Clinical and Microperimetric Predictors of Reading Speed in Low Vision Patients: A Structural Equation Modeling Approach

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Purpose. To investigate the simultaneous association of several psychophysical measures with reading ability in patients with mild and moderate low vision attending rehabilitation services.

Methods. Standard measurements of reading ability (Minnesota Reading [MNREAD] charts), visual acuity (Early Treatment of Diabetic Retinopathy Study [ETDRS] charts), contrast sensitivity (Pelli-Robson charts), reading contrast threshold (Reading Explorer [REX] charts), retinal sensitivity, and fixation stability and localization (Micro Perimeter 1 [MP1] fundus perimetry) were obtained in 160 low vision patients with better eye visual acuity ranging from 0.3 to 1.0 logarithm of the minimum angle of resolution and affected by either age-related macular degeneration or diabetic retinopathy.

Results. All variables were moderately associated with reading performance measures (MNREAD reading speed and reading acuity and REX reading contrast threshold), as well as among each other. In a structural equation model, REX reading contrast threshold was highly associated with MNREAD reading speed (standardized coefficient, 0.63) and moderately associated with reading acuity (standardized coefficient, −0.30). REX test also mediated the effects of Pelli-Robson contrast sensitivity (standardized coefficient, 0.44), MP1 fixation eccentricity (standardized coefficient, −0.19), and the mean retinal sensitivity (standardized coefficient, 0.23) on reading performance. The MP1 fixation stability was associated with both MNREAD reading acuity (standardized coefficient, −0.24) and MNREAD reading speed (standardized coefficient, 0.23), while ETDRS visual acuity only affected reading acuity (standardized coefficient, 0.44).

Conclusions. Fixation instability and contrast sensitivity loss are key factors limiting reading performance of patients with mild or moderate low vision. REX charts directly assess the impact of text contrast on letter recognition and text navigation and may be a useful aid in reading rehabilitation.

Keywords: low vision, reading

Reading impairment has been found to be the most common complaint among low vision patients attending focus groups in quality-of-life investigation settings.[1–3] Reading ability is not only an important function in daily living tasks but also a complex psychophysical measure, including two related dimensions, reading speed (RS) and reading acuity (RA).[4] Reading ability is not routinely measured during most clinical examinations; nonetheless, detecting people with reading disability is important so that clinicians can refer these patients to low vision services. Visual acuity (VA), as the worldwide standard measure of vision function, is a simple criterion for assessing the need for referral, but reduced VA predicts only in part the level of reading impairment in low vision people and, particularly, has a poor correlation with RS.[5] Research has found that contrast sensitivity (CS) is also a predictor of RS.[6,7]

The investigation of the complex associations among clinical predictors of reading ability in low vision patients may be useful to set realistic expectations of low vision rehabilitation and personalize the rehabilitation plan. Previous research has identified several predictors of reading performance in low vision patients, including reading and letter CS,[6,7] the presence of a deep scotoma in the retinal reading area,[5,8–11] fixation features (such as eccentricity, usually related to scotoma size),[12–14] and fixation stability.[15–17] Although microperimetry has increasingly been used in low vision research,[9,10,13,18–20] Micro Perimeter 1 (MP1; Nidek Technologies Inc., Padova, Italy) retinal sensitivity has not been compared with other psychophysical measures as a predictor of reading ability in low vision patients to the best of our knowledge. Moreover, we have recently introduced Reading Explorer (REX) charts to directly measure the effect of reading material contrast on RS,

finding that the impact of reduced contrast on reading is undervalued,[7] and we expanded on this finding in a larger, multicenter study. Furthermore, previous studies have mainly used regression methods to analyze their data, thus analyzing the effect of predictors on a single variable at a time. To overcome all these limitations in the present study, we aimed to investigate the simultaneous association of several psychophysical measures with reading ability in patients with mild and moderate low vision attending rehabilitation services. We used structural equation modeling (SEM) statistical techniques to achieve this goal because, among their many applications, they can assess complex patterns of associations among several variables and decompose such relationships into direct and indirect effects or mediated effects.[21]

Methods

Patient Selection

We studied 160 patients with visual loss due to advanced age-related macular degeneration (AMD) or diabetic retinopathy (DR) complicated by macular edema. Patients had been referred to five low vision clinics for reading rehabilitation. All patients were older than 50 years and were included only if they had clinically stable macular changes and visual function during the previous 6 months. Exclusion criteria were maculopathy due to causes other than AMD or DR, cataract exceeding Lens Opacities Classification System (LOCS) III grade 3, education lower than grade 3, and informed consent not obtained. Patients who had undergone previous visual training were also excluded because it could have changed their fixation pattern and location and may have altered the relationship among the variables considered in this study.

Patient enrollment was stratified in the following two groups according to VA in the better eye: mild low vision (VA 0.3–0.5 logarithm of the minimum angle of resolution [logMAR]) and moderate low vision (VA 0.6–1.0 logMAR). The logMAR values were rounded up or down to the nearest first decimal (e.g., 0.26 logMAR was included in the mild low vision group). Inclusion was also stratified by disease (AMD or DR) to ensure balanced VA across the two disease groups. Patient enrollment was consecutive within each stratum.

Psychophysical Testing

Only the eye with better Early Treatment of Diabetic Retinopathy Study (ETDRS) VA was considered for each patient in the study. If a patient had similar VA in both eyes (i.e., within 5 ETDRS letters), the patient was asked which eye he or she preferred more for reading and other near tasks. An appropriate optical correction was used for all tests.

Visual acuity was measured with ETDRS charts at 2 meters (m) and recorded as logMAR.[22] Contrast sensitivity was measured with Pelli-Robson charts at 1 m and recorded as log10 CS.[23] Reading ability was measured with the Italian version of Minnesota Reading (MNREAD) charts at 20 cm to obtain maximum RS (log10 words per minute), RA, and critical print size (recorded as logMAR) according to methods previously described.[24] Reading speed at variable levels of text contrast was obtained with REX test[7] at a distance of 20 cm, and the text contrast at which reading became impossible was recorded as log10 reading CS, which for clarity will be referred to as the reading contrast threshold, or the one at which reading became impossible.

A 20-cm distance was adopted because it allows recording of the reading time of at least a few MNREAD sentences at a maximum RS, enabling a more reliable measurement. A +5-diopter near correction was used during reading testing. All measurements were obtained once for each patient.

MP1 Microperimetric Testing

The MP1 (Nidek Technologies Inc.) was used to study the location and stability of fixation and macular sensitivity. To study the sites of the preferred retinal locus (PRL), the patient's task was to fixate a red circle (2° in diameter) and to maintain fixation on the center of this target for 30 seconds. The nontested eye was occluded throughout the procedure. This fixation test was followed by static perimetry using MP1. The sensitivity of the central visual field was tested with a 10° 10-dB program during which "white" test lights (Goldmann III stimulus size and duration of 200 ms) were presented on a dim "white" background (1.27 cd/m^2) using a 4 −2 −1 threshold strategy. A custom grid of 19 stimulation points centered on the fixation area (fovea or PRL if an eccentric fixation was present) was used as shown in Figure 1. Stimuli were spaced 1° apart both in horizontal and in vertical order so as to study a larger area in the right and inferior visual field and achieve a better measurement of retinal sensitivity in areas that are thought to be more used in reading. With reference to Figure 1, an absolute parafoveal scotoma at the four cardinal positions was identified if a retinal sensitivity of 0 dB was detected at P13 (right location), P11 (left location), P7 (inferior location), or P17 (superior location). We used central and parafoveal retinal sensitivity because they are more repeatable[20] and explore an area that is used for reading in subjects with central scotoma. We did not try to measure scotoma size mainly because the definition of complex relative scotoma is subjective. Furthermore, adoption of a much larger MP1 grid on the one hand would lengthen the test time and on the other hand could alter the association of the mean retinal sensitivity with reading performance by exploring retinal areas not used for reading in patients with better vision.

The location of each patient's PRL was referenced to the fovea, and the distance and direction in millimeters were converted to degrees according to strategies described by others.[18,25,26] Fixation stability was previously defined in terms of the percentage of fixation points that fall within a 2°-diameter circle during the visual field test. We did not record fixation stability as the bivariate contour ellipse area because our study was planned and conducted before this measure proved to yield better correlation with RS than percentage 2° stability using MP1 microperimetry.[26]

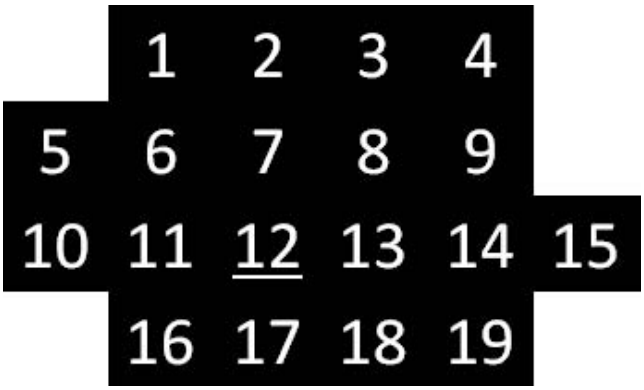

Figure 1. Micro Perimeter 1 stimulation grid on the central retina. These points were distanced 1° from each another. Stimuli were more represented in the right and inferior visual field (left and superior retina) with respect to the fixation point, which is *underlined* in the figure (point number 12).

Table 1. Mean (SD) Values of Relevant Psychophysical Variables of Patients With Mild Low Vision (0.3–0.5 logMAR VA) or Moderate Low Vision (0.6–1.0 logMAR VA) Based on Better Eye VA

Test	Mild Low Vision	Moderate Low Vision
Patients, *n*	82	78
MNREAD reading speed, log10 words/min	1.84 (0.27)	1.64 (0.32)
MNREAD reading acuity, logMAR	0.65 (0.24)	1.03 (0.27)
MNREAD critical print size, logMAR	0.44 (0.23)	0.72 (0.21)
Pelli-Robson CS, log10 CS	1.25 (0.09)	0.96 (0.34)
REX reading contrast threshold, log10 CS	1.03 (0.30)	0.75 (0.34)
MP1 mean sensitivity, db	6.7 (4.3)	4.9 (4.3)
MP1 mean eccentricity, °	1.22 (1.36)	3.00 (3.99)
MP1 fixation stability within 2°, %	0.79 (0.24)	0.56 (0.29)

Statistical Analysis

Structural equation modeling is a popular statistical techniques in psychology and the social sciences mainly due to the ability to specify latent variable models in which unobserved variables, or latent constructs, are estimated using their manifest indicators (measurement model). The relationships among constructs are also modeled (structural model).[18]

Another commonly acknowledged strength of SEM is the availability of measures of global fit that can provide a summary evaluation of even complex models that involve a large number of linear equations, simultaneously investigating direct and indirect effects of the covariates. Most alternative procedures that might be used in place of SEM (e.g., multiple regression) to test such models would provide only separate "minitests" of model components that are conducted on an equation-by-equation basis.[21] In addition, via nested χ^2 tests and other means, users can comparatively evaluate the fit of alternative models that differ in complexity.

Structural equation modeling has limitations, including the fact that users very rarely consider interactions and nonlinear association. Moreover, alternative models may be available that could fit the data equally well or better, and authors tend to overstate the certainty and strength of the conclusions yielded by SEM. Being aware of these limitations, we find that SEM is preferable to carrying out a number of separate multivariate regressions of highly correlated variables such as known predictors of reading performance.

A preliminary investigation of the correlation pattern among the variables included in our model was performed using Spearman rank correlation. We then constructed SEM[21] starting from a model in which MNREAD RA and RS, as well as REX reading contrast threshold, were endogenous variables (i.e., variables with any path pointing at them), which are at the left side of an equation in the model, as opposed to exogenous variables. Correlations among the three endogenous reading variables were allowed in the model because this was not only expected but also interesting to measure after accounting for relationships among variables in the model. We used a two-stage process to build the final SEM. First, we fitted multiple linear regressions using MNREAD and REX testing variables as dependent variables and eliminated nonsignificant variables from each regression using a backward procedure. The base SEM was built using these variables. Second, we introduced each variable according to its significance level in the univariate model in SEM one at a time, and we used modification indexes to identify relevant missing paths. Modification indexes are a goodness-of-fit measure in SEM and report χ^2 significance values for each omitted path in the model.

All coefficients were computed on standardized variables and can be interpreted as the difference from the mean in SD units of the dependent variable per each SD unit from the mean of the independent variable. We used an asymptotic distribution free estimation method because it makes no assumption of joint normality or even symmetry and there was evidence of violation of multivariate normality assumptions. Analyses were conducted using the SEM routine in STATA 12.1 software (StataCorp LP, College Station, TX).

Results

The mean (SD) subject age was 75 (10) years and did not differ between 82 patients with mild low vision and 78 patients with moderate low vision. The mean age was 77 years for 123 AMD subjects and 69 years for 37 DR subjects (some individuals had both AMD and DR), and there were no VA differences between the disease groups, as per the study design. Table 1 gives the mean values of measured psychophysical variables for each VA group.

Correlation of Psychophysical Measures With Reading Performance

Table 2 gives Spearman rank correlation coefficients of MNREAD reading outcomes and REX reading contrast threshold among each other, as well as with all psychophysical measures considered in the study. In this table, correlations of 0.50 or higher are in bold print. REX reading contrast threshold was correlated with MNREAD RA and RS. MNREAD RA was correlated with ETDRS VA to a similar extent. Pelli-Robson CS was correlated with REX reading contrast threshold. All other variables showed a weaker correlation, between approximately 0.11 and 0.44 in absolute value, with the reading variables measured by means of MNREAD and REX tests. Because MNREAD critical print size, although a useful measure for reading rehabilitation, is measured discretely and is thus more prone to error, it was not considered in further analyses.

SEM of the Association Between Reading and Other Variables

The final SEM and estimated coefficients are shown in Figure 2. Each coefficient is simultaneously adjusted for those in all the pathways of SEM. Therefore, their low values are not surprising given the multivariate adjustment. On average, a difference of 1 SD on the scale of a covariate was associated with a 0.2 difference in the independent variable in absolute value, but four paths had a coefficient between 0.3 and 0.6.

The strongest association of MNREAD RA in our SEM (standardized coefficient, 0.43; 95% confidence interval [CI], 0.33–0.53) was recorded with ETDRS VA, which is consistent with the interpretation that letter recognition is the basic requirement for reading. REX contrast threshold was the second strongest association (standardized coefficient, –0.30;

Table 2. Pearson Product Moment Correlations Between Reading Performance Measures and the Variables Collected by Means of Other Tests

Test	MNREAD Reading Speed	MNREAD Reading Acuity	REX Reading Contrast Threshold
MNREAD reading speed	1		
MNREAD reading acuity	**−0.69**	1	
MNREAD critical print size	−0.23	0.50	−0.28
REX reading contrast threshold	**0.61**	**−0.66**	1
ETDRS visual acuity	−0.40	**−0.67**	−0.36
Pelli-Robson CS	0.37	−0.39	**0.54**
MP1 fixation stability within 2°	0.42	**−0.51**	0.34
MP1 mean sensitivity	0.28	−0.18	0.35
MP1 mean eccentricity	−0.34	0.39	−0.26

Correlation coefficients exceeding 0.50 in absolute value are in bold print. All correlations were statistically significant at $P < 0.05$.

95% CI, −0.47 to −0.13), followed by MP1 fixation stability (standardized coefficient, −0.24; 95% CI, −0.34 to −0.13). Differences between coefficients were all statistically significant at $P < 0.001$. R^2 value (i.e., the amount of MNREAD RA variance explained by the covariates) was 0.56.

MNREAD RS was substantially associated with REX reading contrast threshold (standardized coefficient, 0.63; 95% CI, 0.43–0.83) and much less with MP1 fixation stability (standardized coefficient, 0.23; 95% CI, 0.10–0.37). The regression explained 33% of MNREAD RS variability.

REX reading contrast threshold was able to mediate the effect of Pelli-Robson single-letter CS on reading performance, confirming REX test structural validity. In fact, Pelli-Robson CS was associated with REX contrast threshold (standardized coefficient, 0.44; 95% CI, 0.33–0.55) but did not maintain a direct association with MNREAD variables in SEM. Both fixation eccentricity (standardized coefficient, −0.19; 95% CI, −0.29 to −0.09) and the mean retinal sensitivity (standardized coefficient, 0.23; 95% CI, −0.37 to −0.10), measured by MP1 microperimetry, were modestly associated with REX reading contrast threshold. Thirty-seven percent of REX reading contrast threshold variance was explained by these covariates. The standardized indirect effects of Pelli-Robson CS, mean retinal sensitivity, and fixation eccentricity, mediated by REX contrast threshold on MNREAD RS, were 0.28 (95% CI, 0.22–0.33), −0.12 (95% CI, 0.08–0.16), and 0.14 (95% CI, 0.10–0.19), respectively.

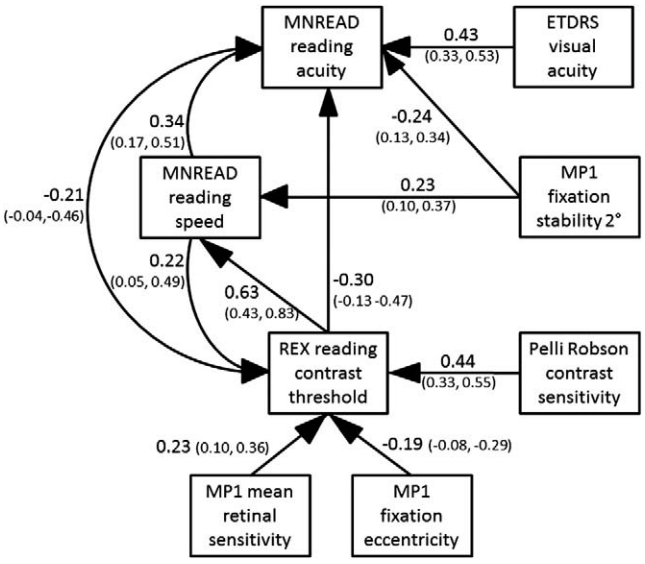

Figure 2. Structural equations model with MNREAD RA and RS and REX reading contrast threshold as endogenous variables (i.e., those with an *arrow* pointing at it, thus being at the left side of an equation) and with the other variables as exogenous variables. All regression coefficients are standardized, and their 95% CI is in *parentheses*. *Curved arrows* are covariances and can be directly interpreted as correlation coefficients using standardized data.

Curved pathways in SEM are covariances among dependent variables and can be directly interpreted as correlation coefficients with standardized variables. Modest residual correlation remained among MNREAD RA and RS and REX reading contrast threshold, which is compatible with unexplained variability. Nonetheless, 65% of the overall variance was explained by the variables in SEM. Model fit was good compared with the saturated model ($P = 0.375$), and all coefficients were statistically significant at $P < 0.05$. Patient age was not associated with any reading variable.

Secondary Analyses of the Effect of VA Group on SEM and the Effect of Scotoma Location on RS

We tested the difference in path coefficients between groups with higher (≥0.6 logMAR) or lower (<0.6 logMAR) VA in SEM. We found that only the effect of MP1 fixation stability on MNREAD RS differed, demonstrating no effect on subjects with better vision (standardized coefficient, 0.00; 95% CI, −0.20 to 0.20; $P = 0.993$) and a great effect on subjects with worse vision (standardized coefficient, 0.42; 95% CI, 0.31–0.54; $P < 0.001$). The potential effect of disease type was not studied due to small numbers of patients with DR compared with patients with AMD, but it would have been limited by VA stratification within disease type.

Finally, as an additional analysis we used linear regression to explore the effect of absolute scotoma location on MNREAD RS. Table 3 gives the mean MNREAD RS for subjects with the presence or absence of absolute scotoma at 1° from fixation in each of the four cardinal directions. Only having an absolute scotoma to the right of fixation led to a statistically significant difference, corresponding to −39% speed in words per minute (95% CI, −0.23 to −0.52; $P < 0.001$). When the mean retinal sensitivity of each subject was taken into account in the regression, the presence of a right absolute scotoma was still associated with lower values of RS (−27.00%; 95% CI, −3.00% to −0.45%; $P = 0.034$). The direction with respect to the fovea is in reference to the patient's perspective so that on the MP1 retinal photographic map the "right" direction is temporal to fixation in the right eye and nasal in the left eye.

Discussion

Research on psychophysical predictors of reading performance may encompass a range of different perspectives. When the study aim is to estimate the effect of specific factors on reading in a clinical setting, common or investigational clinical predictors have been variably considered by researchers,

Table 3. Mean RS for Subjects With the Presence or Absence of Absolute Scotoma at 1° From Fixation in the Four Cardinal Directions

Scotoma Location (Absolute %)	Relative Scotoma, >0 db	Absolute Scotoma, 0 db	*P* Value	% (95% CI) Difference in Words per Minute
Superior (38%)	1.76 (0.29)	1.70 (0.34)	0.319	−14 (−32 to 9)
Inferior (31%)	1.77 (0.28)	1.68 (0.37)	0.159	−19 (−37 to 4)
Right (28%)	1.81 (0.27)	1.60 (0.34)	<0.001	−39 (−52 to −23)
Left (32%)	1.77 (0.28)	1.68 (0.35)	0.199	−12 (−32 to 15)

The *P* value for comparing the difference in means is presented, and the percentage difference is shown for inference, with 95% CIs. Only having an absolute scotoma right of fixation led to a statistically significant difference, corresponding to −39% in words per minute. The direction with respect to the fovea is in reference to the patient's perspective so that on the MP1 retinal photographic map the "right" direction is temporal to fixation in the right eye and nasal in the left eye.

including age and disease type, VA and CS, as well as scotoma characteristics such as scotoma depth, size, and location.[5,10–13,15] The effects on the reading rate of fixation eccentricity and stability and other features of eye movements, including saccade efficiency, have also been investigated.[11,13,16,18,26] Our study has included several of the above-mentioned measures in a large sample of consecutive patients with mild or moderate low vision collected at five low vision service centers in Italy. Because we expected these predictors to be reciprocally correlated and to have at best moderate degrees of independent association with reading performance, including RA and RS, we used SEM to simultaneously explore the network of associations among all variables. Based on the MEDLINE search used to prepare this article, we are not aware of any previous studies on predictors of reading performance using SEM, and we recommend wider use of this statistical technique in clinical and psychophysical low vision research when continuous variables can be obtained.

The most important finding in our study is the dominant and intermediary role of REX reading contrast threshold on MNREAD RS and RA. In fact, we found that the effect of text contrast on letter recognition and text navigation when reading large text as measured using REX charts integrates not only that of single-letter CS, which is expected, but also of fixation eccentricity and the mean retinal sensitivity. The importance of text contrast on the reading rate is consistent with data obtained in the REX test validation study,[7] which estimated that when text size is not a limiting factor one-third of patients with 0.6-logMAR VA and two-thirds of patients with 1.0-logMAR VA suffer from a 20% or more reduction in RS when text contrast decreases from 90% to 45%. The key role of text contrast in reading was recently supported by Crossland and Rubin,[27] who found that reduced text contrast restricts accessibility to the written word for a large number of people in the developed world, who would benefit from making text available in a format that can be presented on an LED computer monitor.

We also found that REX reading threshold mediates effects on MNREAD RA, possibly because contrast influences text navigation. Therefore, in our study a negative difference of 1 SD in REX reading contrast threshold (approximately 0.35 log10 CS) is associated not only with almost 40% lower MNREAD RS (approximately 0.2 log10 words per minute) but also with a reduction in MNREAD RA by approximately one MNREAD sentence (0.094 logMAR).We suggest that testing CS in a larger horizontal retinal area used for reading (compared with testing the ability to recognize single letters such as with Pelli-Robson charts) is a better way to detect the effect of text contrast on the visual span, which is the mechanism through which many visual factors affect RS.[28]

The results of previous studies[14,16] suggested that the size of absolute macular scotoma in AMD patients is a much better predictor of maximum RS than RA and other standard clinical predictors. We used the mean retinal sensitivity to estimate scotoma depth and fixation eccentricity to assess the impact of macular scotoma on reading. We found that the mean retinal sensitivity was weakly associated with REX reading contrast threshold, which mediates its effect on MNREAD reading performance measures. In secondary analyses, we found that having an absolute scotoma right of fixation reduces RS compared with other locations, which was an inconsistent finding in previous research.[9,29] The large sample size and the quantitative approach used could have contributed to this result.

We also found that fixation stability measured by means of MP1 microperimetry is an independent predictor of both RS and RA, which is in agreement with other studies.[12,14,17,18,26] Another study[30] using MP1 microperimetry in patients with wet or dry AMD found that PRL eccentricity was a predictor of RS. The authors argued that the PRL used by patients during a fixation task is also preferentially used during a reading task or is used at least in some critical periods of the reading process. We confirm this finding and found that REX reading contrast threshold was a mediator of this effect.

Strengths of our study are the multicenter, prospective collection of a large number of patients with mild or moderate low vision affected by either AMD or DR, which are leading causes of visual impairment. Our SEM exhibited good fit and was able to explain almost two-thirds of overall variance.

A limitation of our study is that we could not use a bivariate contour ellipse area to measure fixation stability by means of MP1 microperimetry, which may be preferable to the percentage of fixations within 2°, because this function had not been developed when we designed and conducted the study. The modest degree of association found by us could in fact be higher using the bivariate contour ellipse area as suggested by Crossland and Rubin.[27] Also, the results of our study suggest that eye movement patterns should be measured more consistently in studies trying to assess the relative contribution of basic psychophysical variables to reading performance. However, we lacked the appropriate instruments (such as eye trackers) for this purpose.

In conclusion, we simultaneously modeled a complete set of clinical psychophysical predictors of reading performance in a large, multicenter series of consecutive patients that is representative of people with mild and moderate low vision attending rehabilitation services. We found that text contrast as measured by means of REX charts is an important factor limiting RS performance even in patients with mild or moderate low vision. We also found that fixation stability is a consistent predictor of reading performance. We suggest that both of these measurements should be obtained from low vision patients to attempt a correction of text contrast by means of adequate lighting, selective filters, or electronic and computer-aided devices. Low vision therapists may consider fixation training in patients with poor stability to try to improve their reading performance.

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