Contrast Sensitivity and Reading: Assessment and Reliability with the Reading Explorer (REX) Test

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Introduction

It is well known that visual acuity is a fundamental parameter to estimate the visual performance of low-vision patients but another at least as important as visual dimension, affecting in particular reading performance[1], is contrast sensitivity.
Regarding visual acuity the MNREAD eye chart has widely been recognized as one of the most reliable and powerful reading tests available. It has been developed to investigate how letters size affects the reading performance of both normal vision subjects and low-vision subjects[2-6]. By asking the subjects to read phrases with a text size getting smaller and smaller, it is possible to find out a specific text size that yield a dramatic reduction of the reading speed: the so called critical print size (CPS). The CPS provides information about the befitting and most appropriate rehabilitation program a specific low-vision patient has to be aided with.
On the opposite, contrast sensitivity is not commonly measured in low-vision patients although it is unquestionable the role that this dimension plays in reading rehabilitation programs. To investigate reading performance with a text/background contrast level that is not 100% (as that used in the MNREAD chart) is important because most of the reading materials we are used to, are printed at non optimal (from 50% up to 70%) contrast levels. Moreover, a decrease in reading speed due to a reduction of contrast sensitivity can be rectified in some degrees by providing a suitable illumination or by using electronic devices or appropriate filters.
For all these reasons we have set up a new easy-to-use eye chart to investigate the reading performance of low-vision subjects in terms of reading speed for several text/background contrast levels. This clinical tool could be used to examine and identify reading difficulties as well as to decide the best devices to be used in rehabilitation programs.
To accomplish this eye chart named REX (Reading Explorer) test, we combined together photometric and colorimetric expertise for producing a chart with perfectly-defined text/background contrast levels and clinical expertise to test the validity and repeatability of the results obtained by R.Ex chart. The REX test has been developed by the Department of Ophthalmology of the University of Florence in collaboration with the National Institute of Applied Optics (INOA_CNR).
In the present study we aimed at assessing the reliability of the REX test in people with normal and low vision. Furthermore, we wished to evaluate the impact of decreased contrast sensitivity of the reading material on reading speed when print size is not a limitation, i.e. above the critical print size, using the REX test.

Methods

Structure and use of the REX test

The REX eye chart consists of 2 sets of 3 reading charts. Each chart shows 4 different phrases arranged vertically in the middle of the chart. The contrast of each phrase from top to bottom decreases with a logarithmic profile as better explained below.

Testing phrases

The phrases used in the REX chart been developed to request visual information analysis as well as smooth eye movements common of the everyday reading task, as opposed to Pelli-Robson charts which use single letters to explore contrast sensitivity. Moreover, the phrases in the REX chart satisfy the same standards of those of the MNREAD eye chart[2]. In short, each phrase consists of 10 words of 60 characters (including blanks between words and at each line end), printed out on three lines with edges aligned on both sides. The vocabulary used in the REX. chart is picked up by the most frequently words used in the 7-8 years old children reading materials.

Text font

The font used in the REX eye chart is Times New Roman. The Pelli-Robson and Wilkins [] chart is printed out with the uppercase Sloan font that is highly standardized (from a geometric point of view) but it is not suitable as a font to read to. Furthermore, Times New Roman is very common especially in Europe where seldom if ever a book is printed with a monospaced font.

Text size

From a view distance of 40 cm, the letters size (referred to the dimension of the lower case character “x”) on each chart is equal to 1.0 logMAR. By shortening the viewing we get 1.2 logMAR for a view distance of 25 cm that is very common for the close-distance eye chart in Europe.

Text contrast

The text/background contrast of the first line phrase of REX chart is equal to 89,13%. The reading of this contrast level require a contrast sensitivity of at least 1.122 that is 0.05 in logarithmic units.
Each phrase after the first one, is defined by a logarithmic contrast sensitivity 0.15 higher up to a logarithmic contrast sensitivity of 1.7 for the last (12^{th}) phrase.
The logarithmic scale make it easy to calculate the desired foreground/background contrast ratio and what is more is the same procedure applied by Pelli-Robson [*REF Pelli Robson and the missing Wilkins*] for their well known contrast sensitivity reading chart.
Contrast levels of the REX eye chart are defined by the so called Weber formula:

$$C = \frac{L_{bg} - L_{fg}}{L_{bg}}$$

where L_{bg} indicates the luminance of the background, whilst L_{fg} indicates the letter luminance.

Chart illumination

To obtain optimal reading measurements it is important to uniformly illuminate the reading chart to avoid any shadow or reflex. The chart illumination have to be set up to around 80 cd/mq (range 60-120 cd/mq) the same as requested for the Pelli-Robson eye chart or the MNREAD chart.

Clinical applications of R.Ex eye chart

With REX test it is possible to measure three different visual dimensions: Reading contrast limit and reading speed for several contrast levels.
An estimate of the reading contrast limit is given by the lowest text contrast a subject is able to read without significative errors. In the REX eye chart the level (in percent) of the text contrast as well as the corrisponding value of contrast sensitivity in LogCS (logarithm of the contrast sensitivity) is shown next to each testing phrase.
The reading speed, that is the number of words per minute that can be read by a subject, is an objective tool to measure the reading ability. The eye chart REX. can be used to measure the

reading speed for different contrast levels. Reading speed measurements are easy with REX eye chart because, as in the MNREAD test, it consists of different phrases of identical length, equivalent to 10 words of standard length. The reading speed is given by:

reading speed (words/minute)= 600 / time required to read a phrase (secs)

Patient selection

Patient enrollment was stratified by visual acuity level in 3 groups: 1) normal and near-normal vision (VA at least 0.3 logMAR); mild low vision (VA less than 0.3 logMAR but 0.6 logMAR or more); low vision (VA less than 0.6 logMAR but 1.0 logMAR or more). We used the 0.6 and 0.3 logMAR cut-off values since the visual angle doubles between them. We did not include patients with severe low vision (less than 1.0 logMAR) in order to obtain a reliable estimate of the maximum reading speed.

Method of measurements

Visual acuity was measured with ETDRS charts at 2 meters and recorded in letters. Values were converted to logMAR for calculations. Contrast sensitivity was measured with Pelli-Robson charts at 1 meter. Reading ability was measured with the Italian version of the MNREAD charts at 20 cm. Finally, reading speed at variable levels of text contrast was obtained with the REX test at a distance of 20 cm with appropriate near correction, implying a character size subtending a visual angle of 1.3 logMAR. All measurements were obtained by trained personnel according to a standard protocol. Reading speed parameters with the MNREAD charts were computed according to a previously described method (X), while those with the REX test were calculated as described above.

Statistical methods

To assess the reliability of the REX test we obtained two measurements using charts 1 and 2 in a random order. We computed intraclass correlation coefficient and 95% limits of agreement from multilevel or variance component models (X). Particularly, we obtained the reliability of each sentence of the REX test and of global measures of performance such as: 1) the mean of the values of reading speed of all sentences in a single REX assessment; 2) contrast reading acuity, or the contrast threshold at which a few words of a sentences could be recognized. The reliability of maximum reading speed with the REX test was not obtained since a plateau of the reading speed values across sentences with decreasing contrast was not found in most patients with low vision in this series, as explained in the Results section.

To estimate the impact of reduced text contrast on reading speed we used a mixed model to obtain a smoothing of the reading speed curve of each test, with non linearity accounted for by a cubic spline with 2 knots as a level 1 random effect and the individual as a level 2 random effect to include the test-retest assessments in the model. This model showed a very good fit for all tests at a graphical exploration of the predicted vs. observed values for each individual. Then we computed the change in reading speed form the first (90% contrast) to the third (45% contrast) sentence of the REX test. We choose the 45% level since this is commonly found in reading material, such as in newspapers and magazines with a colored background. Finally, we computed the proportion of people with a drop of reading speed of 10% and 20% at the third sentence using the estimates from a logistic regression model. Such a drop means that a maximum reading speed is achieved only at very high text contrast and is usually associated with the need of using electronic aids for contrast enhancement to maximize reading speed. We estimated this proportion according to the level of ETDRS visual acuity as well as that of Pelli-Robson contrast sensitivity. We also obtained receiver operating characteristic (ROC) from logistic regression models to compute the area under the curve (AUC) for the ability of ETDRS visual acuity and Pelli-Robson contrast sensitivity to diagnose a 20% reduction of reading speed, defined as above.

Results

People in the study were 99 individuals selected according to three levels of visual acuity in the better eye. Table 1 presents age and visual function data for each of the three visual groups. Among 33 subjects with normal or near-normal vision minimal cataract was found in 3 subjects and diabetic retinopathy in 1 subjects. Choroidal neovascularization due to age-related macular degeneration was found in 16 out of 33 subjects with mild low vision and in 25 out of 33 subjects with moderate low-vision. Diabetic retinopathy was the primary cause of visual loss in 13 subjects with low-vision, whereas less common causes were cataract, pathologic myopia, genetic retinal diseases, macular pucker.

Reliability of REX test measurements

Figure 1 shows the 95% limits of agreement of reading speed for each REX sentence in the three groups. The larger variability at the contrast acuity limit means that the chart is less reliable at this level, as expected. As seen in Table 2, the reliability of REX test measurements is very good for people with normal vision or mild low vision. For patients with moderate low-vision intraclass correlation coefficients are very high, suggesting good ability to discriminate between subjects, but 95% limits of agreement are relatively large, meaning that small intraindividual variation of speed or acuity should be not regarded as clinically significant in most cases. When $\log_{10}$ limits of agreement are converted to percent change, a significant change of mean reading speed with the REX test is diagnosed if it exceeds the limits of -27% or +36%, which is still close to values found in patients with retinitis pigmentosa (Virgili) and in children (Virgili) with the MREAD charts. For contrast reading acuity the limits would be -33% and +50% in text contrast.
In general, mean reading speed with the REX test was equally correlated (Pearson r between 0.77 and 0.82) with several measures such as Pelli-Robson CS, ETDRS visual acuity, and REX contrast reading acuity. Despite the high correlation this means that only 60% of the variance of REX reading speed (i.e. the R-squared value) can be explained by these variables.
Contrast reading acuity also proved to be correlated well with CS measured with the Pelli-Robson chart (Pearson r = 0.88). However, if the contrast threshold assessed with the REX is matched with that obtained with the Pelli-Robson chart using Bland-Altman methods, a mean difference of 0.51 $\log_{10}$ units was found, i.e. the REX test yielded much higher values, and the 95% limits of agreement were wide (-0.08 to 1.10 $\log_{10}$ units), suggesting that different phenomena are studied with the two charts.

Impact of text contrast reduction on reading speed

Surprisingly, a reduction of the reading speed from the first (90% contrast) to the third (45% contrast) sentence of the REX test was common despite the fact that people with severe low vision were not included in our study. In fact a 10% or 20% drop of reading speed was found in nearly ½ and ¼ of the subjects with mild low-vision, respectively. Using ROC analysis a value of 1.20 $\log_{10}$ contrast sensitivity with the Pelli-Robson charts was 100% sensitive and 75% specific for detecting a 20% drop of reading speed, whereas a visual acuity of 0.4 logMAR was 95% sensitive but only 45% specific and the AUC was 0.95 and 0.81 respectively for the two measures.

Discussion

Contrast sensitivity is the visual requirement for which the largest reserve is needed to allow an individual to reach its maximum reading performance (whittaker). As a matter of fact, fluent

reading is achieved at 2-3 times the print size acuity limit but as many as 5-6 times the contrast acuity limit. Other requirements concern the field of view [number of letters visible], and in cases of maculopathy, central scotoma size and the resulting eccentricity of fixation.
It is common place in low vision rehabilitation that a contrast sensitivity below 10% based on the Pelli-Robson charts determines patient's inability to read at its maximum reading speed, implying the use of special aids such as electronic systems that enable to increase the contrast of the reading material. A surprising finding of this study is that a significant proportion of subjects with moderate visual loss experience a limitation of reading speed related to a modest decrease in text contrast such as found in common reading text. As a result the concept of maximum reading speed used for the relationship between reading speed and character size cannot be applied to many low-vision patients.

REX chart reliability
A consequence of the statement made above is that the reliability of reading speed function measured with the REX chart had to be estimated as the mean speed of all sentences. This measure proved to be very reliable for normal subjects and had a reliability close to that of the maximum reading speed with the MNREAD charts in people with low vision (pigmentosa).
The contrast acuity limit has very narrow confidence limits in subjects with near-normal vision, corresponding to about 3 words of a sentence, and about 12 words or slightly more than one sentence for those with moderate low vision. These results prove that the REX chart is sufficiently reliable to detect a meaningful clinical change of performance in clinical practice. In fact, they are similar to values obtained for CS with the Pelli-Robson chart, despite the fact that the latter were measured in healthy subjects (Lovie-Kitchin 2000).

Implications for clinical practice of reading rehabilitation
Another consequence of our findings is that contrast sensitivity should be tested regularly in all patients attending a reading rehabilitation clinic regardless of visual acuity, since about ¼ of those with moderate low vision has a reduction of speed at relatively good visual acuity levels of 0.3-0.6 logMAR.. We suggest that a contrast sensitivity level of 15% using the Pelli-Robson charts has the maximum sensitivity to detect this type of impairment in a mixed low-vision population such as ours. The use of the REX test is a more direct measure of contrast-related decrease in reading speed. A 1/3 drop of reading speed compared to the first sentence or the one with the highest contrast is a reliable indicator of the need for contrast enhancement to optimize the reading performance.

Limitations of this study
The main limitation of our study is that the effect of contrast on reading speed was investigated only for one spatial frequency, specifically a low frequency corresponding to about 1 cycle/degree. Previous research suggest that the relationship of reading speed with contrast is modified by character size but this can be explained by a scale factor. Therefore, if the overall ordering between these variables is maintained, then our conclusions should apply to the effect of contrast decrease on smaller characters that can be read my people with milder low-vision.
Another limitation is that people with severe low vision was not included in the study. However, the progressively increasing proportion of subjects with contrast-related reading speed impairment, yielding an estimated value of more than 60% for people with 20/200 vision, leads us to think that nearly all subjects below this level suffer from a reduction of reading speed with ordinary texts, that often have a contrast between 50% and 70%.

Conclusion
Our study shows that contrast sensitivity should be always be assessed in low-vision patients undergoing reading rehabilitation even at mild levels of low vision. The Pelli-Robson chart is a

valid instrument for screening for a potential decrease of reading speed associated with decreasing contrast and we suggest a cut-off value of 16%, corresponding to 1.2 log, of contrast sensitivity. A more direct way to measure this is using the REX chart, which proved to be reliable in this study.

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Table 1. Age and visual function data for the whole sample and for subjects in the 3 groups of visual acuity. Abbreviations: WPM: word per minute; logMAR: $\log_{10}$ of the minimum angle of resolution, logCS $\log_{10}$ contrast sensitivity; logCS: $\log_{10}$ contrast sensitivity.

	Overall (n. 99)	*Normal or near-normal (n. 33)*	*Mild low-vision (n. 33)*	*Moderate low-vision (n. 33)*
Age, median (min/max)	67 years (18 to 90)	35 years (18 to 89)	75 years (41 to 90)	67 years (40 to 85)
Visual acuity (ETDRS charts), min/max	0.0 to 1.0 logMAR	0.0 to 0.3 logMAR	0.3 to 0.6 logMAR	0.6 to 1.0 logMAR
Measure	*Mean (standard deviation)*			
Contrast sensitivity (Pelli-Robson charts)	1.21 logCS (0.37)	1.57 logCS (0.21)	1.11 logCS (0.32)	0.95 logCS (0.26)
MNREAD maximum reading speed	1.94 logWPM (0.28)	2.16 logWPM (0.15)	1.96 logWPM (0.17)	1.69 logWPM (0.25)
MNREAD reading acuity	1.21 logMAR (0.37)	0.09 logMAR (0.13)	0.47 logMAR (0.17)	0.69 logMAR (0.15)
REX mean reading speed	1.80 logWPM (0.29)	2.09 logWPM (0.14)	1.77 logWPM (0.19)	1.55 logWPM (0.23)
REX reading contrast acuity	1.37 logCS (0.34)	1.81 logCS (0.22)	1.26 logCS (0.38)	1.05 logCS (0.27)

Table 2. Reliability of reading speed and contrast reading acuity measurement for selected indexes of performance with the REX test. Both 95% limits of agreement (upper line in each cell) and the intraclass correlation oefficient (lower line in each cell, in parentheses) are shown. Abbreviations: WPM: word per minute; logMAR: $\log_{10}$ of the minimum angle of resolution, logCS $\log_{10}$ contrast sensitivity; logCS: $\log_{10}$ contrast sensitivity.

Measure	Overall	Visual acuity 0.0 to 0.3 logMAR	Visual acuity 0.3 to 0.6 logMAR	Visual acuity 0.6 to 1.0 logMAR
Any sentence*	±0.175 logWPM ($\rho = 0.94$)	±0.145 logWPM ($\rho = 0.89$)	±0.172 logWPM ($\rho = 0.90$)	±0.240 logWPM ($\rho = 0.89$)
Mean reading speed of all sentences	±0.103 logWPM ($\rho = 0.99$)	±0.077 logWPM ($\rho = 0.98$)	±0.087WPM ($\rho = 0.98$)	±0.134 logWPM ($\rho = 0.96$)
Contrast reading acuity	±0.109 logCS ($\rho = 0.99$)	±0.049 logCS ($\rho = 0.99$)	±0.051 logCS ($\rho = 1.00$)	±0.175 logCS ($\rho = 0.95$)

(*) except for the 2 sentences closer to the contrast reading acuity limit

Table 3. Percentage of subjects with a drop of 10% or 20% from the first (90% text contrast) to the third (45% text contrast) sentence of the REX test. Percentages are computed from crude data for visual acuity groups and from logistic regression models for Pelli-Robson contrast sensitivity (CS, expressed as log_{10}) and ETDRS visual acuity (in logMAR).

		Change of reading speed from 90% to 45% text contrast with the REX test	
		-10% or worse	-20% or worse
ETDRS visual acuity group (crude data)	0.0 to 0.3 logMAR	3% (1/33)	3% (1/33)
	0.3 to 0.6 logMAR	45% (15/33)	24% (8/33)
	0.6 to 1.0 logMAR	78% (25/32)*	44% (14/32)*
Pelli-Robson contrast sensitivity (model estimated probability)	1.35 logCS	8%	1%
	1.20 logCS	34%	6%
	1.05 logCS	74%	20%
ETDRS visual acuity (model estimated probability)	0.3 logMAR	23%	12%
	0.6 logMAR	66%	32%
	0.9 logMAR	92%	62%

(*) one patient could read only 2 REX sentences

Figure 1. Mean error and measurement error for test-retest of each sentence of the REX test by group of visual acuity.

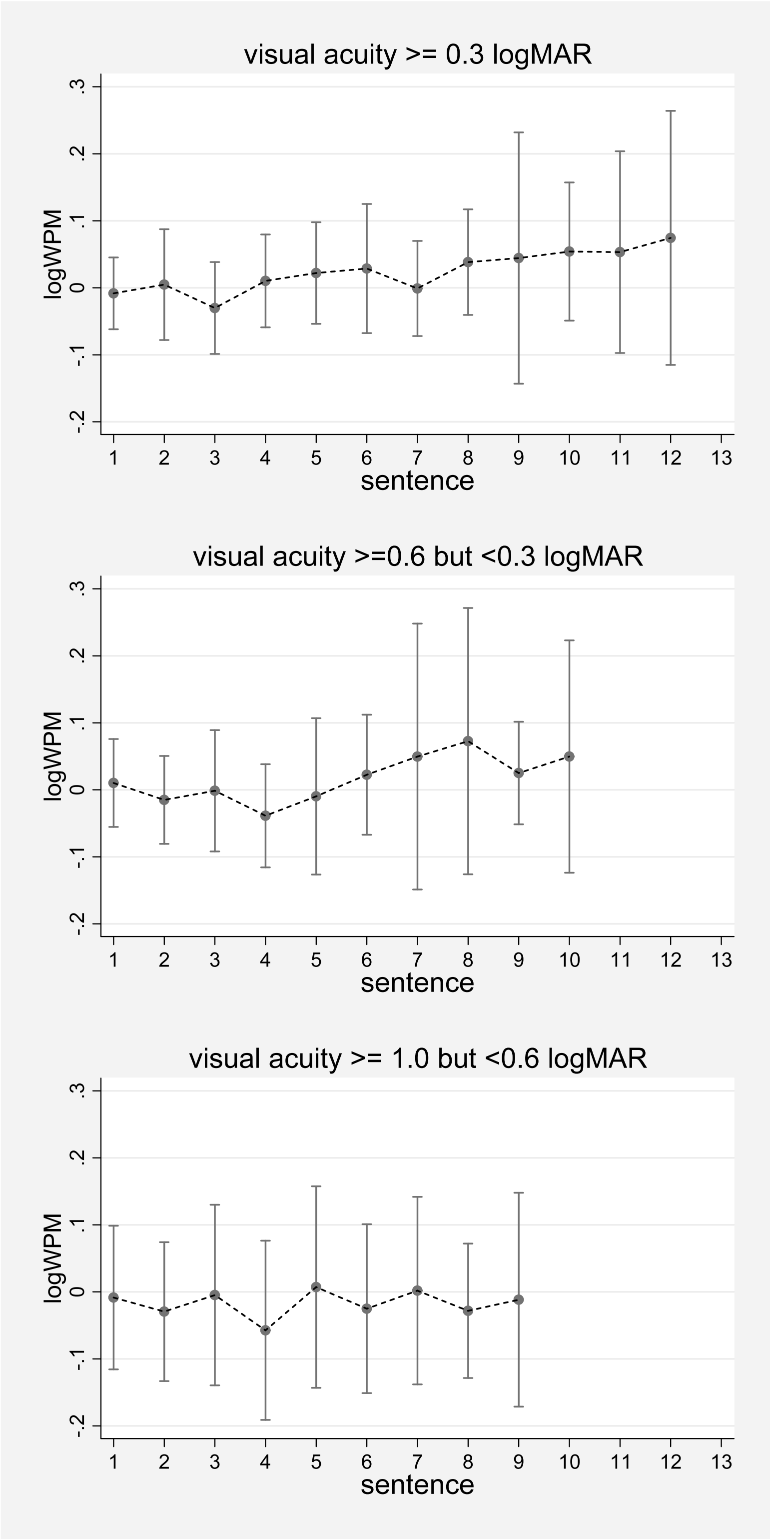

Figure 2. Receiver Operating Characteristic (ROC) curves plotting the sensitivity and (1 minus) specificity of Pelli-Robson contrast sensitivity (expressed as $\log_{10}$ units) and ETDRS visual acuity (in logMAR) for detecting a 20% drop of reading speed from the first (90% text contrast) to the third (45% text contrast) sentence of the REX test.