Eye Movements and Reading with Large Print and Optical Magnifiers in Macular Disease

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ABSTRACT: Purpose. Reading rate has been the main performance measure in studies that have compared reading with large print and optical magnifiers; eye movement characteristics have not been considered. We compared both eye movement characteristics and reading rates for subjects with macular disease reading without and with a range of low-vision devices. Methods. Silent reading rate and eye movement characteristics for text passages at critical print size of 21 subjects aged 14 to 88 years with macular disease were measured with and without their preferred low-vision device. Saccadic frequency was determined from a sequencing task comprising five letters each separated by 5°. Eye movements were recorded using an infrared limbal reflection system. Results. There were no significant differences in reading rate, fixation durations, saccade numbers per word, or percent retrace time when using a low-vision device compared with reading without a low-vision device. The percentage of regressions was, however, lower with the low-vision device. Saccadic frequency in the sequencing task was predictive of reading performance with and without a low-vision device. Conclusions. When reading at critical print size, in terms of reading rate or saccades per word, there was no advantage to using large print over an optical low-vision device. (Optom Vis Sci 2001;78:325–334)

Key Words: reading, eye movements, macular disease, magnifiers, age

The majority of low-vision patients require magnification to resolve and read regular size print (1 to 1.5 M). Most commonly an optical magnifier (a plus-lens in hand-held, stand, or spectacle-mounted form) is used to provide the necessary magnification. This form of magnification is based on the principles of “relative distance magnification” (i.e., reducing the viewing distance to increase the retinal image size). The increased accommodative demand of the close working distance is alleviated by the plus lens. Another form of magnification commonly used by low-vision patients is “relative size magnification,” where the physical size of the print is increased, for example, with large print books.

A few studies1–3 have compared reading performance of low-vision patients using relative-distance magnification and relative-size magnification. If the retinal image sizes are equivalent for the two forms of magnification, then reading performance should be similar. Lovie-Kitchin and Whittaker3 compared reading large print with a +4.00 D addition to reading standard print with high-plus lenses (spectacle-mounted magnifiers) for a group of adult low-vision subjects. They found no significant differences in reading rates for the two methods of magnification. Their experimental conditions differed, however, from “real-world” reading: a scrolling method of text presentation was used, subjects were forced to read aloud as quickly as possible, and the subjects’ habitual low-vision devices (LVD) were not used. In the real world, text is usually stationary, people read silently, and factors such as page-navigation4 and the restricted field of view of a LVD have to be considered. Koenig et al.2 suggested that any differences between reading performance with relative distance and relative size magnification were related to lack of efficiency in using a LVD.

In this study, we used reading conditions that were more representative of real-world reading. We compared the silent reading performance of adult observers with macular disease when reading large print with a standard reading correction (without LVD) to silent reading performance with their preferred LVD (with LVD). The hypothesis that silent reading rates would be similar in both conditions was examined. We extended earlier studies1–3 to provide a more complete assessment of reading performance by recording eye movements as well as determining reading rates.

Previous investigations of fully sighted observers reading with...
LVDs (plus-lens magnifiers) have demonstrated that retrace times are longer and saccades are more numerous when using a magnifier compared with reading without a magnifier.\(^5,6\) In such studies, the without-LVD condition involved reading standard print, not large print, therefore the retinal image sizes (level of magnification) with and without LVD were not equivalent. Nevertheless, for the current study, we predicted that retrace times would be longer when using the LVD than when reading large print because of the manipulation of the magnifier required.

Bowers\(^6\) suggested that the main factor accounting for the increase in the number of saccades per word when fully sighted observers used a LVD was the increase in retinal image size (magnification) with the device, rather than its restricted field of view. For the current study, where retinal image sizes when reading with and without LVD were similar, we predicted that saccade numbers would be similar for the without- and with-LVD conditions, except perhaps in cases where the field of view was very restricted.

In an earlier paper,\(^7\) we examined a variety of possible clinical predictors of LVD reading rate for subjects with macular disease. One relevant predictor, which was not included, is saccadic frequency. McMahon et al.\(^8,9\) demonstrated a strong relationship between saccadic frequency and reading rate for subjects with macular disease. Saccadic frequency was determined for a simple sequencing task, resembling reading, where subjects were asked to fixate, in turn, each of five letters that were separated by 5° (total 25°). Saccadic frequency was defined as the ratio of the actual number of saccades to the ideal number when performing this task. There was an inverse relationship between saccadic frequency and reading rate (i.e., increased saccadic frequency was associated with decreased reading rate). Bullimore and Bailey\(^10\) confirmed that in macular disease, slower readers make more saccades than do faster readers. We extended those evaluations by comparing saccadic frequency for a sequencing task, saccadic frequency when reading, and reading rate.

**METHODS**

**Subjects**

Twenty-one subjects with a primary diagnosis of macular disease participated in the study (Table 1). The sample included 12 older subjects with age-related macular degeneration, mean age 76.8 ± 5.7 years, and distance visual acuity range 0.30 logarithm of the minimum angle of resolution (logMAR) (20/40) to 1.22 logMAR (20/320).\(^{-1}\) and nine younger subjects with juvenile macular dystrophy, mean age 36.0 ± 13.8 years, and distance visual acuity range 0.20 logMAR (20/32) to 1.26 logMAR (20/400).\(^{10}\) All subjects gave signed, informed consent before participating in the study.

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**TABLE 1.** Subject details.

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Age (yr)</th>
<th>Cause of Low Vision(^a)</th>
<th>Yrs Since Onset of Vision Impairment</th>
<th>Low-Vision Device(^b)</th>
<th>Distance Visual Acuity (logMAR)</th>
<th>CPS without LVD at 25 cm (M units) (Points)</th>
<th>CPS with LVD (M units) (Points)</th>
<th>Equivalent Viewing Distance with LVD (cm)</th>
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</thead>
<tbody>
<tr>
<td>14</td>
<td>75.0</td>
<td>AMD(D)</td>
<td>1</td>
<td>4</td>
<td>0.30</td>
<td>0.63 N5</td>
<td>0.31 N2.5</td>
<td>17.2</td>
</tr>
<tr>
<td>18</td>
<td>75.5</td>
<td>AMD(D)</td>
<td>1.7</td>
<td>2</td>
<td>0.30</td>
<td>0.75 N6</td>
<td>0.63 N5</td>
<td>15.4</td>
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<tr>
<td>15</td>
<td>80.2</td>
<td>AMD(D)</td>
<td>1</td>
<td>2</td>
<td>0.34</td>
<td>1.25 N10</td>
<td>0.63 N5</td>
<td>18.7</td>
</tr>
<tr>
<td>3</td>
<td>75.9</td>
<td>AMD(D)</td>
<td>1.5</td>
<td>3</td>
<td>0.40</td>
<td>1.00 N8</td>
<td>1.00 N8</td>
<td>13.5</td>
</tr>
<tr>
<td>7</td>
<td>83.3</td>
<td>AMD(D)</td>
<td>22</td>
<td>5</td>
<td>0.48</td>
<td>0.75 N6</td>
<td>0.75 N6</td>
<td>16.0</td>
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<td>16(^c)</td>
<td>68.3</td>
<td>AMD(D)</td>
<td>4</td>
<td>1</td>
<td>0.66</td>
<td>3.00 N24</td>
<td>1.25 N10</td>
<td>8.0</td>
</tr>
<tr>
<td>21</td>
<td>70.2</td>
<td>AMD(W)</td>
<td>0.7</td>
<td>5</td>
<td>0.68</td>
<td>1.25 N10</td>
<td>1.25 N10</td>
<td>21.2</td>
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<tr>
<td>1(^c)</td>
<td>88.4</td>
<td>AMD(D)</td>
<td>6</td>
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<td>0.92</td>
<td>6.00 N48</td>
<td>3.00 N24</td>
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</tr>
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<td>8</td>
<td>76.6</td>
<td>AMD(W)</td>
<td>3</td>
<td>5</td>
<td>0.94</td>
<td>8.00 N64</td>
<td>2.50 N20</td>
<td>21.0</td>
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<td>4(^c)</td>
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<td>AMD(W)</td>
<td>0.6</td>
<td>5</td>
<td>0.96</td>
<td>2.50 N20</td>
<td>1.00 N8</td>
<td>5.0</td>
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<tr>
<td>20(^c)</td>
<td>74.9</td>
<td>AMD(D)</td>
<td>4</td>
<td>5</td>
<td>1.18</td>
<td>10.00 N80</td>
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<td>2</td>
<td>1.22</td>
<td>10.00 N80</td>
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<td>10.9</td>
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<td>19</td>
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<td>JMD(-)</td>
<td>2.8</td>
<td>3</td>
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<td>1.00 N8</td>
<td>0.38 N3</td>
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<td>14.3</td>
<td>JMD(S)</td>
<td>6</td>
<td>0</td>
<td>0.24</td>
<td>1.00 N8</td>
<td>1.00 N8</td>
<td>25.0</td>
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<tr>
<td>2</td>
<td>35.8</td>
<td>JMD(S)</td>
<td>0.8</td>
<td>0</td>
<td>0.26</td>
<td>0.75 N6</td>
<td>0.50 N4</td>
<td>20.0</td>
</tr>
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<td>10(^c)</td>
<td>18.6</td>
<td>JMD(S)</td>
<td>1.5</td>
<td>4</td>
<td>0.94</td>
<td>2.50 N20</td>
<td>1.00 N8</td>
<td>6.8</td>
</tr>
<tr>
<td>22(^c)</td>
<td>48.4</td>
<td>JMD(S)</td>
<td>23</td>
<td>1</td>
<td>1.06</td>
<td>8.00 N64</td>
<td>5.00 N40</td>
<td>12.5</td>
</tr>
<tr>
<td>23(^c)</td>
<td>35.3</td>
<td>JMD(S)</td>
<td>20</td>
<td>2</td>
<td>1.06</td>
<td>4.00 N32</td>
<td>1.25 N10</td>
<td>5.0</td>
</tr>
<tr>
<td>17</td>
<td>50.5</td>
<td>JMD(S)</td>
<td>9</td>
<td>4</td>
<td>1.16</td>
<td>8.00 N64</td>
<td>1.25 N10</td>
<td>4.8</td>
</tr>
<tr>
<td>6(^c)</td>
<td>26.0</td>
<td>JMD(S)</td>
<td>14</td>
<td>2</td>
<td>1.20</td>
<td>8.00 N64</td>
<td>1.00 N8</td>
<td>3.0</td>
</tr>
<tr>
<td>12(^c)</td>
<td>49.5</td>
<td>JMD(S)</td>
<td>41</td>
<td>1</td>
<td>1.26</td>
<td>8.00 N64 at 10 cm</td>
<td>3.00 N24</td>
<td>4.0</td>
</tr>
</tbody>
</table>

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\(^a\) AMD, age-related macular degeneration; D, dry; W, wet; JMD, juvenile macular dystrophy; S, Stargardt’s; -; specific dystrophy not identified by ophthalmologist.

\(^b\) 0, own accommodation (working distance of ≤25 cm); 1, high add spectacles (+4D add or greater); 2, hand-held magnifier (nonilluminated); 3, hand-held magnifier (illuminated); 4, stand magnifier (nonilluminated); 5, stand magnifier (illuminated).

\(^c\) These subjects read fewer lines of print with than without LVD. The remaining subjects read the same number of lines of print with and without LVD.

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\(^1\) Retrace time is the time taken to return from the end of one line to the start of the next.
The reading habits of the subjects ranged from daily reading to occasional reading. Their LVDs (all plus-lens magnifiers) were typical of those prescribed to low-vision patients attending hospital and university low-vision clinics in the United Kingdom (Table 1).11–13 For this study, a LVD was defined as any optical magnifying device, including spectacle near additions, of +4 D or greater. With the exception of subjects 2 and 13, who used natural accommodation, all participants used at least one LVD when reading. For data collection with LVD, subjects used their preferred LVD (i.e., the one used most frequently). No attempt was made to determine whether this preferred LVD gave optimal reading performance, but all subjects were experienced in the use of their LVD. Subjects 2 and 13 did not habitually use an optical magnifying device; instead they achieved relative distance magnification by using a short working distance (±25 cm) and natural accommodation. The use of natural accommodation of + 4 D or greater by a young subject is the equivalent of an older subject using a LVD (i.e., the one used most frequently). No attempt was made to include in the with-LVD condition. The implications for including these two subjects in some of the data analyses are discussed below.

Vision Measures

The following vision measures were recorded for all subjects: distance visual acuity (Bailey-Lovie high-contrast letter chart), letter contrast sensitivity (Pelli-Robson chart), scotoma size and position (Tangent screen, 10-mm white target), near word visual acuity with and without LVD (Bailey-Lovie word reading chart; unrelated words), and near text visual acuity with and without LVD (MNREAD Acuity Chart 1; sentences). Full details of the vision measures, test conditions, and instruments used were reported previously.7 Vision was assessed monocularly with the eye normally used for reading or, if the subject usually read binocularly, the eye with the better visual acuity (VA). Each subject was optimally corrected with spectacles or full aperture trial lenses for all clinical vision tests and reading trials.

Eye Movement and Reading Measures

After the vision assessments, saccadic frequency, reading rates, and reading eye movements were measured. The order was the same for all subjects: calibration of eye movement equipment, saccadic frequency assessment, calibration, reading without LVD, calibration, and reading with LVD. Each subject set his or her preferred illumination for these measures.

Eye Movement Apparatus

Horizontal eye movements were recorded using a spectacle-mounted, infrared limbal reflection system (Type 54 balanced eye movement measurement system, Optoelectronic Developments, Havant, Hampshire, UK). This system is linear over a ±15° range with a spatial resolution of at least 0.5°. It was selected because it provides minimal obstruction of the reading field14 and was suitable for eye movement recording when reading with a LVD. Most subjects were able to read with their own LVDs in a reasonably natural position while wearing the eye movement monitor. The only exception was for the three subjects who used Keeler high-addition spectacles. It was impossible for these subjects to use their own LVD; instead an equivalent plus-lens was placed in the cell at the front of the trial frame on which the eye movement monitor was mounted. Head restraints were not used. Data were collected using specialized software (Viewdac) at a sampling rate of 100 Hz.

Calibration was performed using a row of five letters (±10°, ±5°, and 0°); letter size was equivalent to the critical print size (CPS) for each subject when reading without LVD. These same letter targets were also used for the saccadic frequency assessment. Calibration procedures aimed to ensure a roughly equal deflection of the trace to ±5° and ±10°. Although head restraints were not used, subjects were instructed to hold the head as still as possible. Accurate and absolute calibration was not possible for four of the subjects due to the presence of significant central visual field loss. However, such calibration was not required for this experiment; eye movement analysis was primarily related to saccade detection, and absolute saccade amplitude was not measured.

Saccadic Frequency in Sequencing Task

Following the paradigm of McMahon et al.8, 9, the target for the sequencing task comprised five letters separated by 5° (±10°, ±5°, and 0°). A viewing distance of 250 mm was used, and letter size was equivalent to the CPS for each subject when reading without LVD. Subjects were asked to fixate each letter, in turn, moving from left to right; when the fifth letter was reached, subjects were asked to return directly to the first letter and repeat. Several practice trials were completed before data recording commenced. Two 30-s recordings of the sequencing task were obtained for each subject.

Saccadic frequency in sequencing was determined from the ideal number of saccades (one per letter) divided by the total number of saccades, summed across the two trials of the sequencing task. Saccadic frequencies were also calculated in a similar fashion for the forwards (left to right) section and the return (right to left) section of the sequencing task (Table 2). Here we report saccadic frequency in sequencing as the number of “letters per saccade.” This convention was adopted to be comparable with the measure “words per saccade,” which was used for saccadic frequency in reading. Note that our measure of saccadic frequency in sequencing was the inverse of that used by McMahon et al.8, 9 The eye movement data recorded during the sequencing task were used to generate eye position and velocity traces from which the total number of saccades executed by each subject could be determined (Fig. 1). The threshold for detection of a saccade was set at 1°, which was equivalent to the average angular subtense of the letter targets used. All subjects demonstrated a pattern of multiple hypometric saccades when performing the sequencing task (Fig. 1).

Reading Assessments

Reading rates and eye movement parameters were assessed in two situations: reading large print without LVD and reading smaller print with LVD. In both cases, the print size used was equivalent to the critical size for that condition. CPS, the smallest print size to achieve a maximal reading rate, was determined from measurements of oral reading rates for a range of print sizes on the
The majority of low-vision patients use optical LVDs for short-duration reading, for example to read a short passage from a newspaper or magazine, or for personal correspondence. When assessing reading performance with and without LVD, we therefore selected to use short, simple passages (mean length 64.1 ± 3.0 standard words) and instructed subjects to read silently at a normal rate to obtain meaning from the passage (i.e., read for understanding). This type of reading has been termed *reading*. Subjects were explicitly told not to read as fast as possible. Comprehension was checked informally by either asking occasional questions about the story or asking for comments on the story line. All subjects demonstrated a good level of understanding of the passages they read.

The reading passages were taken from two standardized tests of reading ability for children: the Neale Analysis of Reading Ability—Revised British Edition and the New Reading Analysis for levels 4 (9 to 10 years old) and 5 (10 to 11 years old). These passages were therefore well within the reading capability of all subjects. The passages were formatted with a minimum of six lines of text at each print size, thus ensuring that subjects would use eye and magnifier movements typically made when reading a paragraph. For print sizes ≤2 M (N16), the number of words per line averaged 11.5, and line width increased with increasing print size. To maintain 11.5 words per line for print sizes >2 M, line widths greater than the maximum available on A4 paper (21 × 29.7 cm) would have been required. It is unusual to read paragraphs with a line width greater than the width of a typical page, therefore for print sizes >2 M, line width was constant, equal to the maximum width available on A4 paper. As a direct consequence, the number of words per line decreased with increasing print size.

### TABLE 2: Summary of the reading and eye movement measures.

<table>
<thead>
<tr>
<th>Eye Movement and Reading Measures</th>
<th>Scoring Method</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical print size (CPS)</td>
<td>Smallest print size to give maximum reading rate—determined from oral reading of MNREAD Acuity Chart 1</td>
<td>LogMAR, M units, or N points</td>
</tr>
<tr>
<td>Saccadic frequency in sequencing</td>
<td>Ideal number of saccades (one per letter) divided by the number of saccades in sequencing task; analyzed forward (left to right), return (right to left), and total (all saccades in both forward and return sections) saccadic frequency.</td>
<td>Letters per saccade</td>
</tr>
<tr>
<td>Saccadic frequency in reading</td>
<td>Total number of standard words divided by the total number of saccades (forward and regressive) made during the line reading (forward: left to right) phase of reading.</td>
<td>Words per saccade</td>
</tr>
<tr>
<td>Percent regressive saccades</td>
<td>Number of regressive saccades divided by the total number of saccades (forward and regressive) during the left to right phase of reading as a percentage.</td>
<td>%</td>
</tr>
<tr>
<td>Fixation duration</td>
<td>Average intersaccadic period for all fixations during the line reading (left to right) phase of reading.</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>Retrace time per line</td>
<td>Average time from initiation of return sweep saccade to the beginning of the first fixation on the next line (i.e., right to left phase).</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>Percent retrace time</td>
<td>Sum of retrace times per line divided by total reading time as a percentage.</td>
<td>%</td>
</tr>
<tr>
<td>Total reading time</td>
<td>Time between initiation of the first fixation on the second line and the initiation of the return sweep at the end of the penultimate line.</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>Reading rate</td>
<td>Number of words on the second line to the end of the penultimate line divided by total reading time.</td>
<td>Words per minute (wpm)</td>
</tr>
</tbody>
</table>

MNREAD Acuity Chart 1 (MNREAD 3.1-1 3600; Lighthouse, New York). For full details of CPS assessment, see Lovie-Kitchin et al. The comparison of reading with and without LVD was made at CPS to ensure maximal reading rates for both conditions as well as to ensure that reading rate was not limited by print size and similar levels of magnification were achieved. To maintain 11.5 words per line for print sizes >2 M, line widths greater than the maximum available on A4 paper (21 × 29.7 cm) would have been required. It is unusual to read paragraphs with a line width greater than the width of a typical page, therefore for print sizes >2 M, line width was constant, equal to the maximum width available on A4 paper. As a direct consequence, the number of words per line decreased with increasing print size.

Subjects were encouraged to make as natural a use of their LVD as possible in an attempt to simulate their habitual reading conditions. This included adopting natural head, hand, and LVD positions, making normal head and eye movements, and using the habitual LVD reading distance. For...
the two subjects who used natural accommodation to achieve magnification, measures were taken using their habitual reading positions. For the reading trials without LVD, a standard 250-mm working distance, controlled by a reading stand, was used, and subjects were optimally corrected for that distance. Although 250 mm is a shorter working distance than is typically adopted by fully sighted readers, it was not unnatural for our visually-impaired subjects who habitually used working distances $\geq$250 mm with their LVDs.

Before recording the eye movements, subjects read through a practice passage to ensure familiarity with the procedure and to ensure that the experimental set up was as close to their natural reading position as possible. This was carried out before recording silent reading of a passage both without and with LVD. Recording only commenced when the subject indicated that he or she was comfortable.

**Analysis of Reading Eye Movements**

The typical staircase pattern of reading eye movements (Fig. 2) is characterized by fixation pauses separated by saccades. When reading along a line, forward saccades move the eyes rightward and regressive saccades move the eyes backward or leftward. At the end of each line, the eyes are returned to the start of the next line by a large-amplitude return sweep saccade. If the return sweep is inaccurate, small corrective saccades are sometimes made. When using a magnifier, the staircase pattern of normal reading eye movements is modified to a saw-tooth. There is a slow pursuit movement to the left during each fixation pause that is induced either by the apparent leftward movement of the text as a hand-held or stand magnifier moves to the right or by the actual movement of the text (and/or head) when using a spectacle-mounted magnifier. This saw-tooth pattern has been observed when fully sighted and visually impaired subjects read with LVDs5, 6, 19–21 and was clearly demonstrated by our macular disease subjects when reading with LVDs (Fig. 3).

The same procedures were used to analyze eye movement traces for the with- and without-LVD conditions. First, the recordings from the first and last lines read were excluded from the analysis. The following parameters were then determined for the remaining lines: saccadic frequency in reading, fixation duration, percent regressive saccades, retrace time per line, percent retrace time, and total reading time (Table 2). Saccadic frequency in reading (words per saccade) was defined as the total number of standard words divided by the total number of saccades (forward and regressive) made during the line reading (left to right) phase of reading. This convention was adopted because the words per saccade data were normally distributed, whereas the inverse data, saccades per word, were not normally distributed. Our definition of saccadic frequency in reading is analogous to our definition of saccadic frequency (letters per saccade) for the forward section of the sequencing task. A similar measure “letters per forward saccade” has been used in the eye movement analysis of low-vision subjects reading with22 and without LVDs.10

Fixation duration was defined as the average intersaccadic period, measured in milliseconds, for all fixations during the line reading (left to right) phase of reading. Percent regressive saccades was expressed as a percentage of the total number of saccades (both forward and regressive) during line reading. Retrace time per line was defined as the average period from the initiation of the return sweep saccade to the beginning of the first fixation on the next line (Fig. 2). On some eye movement traces (about 20%), it was not possible to distinguish the initial fixation. In this case, an estimation of the time for retrace was derived by measuring the time period between the initiation of the return sweep and the first forward saccade on the next line and then subtracting the mean.
Saccadic Frequency

For the five-letter sequencing task, the mean total saccadic frequency was 0.53 ± 0.15 letters per saccade. The mean forward saccadic frequency in sequencing was 0.58 ± 0.15, and the return saccadic frequency in sequencing was 0.42 ± 0.17 letters per saccade. These values are similar to those reported by McMahon et al. and indicate a significantly greater number of saccades above the ideal during the return than for the forward section of the sequencing task (paired t-test, p = 0.001). Forward saccadic frequency in sequencing was significantly associated with visual acuity: there were fewer letters per saccade (i.e., greater number of saccades above the ideal) as visual acuity worsened (distance VA, r = −0.45, p = 0.04; near word VA, r = −0.46, p = 0.04). Also, there were significant relationships between forward saccadic frequency in sequencing and reading rate for the without-LVD (r = 0.51, p = 0.02) and with-LVD (r = 0.58, p = 0.006) (Fig. 4A) conditions.

Because reading eye movements were recorded in this study, it was possible for the first time to examine the relationship between saccadic frequency in a sequencing task and saccadic frequency when reading. As expected, there was a significant relationship between forward saccadic frequency in sequencing and saccadic frequency in reading with LVD (r = 0.56, p = 0.009) and without LVD (r = 0.55, p = 0.01); those subjects with higher saccadic frequencies in sequencing exhibited similar behaviors when reading. There were no significant correlations between the saccadic frequency for the return section of the sequencing task and any vision, reading rate, or reading eye movement measures. The correlations between total saccadic frequency in sequencing and vision, reading rate, and reading eye movement measures were similar to those for the forward saccadic frequency score.

In our earlier analysis for this cohort of subjects, we concluded that near word acuity alone was the best predictor of silent reading rate when using a LVD. To determine whether the saccadic fre-
frequency in sequencing score significantly improved the prediction of LVD reading rate, a stepwise multiple regression was performed with vision measures (distance VA, near word VA, letter contrast sensitivity, percent visual field loss, and scotoma position), saccadic frequency in sequencing (total, forward, and return), and duration of vision loss entered as the independent variables. Near word acuity was still the single best predictor of LVD reading rate (adjusted $r^2 = 0.68$, $p < 0.0001$). Alternatively, combining either forward or total saccadic frequency in sequencing with near word VA accounted for only an extra 5% of variance in LVD reading rates.

**Reading Performance**

Reading performance was compared without LVD and with LVD. CPS, corrected for equivalent viewing distance, was not significantly different without (1.04 ± 0.47 logMAR) and with LVD (1.08 ± 0.51 logMAR; paired t-test, $p = 0.35$). This confirms that magnification levels (retinal image sizes) were similar in the two conditions. No significant differences were found between the two conditions for reading rate (paired t-tests, $p = 0.24$), fixation duration ($p = 0.45$), or saccadic frequency in reading ($p = 0.18$). Significant differences were apparent, however, for retrace time per line ($p = 0.003$) and the percent regressive saccades ($p = 0.004$). When reading with LVD, retrace time per line was longer and fewer regressive saccades were made than when reading without LVD (Fig. 5). Although the absolute time per line for retrace was greater with LVD, the percentage of reading time devoted to retrace, percent retrace time, was similar (paired t-test $p = 0.2$) with LVD (14.8% ± 5.2%) and without LVD (13.1% ± 5.4%).

Due to decreasing numbers of words per line for print sizes >2 M, 12 subjects read fewer lines and made fewer retraces with than without LVD, whereas the remaining nine subjects read similar numbers of lines and made similar numbers of retraces in the two conditions. We therefore examined the data to determine whether there were any differences in absolute retrace time per line and percent retrace time with and without LVD for these two groups of subjects. Absolute retrace time per line was significantly longer ($p < 0.05$) with than without LVD for both groups. For the subjects who made fewer numbers of retraces with than without LVD,

**FIGURE 4.**

Reading rate with LVD was highly correlated with (A) saccadic frequency in sequencing ($r = 0.58$, $p = 0.006$) and (B) saccadic frequency in reading ($r = 0.97$, $p < 0.001$). The open triangles labeled NV represent data from Bowers for fully sighted subjects measured under similar conditions. AMD, age-related macular degeneration; JMD, juvenile macular dystrophy.

**FIGURE 5.**

Reading rates were the same without and with LVD, but (A) retrace time per line was significantly longer with LVD than without LVD ($p = 0.003$); and (B) the percentage of regressions was significantly lower with LVD than without LVD ($p = 0.004$). Error bars represent 95% confidence limits.
percent retrace time was similar (p = 0.47) with and without LVD. By comparison, for the subjects who made similar numbers of retracts with and without LVD, percent retrace time was significantly (p = 0.02) greater with than without LVD.

In addition, we examined the relationship between eye movement parameters and reading rate without and with LVD (Table 3). For both conditions, the strongest correlation occurred between reading rate and saccadic frequency in reading. In general, slower reading rates were associated with fewer numbers of words per saccade (i.e., more saccades per word) (Fig. 4B), a higher percentage of regressions, longer retrace times, and longer fixation durations. Interestingly, as shown in Fig. 4B, the approximately age-matched, fully sighted subjects reported by Bowers et al. ("old" group), who used LVDs for a similar reading task, had a similar relationship between saccadic frequency in reading and their reading rates. These fully sighted subjects (with limited experience with LVDs) were in the same range as the low-vision subjects.

**DISCUSSION**

**Reading with and without LVD**

The main purpose of this study was to compare reading performance at CPS (minimum print size for maximal reading rate) with and without the subject’s preferred LVD. Subjects represented a cross-section of the population with macular disease, and experimental conditions were representative of real-world reading. No significant differences were found in reading rate, fixation duration, saccadic frequency in reading, or percent retrace time, but retrace time per line was longer, and a lower percentage of regressive saccades were made when using the LVD. These results support the hypothesis that when magnification levels are equal (i.e., equal retinal image sizes), reading rates will be similar for relative distance and relative size magnification. Lovie-Kitchin and Whittaker found this to be true for low-vision subjects reading scrolling text without manipulating a magnifier; this study demonstrates similar findings when subjects read stationary text and are manipulating LVDs with moderately restricted fields of view. Presuming that reading with large print (at CPS) gives maximal reading rate for low-vision subjects, our results indicate that subjects with macular disease who are familiar with and well-practiced in the use of their LVDs can achieve their maximal reading rate with optical magnification. Conversely, the maximal reading rate with large print can be used to predict the best reading rate expected with LVDs after training and practice.

Fixation durations were similar with and without LVD. This was not unexpected because fixation durations are primarily affected by text visibility, and the text was equally visible in both conditions with subjects reading at CPS. As visibility decreases, for example, as print size approaches threshold, fixation durations increase significantly, whereas above CPS, there is little change in fixation duration with increasing print size. Each fixation comprises the time required for conceptual processing of words and the time for planning the next eye movement. Our results suggest that using a LVD did not significantly affect the total time required for these processes.

The fact that saccadic frequency in reading was similar with and without LVD suggests that in general, saccade lengths were similar in the two conditions. One factor that affects saccade length is visual span, the number of characters that can be recognized on a single fixation. Visual span is limited both by magnification and visual impairment. Using serially presented words (rapid serial visual presentation), Legge et al. found the average visual span of seven low-vision observers to be 2.4 characters for very large, 6° letters, compared with 5.3 characters for six fully sighted subjects tested using the same paradigm. The smallest field of view in the with-LVD condition in our experiment was 10 characters. Although we have no estimate of the visual spans of our subjects, it would seem reasonable to assume that they were <10 characters. It is therefore unlikely that field of view had a significant effect on visual span, saccade length, or saccade numbers in this experiment.

Two measures of retrace time were used in this study: percent retrace time and retrace time per line. Percent retrace time is based on the total time devoted to retrace in reading a passage and takes account of the overall number of lines read, whereas retrace time per line does not. As previously noted, 12 subjects read fewer lines of print and made fewer retracts with than without LVD. For these subjects, retrace time per line was longer with than without LVD, but percent retrace time was similar in the two conditions; the fewer number of retracts offset the increase in absolute retrace time with LVD and percent retrace was consequently similar with and without LVD. By comparison, for the nine subjects who read the same number of lines of print with and without LVD, both retrace time per line and percent retrace time were greater with than without LVD. For these subjects, similar numbers of retracts were made with and without LVD, therefore the increase in retrace time per line with LVD was not offset by fewer numbers of retracts, and percent retrace time was greater with than without LVD. These findings suggest that the paragraph format might have a significant effect on the percentage of total reading time devoted to retrace. It

<table>
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<th>TABLE 3. Correlations (Pearson’s r) between reading rate and eye movement parameters without and with LVD.</th>
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<td><strong>Fixation Duration (ms)</strong></td>
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<tr>
<td>Reading rate without LVD (wpm)</td>
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<td>Reading rate with LVD (wpm)</td>
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would be interesting to determine the optimal page layout to minimize percent retrace time when reading with and without LVDs.

The longer retrace time per line with LVD suggests that page navigation was a limiting factor for reading with LVD and that if page navigation could be eliminated or controlled accurately, reading rates with optical magnifiers could be increased. Kuyk et al. endeavored to do this with a mechanized reading stand, but for their subjects with central visual field loss (almost all with age-related macular degeneration), reading rate was not significantly improved by the removal of page navigation requirements.

Retrace time per line increased on average by 350 ms when using the LVD compared with reading without a LVD (Fig. 5A). Fully sighted observers similarly showed increased retrace time per line reading with LVDs compared with reading with their habitual spectacle correction. There is one important difference, however: the increase in retrace time when our macular disease subjects read with LVDs was much less than that which occurred for fully sighted observers reading with LVDs. Although the mean retrace time per line for our macular disease subjects in the with-LVD condition was similar to that previously recorded for fully sighted subjects reading with LVDs, the retrace time per line for the without-LVD condition was much longer by about 500 ms. Reduced saccadic accuracy in macular disease is one factor that would partly account for this difference. The majority of our macular disease subjects demonstrated poor saccadic accuracy during retrace in the without-LVD condition, making several corrective saccades at the end of the return sweep. Poor saccadic accuracy was also evident in the return phase of the sequencing task.

Percent regressive saccades was the final eye movement parameter quantified when reading with and without LVD. It was noted that there was a small but significant reduction in the percentage of regressions when using a LVD (Fig. 5B). Similar results have also been found for fully sighted observers. It thus appears that regressive saccades are less likely to occur when using a magnifier. The constant movement of a magnifier along a line and the pattern of reading eye movements thus generated (Fig. 3) may make the execution of a regressive saccade more difficult than when reading without a magnifier. Anecdotal observations during eye movement recordings of low-vision subjects in our laboratory indicate that at the point when regressive saccades occur, a subject has halted the movement of the magnifier and in some cases moved it backward along the line.

**Saccadic Frequency**

In addition to comparing reading rates and eye movements with and without LVD, we also examined the relationship between saccadic behavior in a sequencing task, saccadic behavior when reading, and reading rate. All of our subjects demonstrated poor saccadic accuracy in the sequencing task, primarily making a series of hypometric saccades across the line of five spaced letters (Fig. 1). As expected, there was a significant relationship between saccadic frequency in the simple sequencing task and saccadic frequency in the more complex reading task. Those subjects with the worst saccadic accuracy during the sequencing task (i.e., more saccades per letter) made the greatest numbers of saccades when reading and had the slowest reading rates (Fig. 4). Our findings confirm the relationship between saccadic frequency and reading rate reported by McMahon et al. for a sequencing task and extend these findings to the actual reading task with LVDs.

Of the various eye movement parameters quantified during the reading task, saccadic frequency in reading accounted for the majority of the variance in reading rates both with and without LVD (Table 3). This is supported by Bullimore and Bailey, who reported a similarly strong relationship between “number of letters per forward saccade” and reading rate for macular disease subjects reading at optimal print size without a LVD. For low-vision subjects reading with LVDs, Rumney and Leat also found a strong relationship between letters per forward saccade, derived from a sentence reading task, and an independent measure of reading rate on an “unrelated” words task (Pepper Visual Skills for Reading Test). The slope of the regression line between saccadic frequency in reading and reading rate (Fig. 4B) has units of saccades per minute, i.e., the rate at which saccades were made: all subjects, independent of their level of visual impairment, made saccades at a similar rate. A similar relationship is apparent in the data presented by Rumney and Leat. Also, as shown in Fig. 4B, fully sighted subjects performing the same task made saccades at a similar rate to our macular disease subjects.

Rumney and Leat made the point that when eye movements and reading rate are assessed from the same reading trial, the measures are not independent. However, it is clear from our results (Table 3) that some eye movement parameters (fixation duration and percent regressive saccades) do not correlate well with reading rate, even when taken from the same trial. We also investigated the relationship between eye movement parameters measured during silent reading and the reading rate of our subjects for two independent measures of reading rate: oral reading of single sentences (MNRead acuity chart) and oral reading of short passages (these oral reading rate data were reported in Lovie-Kitchin et al. ). For each eye movement parameter derived from the silent reading task, the correlation coefficient with oral reading rate was of a similar magnitude to the correlation coefficient with silent reading rate. Saccadic frequency in reading was again the eye movement parameter with the strongest correlation with reading rate, both for oral reading of single sentences (with LVD \( r = 0.74 \); without LVD \( r = 0.71, p < 0.001 \)) and oral reading of short passages (with LVD \( r = 0.84; \) without LVD \( r = 0.84, p < 0.001 \)). Thus the saccadic frequency (words per saccade) in reading score is the main eye movement parameter determining reading rates of subjects with macular disease, with and without LVD, for oral and silent reading. Our results therefore confirm the findings of Rumney and Leat, Bullimore and Bailey, and Legge et al. for the main factor limiting low-vision reading rate is the number of letters (or words) covered by each saccade.

**CONCLUSIONS**

In summary, the results of this study suggest that the physical restrictions imposed when reading with a LVD, compared with reading without a LVD, have no significant effects on reading rate when magnification levels (retinal image sizes) are similar. It should be stressed that the similarity in reading rates with and without LVD occurs when critical print size is established for each condition, that is, relative distance and relative size magnifications are provided for maximal reading rate. It is still not uncommon for
practitioners to prescribe magnification for reading based on threshold print size rather than print size required for fluent reading. Higher magnifications than have been traditionally given should be prescribed to ensure that print size is magnified well above threshold to provide maximal or near-maximal reading rates. Recent guidelines on how to determine these magnifications have been published. From the clinical viewpoint, our findings indicate that when sufficient magnification and practice with LVDs are provided, the reading performance achieved with a LVD can be just as good as that achieved with large print. Thus, there is no real advantage, in terms of reading rate or eye movement parameters, of providing large print as an alternative to using a LVD. In practical terms, large print is only a viable option for patients requiring modest levels of magnification. For such patients, reading large print might be more comfortable and less frustrating than using a LVD. Of course, every low-vision patient should be treated as an individual and provided with the best means of accessing print material that suits his/her needs.

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