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ORIGINAL ARTICLE

Developing a Logarithmic Chinese Reading Acuity Chart

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ABSTRACT

Purpose. An individual's reading ability cannot be reliably predicted from his/her letter acuity, contrast sensitivity, and visual field extent. We developed a set of Chinese reading acuity charts (C-READ) to assess the reading ability of Chinese readers, based on the collective wisdom of previously published reading acuity charts, especially the MNRead and the Radner Reading Charts.
Methods. The C-READ consists of three charts. Each consists sixteen 12-character simplified Chinese sentences crafted from first- to third-grade textbooks. One hundred eighteen native Chinese-speaking college students (aged 22.1 ± 2.1 years) with normal or corrected to normal near vision (−0.26 ± 0.05 logMAR) were included in the study to develop the C-READ charts, to test the homogeneity of the three charts, and to validate the C-READ against the text paragraphs from the International Reading Speed Texts (IReST) with corrected and uncorrected near vision.
Results. The reading acuity, critical print size, and maximum reading speed for young normal native Chinese-speaking readers were 0.16 ± 0.05 logMAR, 0.24 ± 0.06 logMAR, and 273.44 ± 34.37 characters per minute (mean ± SD), respectively. The reliability test revealed no significant differences among the three C-READ charts and no significant test order effect in the three reading parameters. Regression analyses showed that the IReST reading speed could be reliably predicted by the C-READ maximum reading speed under the corrected near-vision condition (adjusted R^2 = 0.72) and by C-READ maximum reading speed and critical print size under the uncorrected near-vision condition (adjusted R^2 = 0.69).
Conclusions. The three C-READ charts are very comparable to each other, and there is no significant order effect. Reading test results can accurately predict continuous text reading performance quantified by the IReST reading speed over a wide range of refractive errors. The C-READ is a reliable and valid clinical instrument for quantifying reading performance in simplified Chinese readers.
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Key Words: C-READ, reading acuity chart, simplified Chinese

A dedicated instrument to assess a person's ability to read regular text is needed because this ability cannot be reliably predicted by letter acuity, contrast sensitivity, and visual field extent.[1,2] There has been a long history of developing continuous text reading tests and applying them to vision care.[3–7] The Minnesota Low-Vision Reading Test (MNRead) and the Radner Reading charts are the two most notable ones.[5,6,8] Both tests characterize reading performance by reading acuity, critical print size, and maximum reading speed. They share some time-tested design principles, such as standardized continuous text test items that closely resemble everyday reading materials, high-frequency vocabulary at the third-grade reading level, most popular typefaces, logarithmic progression of print sizes, and uniformity in text spatial layout,[5,8] but they also differ in several ways. The MNRead uses simple, 60-character (including spacing) declarative sentences shown in three lines.[5] The German version of the Radner Reading charts uses "sentence optotypes," which are highly comparable in terms of the number of words per sentence and format (14 words, 82 to 84 characters, printed in three lines), the number of words per line (five words in lines 1 and 2, four words in line 3), the word length in specific sentence locations, the position of the relative clause (following the second word of line 2), and the distribution of syllables within a sentence.[8]

While these design principles have been adopted in developing reading charts in multiple languages,[9–15] their applications to Chinese text may not be straightforward. The logographic Chinese differs from the linear alphabetic Latin languages in several ways, which on one hand demands modifications of some of the principles mentioned previously, but on the other hand makes implementation of other principles more natural. The following unique features of the Chinese text need to be considered in designing a Chinese reading test.

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Sentence Composition

The Chinese language lacks the relative pronouns, such as who, which, and that. Therefore, sentence compositions that are more complex than simple declarative sentences, such as those used in Radner Reading chart, may introduce uncertainties such as pauses between clauses and repetitions of subject nouns.

Sentence Length Measurement

The smallest meaningful unit of written Chinese is a character. It is therefore natural to measure sentence length in terms of characters instead of words. The IReST uses characters as the basis for measuring reading speed.[16,17] All 60-character MNRead sentences are evaluated based on 10 "standard-length" (six characters) words,[14] whereas each Radner Reading sentence contains 14 words.[8]

Physical Layout

Each sentence of the MNRead and Radner Reading charts is printed in three lines, 20 characters per line for MNRead and 24 or 25 characters per line for Radner Reading chart.[8,14] Considering the printing practice of 65 characters or approximately 10 words per line for paperback English books, breaking these test sentences into three lines is not too far from normal reading practice.

Chinese text is more compact than Latin language texts.[18,19] Chinese paper books have 28 to 32 characters per line. Breaking a 12-character sentence into three lines would not reflect normal Chinese reading habits. Using text lines this short also increases the risk of breaking a compound word and thus introduces unwanted pauses or hesitation.

All Chinese characters of the same typeface and font size occupy the same square area, and there is no spacing between words. Sentences that contain the same number of characters naturally have the same horizontal extent.

Number of Syllables

Each Chinese character is one syllable. Therefore, equalizing the number of characters in the testing sentences also equalizes the number of syllables, making quantification of verbal reading more accurate.

Inclusion of Simpler and More Complex Characters

The Latin alphabets are quite simple and relatively uniform in spatial complexity. In comparison, even Chinese text for beginners is a mixture of characters of very different spatial complexities. The number of strokes of the first 1000 most frequently used Chinese characters ranges from 1 (一, one) to 25 (

strokes of the 283 unique characters included in these sentences was 7.13 (range, 1 to 15 strokes), which was fewer than the mean number of strokes of the 2570 characters listed in the textbooks of all six primary school grades (9.45 strokes).[23] This was because the sentences used for developing the C-READ were selected from the textbooks of grades 1 to 3 and because textbooks for higher grades contained more complex characters.

The final 48 sentences were randomly assigned to three 16-sentence charts. Each chart covered a print size range from −0.3 to 1.2 logMAR (20/10 to 20/320) in 0.1 logMAR steps for a 40-cm reading distance. The mean strokes per sentence were 85.3 ± 3.5, 85.6 ± 3.0, and 85.9 ± 3.2 for charts A, B, and C, respectively. The character height was determined by the vertical extent of characters that have horizontal strokes on the top and bottom and have a sufficient number of strokes, such as 困 and 面. The vector font size in points for each line of the chart was first adjusted to match the nominal character height (e.g., the nominal height of the 20/20 line characters is 5 arc minutes or 0.582 mm at 40 cm) in Adobe Illustrator during chart characterization. After the chart was printed on paper, the actual character heights were verified under a 15 times measuring loupe.

The reading charts used typeface Song Ti (宋体), the most popular typeface for Chinese printing and online reading materials. Although all Chinese characters occupy the same square area, not all characters fill the square area to the brim. For aesthetic reasons, characters with only a few strokes tend to be slightly shorter or narrower. No adjustment was made to equalize individual character heights or widths in the chart sentences.

Production of the C-READ

The Adobe Illustrator productions of the charts were printed on heavyweight coated semiglossy paper using a 1219 dpi (2438 dpi addressable) HP Indigo 5500 digital press. To empirically determine the smallest print size that was minimally impacted by print quality, a set of charts for a viewing distance of 80 cm was printed, so that the number of dots per character was quadrupled. Thirty-six young native Chinese readers were tested with these charts (12 readers per chart). If an observer's acuity was worse than 0 logM

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FIGURE 1.
Chart A of the logarithmic C-READ. The chart is made of sixteen 12-character simple declarative sentences, covering an acuity range from 20/10 to 20/320. The acuity of each line is labeled by decimal acuity and logMAR on the left side and by Snellen fractions for 40 cm and 20 feet on the right side.

errors. The reading time was adjusted by the number of uncorrected errors before being converted to reading speed in characters per minute, as recommended by the developers of IReST.[16] Each observer was also tested with two randomly selected versions of the C-READ with corrected and uncorrected near vision.

Data Analysis

Three algorithms for extracting C-READ reading performance parameters were compared. Both the original MNRead scoring algorithm and the two-limb algorithm used a sloped line to fit the increasing reading speed at the smaller print sizes and a horizontal line to fit the reading speed plateau at larger print sizes.[14,24] The two line segments were determined separately in the MNRead algorithm but were fitted together based on one model in the two-limb algorithm. The third algorithm used an exponential-decay function to fit the entire reading speed curve.[24] The original MNRead algorithm defined reading acuity as the size of the last sentence attempted, plus the number of uncorrected word errors in that sentence timed 0.01 (10 words in each 0.1 logMAR line). The other two algorithms defined reading acuity as the intersection of the best-fitting line/curve with the horizontal axis (the print size when the reading speed dropped to zero).

These algorithms were modified to better fit the C-READ data. First, the MNRead assumed that each sentence contained 10 standard-length words (six characters per word), and each word was worth 0.01 log unit. Because each C-READ sentence had 12 characters, each character was worth 0.1/12 = 0.00833 log unit. Second, a "floor effect" was frequently observed in C-READ tests, in that the observers could only correctly read one or two characters in the two or three smallest sentences before they finally gave up. Consequently, there was a flat floor at the small print-size end of the differences for each of the three C-READ parameters.[25] The measurement errors for using the three charts as a set were quantified by within-subject SDs of the C-READ parameters.[26]

A variance component analysis with individual observers and C-READ versions as the random factors, test order as the fixed variable, and reading acuity, critical print size, and maximum reading speed as dependent variables was conducted to determine the sources of variability in the C-READ parameters. Pearson r was calculated to assess the agreement between the C-READ and the IReST reading speed, as well as the relationship among C-READ parameters and uncorrected near acuity. A linear regression analysis with the IReST reading speed as the dependent variable and the C-READ parameters as the independent variables was performed to establish the relationship between the C-READ parameters and the continuous text reading performance.

The data are presented as mean ± SD throughout the article.

RESULTS

Normative Data of the C-READ

Table 1 shows the reading parameters of reading acuity, critical print size, and maximum reading speed of individual charts and their averages obtained from 30 native Chinese-speaking colleague students. There were no significant differences in the reading parameters among the three charts ($F_{2,27}$ = 2.64, P = .09, for reading acuity; $F_{2,27}$ = 2.68, P = .09, for critical print size; and $F_{2,27}$ = 1.93, P = .17, for maximum reading speed). Intraclass correlations among the reading parameters derived from the three versions of the C-READ were excellent (intraclass correlation = 0.98, 0.93, and 0.91 for reading acuity, critical print size, and maximum reading speed, respectively), suggesting good interchart reliability.[27] There was no significant test order effect of the same charts on the three parameters either ($F_{2,27}$ = 1.13, P = .34, for reading acuity; $F_{2,27}$ = 1.21, P = .32, for critical print size; and $F_{2,27}$ = 1.46, P = .25, for maximum reading speed). Intraclass correlations for testing order were good to excellent (intraclass correlation = 0.85, 0.72, and 0.99 for reading acuity, critical print size, and maximum reading speed, respectively), suggesting adequate test-retest reliability.

The pairwise Bland-Altman plots for the three reading parameters are shown in Fig. 3. For reading acuity, the 95% limits of agreement, the interval demarked by the pair of black dashed lines, were −0.004 ± 0.066, −0.001 ± 0.047, and 0.003 ± 0.061 for chart pairs A versus B, A versus C, and B versus C, respectively. If any pair of the C-READs is used for repeated tests, 95% of the measurement differences in reading acuity would be smaller than one line (0.1 logMAR). The assessments of the limits of agreement were accurate. The SEs (the dotted lines around each dashed line) were 0.011, 0.008, and 0.010 logMAR, respectively. Similarly, critical print sizes measured using any two versions of C-READ would not differ more than two lines (the 95% limits of agreement were −0.011 ± 0.170, −0.006 ± 0.162, and 0.005 ± 0.167). The maximum reading speeds obtained with any two charts would not differ more than 27 characters per minute (95% limits of agreement were 0.709 ± 26.485, −5.245 ± 24.612, and −5.954 ± 26.775). If all three charts are used on the same subject, the within-subject SDs for reading acuity, critical print size, and maximum reading speed were 0.02 logMAR, 0.06 logMAR, and 9.8 characters per minute, respectively, suggesting good interchart reliability.[26]

The variance component analysis revealed that the observers were the predominant factor influencing the C-READ variability, contributing 96.5%, 65.1%, and 81.7% to the total variances of reading acuity, critical print size, and maximum reading speed, respectively (Table 2). The test orders influenced maximum reading speed only, whereas the three versions of the C-READ did not influence any of the parameters. A considerable proportion of the critical print size and maximum reading speed variability came from the interaction between the observers and the charts (32.5% for critical print size, 10.1% for maximum reading speed). The interaction of charts and test orders also contributed a small proportion of variance to the three parameters. These data suggested that most of the chart parameter variances were caused by interobserver variability, not by the charts or the test orders.

The Relationship between C-READ Parameters and IReST Reading Speed

Fig. 4 shows that the observers in this experiment had uncorrected near acuities spreading over a 1-log-unit range. Table 3 sho34.6(he)rm.that the IReST readingrm.speedrm.wasignificantly fasterrr C-REA4.6(heD)-516.4(ma)-15.1(xi)-7.2(m)-11.4(u)0(m)-520(r)0(e)11(ac significant (t_{31} = 8.37, P < .001, with corrected vision; t_{31} = 3.22, P = .003, with uncorrected vision; two-tailed paired t test). The IReST reading speed and the chart maximum reading speed were highly correlated when near vision was corrected (r = 0.87, P < .001) and were moderately correlated when near vision was not corrected (r = 0.59, P < .001).

Assessing IReST Reading Performance with C-READ at Various Refractive Errors

Fig. 5 is the scatter plot of the chart maximum reading speed versus the IReST readingspeed. A linear regression analysis in-

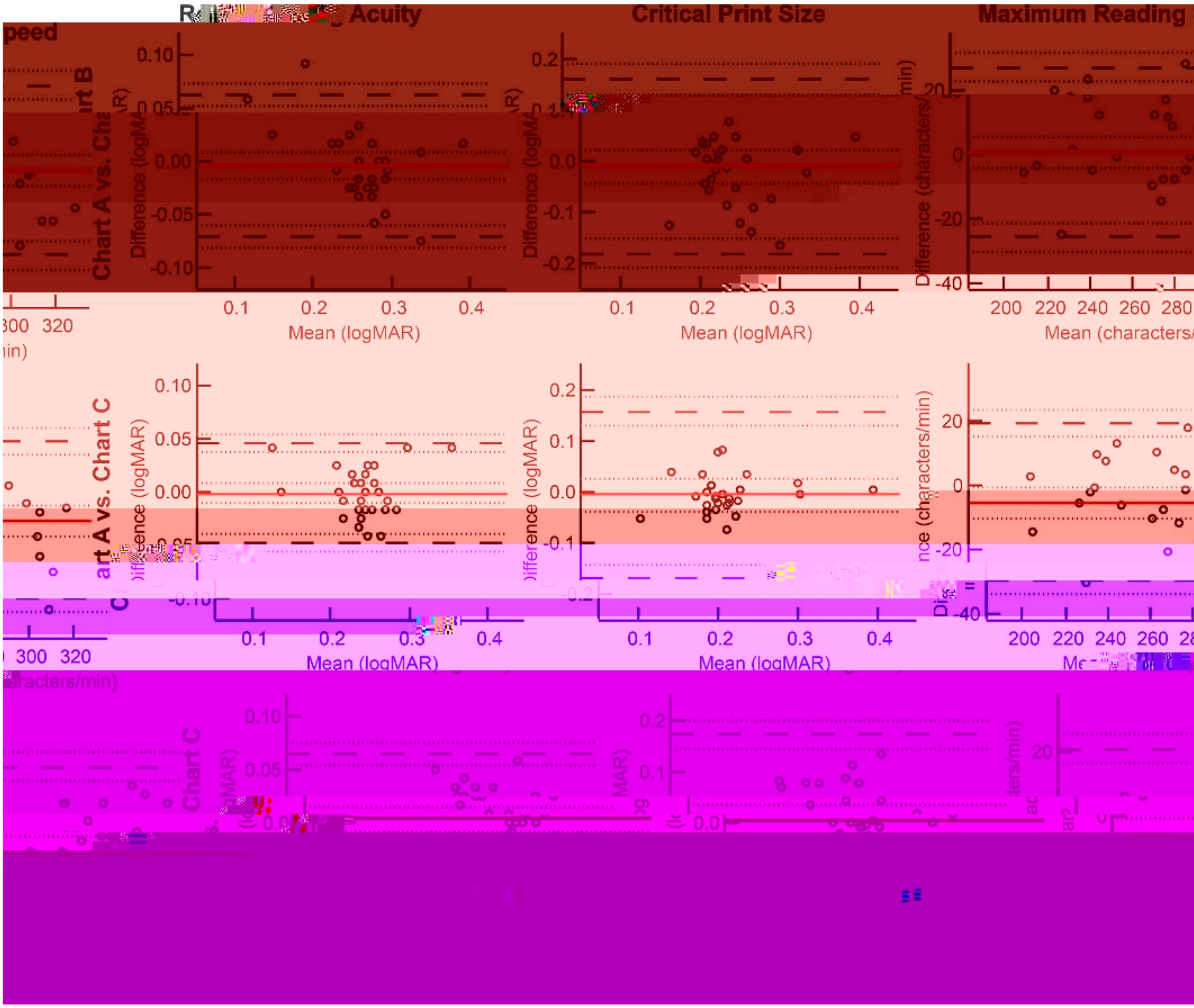

FIGURE 3.

Equation 1 is the regression model for the corrected near-vision condition.

$$\text{IReST reading speed} = 1.21(\text{maximum reading speed}) - 25.53 \quad [1]$$

Under the uncorrected near-vision condition, both critical print size and maximum reading speed contributed to the variance in the IReST reading speed (R = 0.84, adjusted R^2 = 0.68, P < .001). Equation 2 is the regression model:

$$\text{IReST reading speed} = 0.56(\text{maximum reading spead}) - 97.04(\text{critical prise size}) + 199.80 \quad [2]$$

The uncorrected near acuity was significantly correlated with reading acuity and critical print size of the C-READ (r = 0.89,

TABLE 2.

The Contributions of Different Variables and Their Interactions to the Total Variances of C-READ Parameters

Variables Parameters	Observer	Order	Chart	Observer × Chart	Chart x Order	Error
Reading acuity	96.5%	0%	0%	0%	3.5%	0%
Critical print size	65.1%	0%	0%	32.5%	2.4%	0%
Maximum reading speed	81.7%	7.5%	0%	10.1%	0.7%	0%

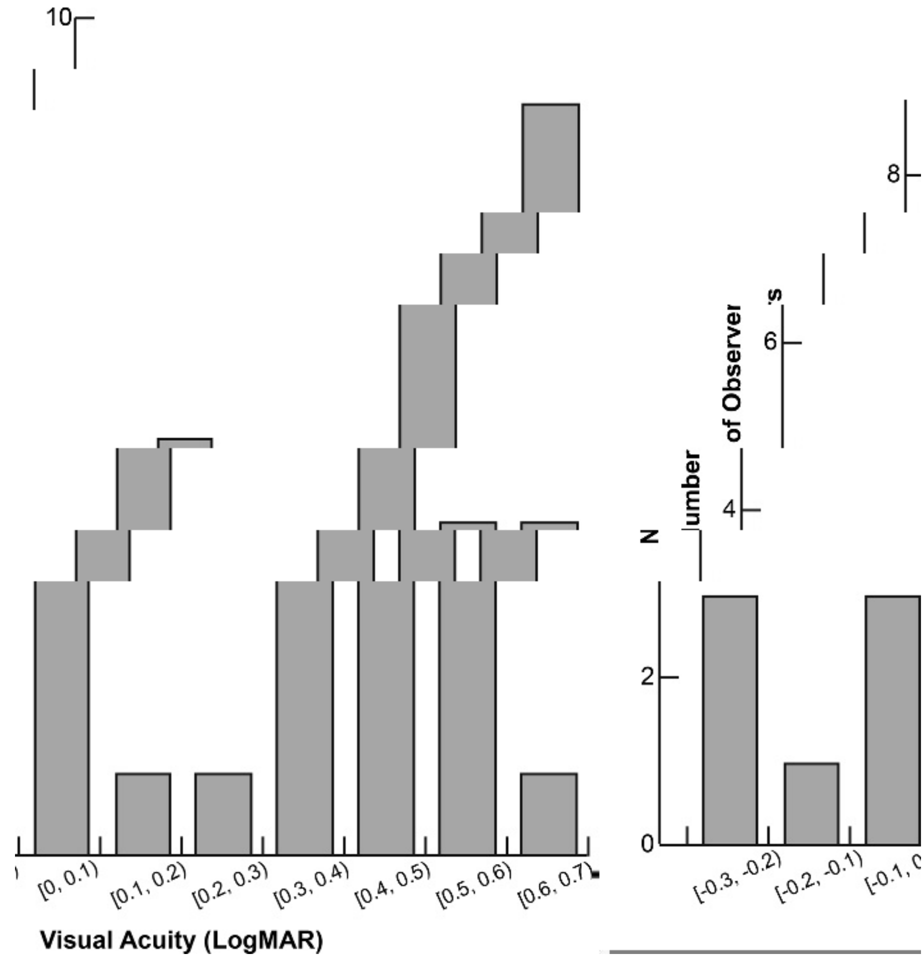

FIGURE 4.
Distribution of uncorrected near visual acuities of observers.

P < .001, for reading acuity, and r = 0.91, P < .001, for critical print size) and with the IReST reading speed (r = −0.63, P < .001), but was insignificantly correlated with maximum reading speed (r = −0.34, P = .06).

DISCUSSION

Written Chinese is quite different from alphabetic languages in several important ways. The final design of the C-READ was the outcome of increasingly deeper understanding of the impacts of these unique characteristics of written Chinese on reading. In particular, not only the sentence-level spatial complexities, quantified by the total number of strokes per sentence, but also the distribution of the strokes in the characters of the sentence could have great influence on reading performance, especially on reading acuity and critical print size.[20,28] Only through iterative refinements could a high level of consistency among the charts and good construct validity be achieved.

The fact that the uncorrected near acuity was uncorrelated with the maximum reading speed of the C-READ and only moderately correlated with IReST reading speed demonstrated the limitation of letter acuity tests in assessing reading performance, as well as the necessity for a dedicated reading instrument. The C-READ meets this need because its parameters could accurately predict the IReST passage reading speed (Equations 1 and 2). It also provides the important clinical parameters of reading acuity and critical print size, which the IReST cannot provide.

The result that critical print size was a significant predictor of the IReST reading speed under the uncorrected near-vision condition (Equation 2) was not unanticipated. When the observers were

TABLE 3.
C-READ Parameters and IReST Passage Reading Speeds with Corrected and Uncorrected Near Vision

	Reading Acuity (logMAR)	Critical Print Size (logMAR)	Maximum Reading Speed (Characters/min)	IReST (Characters/min)
Corrected vision	0.20 ± 0.05	0.30 ± 0.07	265.00 ± 29.61	298.17 ± 42.47
Uncorrected vision	0.58 ± 0.29	0.70 ± 0.31	249.26 ± 36.43	271.85 ± 48.42

fully corrected for the reading distance, there was only a small variation in their critical print sizes. Moreover, the font size of the text passage, 1.1 logMAR, exceeded the critical print sizes by at least 0.66 log unit. With this substantial amount of acuity reserve, the observers' passage reading speeds could be predicted solely by their C-READ maximum reading speed (Equation 1). In comparison, when the refractive errors were not corrected, the variance accounted for by critical print size was large. The larger the critical print size, the smaller the acuity reserve for reading and the slower the reading speed. In fact, the critical print size was only 0.1 to 0.2 log unit larger than 1.1 logMAR in six observers, 0.0 to 0.1 log unit larger in four observers, equal to 1.1 logMAR in two observers, and larger than 1.1 logMAR in two observers. Therefore, a large portion of the observers had small or no acuity reserves when they read the text passages with uncorrected vision. Consequently, critical print size, a parameter related to the acuity reserve, became the major predictor of the text passage reading speed (Equation 2).

The C-READ has good interchart reliability. Ninety-five percent of the repeated measurement errors would fall within 0.04 logMAR, 0.12 logMAR, and 19.2 characters per minute from the true reading acuity, critical print size, and maximum reading speed, respectively.[26] Because the interchart error for the C-READ is only a few characters for reading acuity, is approximately one line for critical print size, and is no larger than 7% of the average maximum reading speed, clinicians should feel confident to use the three charts interchangeably. They can use different charts to test the left eye, right eye, and both eyes of one patient or to monitor the change of reading performance at up to three time points.

The variance component analysis of the C-READ parameters showed that interobserver variability accounted for most variance in reading acuity and maximum reading speed (Table 2), indicating that the charts can detect individual differences in reading acuity and speed. This is similar to the finding of Stifter and colleagues,[29] who validated the Radner Reading charts. However, in contrast to Stifter and colleagues'[29] study, which found that the majority of the variance in critical print size came from "unidentified sources," two-thirds of the C-READ critical print size variance came from the observers, and one-third came from the interaction between the observers and the three versions of the C-READ. Because critical print size plays an important role in determining the magnification of the reading aid for a patient with visual impairment,[14] clinicians may consider testing reading twice using two charts to improve the accuracy of critical print size assessment.

Within-subjects comparison of MNRead–English and C-READ is difficult, because of the obvious language barrier in performing reading tasks using one's native tongue and a foreign language. However, between-subjects comparisons of native English readers reading MNRead–English and native Chinese readers reading C-READ may help illustrate the cross-language

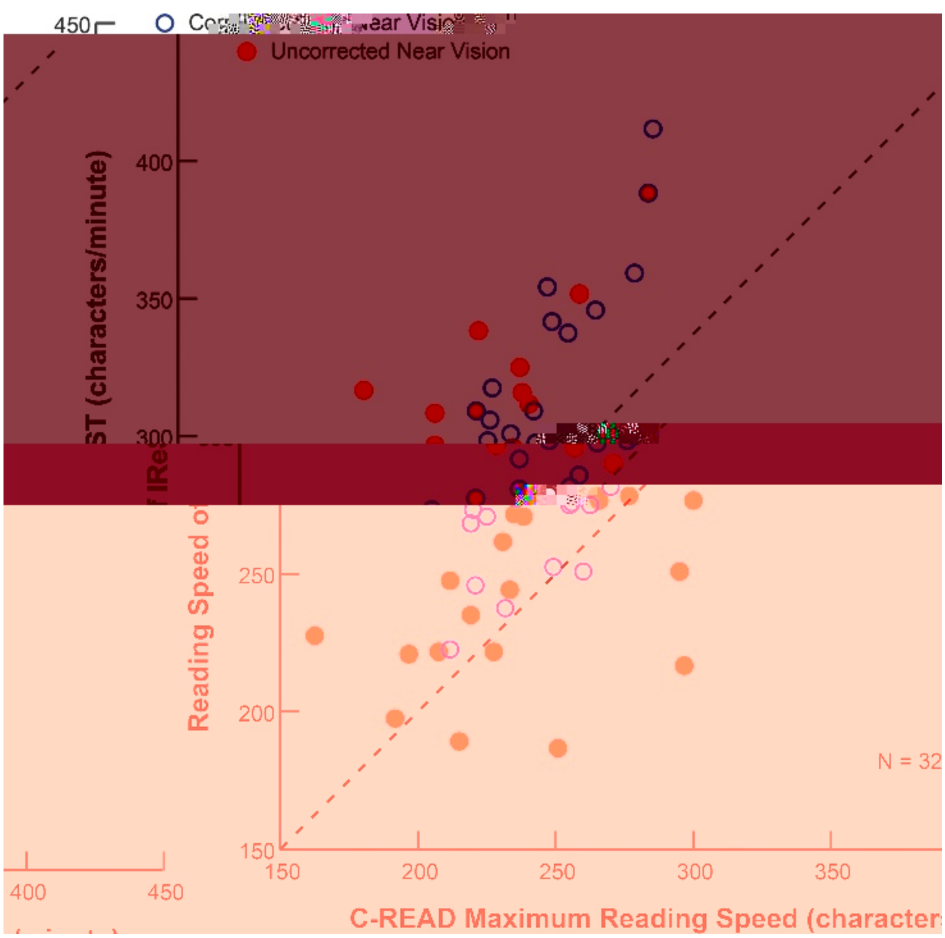

FIGURE 5.

IReST passage reading speed versus C-READ maximum reading speed. Circles above the diagonal line indicate that the IReST reading speeds exceed C-READ maximum reading speeds.

differences in reading assessment. In a recent study, Calabrèse et al.[30] compiled a large set of MNRead–English data from English readers of a wide range of ages. From their age regression models, it was estimated that MNRead reading acuity, critical print size, and maximum reading speed for age 22 were −0.168 logMAR, 0.077 logMAR, and 201.6 words per minute, respectively. In comparison, the reading acuity and critical print size for the Chinese readers, as determined by the C-READ, were 0.34 and 0.16 logMAR larger than the corresponding MNRead parameters, respectively (Table 1). This was not surprising because we have shown that visual acuity obtained using Roman letters (Sloan letters) was one line better than that obtained using two- to four-stroke simple Chinese characters and that the difference became even larger with more complex Chinese characters.[20] The difference between the MNRead–English maximum reading speed (202 words per minute) and that of the C-READ (273 characters per minute) was more difficult to comprehend because a Chinese word may contain one or more characters. On the other hand, the MNRead sentences have 10 six-character "standard-length" words with 12 to 15 syllables. The maximum reading speed of 202 words per minute of the MNRead can thus be converted to 242 to 303 syllables per minute. Because one Chinese character is one syllable, the reading speed of 273 characters per minute of the C-READ is 273 syllables per minute. Therefore, MNRead–English and C-READ maximum reading speed are comparable if the number of syllables uttered per minute is considered.

The C-READ is made of simplified Chinese characters, which are read by the majority of Chinese readers. Recently, Cheung et al.[31] and Cheong et al.[32] developed a logarithmic reading acuity chart for traditional Chinese readers, who reside mainly in Taiwan and Hong Kong. This reading chart differs from the C-READ in several important ways. First, many simplified Chinese characters have much fewer strokes and thus are visually simpler and have lower spatial frequency components than their traditional counterparts. The following are one of the C-READ sentences (89 strokes) and its traditional rendering (121 strokes):

我们都来画一画家乡的景物 (simplified Chinese)
我們都來畫壹畫家鄉的景物 (traditional Chinese)

Notice the difference between characters "一" and "壹" (one) and "乡" and "鄉" (home land). The difference in spatial complexity between simplified and traditional Chinese is much greater than that among most languages using Roman alphabets. As mentioned in Methods, special considerations had to be given to the presence of very simple characters in the C-READ sentences to ensure within- and between-charts consistency. Because characters with more strokes are known to have larger recognition threshold sizes,[20] the low vision aid magnification or school textbook font size determined using the C-READ critical print size is likely to be too small for patients or school pupils who read traditional Chinese. Indeed, the C-READ critical print size for 22-year-olds (Table 1) was smaller than that measured using the traditional Chinese charts (0.24 ± 0.06 logMAR vs. 0.51 logMAR).[32] Finally, many Chinese do not read simplified and traditional Chinese with equal fluency. It depends on where they are brought up. In summary, the simplified and traditional Chinese reading charts should be considered as two different instruments for two different populations.

This study examined only the effects of refractive errors on the C-READ in a group of highly uniform young normal observers. Other pathological conditions, such as cataract, macular degeneration, glaucoma, and hemianopia, are known to affect reading performance but for different reasons. A recent study of reading performance in normally sighted English readers of different ages demonstrated significant age dependence of the MNRead–determined maximum reading speed, critical print size, and reading acuity.[30] Future studies are needed to expand the scope of the applications of the C-READ to these conditions.

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