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The Limitations Imposed on Reading by Low Vision Aids

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ABSTRACT: *Introduction:* The changes that occur in the reading eye movements of normally sighted readers were measured as they used hand magnifiers to identify how these devices contribute to the slow reading of visually-impaired patients. *Methods:* Subjects inexperienced in magnifier use read texts containing two sizes of print, using hand magnifiers of two different powers, held at two different eye-to-magnifier distances. The effect of magnification (up to 13.5×) and field-of-view (FOV) (2–45 characters) could be assessed independently. *Results:* Reading speed decreased with increasing magnification because the size of the saccades did not increase in proportion to the magnification: for a given level of magnification, decreasing the FOV and decreasing the viewing distance both reduce the size of the saccades even further. The overall reading speed is only slowed significantly when the FOV restriction is extreme (two characters' width). *Conclusions:* Two mechanisms seem to be used spontaneously by normally sighted readers to mitigate the limitation of reading speed created by the shortened saccades: head movement in the direction of reading and retinal image slip during fixation. (Optom Vis Sci 2000;77:364–372)

Key Words: reading speed, reading eye movements, magnification, hand magnifier

The reading eye movements of normally sighted subjects are an ordered sequence of forward saccades, each about seven characters long, to move successive parts of the text onto the high-resolution fovea. This indicates the size of the "recognition field" or "visual span"[1, 2] which is the area from which words can be identified during each fixation. Each section of text remains in the foveal region for a "fixation" lasting about 250 ms during which time the text is analyzed and the next saccade planned. Although the recognition field has limited extent, Rayner et al.[3] found that increasing the available clear window of text up to 15 characters to the right of fixation, increased reading speed by increasing the forward saccade size. They suggested that this "location field" or "perceptual span" is the area from which the information required to plan the next forward saccade is drawn.

It has been repeatedly demonstrated that visually impaired patients usually read more slowly than normally sighted subjects, even when optimal magnification of the print has been provided.[4–8] Magnification (defined as the ratio of the enlarged retinal image size to the unmagnified image size under standard viewing conditions) is essential for low vision patients to enable them to resolve print. Increasing the size of the object is the simplest method of magnification, and for reading this involves the use of "large print." Decreasing the viewing distance creates magnification by the ratio of the respective distances. To avoid the need to accommodate for a close viewing distance, the patient may use a plus-lens magnifier (which can be hand-held or stand/spectacle-mounted) with the object at the focal point such that a virtual image is formed at infinity.

By measuring the eye movements, Bullimore and Bailey[6] found that the reading of enlarged print by patients with age-related macular degeneration (ARMD) was slower because of an increased number of regressions and shorter forward saccades. Rumney and Leat[7] also found that forward saccades were shorter in patients with various ocular pathologies who were using their optimum low-vision aid (LVA). It is thus not clear whether the change in the eye movement was caused by the underlying eye disease or by some aspect of the magnification method used.

Magnification might disrupt the reading process in several ways. The change in size of the characters means that the forward saccades would need to increase in proportion (in terms of their angular size) if each were to cover the same amount of text. Increasing the size of the text, however, has been shown to have little effect on maximum reading speed for scrolled text, being optimal from approximately 0.3° to 2° in normally sighted subjects[9] (equivalent to approximately 10 point to 70 point at a 40-cm viewing distance).

Using an optical LVA limits field-of-view (FOV), particularly at higher magnifications where there is a limit on the physical size of the lenses used because of aberrations, Legge et al.[4, 9] suggested that a FOV of only four characters was adequate to maximize reading speed, although they presented text on a monitor screen. Whittaker and Lovie-Kitchin[10] have suggested that this finding was strongly influenced by the "scrolled text" presentation, because the subject did not have to manually control the text position. Experiments that have required manual scanning on the closed circuit TV (CCTV)[11, 12] and with optical magnifiers[13] have found FOV requirements close to normal reading, suggesting that a wider FOV is needed for "page navigation."

The limited FOV also means that for text laid out in lines it is necessary to move the magnifier across the page to read the whole line.[14, 15] This produces a corresponding movement of the image in the opposite direction: if the magnifier movement is smooth, the "fixations" will need to be replaced by a slow pursuit by the eyes as they lock onto the section of the text that is to be analyzed, and then saccade to the adjacent section of text. The resultant eye movement has been described as "optokinetic nystagmus"[16] because the rhythmic alternation of pursuits and saccades resembles jerk optokinetic nystagmus. This eye movement pattern has not been studied in detail, and there has been no quantitative comparison with the normal staircase reading eye movements.

In the present study, the effect of reading with hand magnifiers on the natural reading speed and reading eye movements of normally sighted subjects was analyzed. Two hand magnifiers were used (3× and 7.5×) to read text of two different print sizes (10 point and 18 point), with two different eye-to-magnifier distances (10 cm and 35 cm). These conditions allowed both FOV and magnification to be varied to identify the nature of any restrictions they place on the reading process. This will allow for the suggestion of strategies that patients could use to overcome these limitations.

METHODS

Subjects

Twelve normally sighted subjects with Snellen visual acuity at least 6/6, able to read 5-point near text, and who did not habitually wear refractive correction participated in the experiments. All were university students with an age range of 18–38 years, and they were all fluent in English. No subjects were found who had significant visual anomalies, and cover testing revealed no gross oculomotor anomaly. Normally sighted subjects were chosen to assess the effects of magnification on the reading performance, because low-vision patients may show confounding effects of the ocular pathology and may have been taught (or learned spontaneously) to modify their eye and head movements as part of the rehabilitation process. Goodrich et al.[17] have suggested that after 10 days of daily use of both optical and CCTV magnifiers, the reading speed is still improving. It was impossible to allow the subjects to reach this level of expertise, so they were tested as naive observers. The subjects were told about the aims of the experiment and the task they would be asked to perform, and informed consent was obtained. The experiment did not attempt to force a maximum performance, but an average or "natural" performance, and subjects were instructed to read as if they were reading a newspaper or magazine for general interest. A tape recorder and microphone were used to record the oral reading performance of the subjects. No subject made any error in reading that was not corrected spontaneously: such corrections simply added to the time taken to read a given number of words. Subjects were aware they were being recorded, but were not informed that their reading speed was to be measured, so as not to artificially speed up their natural reading.

Text Samples

The text samples used consisted of 10 sentence-lines; 5 lines of 10-point (1.25 M) print (height of lower-case letter is 1.75 mm) and 5 lines of 18-point (2.3 M) print (height of lower-case letter is 3.2 mm). These print sizes were chosen as representative of those found in standard and large-print book formats, respectively. Each line started with a capital letter, and there was meaning within each line, but there was no meaning across consecutive lines. These texts were intended to control context effects so that subjects would not be able to "skim" the texts and still guess the next word. Similar reading materials have been used by other researchers.[18] The texts were printed with black letters on white A4 paper (measured contrast 85%) by a laser printer, in Courier font. Each line of text was taken from a newspaper or magazine article, and consisted of 9 words varying in size from 1 to 10 letters per word, and 45 character spaces, defined as the center-to-center distance between each letter.[4] The lines of 10-point print occupied a horizontal linear distance of 90 mm, subtending 12.8° of visual angle at 40 cm, and the size of one character space (and the between-line spacing) was 2 mm. The 18-point texts featured correspondingly longer lines: a linear length of 162 mm subtending 23.4° at a viewing distance of 40 cm, with a character and between-line spacing of 3.6 mm. A series of different texts were employed throughout each session to eliminate familiarity effects.

Eye Movement Recording

Infra-Red Oculography (IRO) (ASC Applied Research Developments Limited, Manchester: Eye Movement Monitor Model EM 130) with a spatial resolution of 3 min arc and a temporal resolution of 10 ms, was used to record the eye movements of the subjects. The IR sources and receivers were mounted on a lens ring carried on a spectacle trial frame worn by the subject, and records of eye position were obtained on a linear chart recorder. The spectacle trial frame containing the IRO lens was adjusted for the subjects: the system was calibrated several times in each session by asking the subject to make saccades of known angular size. The linearity was confirmed within a range of ± 15° from the straight-ahead gaze position, which included the eye positions required by the reading task.

Procedure

The reading speed and the eye movements of the subjects were recorded as they read material containing both 10- and 18-point sentences, through two hand magnifiers of different power (Coil Models 5203 and 5206) held at two different eye-to-magnifier distances. The magnifier-to-text distance was constant, and equal to the focal length of the magnifier. The hand magnifiers used were representative of those usually prescribed to low vision patients.[19] The equivalent power (F_{eq}) of each magnifier was measured according to the method suggested by Bailey,[20] and magnification (M_M) was then calculated from $M_M = F_{eq}/2.5$. This formula for magnification was used because the control condition in this experiment involved reading of text without a magnifier at a viewing distance of 40 cm, the focal length of a +2.50 D lens. The +2.50 D power in this case is provided by the accommodation of the subject's eye, and this is arbitrarily defined as 1× magnification. When using a hand magnifier, the total retinal magnification (M_T) that the subjects experienced was the combination of the magnification provided by the magnifier (M_M) and that derived from any increase in print size (M_P), with 10-point print being arbitrarily designated as $M_P = 1$. It is given by the formula:

$$M_T = M_M \times M_P$$

The effect of "large print" (18-point) was examined because this constitutes a common and straightforward method of increasing the retinal image size of printed material, magnification being provided free from optical distortions and aberrations. In clinical practice, large print can be employed alone, or in combination with an optical low vision aid. In the latter case, an alleged advantage of large print is that it allows the reader to use a weaker magnifying device featuring a wider aberration-free FOV than the stronger aid that would have been prescribed if smaller print was to be read. Earlier studies, however, have suggested that this potential advantage is not always apparent clinically.[21, 22]

Two different eye-to-magnifier distances, short (10 cm) and long (35 cm), were employed: the "short" distance is representative of the optimum positioning of the magnifier close to the eye to give a wider FOV, and the "long" distance is that likely to be used by a naive patient without instruction. The shorter eye-to-magnifier distance gives an increased FOV, but does not change the magnification, providing that the object is kept at the focal point of the magnifier. The FOV in each condition was measured in character spaces by direct viewing through the lens positioned as it would be during the experiment.

The subjects read under the five different conditions, in random order: one without a magnifier and four with the two magnifiers held at the two eye-to-magnifier distances. A different text sample was used for each condition, and because each text contained both print sizes, there were a total of 10 experimental conditions. Their main features are summarized in Table 1. Each experimental session lasted approximately 40 min. Subjects were allowed a short practice session (up to 10 min) during which they read short passages with the magnifiers at different eye-to-magnifier distances. For the experiment, the subjects were asked to maintain the required eye-to-magnifier and magnifier-to-text (equal to the magnifier focal length) distances. To use the magnifiers in conditions like those experienced by real low-vision patients, the subjects were not physically restrained and so the distances were not absolutely fixed. Any condition during which the experimenter observed changes in position was not analyzed, and the condition was repeated later.

The text was placed onto a reading stand in front of the subject and its luminance was approximately 550 lux, dropping to 200 lux with the shorter eye-to-magnifier distance.

Throughout this study, statistical analysis of the data was performed by means of a Wilcoxon non-parametric test, because tests on the data showed that they were not normally distributed.

RESULTS

In the control conditions, in which no magnification was used, the subjects showed the normal "staircase" reading eye movement pattern, a sequence of saccades and fixation pauses. The use of 18-point print did not alter the eye movement pattern, but there was an increase in the angular size of the forward saccades. A change in the reading eye movements was seen, however, when the hand magnifiers were employed. In these conditions, as expected, a "saw-tooth" eye movement pattern was observed, featuring smooth leftward eye movements instead of fixation pauses (Fig. 1). The rightward movement of the magnifier (which is a strong plus lens) along the text causes this "saw-tooth" eye movement pattern. This creates an apparent leftward movement of the reading stimulus that is "followed" by the eyes. Thus, the eyes appear to fixate on a point in the text, follow its leftward movement for a certain time (equivalent to the average time of a fixation pause in "normal" reading) and then jump with a saccade to the next "fixation." Because of saccadic suppression, one can assume that when such a reading eye movement pattern is adopted, textual information is only extracted during the smooth leftward eye movement. A "reverse" saw-tooth pattern sometimes occurs when the reader reaches

TABLE 1.
The magnification and field-of-view (FOV) in each of the reading conditions used.

Print Size	Condition	Eye-to-Text 40 cm		Eye-to-Magnifier 35 cm		Eye-to-Magnifier 10 cm	
		$M_P = 1$ 10-point	$M_P = 1.8$ 18-point	$M_P = 1$ 10-point	$M_P = 1.8$ 18-point	$M_P = 1$ 10-point	$M_P = 1.8$ 18-point
No magnifier (NM)	M_T	1	1.8				
	FOV (characters)	>45	>45				
Coil 5203	M_T			3	5.4	3	5.4
F_{eq} + 7.50 D diameter = 81 mm	FOV (characters)			14.2	7.9	>45	27.3
$M_M = F_{eq}/2.5 = 3\times$							
Coil 5206	M_T			7.5	13.5	7.5	13.5
$F_{eq} = +18.70$ D diameter = 50 mm	FOV (characters)			3.5	2	12.2	6.8
$M_M = F_{eq}/2.5 = 7.5\times$							

M_M, magnifier magnification; M_P, print magnification; M_T, total magnification.

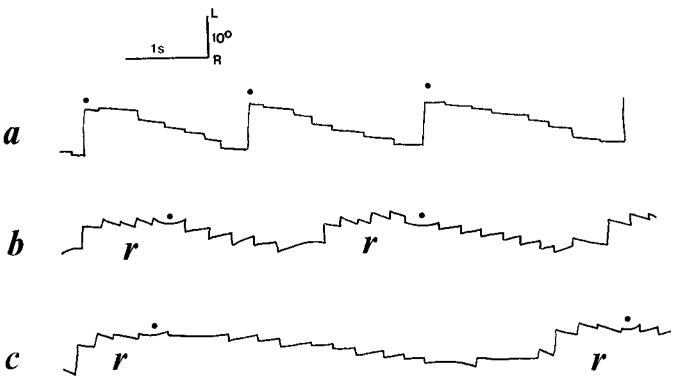

FIGURE 1.

Examples of the eye movements recorded during reading. *a* shows the normal "staircase" pattern when reading 10-point text at 40 cm without a magnifier. Reading 10-point text with a 3× (*b*) and 7.5× (*c*) hand magnifier at an eye-to-magnifier distance of 35 cm in each case, shows the slower reading in *c* with the larger number of fixations per line. ● shows the start of a new line of text and *r* indicates a section of "reversed" sawtooth eye movements.

the end of one line and moves back to the beginning of the next. This is caused by the apparent rightward movement of the text under the leftward-moving magnifier, and may contribute to the difficulty in locating the beginning of the next line, and to the decrease of reading speed when magnifiers are used.[15]

Compared to reading 10-point print without a magnifier, mean reading speed for all subjects declined significantly ($p < 0.01$) with increasing magnification, for both eye-to-magnifier distances (Fig. 2). Regardless of which magnifier and eye-to-magnifier distance was used, all 18-point print conditions featured significantly ($p < 0.05$) lower reading speeds than the equivalent 10-point print condition (compare 5.4× to 3×, and 13.5× to 7.5× total magnification). This means that an increase in letter size of just 1.8× gives

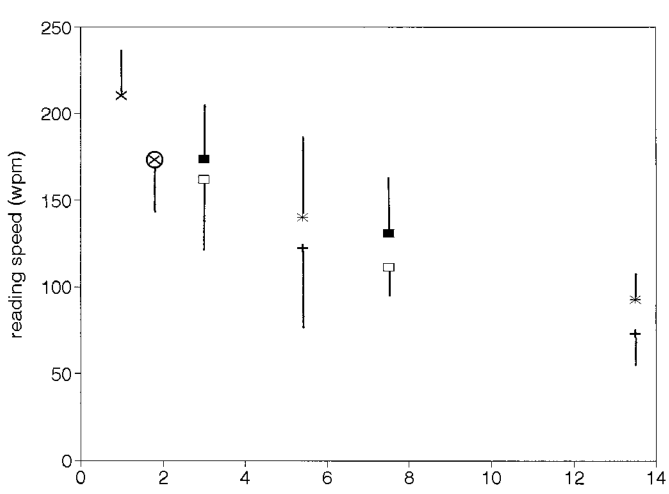

FIGURE 2.

Mean (and 1 SD: for clarity only + or − is shown) reading speed (in wpm) plotted against total magnification for each of the 10 reading conditions used. The viewing conditions shown are: ×, NM/10-point; ⊗, NM/18-point; ∗ and + represent 18-point print; □ and ■ represent 10-point; ■ and ∗, 10-cm eye-to-magnifier distance; □ and +, 35 cm eye-to-magnifier distance.

a statistically significant decrease in the reading speed of normally sighted readers under these conditions.

The slowing of reading seems directly proportional to the magnification: reading speed seems to vary monotonically with magnification in Fig. 2, even though the reading conditions featured differ considerably. Employing a short (10 cm) eye-to-magnifier distance—thus increasing FOV—tended to give higher reading speeds than the 35-cm eye-to-magnifier distance, but the effect was not statistically significant ($p > 0.05$) except when 18-point print was viewed through the 7.5× hand magnifier and total magnification of the retinal image of the print was 13.5×. In this case, the short eye-to-magnifier distance which gave a FOV of 6.8 characters showed a significantly higher reading speed than when the longer distance was used and FOV was only two characters.

The reading speed represents the global effect of all the individual parameters that go to make up the reading eye movement. The contribution of each of these factors to the reading speed under the different conditions was assessed. The variables measured were:

1. Reading speed in words per minute (wpm).
2. Length of the forward saccades in degrees, character spaces, and as a percentage of the overall FOV.
3. Fixation duration (that is, the time between successive saccades) in milliseconds
4. Number of fixations, forward saccades and regressions (backward saccades) per line of text.

The mean length of forward saccades in character spaces was calculated from the theoretical magnification obtained. For the 10-point print, for example, an individual character was 2 mm in horizontal size, which when viewed from 40 cm subtends 0.285°. This would then give an angular subtense per character for 3× magnification, for example, of 0.855° (=3× 0.285) Dividing the angular size of the forward saccade by this value gives the result in terms of number of characters: the size of the forward saccade is also given as a percentage of the overall FOV. The means and standard deviations (all subjects) for each of the parameters are summarized in Table 2.

Fixation durations show very little variation across conditions—only the 7.5×/long/18-point had significantly shorter fixation durations than the 7.5×/long/10-point, and the NM/18-point had significantly shorter fixation durations than no magnification (NM)/10-point. There was little change in the number of regressions per line with any of the conditions: in fact, the only significant difference was that the number of regressions in the 7.5×/short/10-point was less than in the NM/18-point condition.

Forward saccade size does, however, alter significantly. In all but one case, in which a particular magnifier was used at a given eye-to-lens distance, the forward saccades were significantly larger ($p < 0.05$) with the 18-point compared with the 10-point print: the NM condition also showed a significantly increased forward saccade with 18-point print. These saccades must, however, be smaller in terms of character size because they have not increased by the required factor of 1.8× (Table 3).

If the forward saccades get smaller (in terms of characters), then it is not surprising that the number of forward saccades and fixations increases significantly, being in inverse proportion to the size of the forward saccades. These parameters are each plotted against reading speed in Fig. 3, showing how they contribute to it—as the saccades get smaller, there have to be more of them to traverse a line

TABLE 2.
The eye movement parameters shown as mean ± 1 SD.

	Eye-to-Text = 40 cm		Eye-to-Magnifier = 35 cm		Eye-to-Magnifier = 10 cm	
	M_P = 1 10-point	M_P = 1.8 18-point	M_P = 1 10-point	M_P = 1.8 18-point	M_P = 1 10-point	M_P = 1.8 18-point
No magnifier (NM)						
Reading speed (wpm)	210.2 ± 25.9	173.5 ± 27.7				
Length of forward saccade						
Degrees	1.5 ± 0.2	2.1 ± 0.3				
Characters	5.26	4.09				
As % of FOV	11.7	9.1				
Fixation duration (ms)	247.7 ± 14.3	236.5 ± 16.7				
Fixations per line	8.3 ± 1.6	9.5 ± 2.5				
Forward saccades per line	7.0 ± 1.0	8.1 ± 1.5				
Regressions per line	1.2 ± 0.8	1.6 ± 1.0				
Coil 5203 (M_M = 3×)						
M_T			3	5.4	3	5.4
Reading speed (wpm)			161.9 ± 40.7	122.7 ± 45.3	173.7 ± 31.6	140.2 ± 45.9
Length of forward saccade						
Degrees			2.3 ± 0.6	2.9 ± 0.6	3.1 ± 0.9	3.8 ± 0.9
Characters			2.67	1.88	3.6	2.47
As % of FOV			18.8	23.8	8.0	9.0
Fixation duration (ms)			252.5 ± 17.9	255.7 ± 14.6	239.9 ± 22.4	246.7 ± 15.4
Fixations per line			9.7 ± 2.9	12.0 ± 3.3	9.5 ± 2.5	11.2 ± 3.3
Forward saccades per line			8.2 ± 1.5	10.3 ± 2.0	8.4 ± 1.0	10.4 ± 2.3
Regressions per line			1.7 ± 1.5	1.6 ± 1.5	1.2 ± 0.7	0.8 ± 1.0
Coil 5206 (M_M = 7.5×)						
M_T			7.5	13.5	7.5	13.5
Reading speed (wpm)			111.6 ± 16.6	73.1 ± 18.3	131.4 ± 31.8	92.8 ± 13.8
Length of forward saccade						
Degrees			2.3 ± 0.5	2.4 ± 0.5	3.8 ± 0.8	4.2 ± 0.8
Characters			1.07	0.62	1.78	1.09
As % of FOV			30.6	31.0	14.6	16.0
Fixation duration (ms)			265.8 ± 15.4	258.7 ± 12.7	248.2 ± 22.5	254.7 ± 20.3
Fixations per line			12.6 ± 1.3	18.4 ± 1.7	11.4 ± 2.1	15.6 ± 2.0
Forward saccades per line			11.6 ± 1.1	17.4 ± 1.8	10.7 ± 1.6	14.4 ± 1.4
Regressions per line			1.0 ± 0.7	1.0 ± 0.7	0.7 ± 0.6	1.1 ± 0.7

M_M, magnifier magnification; M_P, print magnification; M_T, total magnification.

of a given number of characters. After each saccade there is a "fixation," and because the fixation durations alter very little, reading is progressively slowed as the number of fixations increases.

But what determines the size of the forward saccades? Fig. 4a illustrates clearly that the failure of the forward saccades to increase in proportion to the magnification is even more obvious at higher magnification. It can also be seen in Table 3 that in the 7.5×/long/10-point condition, the forward saccades are only 1.53× larger than in the NM/10-point condition, yet the retinal image is 7.5× larger. Forward saccade size is significantly longer for the short working distance than the long for each pair. This is shown in Fig. 4b, in which the angular size seems to increase toward a maximum value, which depends little on magnification. Although the 10-cm working distance obviously has a larger FOV, this is not the only factor at work here: FOV differs by a factor of 3.5× between the two eye-to-magnifier distances, but the saccade size increases by < 50% of that value (Table 4). The forward saccade size is almost identical for 3×/long/10-point and 7.5×/long/18-point (total magnification 3× and 13.5×, respectively) and yet the FOV is 14.2 characters in the first case, and two characters in the second.

It is possible that the restricted FOV of the magnifying system (which becomes narrower as the magnification increases) is creating a "window" effect for the reader. Obviously, in the extreme case, the reader is unlikely to make eye movements that are larger than the visible field. In fact, Table 2 shows that when FOV is unrestricted, each saccade is approximately 10% of the total line length. Surprisingly, restricting the FOV causes this proportion to increase, and when the eye-to-magnifier distance is 35 cm and FOV is most restricted, the forward saccades are equivalent to approximately 30% of the overall FOV. Thus, although the restricted FOV decreases saccade size, the decrease is not as great as would be expected, because the physically

TABLE 3.
The relative increase in size of forward saccades between the different magnification conditions used (all increases statistically significant except *).

Magnification conditions used to read 10-point print	Increase in forward saccade size with magnifier compared with NM/10-point	Increase in forward saccade size reading 18-point vs. 10-point print
NM (1×)		1.40
3×long	1.53	1.26
3×short	2.06	1.23
7.5×long	1.53	1.05*
7.5×short	2.53	1.10

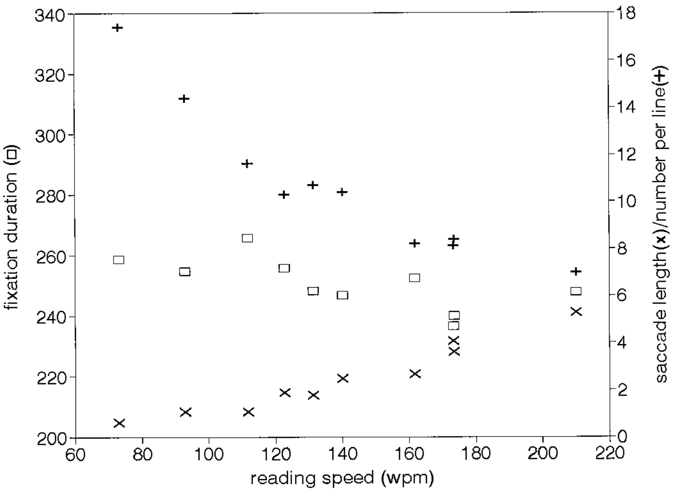

FIGURE 3.
The relationship between reading speed (in wpm) and several eye movement parameters. These are: □, fixation duration (in ms) (left-hand ordinate scale); ×, length of forward saccades in degrees; and +, number of forward saccades per line (common right-hand ordinate scale).

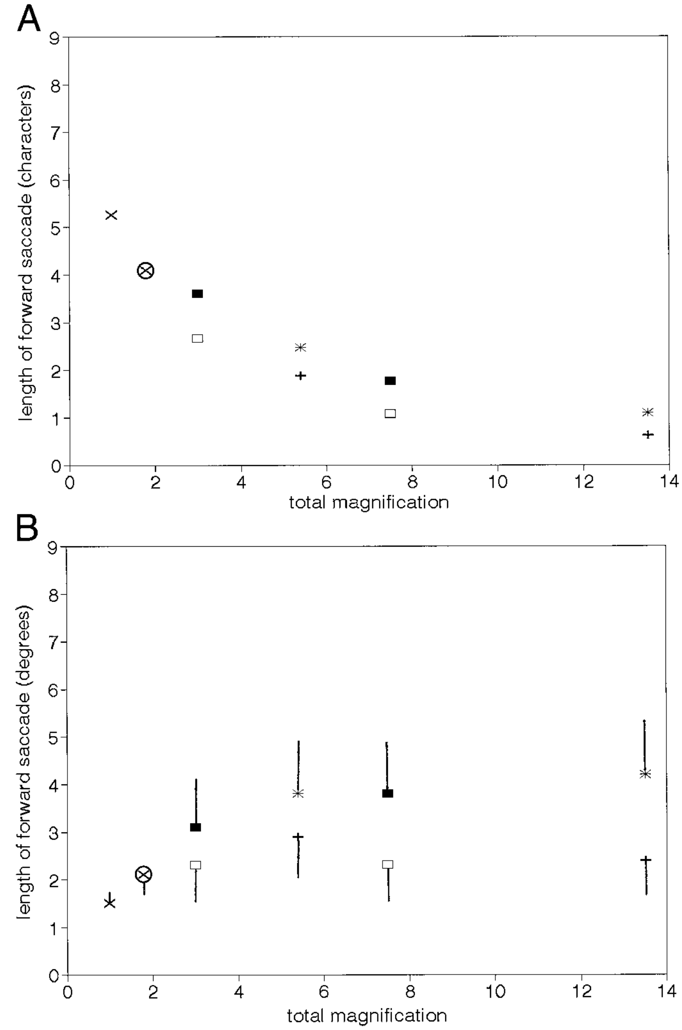

FIGURE 4.
The mean length of forward saccade in characters (A) and the mean (and 1 SD: for clarity, only + or − is shown) length of forward saccades in degrees (B), plotted against total magnification. The viewing conditions shown are: ×, NM/10-point; ⊗, NM/18-point; * and + represent 18-point print; □ and ■ represent 10-point; ■ and *, 10-cm eye-to-magnifier distance; □ and +, 35-cm eye-to-magnifier distance.

longer eye-to-magnifier distance seems to give proportionately longer saccades.

DISCUSSION

The results obtained in this study with normally sighted subjects reading magnified text help to explain why low vision patients usually read slowly, even when provided with optimal magnification of the reading material. Magnification, despite being essential for the low vision patients to resolve print, will presumably impose the same visual and oculomotor limitations on reading speed as with the normally sighted observers in this study. It is unlikely that the low-vision patient has any visual or reading capabilities that would reduce the disadvantages of using magnification (at least when untrained). They may experience greater difficulty because of their pathology (for example, features of existing scotomata), their general health (mental and physical), and their motivation to read. The possible influence of these factors has not been considered. In this study, subjects were tested on their first exposure to using a magnifier, and the significant positive effects that training, practice, and strong motivation might have on reading performance must be borne in mind. Despite these shortcomings, a patient must overcome the difficulties that occur during this initial phase (either by trial-and-error or by appropriate instruction) if they are to persist with use of the magnifier.

This study found a decreased reading speed at even modest levels of magnification: even the NM condition showed a significant slowing with 18-point print compared with 10-point print. This seems to contradict the findings of Legge et al.,[9] who found very little change in reading speed over a wide range of letter sizes (0.2° to 3°, comparable to 0.7× to 10.5× as defined by this study). Their experiments, however, used a paradigm that forced subjects to read at a maximum rate, and the subjects had no need to manipulate the text or a LVA in any way. By contrast, in the present study, subjects selected their own preferred rate, and (in most cases) they had to move the hand magnifier across the page, because the available FOV was usually less than the length of a line of text.

TABLE 4.
The length of forward saccades (in characters) in each magnification condition. The ratio of saccade size between the two conditions is calculated.

Total magnification	Length of forward saccade (characters): Eye-to-magnifier distance		Ratio of forward saccade size
	10 cm	35 cm	
3	3.6	2.67	1.35
5.4	2.47	1.88	1.31
7.5	1.78	1.07	1.66
13.5	1.09	0.62	1.75

As can be seen from the smooth progression of the data for 10- and 18-point print in Fig. 2, whether the subject reads "normal" print with a more powerful magnifier or "large" print with a weaker magnifier to achieve a given level of magnification seems to make little difference to reading speed. This finding is consistent with previous studies.[21, 22]

The eye movements of the subjects were recorded and analyzed, and the decline in reading speed was found to be caused primarily by changes in the size of the forward saccades. Forward saccades increased in angular size with magnification but not in proportion to the increase in letter size. Thus, they actually become shorter in terms of character spaces, forcing the reader to execute more saccades and fixations per line of text than is the case when reading without magnification. As fixation duration changes very little with increased magnification, the result is slower reading.

This reading, however, is not as slow as might have been expected. Fig. 4a shows that over the range of magnification tested, the size of forward saccades (in characters) fell by a factor of more than fivefold. The reading speed, however, fell by only 1.5- to two-fold, yet Fig. 3 shows that the two should be closely related.

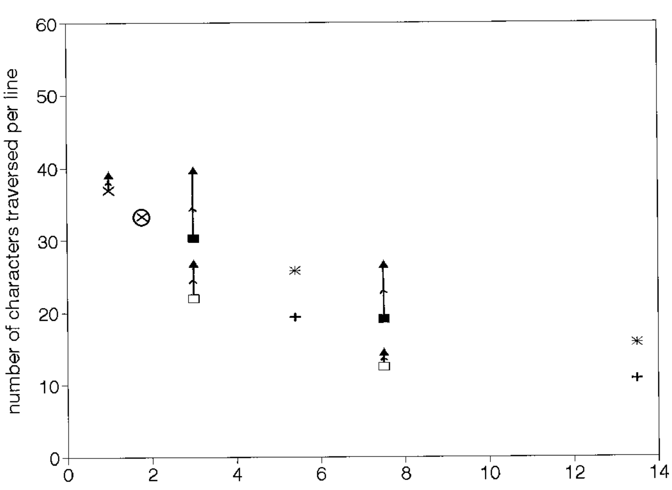

FIGURE 5.
The calculated number of characters traversed per line when reading. Head unrestrained conditions are represented as: ×, NM/10-point; ⊗, NM/18-point; * and + represent 18-point print; □ and ■ represent 10-point; ■ and * 10-cm eye-to-magnifier distance; □ and +, 35 cm eye-to-magnifier distance. ▲ is a repeat of the 10-point conditions using a "head fixed" paradigm. Arrowed lines join conditions with the same magnification and FOV. Nominal line length is 45 characters.

This anomaly can be explained by multiplying the number of forward saccades per line by the size of the saccades in characters to determine the overall number of characters traversed by the eyes along each line of text. In this study, the lines were 45 characters long, and Fig. 5 shows the overall distance traveled along the lines under the different conditions employed in this study. In the NM conditions, the eyes traverse approximately 35 characters while reading the line. This seems a realistic result, because the reader probably does not fixate on the first or last letter on the line but in the middle of each of the corresponding words. All the magnified conditions also show less than the maximum value of 45 characters and, as the magnification increases, the discrepancy becomes considerable. In the most extreme case, only about 10 characters are covered and the mean forward saccade is only 0.62 characters long.

So how did the reader move along the line if not using forward saccades? There seem to be two possibilities:

1. It is possible that fast head movements from left-to-right (that is, in the direction of reading) were occurring at the same time as the saccadic eye movements: in effect, the head is "saccading" as well.
2. In standard "staircase" reading eye movements, the eyes are completely stationary during the fixations as the text is analyzed. In reading with a magnifier, however, the object is now a moving target, and the equivalent to fixation would now be smooth pursuit matched to the speed of apparent text movement. Faster reading may be achieved, however, by allowing retinal slip, where the eyes lag behind the text.

The experiment used "natural" reading conditions, and thus subjects did not experience any head restraint. The experimenter did not notice head movements of this extent, but to check for the first possible explanation, a control experiment was conducted. Three subjects repeated those experimental conditions that used 10-point print; however, this time the head was fixed by the use of a chin rest. The forward saccade size was then compared for the "unrestrained" and "head fixed" conditions, and the results are illustrated in Table 5. This shows that the forward saccades were larger in the head fixed condition, suggesting that head movement from left to right can achieve some of the movement of the image across the retina if unrestrained. The ratio of the increase in saccade size for the head fixed condition was calculated, and then the *measured* forward saccade sizes in the original "unrestrained" experiment were recalculated, assuming that they would have been increased in this way if the experiment had been performed under more restricted conditions. Using these forward saccade sizes, the number of characters traversed by the eyes in traveling along each line was determined, and these are plotted in Fig. 5. This suggests that [particularly for the lower degree of magnification and the larger FOV (the shorter eye-to-magnifier distance)],the subject uses a combination of a head and eye movement to make a jump of the required size. In comparing "head fixed" and "unrestrained" reading, it can be seen that head movements achieve some 20–30% of the required travel along the line. This may simply be because at this close eye-to-mag distance, the angular subtense of the lines is greater and it is natural to use head movements to supplement the eye excursion. The 18-point text, however, was

TABLE 5.
The mean (±1 SD) length of forward saccade (in degrees and characters) for the head fixed control, compared with the head unrestrained condition. The ratio of saccadic size between the two conditions is calculated.

		Eye-to-text, 40 cm Length of forward saccade		Eye-to-magnifier, 35 cm Length of forward saccade		Eye-to-magnifier, 10 cm Length of forward saccade	
		Degrees	Characters	Degrees	Characters	Degrees	Characters
No magnifier (NM)	Head fixed	1.7 ± 0.1	6.07				
	Unrestrained	1.6 ± 0.2	5.71				
	Ratio	1.06					
Coil 5203	Head fixed			2.8 ± 0.1	3.33	3.8 ± 0.4	4.52
$M_M = 3\times$	Unrestrained			2.3 ± 0.5	2.74	2.9 ± 0.5	3.45
	Ratio			1.22		1.31	
Coil 5206	Head fixed			2.2 ± 0.3	1.05	4.3 ± 0.4	2.05
$M_M = 7.5\times$	Unrestrained			1.9 ± 0.4	0.90	3.1 ± 0.9	1.48
	Ratio			1.16		1.39	

laid out in longer lines; there, a "head movement strategy" would seem even more likely. This is not borne out because, as discussed previously, total magnification is more significant than the way in which it is produced. Bowers and Reid[23] found that subjects with simulated visual impairment spontaneously used much more head movement as the degree of visual loss increased. These subjects were not reading with magnifiers but the FOV may have been restricted perceptually by the acuity and contrast limitation (Legge et al.[2] suggest visual span may be reduced by fivefold in low compared with high contrast), so that forward saccades were small. Therefore, it may be that the head movement is a deliberate strategy to compensate for short saccades. If low-vision patients were encouraged to deliberately use a very high degree of head movement—to point their heads at each word they were reading—it might be possible to train an increased reading speed.

At high magnification (particularly with a small FOV created by a long eye-to-magnifier distance), however, Fig. 5 shows that head movement is still not sufficient to explain how the eyes traverse the full line length, and the second possibility must be tested. If we consider the total fixation time for a complete line to be mean fixation duration × number of fixations per line, then for reading 10-point print without a magnifier, this gives a time of 2.06 s. The line subtends 12.8° at 40 cm, and this value can be multiplied by the magnification in each condition to find the maximum angular traverse required. For 3× total magnification, this is 38.4°, and a simple calculation suggests pursuit would need to be at 18.7°/s if the same reading speed was to be maintained. This rises to more than 85°/s at 13.5× magnification, and this is not achievable. Even to read at the rate actually achieved for 13.5× magnification would require pursuit to be matched to a target motion of almost 45°/sec. It seems (Fig. 4b) that as magnification increases, the forward saccades increase to a maximum angular size (which depends on the available FOV) that is considerably less (in characters) than would occur in normal reading. Even if a pursuit eye movement of the correct speed could be produced in the fixation pauses, the limited saccade size would slow reading dramatically because it would require a considerable increase in the number of saccades needed to traverse each line of text. The reading is therefore speeded up by the moving image slipping across the retina, so that some of the traverse along the line happens during the apparent "fixations." Tolerance of this retinal slip, and the ability to "read" the moving retinal image, may occur more for the normally sighted subjects reported here than for visually impaired observers for whom the print size will be much closer to threshold. This may be one of the reasons why a visually impaired observer can only read quickly with a greater acuity reserve[10]: although using higher magnification (and the consequent further reduction in FOV) would be expected to reduce reading speed, this is outweighed by the improved ability to interpret the moving image.

Alternatively, the strategy of using retinal image slip to increase the reading speed may be one that low-vision patients develop to an increasing extent as they become practiced in reading with a magnifier over the first few days or weeks of use. The amount of retinal slip seems greater for the longer working distance, because this is the biggest mismatch between number of characters traversed with saccades compared with the total line length. In this case, the eyes may find it easier not to match the speed of the moving words, because they do not occupy so much of the visual field. In fact, subjects may even be able to use the edge of the magnifier as a "fixation target," because this is not moving as fast as the text.

Although there is a strong tendency for reading to be faster as FOV increases, the restriction in field has to be extreme before the slowing of overall reading speed is significant. In fact, reading was only slowed significantly ($p < 0.05$) as the eye-to-magnifier distance was increased for the highest magnification condition (7.5×/long/18-point compared with 7.5×/short/18-point). This decreased the FOV from 6.8 to two characters. It is interesting to compare this with results reported for CCTV reading. Whittaker and Lovie-Kitchin[10] proposed that the critical FOV was at least 12 characters for CCTV viewing in which the text had to be manipulated manually. Beckmann and Legge[24] have confirmed this difference more recently, showing that for normally sighted subjects reading text on a CCTV, the window widths are three times greater to achieve 85% of maximum speed for stationary text compared with drifting text. This suggests that the manipulation of the X-Y platform of a CCTV is much more difficult with a limited FOV for the naive subject than the movement of the hand magnifier across the page: this may be the reason why CCTV users require much greater training time to achieve optimum performance than does the user of optical magnification.[25] The finding also suggests that conclusions concerning FOV requirements for reading need to be determined using experimental conditions which are equivalent to the practical clinical conditions which the patient is to experience. This is probably why previous studies have yielded contradictory evidence concerning the effect of FOV on reading speed with magnification.

In summary, for a naive observer reading magnified text, the natural reading rate is reduced. There are several contributing factors. The forward saccades do not increase in size in proportion to the magnification, and so more are required to traverse a line of text. The use of a physical magnifying aid creates additional reductions, because restrictions in the FOV cause the forward saccades to decrease still further. Fixation duration is typically unchanged, so reading is slower, and difficulties in manual manipulation of a LVA can produce further slowing. However, two factors help to mitigate these reductions in speed. Head movement in the direction of reading can help to compensate for the restricted ocular saccades, and retinal image slip occurring during the slow phases of the eye movement also allows faster progression along the line of text.

Future research needs to be directed to determining how much these strategies are adopted by experienced visually impaired LVA users and how they might be encouraged by rehabilitation and training.

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