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Relative locations of macular scotomas near the PRL: effect on low vision reading

Donald C. Fletcher, MD; Ronald A. Schuchard, PhD; Gale Watson, MEd

Retinal Consultants of Southwest Florida, Ft. Myers, FL 33901; University of South Florida, Dept of Ophthalmology; Schepens Eye Research Institute, Boston, MA 02114; VA Rehabilitation Research & Development Center, Decatur, GA 30033-4004

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Address all correspondence to Donald C. Fletcher, MD, Retinal Consultants of Southwest Florida, 2668 Winkler Ave, Ft. Myers, FL 33901; email: floridafletch@msn.com

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Abstract —

Patients referred for low vision rehabilitation had MNREAD Acuity (MNRead), visual acuity (VA), and scanning laser ophthalmoscope (SLO) macular function testing performed in their initial evaluation to determine whether dense macular scotomas near the preferred retinal locus (PRL) have a significant effect on the characteristics of reading based on rate. The 99 subjects had macular scotoma characteristics relative to the fovea/PRL of: 22% only to the right; 15% only to the left; 26% to both the right and left; 19% above or below; and 17% had no dense scotomas. Reading performance (maximum reading speed, critical print size, and reading acuity) was significantly different between the non-scotoma group and all of the scotoma groups. There was no statistically significant difference in the characteristics of reading based on rate between the four scotoma groups: within each there was a wide variation in the characteristics of reading based on rate not fully explained by either VA or scotoma location. The position of the scotoma relative to the PRL was not a statistically significant factor in determining reading rate as found in studies on normally sighted people with artificial scotomas. Other factors (e.g., maybe PRL ability in fixation and saccadic eye movements and/or cognitive ability) are significantly involved in determining reading rate characteristics in people with macular scotomas.

Key words: low vision, PRL, reading, scotomas, SLO, vision rehabilitation.

INTRODUCTION

At the onset of visual damage severe enough to affect visual functioning for reading or other daily life tasks, many people are referred to vision rehabilitation services. Clinicians working in this field quickly appreciate that patient performance cannot be predicted from visual acuity (VA) alone: the reading performance in persons with the same VA can vary widely. There are likely many factors at play in this patient-to-patient variation. This study addresses the role of macular scotoma disruptions in the characteristics of reading based on rate: maximum reading rate, critical print size, and reading acuity. Studies undertaken to examine the role of scotomas near fixation on reading performance have typically used normally sighted subjects with artificially induced scotomas. For example, Cummings and Rubin (1) reported results on normally sighted individuals that showed artificially induced scotomas to either the right or left of fixation significantly slowed the maximum reading rate, while artificial scotomas above or below fixation had no effect on that rate. Furthermore, an artificial scotoma immediately to the right of fixation slowed reading rate by 64 percent, and one immediately to the left slowed it by 36 percent. A theoretical basis for vision rehabilitation therapy has been developed on these artificial scotoma results (2). The effect of scotomas on reading is not as well studied in people with permanent pathology, whose visual systems have adapted to the macular scotomas. When a person lives day-in and day-out with a macular scotoma, it is possible or likely that compensations develop that are not seen in those who only experience an artificial scotoma in a laboratory setting. It is also possible that a preferred retinal locus (PRL) in compromised retina performs differently than a PRL at the same location but in healthy retina. To begin testing these hypotheses, we studied the relationship of macular scotomas to reading rate characteristics in people whose visual system had adapted to well-established macular scotomas.

Scotomas are retinal areas with reduced light sensitivity compared to sensitivity results of normally sighted subjects. Scotomas are specified by the retinal location, in that central scotomas involve the fovea and macular scotomas involve the maculae, the retinal region within the central 5 to 7° around the fovea. Scotomas are further defined by the light intensity used to map their extent. For example, dense scotomas (sometimes labelled absolute scotomas) are insensitive to very bright objects, while relative scotomas are insensitive to a light level relatively less than the very bright object.

The visual system of a person with a central scotoma unconsciously chooses an eccentric retinal area, the PRL, to perform the visual tasks that the non-functioning fovea used to perform: fixation, reading, or tracking. Such persons perform these tasks by aiming the eye to place the image of the visual target of regard within their PRL. There have been no consistent reports as to the retinal location of these PRLs, except that previous studies using the scanning laser ophthalmoscope (SLO) demonstrated that the vast majority of them are close to the dense scotomas (3,4). It would seem reasonable to think that the PRL would be established below the central scotoma in the visual field to keep the scotoma out of the important parts of the visual field. However, PRLs are found in all directions around a central scotoma (5-8). Fletcher and Schuchard (8) reported that the distribution of scotoma locations relative to the fovea or PRL were: above, 46 percent; below 29, percent; right, 49 percent; and left, 32 percent. Therefore four out of five (81 percent) such persons are reading using strategies that must compensate for scotomas along the horizontal axis of the PRL.

People with macular scotomas report that reading is one the activities most inhibited, and better reading performance is one of their primary rehabilitative goals. Magnification can compensate for the loss of acuity to attain better reading performance; however, even after magnification devices are prescribed, readers with scotomas have slower reading rates (1,9-11) and read inaccurately, missing the ends or beginnings of words and skipping lines of text, (12,13); they read with reduced comprehension, (14,15); and they experience decreased endurance for reading, compared to normally sighted readers (16). Such readers then may have to supplement their reading with speech output devices such as audio tapes (Library for the Blind and Visually Impaired), electronic computer speech output devices, radio reading programs that provide local news for the blind, and television. Even for successful visual readers with scotomas, reading stamina and rate are limited; therefore, visual reading may be confined to activities that cannot be accessed in another way, such as managing finances, bills, mail, labels, price tags, medications, and short-term continuous text activities such as scanning the local newspaper or religious texts. Clinicians and researchers in vision rehabilitation seek to understand the reasons behind the slow reading rate and visual fatigue of these patients in order to devise strategies to assist them in regaining more of their former visual abilities.

METHODS

Subjects

A retrospective study was performed with 99 patients referred for low vision rehabilitation who had visual function/performance testing as part of their initial evaluation. All were referred on the basis of complaints of difficulty performing activities of daily living including reading. After all surgical, medical, and/or refractive interventions, they were still unable to read to their satisfaction due to a visual function loss. Inclusion was based on testing by the confocal SLO: subjects were selected by macular perimetry results that showed symmetrical relative macular scotoma locations to the PRL between the two eyes. Also included were those with a strong dominant eye (eye with much better visual function than the fellow eye), which led to either no PRL in the fellow eye or a PRL with much poorer ability than that of the dominant eye. Patients with best corrected VA that could not be measured by the ETDRS chart at 1 m, poorer than

20/800, were excluded, as were those with visual function test results considered unreliable, most commonly due to PRLs with poor fixation stability in both eyes.

Instruments

Retinal visual function was evaluated with the SLO (Model 101, Rodenstock USA, Inc., Danbury, CT). The graphics capabilities of this device allows the investigator to determine the retinal location of visual stimuli directly on the retinal image in real time. The confocal imaging selectively chooses between direct and scattered components of the laser light to give high contrast and clear retinal images without dilation of the pupil. The SLO obtains images continuously with a nearly invisible infrared laser (780 nm), and scans graphics on the retina with a modulated visible red-light laser (632 nm). The stimuli are thus observed by the subject and seen directly on the subject's retina by the investigator. The retinal illuminance of the stimuli is adjustable by 256 steps within the range of the visible light laser, about 50 to 50,000 Trolands. The SLO provides a 32×22° image of the retina with a minimum resolution of about 3.5 minutes of arc (17.5 μm) for measurement of the retinal areas and the positioning of targets.

The MNREAD Acuity (MNRead) charts are continuous text reading charts that can be used to measure the characteristics of reading based on rate in patients with low vision. They measure: 1) Reading acuity (RA): the smallest print that the patient can read without making significant errors; 2) Critical print size: the smallest print that the patient can read with maximum reading rate; and 3) Maximum reading rate: the patient's reading rate when reading is not limited by print size. The MNRead charts contain sentences with 19 different print sizes (11.61 mm to 0.184 mm high) that at the recommended viewing distance of 40 cm are from 1.3 LogMAR to -0.5 LogMAR (Snellen equivalents from 20/400 to 20/6). Each sentence contains 60 characters (including spaces), printed as three lines with even left and right margins. The vocabulary is selected from words appearing with high frequency in 2nd- and 3rd-grade level equivalent reading material.

Procedures

All visual function tests were performed by the same technician before any rehabilitation interventions were initiated. VA was measured with the ETDRS chart at 1 m, so at least the top line of the chart was read, and then scored letter-by-letter (17). Testing with the MNRead charts was performed binocularly in standard room lighting using the subject's regular bifocals or reading glasses (none stronger than a +3.50 add) without the use of magnifiers. The subjects read the text aloud and were discouraged from going back to correct previous mistakes, but encouraged to guess even when they believed the words were unreadable; any words missed or read incorrectly were marked on the score sheet. They were instructed to hold material at the distance where the text was in focus with their current spectacle correction. The distance was then adjusted and maintained at a reading distance between 10 and 40 cm in 5-cm increments that was closest to their preferred distance and recorded. Thus, reading distances were from 10 cm to 40 cm, resulting in the largest sentence text (11.61 mm high) being from 1.9 LogMAR (20/1600) to 1.3 LogMAR (20/400). Subjects started the RA test at that largest text size and continued down the smaller text sizes until it took them longer than 30 s to read a sentence.

SLO testing consisted of macular perimetry and locating the PRL. Macular perimetry was used to determine the presence and characteristics of dense macular scotomas by using a hybrid perimetry technique with the SLO (18). Briefly, the hybrid perimetry technique combines elements of kinetic and static methods. The stimulus is presented in stationary flashes, as in static perimetry, but successive flashes are moved randomly on the retina to map isopters, as in kinetic perimetry. Scotomas of 1° in linear dimension or larger can be detected with this technique. Dense macular scotomas (DMS) were defined as the retinal points where the subject no longer had appreciation for the target with retinal illuminance levels of the red-light laser at about 50,000 Trolands. The perimetry target was a square subtending 12 minutes of arc. Patients were divided into 5 groups on the basis of scotomas found symmetrically in both eyes or in the dominant eye with the macular perimetry:

1. No Scotoma: no DMS noted within the central visual field.
2. Vertical Scotoma: a DMS was noted above or below the PRL or fovea but not along the horizontal axis (right or left).
3. Right Scotoma: a DMS was noted along the horizontal axis to the right of the PRL or fovea but not to the left.
4. Left Scotoma: a DMS was noted along the horizontal axis to the left of the PRL or fovea but not to the right.
5. Right and Left Scotomas: DMSs were noted along the horizontal axis both to the right and to the left of the PRL or fovea.

The statistical examination of the distribution of variables as conditioned by the groups formed by the scotoma characteristics was done with a one-way analysis of variance (ANOVA). In addition, the statistical significance between the means of the groups was done with a Tukey-Kramer HSD (honestly significant difference) test which is a test that is sized for all differences among the means. This test is a conservative test even though the sample sizes determining the means are different. Significance was determined at the $\alpha=0.05$ level.

RESULTS

Of the 99 subjects, 17 percent had No Scotoma, 22 percent had Right Scotoma, 15 percent had Left Scotoma, 26 percent had a macular scotoma to both the right and left, and 19 percent had Right and Left Scotomas. These patients had best corrected VAs ranging from 0.31 to 1.46 LogMAR (20/40 to 20/580), with a median acuity of 0.88 LogMAR (20/150). Fifty percent had an acuity score between 0.53 and 1.14 LogMAR (20/100 and 20/280), while the best 10 percent had acuity scores between 0.31 and 0.52 LogMAR (20/40 and 20/70) and the worst 10 percent had acuity scores between 1.34 and 1.46 LogMAR (20/440 and 20/580). By scotoma group, the median VA values were 0.60 LogMAR (20/80) in the No Scotoma group, 1.03 LogMAR (20/210) in the Vertical Scotomas group, 0.85 LogMAR (20/140) in the Right and Left Scotomas group, 0.91 LogMAR (20/160) in the Left Scotoma group and 1.09 LogMAR (20/240) in the Right Scotoma group (see **Figure 1**). The mean VA values for all groups were significantly different than the mean for the No Scotoma group. The mean VA for the Right and Left Scotoma group was also significantly different from that of the Right Scotoma group. There was no significant difference in the mean acuity values between the other groups.

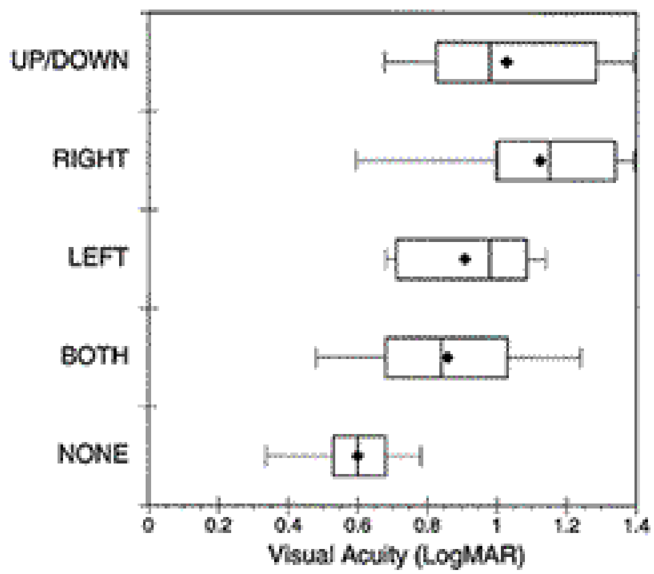

Figure 1. Visual acuity (VA) values as measured with an ETDRS chart at 1 m as a function of macular scotoma characteristics. The left, right, and line inside the box correspond to the 25th (bottom quartile), 75th (top quartile), and 50th percentile (median) respectively. The whiskers extend from the 10th percentile (bottom decile) to the 90th percentile (top decile). The mean is shown by the diamond inside the box.

The mean maximum reading rates were significantly slower for all of the scotoma groups compared to the mean for the No Scotoma group (see **Figure 2A**) that had a mean maximum reading rate of 232 words per minute (wpm); the mean maximum reading rates for the scotoma groups were about half that: Right Scotoma, 99 wpm; Right and Left Scotoma, 100 wpm; Left Scotoma, 123 wpm; and Vertical Scotoma, 124 wpm. There was no significant difference in the mean maximum reading rates between the four scotoma groups as shown in **Figure 2a**; **Figure 2b** shows the typical relationship between maximum reading rate and VA. Scotomas accounted for 33 percent of the variance in maximum reading rates, while VA accounted for 42 percent of the variance.

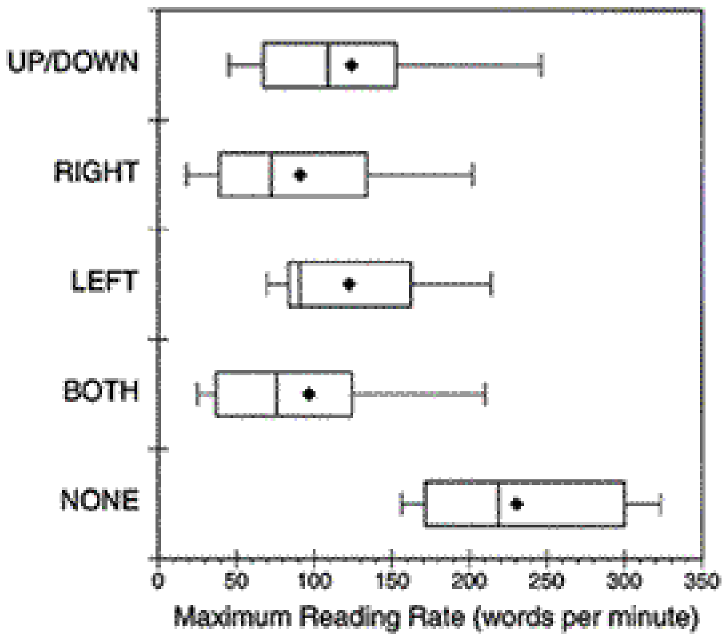

Figure 2a. Maximum reading rate as measured by MNRead as a function of scotoma characteristics (symbols as in **Figure 1**).

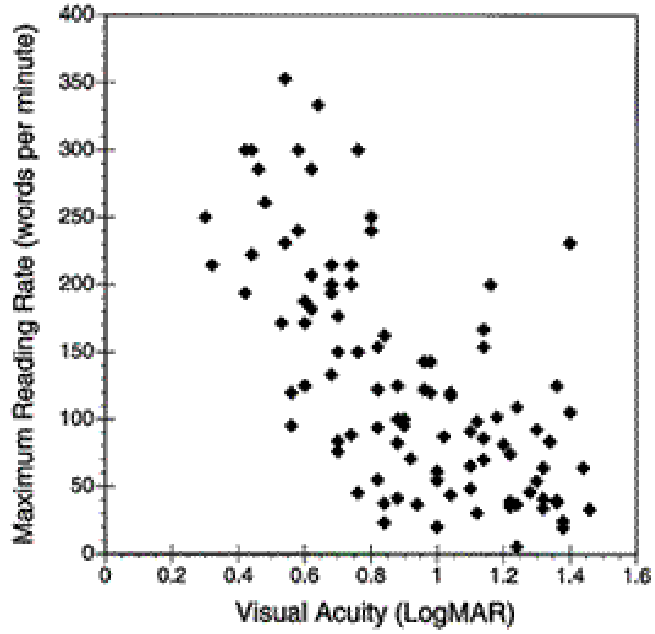

Figure 2b. Maximum reading rate as measured by VA.

The mean critical print sizes were significantly larger in all of the scotoma groups compared to the mean for the No Scotoma group (see **Figure 3A**) that had a mean critical print size of 0.65 LogMAR; those of the scotoma groups were larger: 1.33 LogMAR for Right Scotoma, 1.02 LogMAR for Right and Left Scotoma, 1.16 LogMAR for Left Scotoma, and 1.27 LogMAR for Vertical Scotoma. There was a significant difference in the mean critical print sizes between the Right and Left Scotoma group and the Right Scotoma group, but no significant difference in the other comparisons between the four scotoma groups as seen in **Figure 3a**. Scotoma characteristics accounted for 37 percent of the variance in critical print sizes while VA accounted for 57 percent of the variance (**Figure 3b**).

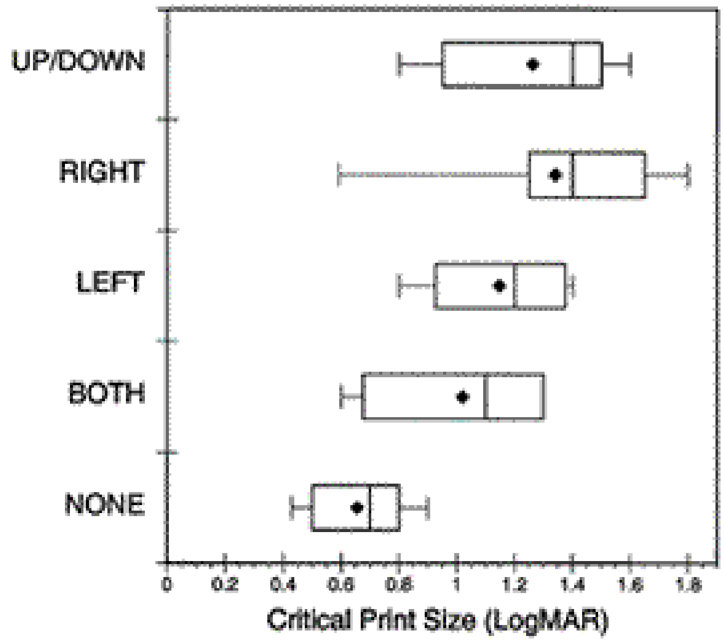

Figure 3a. Critical print size as measured by MNRead as a function of scotoma characteristics (symbols as in **Figure 1**).

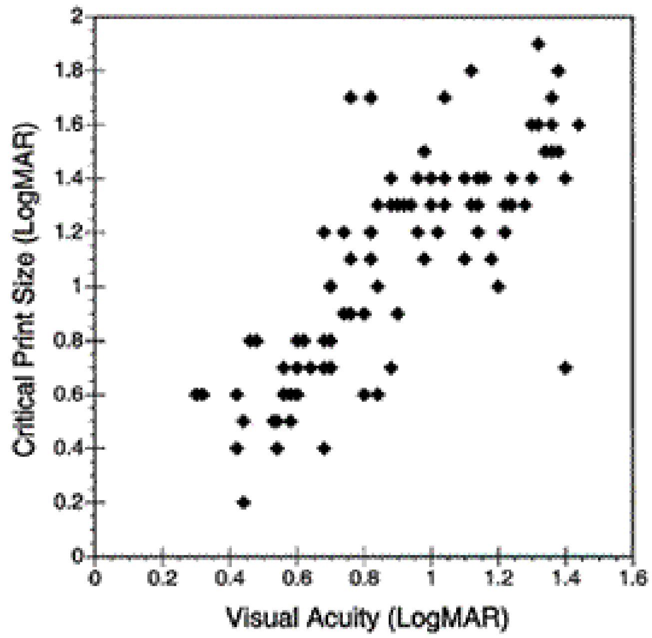

Figure 3b. Critical print size as measured by MNRead as a function of VA.

The mean RA values were significantly greater for all of the scotoma groups compared to that of the No Scotoma group (0.41 LogMAR; see **Figure 4a**): 1.11 LogMAR for the Right Scotoma group, 0.84 LogMAR for Right and Left Scotoma group, 0.89 LogMAR for the Left Scotoma group, and 1.05 LogMAR for the Vertical Scotoma group. As the figure shows, there was no significant difference in the RA between the four scotoma groups. Scotoma characteristics accounted for 33 percent of the variance in RA values, while VA accounted for 61 percent (**Figure 4b**).

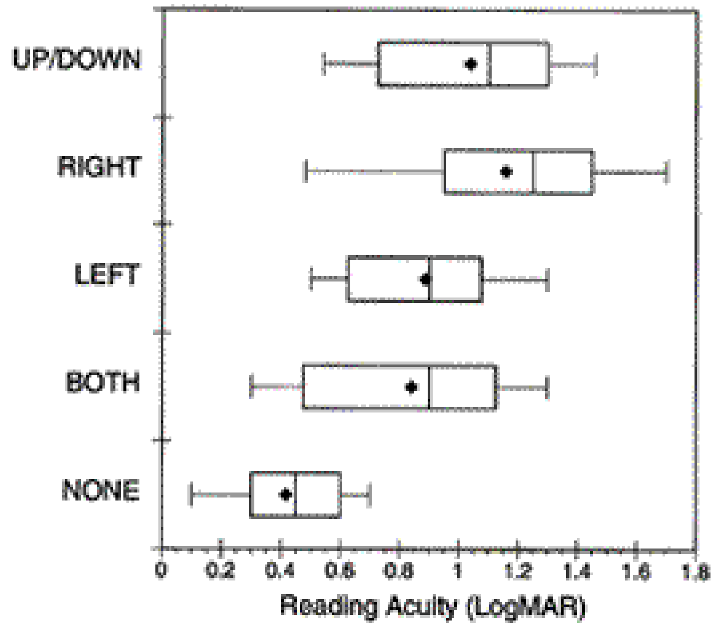

Figure 4a. Reading Acuity as measured by MNRead as a function of scotoma characteristics (symbols as in **Figure 1**).

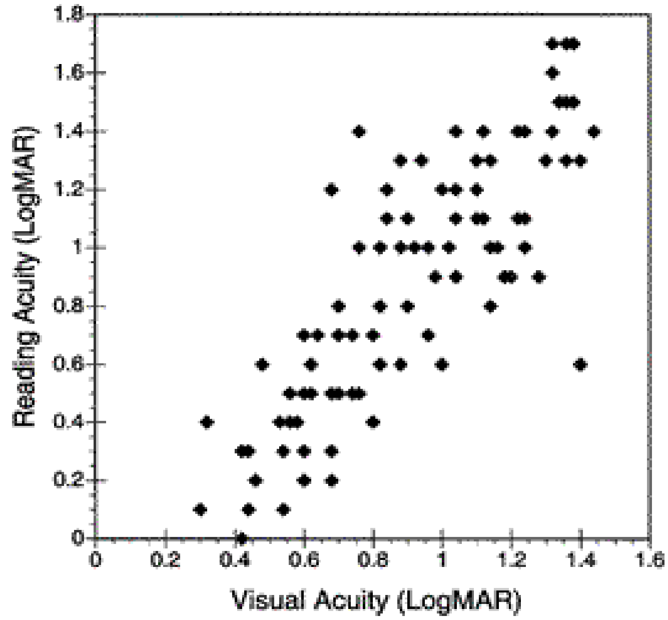

Figure 4b. Reading Acuity as measured by MNRead as a function of VA.

Finally, the results of the remaining reading performance factors were as follows. In comparing the slope of the reading rate as a function of the text size, the mean slope values were significantly smaller for all of the scotoma groups compared to the mean for the No Scotoma group. There was no significant difference in the slope values between the four scotoma groups. Scotoma characteristics accounted for 31 percent of the variance in the slope values, while VA accounted for only 16 percent. One third of the patients (34 percent) had no errors while reading the MNRead sentences. There was no significant difference in the mean error values between any of the groups. Scotoma characteristics accounted for only 4 percent of the variance in errors while VA accounted for only 8 percent. Nearly three quarters of the patients (73 percent) read 5 or more of the MNRead sentences. The mean number of sentences read was significantly less for all of the scotoma groups than for the No Scotoma group, who read 10.6 sentences. The Right Scotoma group read 5.7 sentences; the Right and Left Scotoma group read 7.2 sentences; the Left Scotoma group read 7.5 sentences; and the Vertical Scotoma group read 6.4 sentences. There was no significant difference in the number of sentences read between the four scotoma groups. Scotomas accounted for 26 percent of the variance in number of sentences read, while VA accounted for 61 percent.

DISCUSSION

In this study of patients with macular scotomas, the mean maximum reading rate decreased with declining VA and with the presence of scotomas. Both the range of acuity values and the scotoma presence had a significant influence on reading speed but VA was not related to the characteristics of the scotomas statistically. The presence of a scotoma close to the PRL (within 2°) in any direction significantly decreased reading rate. Interestingly though, the position of the scotoma relative to the PRL was not a statistically significant factor in determining maximum reading rate, as was the case in studies on normally sighted people with artificially induced scotomas. Therefore it cannot be said categorically that scotomas above or below fixation do not affect reading rate in low vision patients, as has been inferred from studies on normal subjects with artificial scotomas. Within the scotoma group there was a wide variation in reading rate characteristics not explained by relative scotoma location. That is, declining acuity and presence of scotomas does not explain all of the variance in reading rate characteristics (r^2=0.33 and r^2=0.42 respectively). It would appear that a major factor for reduced reading rate is the mere presence of a scotoma or scotomas near the PRL, while other factors besides the characteristics of the relative scotoma location influence the range of reading rate characteristics.

Other additional factors that influence reading rate characteristics in these subjects could include the ability of the PRL to maintain fixation stability and make efficient saccadic eye movements, as well as the cognitive abilities to process the abnormal visual information. Further studies may help to identify these factors and what rehabilitation techniques could be used to minimize their effect. The skill in using the PRL, including fixation losses into the scotoma, has been reported in previous studies. (11,19) These studies reported that subjects with macular scotomas accurately place the reading text within the PRL but average fewer letters per forward saccade and make more frequent regression eye movements. Patients in this study were evaluated with MNRead and the SLO prior to rehabilitation intervention. Other studies have demonstrated the effectiveness of eccentric viewing techniques in rehabilitation intervention on reading rate (2,20,23). The patients of this study may have shown differences in rate performance related to scotoma placement following such intervention. Another factor may be the eccentric location of the PRL, how far from the fovea the PRL is located. Studies have indicated that the central portion of the visual field is better than the eccentric or peripheral visual field for reading performance (21,22). This better reading performance is not related to the differences in visual sensitivity or spatio-temporal resolution between the fovea and the eccentric retinal locations but with some aspect of the visual cortical processes.

The role of cognition and comprehension in relation to reading cannot be ignored. For normally sighted individuals, slow reading is associated with poor comprehension, but this has proven untrue for readers with scotomas. In adults with scotomas who have good visual skills and cognitive abilities, rate and comprehension are unrelated, in that good comprehension can be obtained even with a very slow reading rate (14,15,23). Readers with scotomas appear to slow down their rate of reading to make sure they have read correctly, and to make sure they are deriving meaning from the print they view. A slow transmission of information from the printed page to the language centers of the brain would create an information "bottleneck" (24). The MNRead charts consist of easy, meaningful sentences that are made more difficult to read only by reducing the size of print. Although the sentences from MNRead are low vocabulary, they do contain longer words (up to 9 characters). There is no information on the intelligence or comprehension level of the readers in this study, and despite their low readability level, these sentences could be more challenging to some subjects than to others.

The distribution of VA and presence of scotomas relative to the PRL found in this study are similar to other studies of low vision patients. It is interesting to note that in similar studies using the SLO there is a consistent finding that scotomas are more common in the field to the right of the PRL than to the left (5,6,8). This, at first, may seem perplexing in that all subjects were English speaking, reading from left to right and thus had a blind spot leading the way across a line of text. A scotoma to the right of the PRL could interfere with predicting appropriate future eye movements, including accurately determining the end of the text line. Scotomas to the left of the PRL could interfere with predicting the starting location of the next line of text. Thus, scotomas to the right of fixation may indeed cause a little more reading difficulty than to the left of fixation, but clearly this is not the deciding factor in the development of the PRL in relation to the scotoma. It is likely prudent to remember that reading is not the only activity of significance undertaken by the visual system. For other activities there may be a strong advantage to having the scotoma in the right visual field.

Interestingly, the mean maximum reading rate was essentially the same for the Right Scotoma group and the Right and Left Scotoma group, in spite of the latter having significantly better mean VA. In individuals with a small central island of vision, long words or large size fonts may not fit in the available functioning retina, requiring scanning movements to visualize all pertinent detail. The Right and Left Scotoma patients may have PRLs located in retina areas with higher resolution closer to the fovea but have this advantage counteracted by more scotoma interference. These results are consistent with the concepts of visual span and visual perception in reading (25). The visual span in reading is thought to be the number of characters that can be recognized at a single glance. Perceptual span is defined as the extent of the visual field that influences eye movements while reading. The amount of retina that can be used for reading will be more limited for PRLs that have scotomas on both the right and left than PRLs that have a scotoma only on the right. Thus the width of both the visual span and perceptual span will be affected by the scotoma characteristics around a PRL.

CONCLUSION

The results of this study indicate that designation of a "best" scotoma and PRL placement for reading performance is premature, according to the results of a MNRead evaluation. Readers with scotomas read at about half the rate of readers without them, but within the scotoma groups there was no discrimination between the relative scotoma location around the PRL for maximum reading rate, RA, or critical print size. MNRead does not give a complete picture of the reading performance of these subjects in relation to 1) accuracy of word recognition, 2) rate of reading difficult text, 3) comprehension and 4) stamina for reading long periods. However, it does give a snapshot of how fast and accurately the subjects read easy meaningful sentences one at a time. One might characterize reading ability measured by MNRead as the "best case scenario," in that requirements for comprehending difficult text or reading for long duration are removed. Subjects were measured without magnification devices: the restricted field of view and motor requirements for manipulating the devices and text are absent; therefore, the accuracy and rate of reading measured by this test is probably the best performance the reader can muster. Because we know so little about why the persons with low vision develop the PRLs that they do, and research thus far has not determined a PRL/scotoma relationship that is best for reading performance, more research is required before advocating the training of certain locations for the PRL in relation to the scotoma for reading. In addition, it is unknown whether persons with central scotomas can be instructed in the development of another retinal locus for long term use during reading besides the naturally occurring retinal locus; the PRL. Also, the effectiveness of another retinal locus for reading relative to the effectiveness of naturally occurring PRL with training is unknown.

More information about readers with scotomas is required in order to assist them in developing the most appropriate reading strategies, including relative scotoma location. Because reading requires skills that are both visual and cognitive, relevant research that will lead to best rehabilitation strategies must attend to the interaction of the two. It is possible that with print text assessments that are more challenging to the reader with scotomas, more differentiation between PRL/scotoma placement might occur. Further, it is unreasonable to expect a set performance level from a given VA score alone. Clearly macular scotomas play an important role in reading performance. Because of perceptual completion most patients are not aware of their scotomas even though they may occupy as much as 20° of the central field (26,27). Evaluation of the central visual field and the proximity of a scotoma to the PRL or fovea should be considered an essential component of any low vision rehabilitation evaluation. Patient awareness of their field defects may facilitate adaptations including improved reading performance. Further studies in the effectiveness of rehabilitation interventions relative to macular scotomas and the ability to compensate for macular scotomas would help define efficient reading rehabilitation interventions.

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