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Psychophysics of Reading—XIV. The Page Navigation Problem in Using Magnifiers

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Most people with low vision require magnification to read. A magnifier's field of view often contains only a few letters at a time. Page navigation is the process by which the reader moves the magnifier from word to word, and from the end of one line to the beginning of the next line. Page navigation takes time and reduces reading speed. The major questions addressed in this paper are: (1) What role does page navigation play in limiting reading speed? and (2) Are the window width requirements for reading (number of characters in the field for a criterion performance level) increased by the need for page navigation? We measured the reading speeds of three normal-vision and seven low-vision subjects in two ways: with drifting-text requiring no page navigation, and with a closed-circuit TV (CCTV) magnifier which required page navigation. We built special hardware to record the location of the CCTV's magnified field in the text. These recordings were used to separate forward-reading time (left-to-right movement through the text) from retrace time (navigational movement). For normal-vision subjects, forward-reading and retrace times were about equal. For low-vision subjects, retrace times were shorter than forward-reading times, indicating that the forward-reading performance was limited by visual, not navigational, demands. The retrace time did have an impact, however, ranging from 17 to 50% of the overall time. The window requirements for reading with page navigation (CCTV) were larger than those for reading without page navigation (drifting-text). The difference was more than a factor of three for normal-vision subjects and close to a factor of two for low-vision subjects (10 characters for CCTV vs 5.2 characters for drifting-text for 85% of maximum reading speed). Copyright © 1996 Elsevier Science Ltd.

Reading Magnifier Low vision

INTRODUCTION

Most people with low vision have difficulty reading normal print, but benefit from magnification. Reading with a magnifier involves two separate tasks: processing the visual stimuli and moving the magnifier over the text. For most types of magnification, there is a trade-off between magnification factor (i.e., angular character size) and the number of characters visible in the field, termed *window size*.‡ When magnification is high, the window size is often small. The reader may see only a few characters at a time through the magnifier, and must move the magnifier from word to word, and from the end of one line to the beginning of the next line. This is the *page navigation problem* in using magnifiers.

Previous studies (reviewed below) have examined the effect of window size on reading rate with discrepant findings. These studies varied in the nature of the page navigation demands on the subjects, a factor that may explain the discrepancies. A major goal of the present study was to evaluate the separate effects of visual and navigational limitations on magnifier-aided reading rate. We did this by developing a method for measuring magnifier movements during reading.

Several previous studies of window-size and character-size effects in low-vision reading have used closed-circuit television (CCTV) magnifiers [Archambault *et al.*, 1990; Guerrera *et al.*, 1994; Lovie-Kitchin & Woo, 1988; Lowe & Drasdo, 1990. See Whittaker & Lovie-Kitchin (1993) for an excellent survey]. A CCTV magnifier consists of a monitor, usually quite large, and a video camera equipped with a zoom lens. The camera and lens look down on a movable platform. Printed material is placed on the platform and the reader views the magnified

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‡In this paper, we distinguish between "window size" and "field size". "Field size" refers to the angular subtense in degrees of the magnifier image measured at the reader's eye. "Window size" refers to the number of characters (arranged on a line of text) that fits into the field size.

image on the monitor screen. The reader "navigates" through the text by moving the platform, thereby moving the material through the camera's field of view. For laboratory use, a CCTV magnifier permits convenient control of window size, stimulus luminance and magnification factor.* We modified a CCTV magnifier (see Methods) so that we could measure the platform movements, enabling us to analyze the reader's page navigation.

The total time to read a passage of text with a magnifier can be divided into two components: time spent moving forward (to the right) over the lines of text and time spent retracing to the beginning of new lines. We asked how these two components of reading time are separately affected by window size.

The relative amount of time spent in retrace movements with a magnifier can have a major impact on low-vision reading rate. For example, if a reader takes equal time for forward movements and retrace movements, overall reading rate will be half of the rate when no retrace is required. We analyzed the component times at different window sizes for subjects with normal vision and those with low vision to evaluate the impact of retrace time (i.e., navigation time) on reading rate.

Previous studies have tried to identify the window requirements for reading, that is, the minimum number of characters in the field yielding high reading rate. A key point in this determination is the selection of a performance criterion. (Differences in the performance criteria probably account for some discrepancies in the literature.) From a clinical perspective, the issue of performance criterion is also important: what percentage loss in reading rate is associated with a given reduction in window size? We addressed this issue by measuring reading rate as a function of window size, and then computing the window sizes required for a series of criterion levels of performance.

PREVIOUS LITERATURE

Previous work has investigated the dependence of reading rate on window size when text drifted through the field requiring no page navigation (Legge *et al.*, 1985a,b) and when subjects moved a magnifier across text (Lovie-Kitchin & Woo, 1988; Lowe & Drasdo, 1990).

The drifting-text measurements evaluated the purely visual requirements for reading, without the need for any page navigation. In the Legge *et al.* experiments, 80-character-long lines of text drifted across a display screen under computer control. The experimenter increased the drift rate until the subject made a small number of errors reading the text aloud. The reading rate was calculated as the number of words read correctly in the time the text took to drift across the screen. For subjects with normal vision (Legge *et al.*, 1985a) and low vision (Legge *et al.*, 1985b), reading rate increased with window width up to about 4 characters with little or no increase for larger windows.

Lovie-Kitchin and Woo's (1988) subjects read single lines, (21–30 words long), with a CCTV magnifier using manual scanning. No retrace was required. They found that reading rate for normal-vision subjects increased up to a window width of about 15 characters and then plateaued. Peak reading rates in this study were about 150 words/min. They divided low-vision subjects into two groups based on their performance: readers with rates above about 75 wpm benefited from large windows; slower readers benefited from greater magnification despite decreased window size.

Lowe & Drasdo (1990) measured the time for low-vision subjects to read a 200 word passage aloud using a CCTV magnifier. The passages were formatted into 21 lines, each about 60 characters long. The subjects had to navigate through the entire text, including both forward and retrace magnifier movements. Reading rates were measured for 25 conditions: five field widths (from 25 to 100 deg) by five character sizes (3–15 deg). Their data revealed an increase in reading rate up to a window width of about 24 characters, largely independent of character size (their Table 5 and Fig. 4). The peak reading rates in their study under the best conditions were about 100 words/min.

These findings reveal a large discrepancy in estimates of the window requirements for reading. Whittaker & Lovie-Kitchin (1993) proposed that the differences depend largely on whether subjects themselves controlled the rate of text presentation, as would be the case in manual scanning, or whether the text was presented at a forced rate, as in Legge and colleagues" drifting text method. These alternatives are confounded with different page navigation demands, which the present study is aimed at disentangling. With this in mind, we compared the reading rates of the same subjects for drifting text (no page navigation) and for CCTV reading with full navigational demands.

METHODS

Subjects

Three normal-vision and seven low-vision subjects were paid to participate in this study. Informed consent was obtained. A summary of the ten subjects is shown in Table 1. Each subject participated in both CCTV and drifting-text experiments.

Materials and apparatus

Simple texts were chosen whose difficulty was well below the reading level of the subjects, ensuring that reading rate was not limited by text difficulty (Carver, 1990; Coke, 1974). The text was sixth grade level and all of our subjects had completed at least 12th grade. Many

*This system, although expensive, has a number of desirable features as a practical low-vision magnifier. Among these are continuously variable magnification, the ability to move the magnifier field of view without significant head movement, wide magnification range, wide visual field of view, and the capability of reversing image contrast (changing printed black text on a white background to white text on a black background).

TABLE 1. Subject characteristics

Subject	Snellen acuity	Age	Condition	CCTV experience	Professional history
Low vision					
A	20/160	82	AMD	Little to none	Legal secretary
B	20/40	69	Optic neuropathy	2 years	Statistician/Professor
C	20/960	45	Corneal opacification	15+ years	Professor
D	20/80	51	Lateral field hemianopia	1 year	High-school educator
E	20/500	43	Optic neuropathy	Little to none	Secretary
F	20/50	46	Optic atrophy, amblyopia	About 1 year	Graduate student
G	20/250	80	AMD, cataract	Little to none	Professor
Normal vision					
H	20/20	28	-		PhD Researcher
J	20/10	63			Licensing admin.
K	20/20	23	-		Graduate student

AMD, age-related macular degeneration.

of them were professionals or academics (Table 1). While no formal screening of reading grade level was performed, it is highly unlikely that text difficulty played any role in limiting their reading performance. Text passages were constructed from stories in the 5th book of the McCall & Crabbs (1925) series of reading primers. We did no editing of the stories, although some stories were excluded because of dated or inappropriate content. The passages did contain some obscure proper names.

For CCTV reading, each passage was formatted with column width and type size similar to newsprint. This was done in an effort to emulate an everyday reading task and to place realistic demands on the subjects' motor control. These demands are affected by the physical print size on the page, since smaller print requires finer platform control and better absolute accuracy than larger print.

Each passage was contained in a block of text 13 lines by 30 characters in size. This block had a height-to-width ratio similar to the 1.4:1 aspect ratio of the CCTV screen. The text was left-justified with ragged right margins. Hyphenation was performed using the word processing program "Microsoft Word". Passages began at the start of a story. Stories were truncated after 13 lines and an asterisk was placed at the beginning of the 14th line. This asterisk served as an "end of passage" marker for the subject (see Procedure section below). Use of a 10-point Courier font produced characters with a center-to-center spacing of 2.4 mm on the page. The baselines were separated by 3.5 mm (exactly 10 points).

The same stories were used in the drifting-text measurements. The passages were reformatted into 80-character-long lines with no hyphenation.

A VTEK Voyager XL CCTV magnifier was modified for use in this study. Two low mass non-contact optical encoders were added to the movable platform, one measuring its front-to-back position and one measuring its side-to-side position to an accuracy of 0.5 mm. These modifications were designed to leave the inertia and drag of the platform substantially unchanged. Circuitry allowed an IBM PC-AT computer to read platform position 10 times per second. The recordings were stored in a disk file for later analysis (see "Data analysis").

The text was displayed as black letters on a white background. The background luminance was 200 cd/m^2 and the text contrast was greater than 90% (Michelson definition). The zoom of the CCTV was adjusted to allow the entire 13 line by 30 character passage plus an additional line to be displayed on the unmasked screen. Black construction paper masks were placed on the screen to produce windows of the desired shape and width. The dimensions of these windows are shown in Table 2. (In this study, the window size was specified by its width, in horizontal character spaces.) The subjects read from a distance of 21 cm, resulting in a character size of 3 deg.

The height-to-width ratio of all but the 1 and 2 character windows was the same as the ratio of the non-occluded screen. This was done in an effort to emulate the effects of increased magnification on the visibility of a passage of text through the CCTV. The 1 and 2 character windows had to be made 1 line high, however, since less than a full character height would have been visible if made equal to the aspect ratio of the screen.

The angular character size, luminance and contrast conditions were the same for the drifting text measurements. The apparatus used for the drifting text portion of the study has been described elsewhere (Legge *et al.*, 1987). In brief, a PDP-11/23 computer with Grinnell display interface was used to generate a drifting text pattern on a 19" B/W Conrac SNA 17/Y display with P4

TABLE 2. CCTV window dimensions

Character	Width (cm)	Height (cm)	Aspect ratio
1	1.2	2.4	0.5
2	2.3	2.4	0.96
4	4.6	3.2	1.4
8	9.2	6.6	1.4
16	18.4	13.1	1.4
20	23.0	16.4	1.4

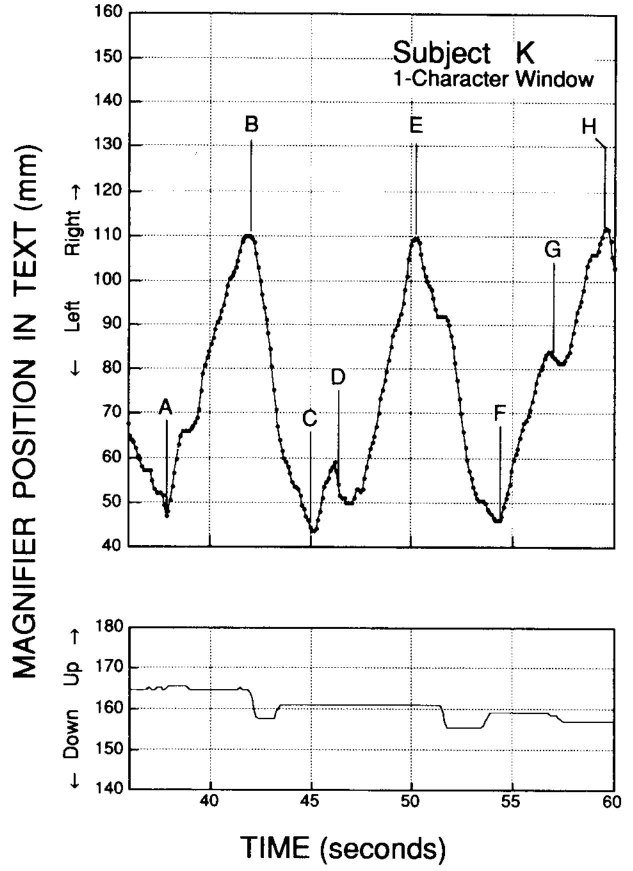

FIGURE 1. Segment of the CCTV magnifier position in text recorded during the reading of three lines of text by subject K through a one-character wide window. Horizontal movement across the page is shown in the upper trace. Simultaneous vertical movement over the page is shown in the lower trace. Samples were taken at 100 msec intervals and are rendered as dots in the upper trace. Printed lines of text were at most 62.5 mm long and were spaced 3.5 mm apart. The segment shown begins 35 sec after the subject began reading.

phosphor. The font consisted of upper- and lowercase characters on a 24 pixel wide by 38 pixel high character cell. The black text was displayed on a white 50 pixel high 200 cd/m^2 background with at least 90% contrast. The experimenter controlled the rate at which the text moved from right to left across the screen. A maximum of 20 characters could be displayed across the face of the monitor at a time. Smaller window widths of 1, 2, 4 and 8 characters were produced by covering portions of the monitor face with construction paper.

Procedure

The subjects alternated between series of window conditions using the CCTV and drifting-text, two series for each. In one series, the window width increased on successive conditions; in the other series, the window width decreased on successive conditions. For a given subject, a new passage was used for each condition in each series. Passages were not used twice in the study for the same condition.

Subjects were given a few minutes of familiarization on the CCTV for each window condition with text having the same physical layout as the testing material. Four of the low-vision subjects had substantial previous experience with CCTV magnifiers (see Table 1) and three did not. Goodrich *et al.* (1977) found that CCTV reading rates for low-vision subjects increase with unpredictable jumps over periods as long as 10 days after initial CCTV use. With practice having an effect over an extended period, it was impractical to bring our naive CCTV users to asymptotic performance levels.

For each CCTV window width, the subject read an entire passage silently. They were instructed to read quickly and accurately, and not to skip text. They were told that they would have to judge the difficulty of the text content on a 5-point scale at the end of each passage.*

Prior to each trial, the experimenter centered the image of the first letter of the passage in the viewing window on the CCTV screen while the subject's gaze was averted. When the experimenter said "Ready.......START", the subject began reading. The subject said "STOP" when the end-of-passage mark was reached, and gave a difficulty rating.

Drifting-text reading rate was measured with the adjustment procedure developed by Legge *et al.* (1985a). The starting drift rate was set at a value estimated to be readable without errors by the subject. The subject read the text aloud as it moved from right to left through the window. On subsequent presentations, the drift rate was increased until a small number of errors were made. The reading of two lines at the same drift rate with at least one error was taken as a valid measurement for a given window condition. The viewing distance of 19 cm resulted in a character width of 3 deg.

Data analysis

The position of the CCTV table determined which portion of the text was visible in the window on the monitor. We refer to the page location imaged at the center of the window as the magnifier position in the text.

Movements of the CCTV magnifier position during reading were analyzed using a program that displayed the left–right position and the up–down position as functions of time (see Fig. 1).

In general, the left–right traces resembled triangular or sawtooth waveforms. The figure shows a portion of the magnifier movements recorded while subject K read through a one-character window. This portion shows the movements he made while reading three lines (A to B, C to E, and F to H). The steep, downward sloping segments of the upper graph (e.g., B to C and E to F) represent retraces. Peaks in the waveform indicate the right end of lines and valleys the start of lines.

To analyze the reading of the first line, for example, the

*It was our intent to have the subject read for meaning. Specifically, we used instructions to induce the "rauding" mode as defined by Carver (1990; Chapter 2). In this mode, an "individual is looking at each consecutive word of a prose passage in order to comprehend the complete thought". (Carver, 1990, p.15.)

times at the valley (A) and at the peak (B) of the first excursion were digitized, and used in later calculations as the beginning and the end of the "forward" time segment.*

The retrace time segment was defined as the difference between the end of that segment (B) and the beginning of the next forward segment (C). These initial estimates were checked and refined using a parametric movie generator described below. The sum of the forward and retrace reading times equaled the total reading time for the line (A to C).

Departures from regular sawtooth waveforms occurred, such as the regressive movements at D and G in Fig. 1. Even though this type of regressive movement is in the "retrace" direction, it was included in the forward time. Another departure was a maneuver connected with finding the beginning of the next line, illustrated by the wobbly segment just before A in Fig. 1. Here, the subject was hesitating as he approached the beginning of the line; he had already moved vertically from the previous line to the current line. This type of maneuver was included in the retrace time. The Appendix contains other examples with comments on their microstructure and corresponding navigational strategies.

Sometimes it was difficult to decide when the subject stopped searching for the beginning of the line and started reading the line of text. To aid analysis in these cases, the data could also be viewed as a movie of the table movements. This was done by plotting the (x,y) positions on the screen for each of the samples within a selected time range in a slow-motion sequence. All ambiguities concerning the start of the forward movement were resolved by observing the movement in this time-sequential format.

In this manner, the left–right trace for an entire passage was divided into forward and retrace components. Each forward-plus-retrace pair, such as A–C in Fig. 1, was treated as a single reading trial. Therefore, the raw data for each reading trial in the CCTV measurements consisted of a forward time and a retrace time. When a subject read a complete passage of 13 lines of text, the resulting trace yielded 13 trials of raw data.

The data from each session were checked by a person other than the original analyst to verify the endpoint placements. The few discrepancies that arose were resolved by a third party.

*The beginning of the forward segment was defined as the first sample showing clear movement to the right. The end of the forward segment was defined as the first sample showing clear movement to the left. This procedure properly placed any time used by the subject to read text already in the window at the end of the line in the forward time segment; any searching or hesitation by the subject before they began to read a line was properly placed in the retrace time segment. However, this procedure was susceptible to two types of error. If the subject did not move the table after retrace but held the magnifier still and read the text visible through the window using eye movements alone, this time would not be included, as it should be, in the forward time. If the subject finished reading the line but did not start the retrace movement immediately, e.g., while planning the movement back or resting, the time would not be correctly placed in the retrace period. From observations of the subjects during the experiment, these events rarely occurred.

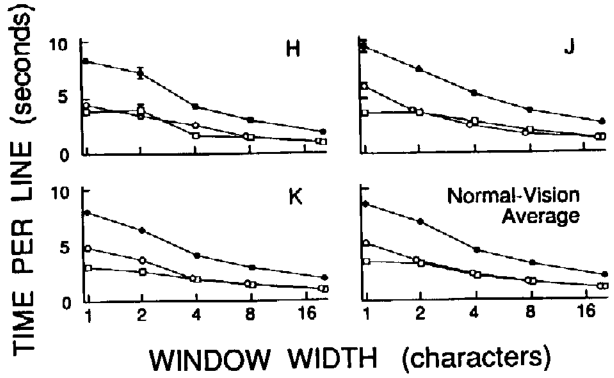

FIGURE 2. CCTV reading time as a function of window width for normal-vision subjects. The three types of symbols show means for total time per line (solid circles), forward-reading time per line (open circles), and retrace time per line (open squares). The total time is the sum of the forward-reading and retrace times. Each point is the arithmetic mean of up to 26 lines read. Standard error bars are shown where they exceed the height of the symbols. The fourth panel shows the pooled normal-vision average. In this and subsequent figures, overlapping data points have been offset horizontally to make them visible.

We used "standard length words" to compute reading rate (Carver, 1990). The number of standard length words is equal to the total number of characters in the text (including spaces) divided by six. Use of standard length words circumvents the confound between word length and text difficulty: mean word length increases with text difficulty. Carver (1990) has reviewed evidence showing that reading rate, measured in standard length words per minute, is independent of text difficulty provided that the reader's grade level exceeds the grade level of the text.

Reading rates for both CCTV and drifting-text conditions were computed as the text length in standard length words divided by time. In the case of drifting-text in which the words were read aloud, reading errors were subtracted.

Statistical analysis

Statistical analysis was performed on the data using SYSTAT version 5.0 for the Apple Macintosh (Wilkinson, 1989). Unless otherwise noted, the level of significance was set at the $P = 0.05$ level.

RESULTS AND DISCUSSION

Reading time

Figure 2 shows mean CCTV reading times as a function of window width for the three subjects with normal vision. The fourth panel shows means pooled across all three subjects. Within each panel, data are shown for the forward-reading time, retrace time, and the total time (sum of forward and retrace times). A two-way ANOVA on the pooled data revealed significant main effects of window width ($F[4,844] = 360.8$), direction, i.e., forward vs reverse ($F[1,844] = 50.0$), and a sig-

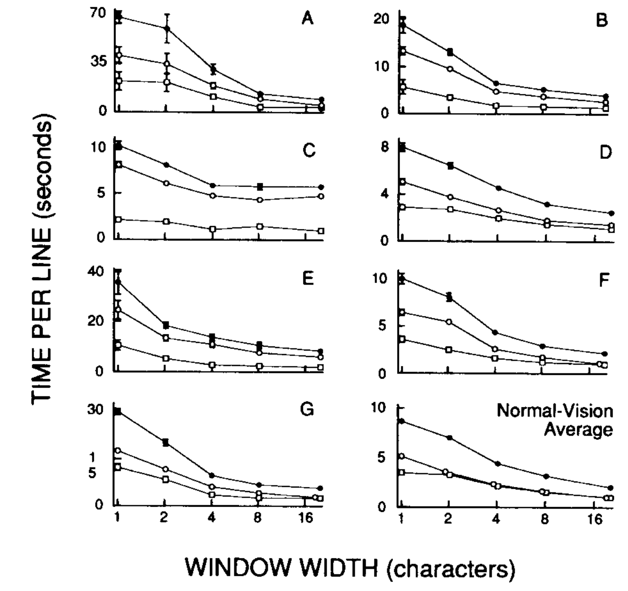

FIGURE 3. CCTV reading time as a function of window width for low-vision subjects. The three types of symbols show means for total time per line (solid circles), forward-reading time per line (open circles), and retrace time per line (open squares). The total time is the sum of the forward-reading and retrace times. Each point is the arithmetic mean of up to 26 lines read. Standard error bars are shown where they exceed the height of the symbols. Seven panels show low-vision data and the eighth panel replots the normal-vision average from Fig. 2.

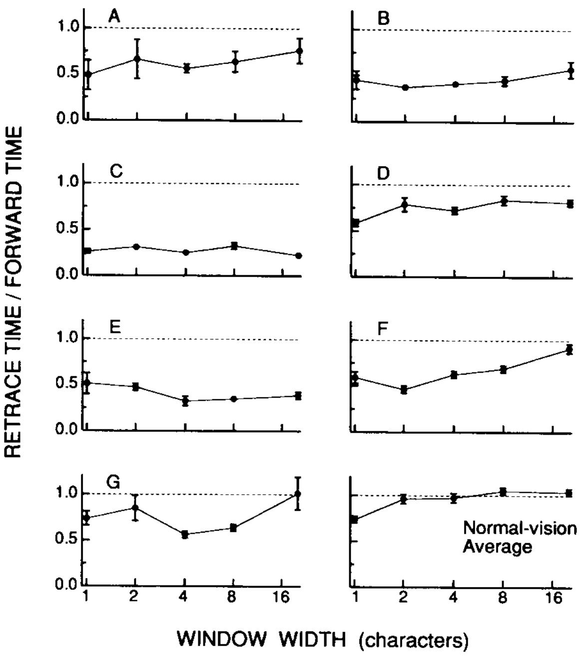

FIGURE 4. Ratio of retrace time to forward reading time. These ratio plots are derived from the data in Fig. 3. Dashed horizontal lines show a ratio of 1.0, indicating that the retrace time per line was equal to the forward reading time per line. Standard error bars are shown where they exceed the height of the symbols. Seven panels show data for low-vision subjects, and the eighth panel shows average data for three normal-vision subjects.

nificant interaction between window width and direction ($F[4,844] = 22.2$). The significant interaction was due to the one-character window condition; the forward-reading times were elevated much more than the retrace times for the smallest window. When the one-character data were excluded, a two-way ANOVA still showed significant main effects for window width and direction, but no significant interaction between window width and direction ($F[3,677] = 1.237$).

These analyses show that, except for the smallest window width, forward-reading time and retrace time were nearly the same and had the same dependence on window width.

Corresponding data for the seven low-vision subjects are plotted in Fig. 3. The eighth panel replots the average normal-vision data from Fig. 2 for comparison. There are different vertical scales for the low-vision panels because of the variation in individual reading times. We conducted two-way ANOVAs for each subject separately. For each of the seven low-vision subjects, there were significant main effects of window width and direction (forward-reading time vs retrace time) and a significant interaction. Unlike the normal-vision subjects, the interaction effect did not disappear when the smallest window was excluded.

The low-vision data differ qualitatively from the normal-vision data in three important ways. First, the reading times are longer than those of the normal-vision subjects, reflecting lower reading rates, for five of the seven low-vision subjects. Second, there is a large difference between forward-reading time and retrace time for low-vision subjects (vertical separation in Fig. 3) where, for the normal-vision subjects, there is little difference between forward and retrace time for any but the one-character wide window. Third, the separation of the forward-reading time and retrace time decreases as window size increases, revealing a generally greater dependence of forward-reading time on window size than retrace time. The forward-reading and retrace times for normal-vision subjects are equally affected for all but the smallest window size.

The retrace time is a measure of how quickly the reader can move a magnifier along a line of text, without the need for visual recognition of the symbols. Retrace time and its relation to forward-reading time provide a way of evaluating the impact of page navigation on reading performance. Figure 4 shows the ratio of retrace time to forward-reading time, R/F ratio, derived from Fig. 3. There are two parts to this comparison. First, if the forward-reading time is almost the same as the retrace time, it is likely that forward-reading time is constrained by navigational demands. This is the case for the normal-vision subjects for all but the smallest window width; the R/F ratio is close to 1.0. If the forward-reading time is longer than the retrace time, it is likely that visual factors limit forward-reading time. This is true of all the low-vision subjects in Fig. 4 with the possible exception of D. D is the only low-vision subject whose R/F ratio stays close to 1.0.

Secondly, even if the forward-reading time is not limited by navigational demands, the retrace time adds to

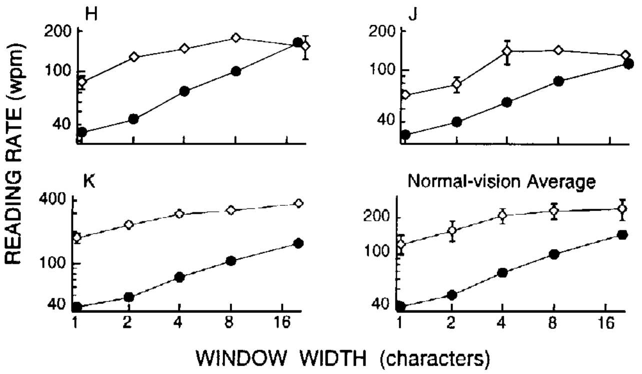

FIGURE 5. CCTV and drifting-text reading rates for normal-vision subjects. The CCTV rate (solid circles) is based on the total time per line (forward-reading time plus retrace time). Drifting-text reading rates (open diamonds) are also shown. Standard error bars are shown where they exceed the height of the symbols. Three panels show data for individual subjects and a fourth panel shows the pooled normal-vision average.

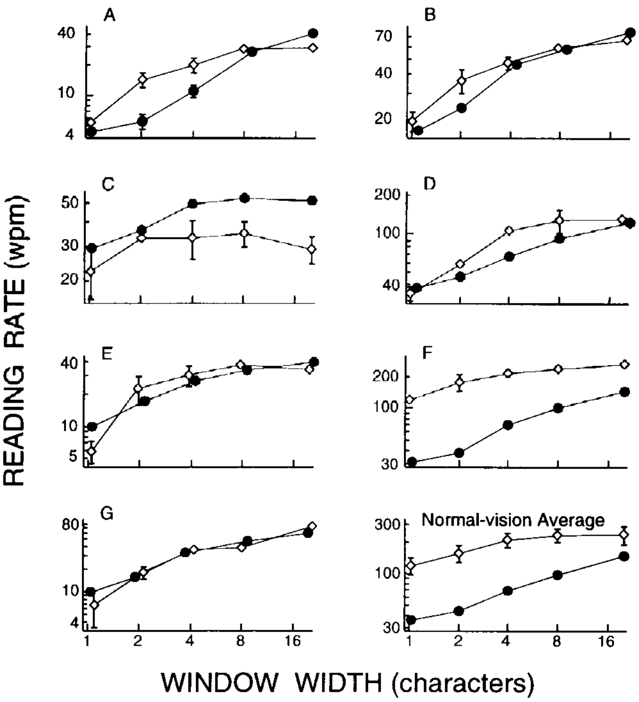

FIGURE 6. CCTV and drifting-text reading rates for low-vision subjects. The CCTV rate (solid circles) is based on the total time per line (forward-reading time plus retrace time). Drifting-text reading rates (open diamonds) are also shown. Standard error bars are shown where they exceed the height of the symbols. Seven panels show data for individual low-vision subjects and an eighth panel shows the pooled normal-vision average.

the total time and ultimately slows down reading. Since the total time is the sum of retrace time R and forward-reading time F, the proportion of time devoted to retrace is R/(R + F). In terms of the R/F ratio, it is (R/F)/[(R/F) + 1]. When the R/F ratio is 1.0, half the total time is devoted to retrace, and reading rate is cut in two. At the other extreme, subject C was the low-vision subject with the lowest R/F ratio, with a value close to 0.2. This corresponds to only 17% of time spent in retrace, meaning that navigational demands have a relatively small impact on his reading rate.

Qualitatively, the R/F ratios of low-vision subjects show no clear dependence on window size. Only a small amount of the variance can be accounted for by linear regression analyses of these data (r^2 between 0.011 and 0.277). However, for a number of subjects (A–E), the R/F ratio only varies 20% or less over an 8-fold change in window size (2–16 characters).

Comparing reading rates: CCTV and drifting-text

Reading rates were computed on a line-by-line basis from the reading-time data: number of standard-length words divided by the total reading time (forward-reading time plus retrace time). Figure 5 shows the CCTV reading rate (solid circles) and the drifting-text reading rate (open diamonds) as a function of window width for the three normal-vision subjects. The CCTV rates rise monotonically from 1 to 20 characters. By comparison, the drifting-text rates start at much higher values for the one-character windows, grow more gradually, and flatten out at smaller window widths. The drifting-text reading rates are higher at all window widths than the CCTV rates.

The drifting-text procedure is free of most of the navigational demands of CCTV reading. The major differences in the curves—absolute rate and shape—can probably be attributed to navigational differences.

Corresponding rates for low-vision subjects are plotted in Fig. 6, along with average values for normal-vision subjects. Despite the wide individual variation, there are two ways in which the low-vision data differ from the normal-vision data. First, the drifting-text rates are not systematically higher than the CCTV rates. Secondly, the dependence on window width (curve shape) is not so strikingly different. In other words, the differences attributed to navigational demands in the case of normal-vision subjects, are less prominent in the low-vision data. This is consistent with the view that the performance of low-vision subjects is limited more by visual factors (and less by navigational factors) than is the case with normal-vision subjects. An exception was subject F (and to a lesser extent subject A) who was consistently faster with drifting-text and was probably limited by navigational demands in CCTV reading.

Critical window widths for criterion reading rates

How large should the window width be to achieve an acceptable level of reading performance? This question is of importance in the prescription and design of reading magnifiers. To answer it, we must adopt a performance criterion. We defined performance criteria relative to peak reading rates.

In Fig. 7, CCTV rates and drifting-text rates from Fig. 6 have been replotted on a normalized scale. In each case, reading rate in words/min was divided by the peak rate for the curve in question. On the normalized scale, the peak reading rate is 1.0. Horizontal dashed lines are

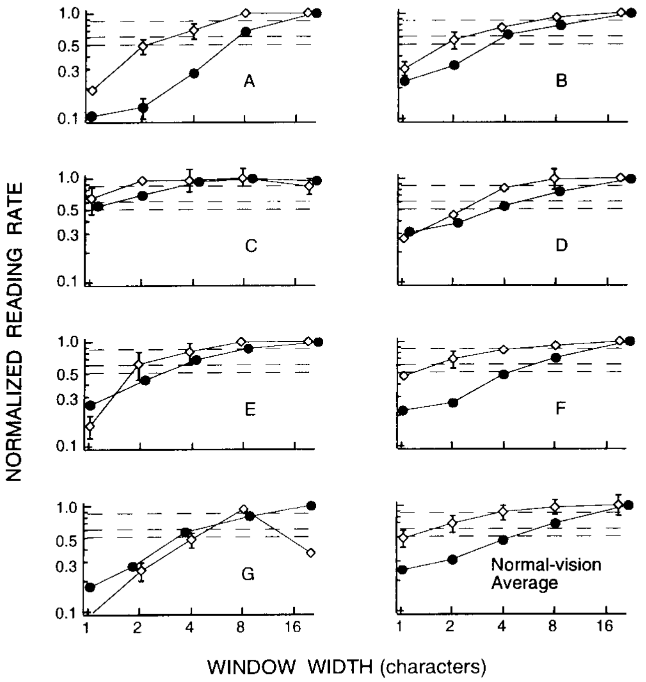

FIGURE 7. Normalized reading rate as a function of window width for normal-vision and low-vision subjects. Reading rates from Fig. 6 are replotted after normalization by peak rates for each curve. Drifting-text data (diamond symbols) and CCTV rates (solid circles) are shown. Standard error bars are shown where they exceed the height of the symbols. The horizontal dashed lines at normalized rates of 0.50, 0.60 and 0.85 cut the curves at window widths yielding 50, 60 and 85% of peak reading rate.

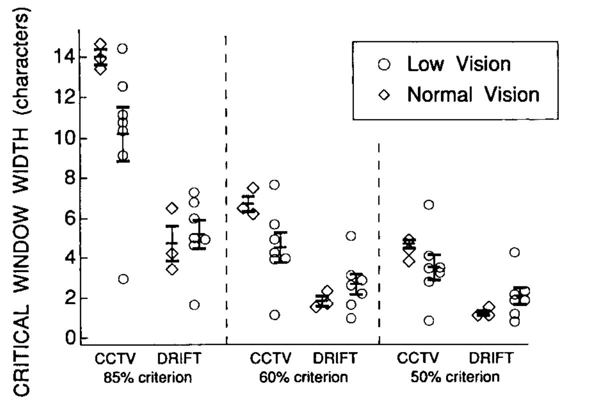

FIGURE 8. Critical window widths for three performance criteria. Critical window widths are defined as the points of intersection of the three criterion lines with the normalized reading rate curves in Fig. 7. The criterion levels were 85, 60 and 50% of peak rates for CCTV and drifting text (DRIFT). Individual low-vision (open circles) and normal-vision (open diamonds) are shown. Means and standard error bars are superimposed on the data.

drawn at normalized rates of 0.85, 0.60 and 0.50. They cut the curves at window widths yielding reading rates of 85, 60 and 50% of peak values. Most of the low-vision subjects achieved their peak CCTV rate for the 20-character window width.*

The average data for normal-vision subjects (bottom right panel) clearly indicate that the drifting-text curves reach criterion rates for smaller window widths than the CCTV curve.† The low-vision data show considerable individual variation. For example, subject C shows a very weak dependence on window width for both drifting-text and CCTV. On the other hand, subject A shows a much stronger window width dependence for CCTV reading, and subject G for drifting-text reading.

Figure 8 plots the critical window widths for the three performance criteria (50, 60 and 85% of peak level) for CCTV reading rate and drifting-text reading rate. The mean critical window widths are summarized in Table 3.

Table 3 makes clear a very important finding of this study: when reading involves manual page navigation, the window width requirements increase. For all three performance criteria, normal-vision subjects had window requirements for CCTV reading that were more than three times larger than for drifting-text reading. The difference was not quite so great for low vision, but approached a factor of two for all performance criteria.

The greater difference between CCTV and drifting-text reading for normal-vision subjects, apparent in Fig. 6, is also evident in Table 3. The normal-vision subjects had slightly larger critical window widths for CCTV reading than the low-vision subjects and slightly smaller critical window widths for drifting-text reading.

For low-vision subjects, the 85% criterion for CCTV yields a critical window width of 10 characters. For a 60% criterion, only 4.5 characters are required. To achieve a half-maximum reading rate (50% criterion), the average CCTV window width need be only 3.5 characters. For drifting-text, the corresponding numbers are even smaller—window widths of 5.2 for 85%, 2.6 for 60% and 2 for 50%.

These findings indicate that when page navigation is necessary, there is an increased window requirement compared with the case of drifting-text (no navigation required).

Comparison with previous results

We pointed out in the Introduction that there are

TABLE 3. Summary of critical window sizes at three levels of performance for normal-vision and low-vision readers on the CCTV and drifting-text tasks

	Critical window sizes					
	85%		60%		50%	
	CCTV	Drift	CCTV	Drift	CCTV	Drift
Normal vision	14	4.7	6.7	1.8	4.7	1.2
Low vision	10	5.2	4.5	2.6	3.5	2.0

*It is possible that reading rate would have increased had we used even larger windows. We believe any such effect would be small for reasons discussed below in connection with Fig. 9.

†It is unlikely that these rates reflect a limitation in speaking rate for two reasons: (1) a previously reported control experiment (Legge *et al.*, 1985a) has shown that silent reading rates and oral reading rates have the same dependence on window width; and (2) subjects were allowed to continue to speak even after the line had completely disappeared from the aperture.

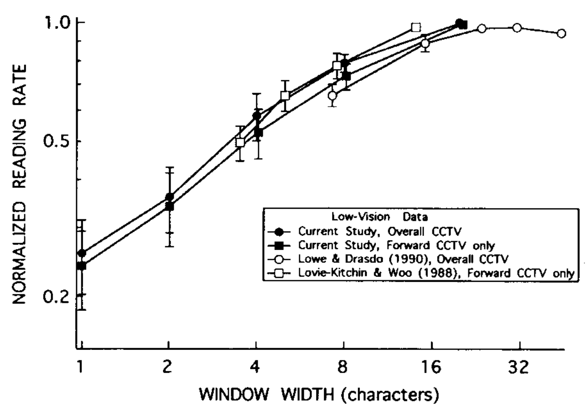

FIGURE 9. CCTV reading rate as a function of window width: comparison of data from the current study with two other studies. Mean low-vision data from the current study are compared with low-vision data reported by Lowe & Drasdo (1990) and Lovie-Kitchin & Woo (1988). See Table 4 for a summary of conditions in the three studies and the text for further explanation.

substantial discrepancies in the literature regarding the window-width requirements of reading. From the previous section, it is clear that a real difference exists between drifting-text reading (no page navigation) and CCTV magnifier reading in which the subject must navigate the magnifier over the text. It is also clear that the selection of a performance criterion is critical in arriving at a numerical value for a required window width.

Once these distinctions are taken into account, are there still discrepancies between studies? Figure 9 shows normalized reading rates as a function of window width from three studies using CCTV magnifiers—the present study, Lowe & Drasdo (1990), and Lovie-Kitchin & Woo (1988). Details of the separate studies are summarized in Table 4. We used normalized rates as a way of factoring out the wide variation in absolute reading rates across low-vision subjects.

We have plotted two sets of numbers from the present study. Solid circles show overall CCTV reading rates, averaged across our seven low-vision subjects. These are most comparable to the Lowe & Drasdo (1990) measurements (open circles); both sets of data include forward-reading and retrace times in the rate calculations. The solid squares show reading rates from the present study based on forward-reading time only (no retrace time included). These are comparable to the rates from Lovie-Kitchin & Woo (1988) who measured low-vision CCTV reading rates for single lines of text (no retrace required). Although the three studies covered different ranges of window widths, the overlap makes comparison across studies possible.

Figure 9 shows good agreement between the three studies for overlapping window widths, despite substantial differences in subject sample, text material, and text format. The figure provides a picture of the dependence of low-vision reading rate on window width from one to 44 characters. Reading rate rises approximately as the square root of window width (slope of 1/2 in log–log coordinates) from 1 to 20 characters, and then levels off.

SUMMARY AND CONCLUSIONS

For normal-vision subjects using a CCTV magnifier, forward-reading time and retrace time were nearly the same for all but the smallest window width, and both had the same dependence on window width. These results imply that the forward-reading performance was limited by navigational demands. The overall reading time increased by about a factor of two due to the time devoted to retracing. For low-vision subjects, however, forward-reading times were longer than retrace times, and more dependent on window width. For these subjects, forward-reading performance was not limited by navigational demands. The retrace time did have an impact, however, ranging from 17 to 50% of the overall time.

Drifting-text places no navigational demands on the subject. Reading with a CCTV magnifier does require page navigation. For normal-vision subjects, drifting-text reading rates were faster than CCTV rates at all window widths. In addition, drifting-text performance had a weaker dependence on window width than CCTV reading. These findings show that page navigation not only slows down reading, but introduces a stronger dependence on window width.

Surprisingly, the differences between drifting-text reading and CCTV reading rates were smaller for low-vision subjects. However, this is consistent with the view

TABLE 4. Particulars of the various studies

Study (Task)	Text format	Character size	Font and size	Contrast
Current study (Forward plus retrace) (Forward without retrace)	31 char./line 13 lines Single spaced	3 deg	Courier 3.5 mm/char.	Black on white
Lowe & Drasdo (1990) (Forward plus retrace)	60 char./line 21 lines Double spaced	3 deg	Artisan 2.1 mm/char.	White on black
Lovie-Kitchin & Woo (1988) (Forward along single line)	21–30 words/line (est. 180 char./line)	2.9 deg	Prestige Elite 2.1 mm/char.	Green on black

that visual factors hamper reading performance to a greater degree in low vision than in normal vision and thus the impact of page navigation is reduced.

One way of stating the window-width requirements for reading is to identify the smallest window that will yield some criterion reading rate. For all criteria we examined, the window requirements for CCTV reading were larger than those for reading drifting-text. The difference was more than a factor of three for normal-vision subjects and a factor of 1.5–2 for low-vision subjects. Normal-vision subjects required larger windows than low-vision subjects at all criterion levels for CCTV reading, and smaller windows for drifting-text. Apparently, normal vision has a larger effective field for handling page navigation. On the other hand, when reading is limited by visual (or possibly oculomotor) factors, normal-vision subjects can read faster and achieve maximum rates with slightly smaller windows than low-vision subjects.

Finally, we compared the results of our study to two other studies (Lowe & Drasdo, 1990; Lovie-Kitchin & Woo, 1988) that used CCTV magnifiers. When the data from all three studies were plotted in the same coordinates, the agreement was striking. The combined data set shows that for a CCTV magnifier, reading rate increases as roughly the square root of window width up to 20 characters and then levels out.

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APPENDIX

How similar are the recordings of CCTV magnifier position in text to the recordings of eye movements in normal reading? Subjects may move the table smoothly so that the magnified text drifts at roughly constant speed across the CCTV screen. Alternatively, subjects may move the table in a saccade-like manner so that a few characters are

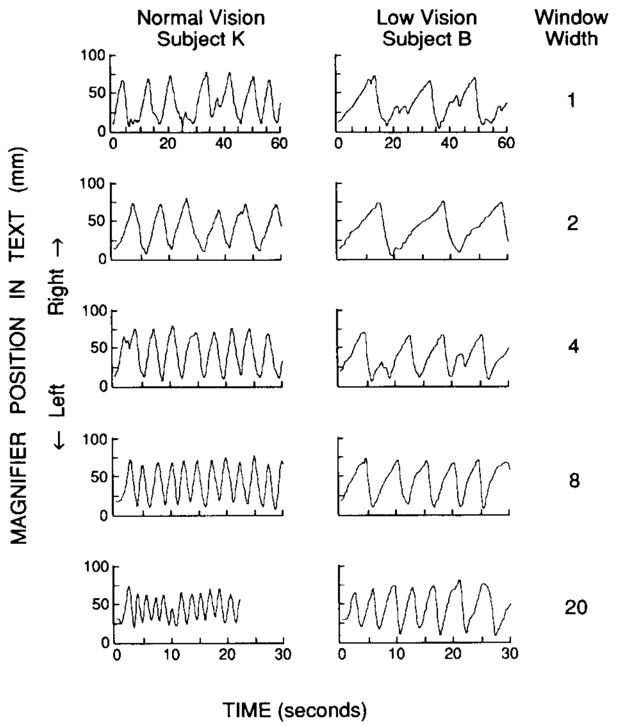

FIGURE A1. Recordings of magnifier position for normal-vision subject K (left column) and low-vision subject B (right column) at the five window widths of the study: 1, 2, 4, 8 and 20 characters. The left–right position of the magnifier field is plotted as a function of time. The upper two plots show the first 60 sec of reading; the other eight plots show the first 30 sec of reading. Samples were taken every 100 msec with a resolution of 0.5 mm.

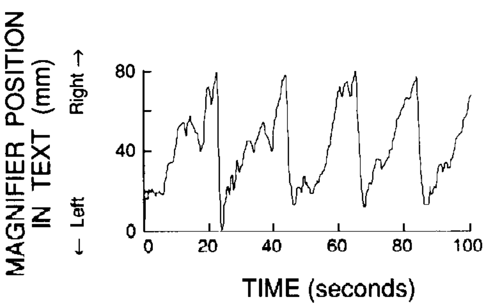

FIGURE A2. Recording of magnifier position for low-vision subject E at the 4-character window width. The left–right position of the field is plotted as a function of time. Samples were taken every 100 msec with a resolution of 0.5 mm.

moved into the viewing window on the screen, left stationary until they are read, and then the next few characters are moved into view.

All normal-vision subjects and most low-vision subjects in our study moved the CCTV table smoothly, causing the text to drift at roughly constant speed across the screen. There was no evidence for saccadic movements. While there were a small number of regressions, about two per passage for small and intermediate window widths, the movements were of nearly constant velocity in the forward direction.

These findings indicate that subjects move the CCTV table in a way that nearly matches the visual stimulus used in the drifting-text method. Eye-movement measurements with drifting-text stimuli have shown that subjects use smooth pursuit to track a fixated point as it drifts from right to left across the screen. Eventually, the eyes saccade back to the right and pick up a new point in the text to track (Buettner *et al.*, 1985; Legge *et al.*, 1985a; Whittaker *et al.*, 1994). Bowers has reported similar eye-movement patterns when optical magnifiers are used (Bowers & Ackerley, 1994). We conjecture that this type of eye-movement pattern accompanies CCTV reading as well.

The left column of Fig. A1 shows a series of traces made by normal-vision vision subject K for 1, 2, 4, 8, and 20-character windows. First, note that the rising portions of the traces (forward movement) are smooth. There is no evidence of a stairstep pattern that would be present if the movements were saccadic. Second, for window widths greater than one character, the sawtooth waveforms are nearly symmetric; the forward and retrace movements take about the same time and look very similar. As the window width increases, the symmetry is retained, but the traces get steeper (i.e., less time spent in forward and retrace movements).

Is the pattern of magnifier movements the same for low-vision readers? A series of traces for low-vision subject B is shown in the right column of Fig. A1. The waveforms are similar to those of the normal-vision subject, except they are asymmetric; more time is devoted to the forward trace than the retrace. Subject B had substantial previous experience with a CCTV magnifier. However, subject E had little previous experience. (See Fig. A2 for an example of movements made by subject E.) Her traces were much more jagged than those of subject B. She had not yet learned to move the table smoothly. On the whole, low-vision subjects who were experienced with CCTV had smoother traces than novices.

Three strategies for retracing to the beginning of the next line are: (1) return along the line just read and then drop down to the beginning of the next line; (2) after completing a line, immediately drop down to the end of the next line, and return along it to its beginning; and (3) make a diagonal movement from the end of the current line to the beginning of the next line. Most readers either started with or quickly adopted the first strategy. The second strategy suffers from the possibility of falling off overhanging lines and missing one or more lines when the text has a ragged right margin. The third strategy, while the most efficient in terms of the distance travelled, is difficult to perform.