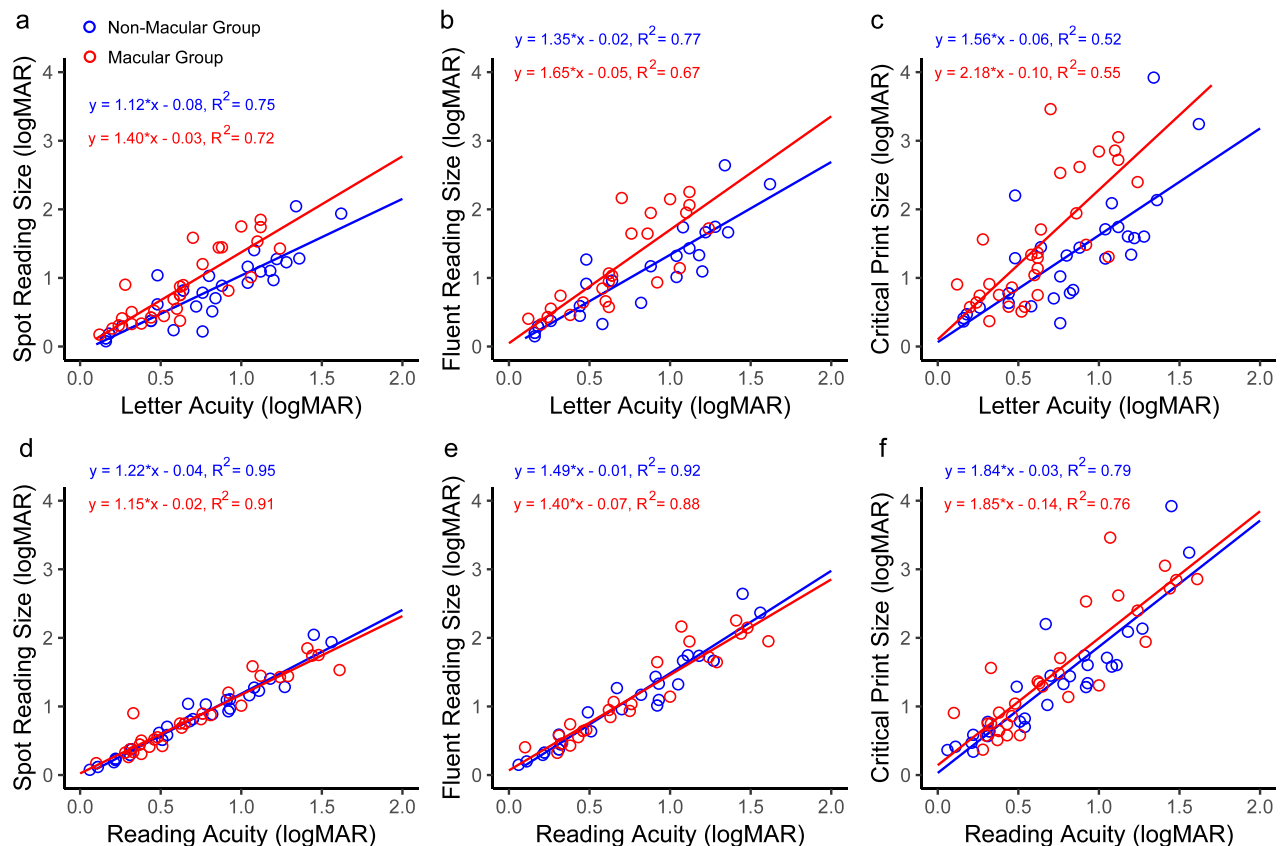


FIGURE 3. Scatterplots of spot reading size (a, d), fluent reading size (b, e), and critical print size (c, f) as functions of LA (upper) and RA (lower). Data from Nonmacular (blue) and Macular (red) groups are plotted along with their respective regression lines.

Using LA and RA to Predict Print Sizes Required for Functional Reading

For each low-vision subject, spot reading size (40 wpm), fluent reading size (80 wpm), and critical print size were derived from individual reading curves. With matched LA, the Macular group showed significantly larger spot reading size ($F_{(1,53)} = 12.40, P < 0.001$; Fig. 3A), fluent reading size ($F_{(1,43)} = 7.28, P = 0.010$; Fig. 3B), and critical print size ($F_{(1,54)} = 8.89, P = 0.004$; Fig. 3C). However, with matched RA, the two groups showed similar spot reading size ($F_{(1,53)} = 0.02, P = 0.88$; Fig. 3D), fluent reading size ($F_{(1,43)} = 0.0001, P = 0.99$; Fig. 3E), and critical print size ($F_{(1,54)} = 1.23, P = 0.27$; Fig. 3F).

Linear regressions showed that, for both low-vision groups, RA is slightly better than LA as a predictor for all three target reading sizes. For the Nonmacular group, LA and RA explained 75.0% and 95.3% of the variance in spot reading size, 76.8% and 92.3% of the variance in fluent reading size, and 52.1% and 78.6% of the variance in critical print size, respectively. For the Macular group, LA and RA explained 75.0% and 90.5% of the variance in spot reading size, 66.6% and 88.4% of the variance in fluent reading size, and 55.2% and 76.4% of the variance in critical print size, respectively. Regression results are presented in Figure 3.

Acuity Reserves for Functional Reading

Acuity reserve is defined as the gap between a subject's goal print size and his/her actual acuity print size,²⁰ the latter being expressed as either RA or LA. The acuity reserve is hence expressed as a difference in logMAR print size or equivalently

as a ratio and can be defined separately for spot reading, fluent reading, and the critical print size. For example, an acuity reserve of 0.3 logMAR for spot reading would mean that the print size for spot reading is 2.0 times greater than acuity print size.

For the two low-vision groups, we first calculated acuity reserves using LA as the acuity reference. ANCOVA analysis showed significant group differences for spot reading ($F_{(1,55)} = 8.58, P = 0.005$), marginally significant group difference for fluent reading size ($F_{(1,45)} = 3.61, P = 0.064$), and critical print size ($F_{(1,56)} = 3.78, P = 0.057$). However, when acuity reserves were obtained using RA as the acuity reference, there were no significant group effects for spot reading size ($F_{(1,55)} = 0.07, P = 0.80$), fluent reading size ($F_{(1,45)} = 0.08, P = 0.78$), and critical print size ($F_{(1,56)} = 0.94, P = 0.34$). The median acuity reserves for Nonmacular and Macular groups expressed in logMAR print sizes and ratios are listed in Table 2. Distributions of acuity reserves for the two low-vision groups, as well as median values for the young and old control groups, are shown in Figure 4.

DISCUSSION

The current study emphasizes the value of RA in reading assessment. For equal values of LA, individuals in the Macular group have significantly worse RA than low-vision individuals in the Nonmacular group, and the group difference increases as LA increases. The between-group differences and within-group variations in reading performance can be largely accounted for by RA. RA is a better predictor than LA for spot reading, fluent reading, and maximum reading. When RA is

TABLE 2. Median Acuity Reserves Expressed in logMAR and Ratio (Referenced to LA and RA)

Groups	Acuity Reserve for Spot Reading (40 wpm) (logMAR [ratio])	Acuity Reserve for Fluent Reading (80 wpm) (logMAR [ratio])	Acuity Reserve for Maximum Reading Speed (logMAR [ratio])
LA			
Nonmacular	-0.03 [0.92]	0.28 [1.91]	0.33 [2.14]
Macular	0.13 [1.35]	0.36 [2.30]	0.63 [4.28]
Group difference	$F_{(1,55)} = 8.58, P = 0.005$	$F_{(1,45)} = 3.61, P = 0.064$	$F_{(1,56)} = 3.78, P = 0.057$
RA			
Nonmacular	0.09 [1.22]	0.28 [1.90]	0.48 [3.02]
Macular	0.07 [1.18]	0.32 [2.07]	0.65 [4.44]
Group difference	$F_{(1,55)} = 0.07, P = 0.80$	$F_{(1,45)} = 0.08, P = 0.78$	$F_{(1,56)} = 0.94, P = 0.34$

used as the acuity reference for acuity reserves, similar acuity reserves are shown for the two low-vision groups.

RA and LA have been compared in previous studies. For normally sighted subjects with optical blur, RA was found to be consistently better than LA.^{17,18} Another study found that low-vision subjects with intact central vision also showed smaller RA (0.41 logMar) than LA (0.60 logMAR),¹⁹ congruent with the current study.

We note as a limitation that habitual corrections were used for the measurement of LA (distance visual acuity) and RA (reading acuity). It has been shown, however, that people with low vision have substantial tolerance to defocus.²⁸ It is unlikely that the difference we found between the Macular and Nonmacular groups was related to refractive errors.

Why don't subjects in the Macular group show the typical advantage for RA over LA? The general advantage of RA over LA can be explained by a "context benefit" from meaningful sentence reading. This effect was absent in the Macular group, possibly because the context benefit was offset by strong crowding in peripheral vision.^{4,5,29} Subjects with central vision loss frequently establish preferred retinal loci (PRLs) as a substitution for the nonfunctioning fovea. The retinal quadrant or retinal eccentricity of the PRL might affect the extent of crowding and thus influence the relationship between RA and LA. In our study, binocular central field maps were available from 14 subjects with macular degeneration. Larger eccentricity of PRL was found to be significantly correlated with larger difference between RA and LA ($r = 0.59, P = 0.027$; Fig. 5). A more extensive study would be required to assess the impact of PRL location, scotoma size, and fixation stability on the relationship between LA and RA.

RA has been found to be better than LA as a predictor of critical print size.⁵ Here we found that it is also a better predictor for spot reading size (the print size yielding a reading speed of 40 wpm) and fluent reading size (the print size yielding a reading speed of 80 wpm). Low-vision individuals usually require magnification to achieve these functional reading sizes,⁶⁻⁸ and the required magnification power can be estimated from the corresponding acuity reserves. Previous study suggested constant acuity reserves for low-vision readers to achieve spot reading (0.1 logMAR, equivalent to a ratio of 1.3), fluent reading (0.3 logMAR, equivalent to a ratio of 2.0), and maximum reading speed (0.5 logMAR, equivalent to a ratio of 3.2), based on low-vision reading observation.⁷ Here we found that when acuity reserves were obtained with RA as the reference acuity, Nonmacular and Macular groups had similar values, and the acuity reserves were similar to the suggested values of Lovie-Kitchen and Whittaker.⁷ These results indicate the value of using RA in magnifier prescription for people with low vision, and they also support the feasibility of using the same acuity reserves in magnification prescription for different low-vision diagnoses.⁷

We separated the low-vision subjects into two groups based on their diagnoses. However, patients with macular disease may have intact central vision in the early stage, and patients with nonmacular diagnoses may have central vision loss in the later stage. Our results showed that RA unifies results across subjects with different diagnoses. The diagnoses in current study represented a broad range of visual and functional deficit. It is possible, however, that eye conditions not sampled in our study could yield results that differ from our unified picture.

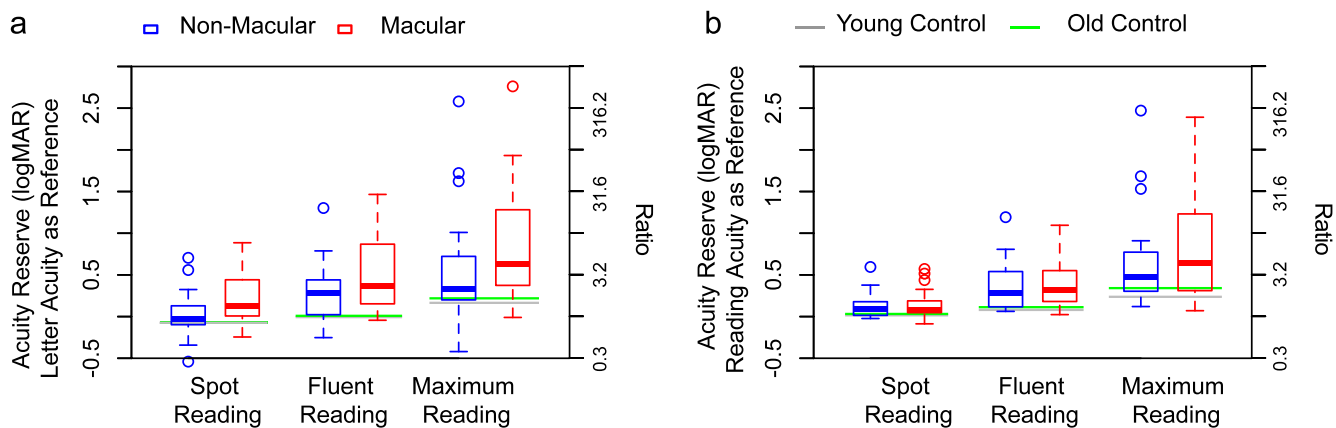


FIGURE 4. Distributions of acuity reserves for spot reading, fluent reading, and maximum reading. LA (a) and RA (b) are used, respectively, as references (i.e., normalizing factor). Data from Nonmacular (blue) and Macular (red) groups are plotted separately. Each quantile boxplot shows the 90th, 75th, 50th (median), 25th, and 10th percentiles. Medians of young control (gray) and old control (green) groups are plotted as solid lines.

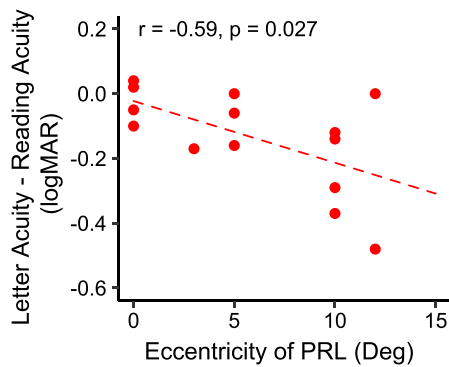


FIGURE 5. Correlation between the LA – RA difference and PRL eccentricity in the Macular group.

In the current study, reading acuity was measured with the MNREAD chart and scored as the smallest print size that subjects can read, corrected by the total number of errors. Such calculation still requires the whole chart to be read. However, the scoring of RA does not require timing of reading and is free from the curve fitting, which is much easier for clinicians and rehabilitation therapist to calculate. Reading charts are considered calibrated and comparable when they meet both the standards of ICO (The International Council of Ophthalmology) and EN ISO 8596.¹³ Adequate charts include the Bailey-Lovie Word Reading Chart,¹⁴ the MNREAD Charts,¹² the SKread Charts,¹⁵ and the RADNER Reading Charts.¹³ These charts provide reliable estimates of reading acuity and should be considered for performance assessment and reading aids prescription in the context of low-vision reading rehabilitation.

Acknowledgments

Supported by National Institutes of Health Grant EY002934.

Disclosure: **Y.-Z. Xiong**, None; **A. Calabrèse**, None; **A.M.Y. Cheong**, None; **G.E. Legge**, (R), P

References

- Elliott DB, Trukolo-Ilic M, Strong JG, Pace R, Plotkin A, Bevers P. Demographic characteristics of the vision-disabled elderly. *Invest Ophthalmol Vis Sci.* 1997;38:2566-2575.
- Owsley C, McGwin G Jr, Lee PP, Wasserman N, Searcey K. Characteristics of low-vision rehabilitation services in the United States. *Arch Ophthalmol.* 2009;127:681-689
- Faye EE. *Clinical Low-Vision*. Boston, MA: Little, Brown; 1976.
- Legge GE, Ross JA, Isenberg LM, LaMay JM. Psychophysics of reading: clinical predictors of low-vision reading speed. *Invest Ophthalmol Vis Sci.* 1992;33:677-687.
- Legge GE, Rubin GS, Pelli DG, Schleske MM. Psychophysics of reading: low vision. *Vis Res.* 1985;25:253-266.
- Cheong AMY, Lovie-Kitchin JE, Bowers AR. Determining magnification for reading with low vision. *Clin Exp Optom.* 2002;85:229-237.
- Lovie-Kitchin JE, Whittaker SG. Prescribing near magnification for low vision patients. *Clin Exp Optom.* 1999;82:214-224.
- Meyniel C, Bodaghi B, Robert PY. Revisiting vision rehabilitation. *Front Syst Neurosci.* 2017;11:82.
- Radner W. Reading charts in ophthalmology. *Graefes Arch Clin Exp Ophthalmol.* 2017;255:1465-1482.
- Arditi A. On the relationship between letter acuity and reading acuity. In: Kooijman AC, Looijestijn PL, Welling JA, van der Wildt GJ, eds. *Low Vision: Research and New Developments in Rehabilitation*. Amsterdam, Netherlands: IOS Press; 1994:38-45.
- Rubin GS. Measuring reading performance. *Vis Res.* 2013;90:43-51.
- Legge GE, Ross J, Luebker A, Lamay J. Psychophysics of reading: the Minnesota low-vision reading test. *Optom Vis Sci.* 1989;66:843-853.
- Radner W, Willinger U, Obermayer W, Mudrich C, Eisenwort B. A new reading chart for simultaneous determination of reading vision and reading speed. *Klin Monatsbl Augenheilkd.* 1998;213:174-181.
- Bailey IL, Lovie JE. The design and use of a new near-vision chart. *Am J Optom Physiol Optics.* 1980;57:378-387.
- MacKeben M, Nair U, Walker L, Fletcher DC. Random word recognition chart helps scotoma assessment in low vision. *Optom Vis Sci.* 2015;924:421-428.
- Lovie-Kitchin JE, Bailey IL. Task complexity and visual acuity in senile macular degeneration. *Austral J Optom.* 1981;64:235-242.
- Xu R, Bradley A. IURead: a new computer-based reading test. *Optical Physiol Optics.* 2015;35:500-513.
- Chung ST, Jarvis SH, Cheung SH. The effect of dioptric blur on reading performance. *Vis Res.* 2007;47:1584-1594.
- Fletcher DC, Schuchard RA, Watson G. Relative locations of macular scotomas near the PRL: effect on low vision reading. *J Rehab Res Develop.* 1999;36:356-364.
- Cacho I, Dickinson CM, Smith HJ, Harper RA. Clinical impairment measures and reading performance in a large age-related macular degeneration group. *Optom Vis Sci.* 2010;87:344-349.
- Whittaker SG, Lovie-Kitchin J. Visual requirements for reading. *Optom Vis Sci.* 1993;70:54-65.
- Cheong AMY, Legge GE, Lawrence M, Cheung SH, Ruff M. Relationship between visual span and reading performance in age-related macular degeneration. *Vis Res.* 2008;48:577-588.
- Calabrèse A, To L, He Y, Berkholtz E, Rafian P, Legge GE. Comparing performance on the MNREAD iPad app with the MNREAD acuity chart. *J Vis.* 2018;18(1):8.
- Ferris FL, Kassoff A, Bresnick GH, Bailey IL. New visual acuity charts for clinical research. *Am J Ophthalmol.* 1982;94:91-96.
- Cleveland WS, Devlin SJ, Grosse E. Regression by local fitting: methods, properties and computational algorithms. *J Econometrics.* 1988;37:87-114.
- Calabrèse A, Mansfield JS, Legge GE. mnreadR, An R Package to Analyze MNREAD Data. Available at: <https://CRAN.R-project.org/package=mnreadR>.
- Cheung SH, Kallie CS, Legge GE, Cheong AMY. Nonlinear mixed-effects modeling of MNREAD data. *Invest Ophthalmol Vis Sci.* 2008;49:828-835.
- Legge GE, Mullen KT, Woo GC, Campbell FW. Tolerance to visual defocus. *J Optical Soc Am.* 1987;4:851-863.
- Levi DM. Crowding-An essential bottleneck for object recognition: a mini-review. *Vis Res.* 2008;48:635-654.