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ORIGINAL ARTICLE

Psychophysics of Reading. XVII. Low-Vision Performance with Four Types of Electronically Magnified Text

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ABSTRACT: Most people with low vision need magnification to read. Page navigation is the process of moving a magnifier during reading. Modern electronic technology can provide many alternatives for navigating through text. This study compared reading speeds for four methods of displaying text. The four methods varied in their page-navigation demands. The closed-circuit television (CCTV) and MOUSE methods involved manual navigation. The DRIFT method (horizontally drifting text) involved no manual navigation, but did involve both smooth-pursuit and saccadic eye movements. The rapid serial visual presentation (RSVP) method involved no manual navigation, and relatively few eye movements. There were 7 normal subjects and 12 low-vision subjects (7 with central-field loss, CFL group, and 5 with central fields intact, CFI group). The subjects read 70-word passages at speeds that yielded good comprehension. Taking the CCTV reading speed as a benchmark, neither the normal nor low-vision subjects had significantly different speeds with the MOUSE method. As expected from the reduced navigational demands, normal subjects read faster with the DRIFT method (85% faster) and the RSVP method (169%). The CFI group read significantly faster with DRIFT (43%) and RSVP (38%). The CFL group showed no significant differences in reading speed for the four methods. (Optom Vis Sci 1998;75:183–190)

Key Words: low vision, reading, magnifier, page navigation

Most people with low vision need magnification to achieve their best reading performance. Sometimes, electronic magnifiers are preferable to optical magnifiers because they can provide higher magnification, greater freedom of eye position, and reverse-contrast (white-on-black) text. In view of the increasing affordability of video and computer technology, it is important for users, clinicians, and designers to know how low-vision reading performance varies with different ways of displaying electronically magnified text. The goal of this study was to compare the reading speeds of low vision subjects on an everyday reading task, using four widely used methods for text presentation.

When viewing highly magnified text on a screen, only a few letters of the line of text are visible at one time. The reader must use some technique, termed page navigation, to advance through the text, revealing successive portions of the line of text on the display screen. We studied four methods of page navigation. Two of them required manual movement [closed-circuit TV (CCTV) and MOUSE]. The other two were "automatic" in the sense that sequencing of text on the display was controlled by the electronic device, rather than the reader (DRIFT and RSVP).

CCTV method

When reading with a CCTV magnifier, a page of printed text rests on a movable X-Y platform under a video camera equipped with a zoom lens. Text in the camera's field of view appears on the TV monitor. The reader can adjust the zoom lens to provide the desired magnification. The reader moves the platform leftward in order to see portions of the text that are more rightward on the printed line. When the end of a line is reached, rightward movement of the platform is necessary to retrace to the beginning of the next line. The reader moves the platform in the Y-direction to move up and down from line to line.

Beckmann and Legge[1] measured these navigational movements during CCTV reading, and computed the proportion of total reading time devoted to retraces. When retrace time reached 50% of total reading time (true for normal subjects), reading speeds were half as fast as those obtained when page-navigation demands were minimal. When the proportion of total reading time devoted to retraces was lower (true for most low-vision subjects), there was considerably less impact of page navigation on CCTV reading speed.

MOUSE method

One practical goal of our study was to compare text navigation by computer mouse to CCTV. Several computer-based magnification systems are available that use a mouse for page navigation. In these systems, a small portion (window) of the regular screen image is presented at high magnification on the computer screen. The reader uses the mouse to move the magnified window over the regular screen image. In reading, the mouse is used to move the window along lines of text.

Although CCTV and MOUSE reading both involve manual navigation through text, there are significant differences. Because a typical X-Y platform is much larger than a computer mouse, a CCTV requires movement of the hand, wrist, and arm, whereas a computer mouse mostly involves movement of the hand and wrist. The X-Y platform also has more inertia than the computer mouse. In addition, the CCTV relies on absolute positioning of a printed text beneath a video camera, whereas a computer mouse codes relative movement of a viewing window through a screen image. It is plausible that these differences could have significant effects on low-vision reading speed.

DRIFT method

Some methods of text presentation do not require manual page navigation. Legge et al.[2] developed a drifting-text method to measure reading speed in the absence of manual page navigation. In this method, a line of text drifts smoothly from right to left across the screen. Although only a few magnified letters are visible at one time, the drift enables an entire text to be displayed. Many video-based electronic magnifiers include a drifting (or "scrolling") method of text presentation. Although manual navigation is eliminated when reading drifting text, readers must still make fairly complicated sequences of eye movements.[2] The eyes track a target letter or word for a distance of several letter widths across the display, and then saccade back to the right to pick up a new letter for tracking. The pattern is similar to optokinetic nystagmus.

RSVP method

In RSVP, a computer presents words of text, one at a time, at the same place on the video monitor. Here, there is no need for manual navigation, and little or no demand on the oculomotor system.

These four display methods vary in their navigational demands, CCTV and MOUSE being most demanding, and RSVP least. We asked if reducing the navigational demands would result in higher reading speeds for low-vision and normal subjects.

Related studies

In addition to the four display methods already discussed, researchers have also measured reading speed for STATIC (sometimes termed PAGE) presentation. This is just the conventional presentation of a block of text on a static page (or screen). The reader navigates through static text with saccadic eye movements. If the magnification is high, relatively little text can be presented in the STATIC display. Legge et al.[3] found that low-vision subjects read drifting text 15% faster than static text, whereas normal subjects read static text 44% faster than drifting text.

Many studies have shown that normal subjects read RSVP text much faster than static text. For example, Rubin and Turano[4] found that normal subjects read RSVP text at rates in excess of 1000 words per minute, 3 or 4 times faster than their rates for static text. In a later study, Rubin and Turano[5] found that low-vision subjects also read RSVP text faster than static text, but low-vision reading speeds increased by a smaller factor. Moreover, the size of the RSVP advantage depended on the status of the subjects' central visual fields. Subjects with central fields intact (CFI group) attained RSVP reading speeds that were two times faster than their static-text reading speeds. However, reading speeds of subjects with central-field loss (CFL group) improved by a factor of only 1.5. The smaller improvement for the CFL subjects was surprising because they were expected to benefit more from a reduction in saccadic eye movements in RSVP.

The CFL/CFI difference found by Rubin and Turano,[5] and previous findings that CFL subjects have especially severe reading deficits,[6–8] motivated us to select and classify our low-vision subjects with this dichotomy.

Fine and Peli[9] investigated how normal and low-vision reading speeds compare for drifting and RSVP text. Normal subjects read significantly faster (30%) in the RSVP than the DRIFT condition, but there was no significant difference for the low-vision subjects (nor for CFL or CFI categories). As noted by Fine and Peli,[9] the results of the low-vision group were contrary to expectations because these subjects did not benefit from the lower saccadic demands of the RSVP condition.

Goals of this study

In contrast to the studies just reviewed, our procedure did not push subjects to reach their maximum reading speeds. Because of the practical focus of this study, we were primarily interested in the subjects' typical reading behavior. We gave instructions that encouraged subjects to adopt the kind of reading behavior they would use in everyday life, such as reading a general-interest magazine article.

The questions addressed in the current study were: (1) Does the reduction in navigational demands across the CCTV, MOUSE, DRIFT, and RSVP text-presentation conditions result in corresponding increases in the reading speeds of low-vision subjects? (2) Do the variations in reading speeds of the low-vision subjects across the four text-presentation conditions show the same pattern as the normal subjects? and (3) How do individual factors such as central-field status and overall reading speed affect the pattern of reading speeds across the four text-presentation conditions?

METHODS

Subjects

Table 1 lists characteristics of the 12 low-vision and 7 normally sighted subjects. The low-vision subjects were selected from our laboratory's subject roster and were paid for their participation. Six of the normally sighted subjects were enrolled in an introductory psychology course and received course credit for participating.

TABLE 1.
Subject characteristics.

	Subject	Age (yr)	Diagnosis	Acuity LogMAR	Character Size[a]	Viewing Distance (cm)	Text Polarity	Frequent Reader	CCTV User	Mouse User
Central field loss[b]	CFL 1	38	Retinal histoplasmosis	0.3	20	36	Normal	Yes	No	Yes
	CFL 2	50	Macular degeneration	1.1	3.5	33	Normal	No	Yes	No
	CFL 3	49	Leber's disease	1.3	2.27	32	Normal	Yes	No	No
	CFL 4[c]	35	Retinal degeneration	1.4	3.0	19	Normal	Yes	Yes	Yes
	CFL 5	56	Unknown	1.5	3.1	15	Normal	Yes	Yes	Yes
	CFL 6	28	Retinitis pigmentosa	1.5	3.8	12	Reverse	Yes	Yes	No
	CFL 7	43	Retinitis pigmentosa	>1.6	1.45	25	Reverse	No	No	No
Central field intact	CFI 1	36	Diabetic retinopathy, cataracts	0.3	16	46	Normal	Yes	No	Yes
	CFI 2	41	Retinal detachment/degeneration	1.0	2.4	59	Reverse	Yes	No	No
	CFI 3	38	Congenital cataracts, nystagmus	1.2	2.9	32	Reverse	Yes	No	Yes
	CFI 4	24	Retinopathy of prematurity	1.2	2.54	36	Reverse	Yes	Yes	Yes
	CFI 5	40	Congenital cataracts, glaucoma	1.2	3.23	28	Normal	Yes	No	Yes

	Subject	Age (yr)	Acuity LogMAR
Normal vision	N 1	19	0.0
	N 2	17	−0.1
	N 3	19	0.0
	N 4	18	−0.1
	N 5	23	−0.2
	N 6	19	0.0
	N 7	24	−0.1

[a] Angular character size is expressed as a multiple of the size of acuity letters. Values are for the CCTV condition. Values for the other 3 conditions are within 10%.
[b] Defined as an absolute scotoma within the central 5° region of the visual field.
[c] This subject has a large scotoma in his peripheral field that appears to extend into a small region of his central field.

Subject N7 was paid for his participation. Informed consent was obtained from all subjects.

The following criteria were used in recruiting subjects: (1) All the subjects were native speakers of English, to ensure that language difficulties would not impede reading performance. (2) None of the subjects had any motor deficits (by self-report), ensuring that poor motor skills did not influence manual navigation. (3) All subjects had completed at least the 11th grade, ensuring that the difficulty of the reading material was well below the subject's reading level (see below). (4) We selected young and middle-aged adults to increase the acceptance and familiarity with high-tech devices, and to minimize the probability of motor control difficulties. (5) The sample of low-vision subjects spanned a wide range of acuities and diagnoses, and included roughly equal numbers with CFL and CFI. Low-vision diagnoses were obtained from medical reports (except for subject CFL5, for whom a medical report was not available).

The mean age of the 12 low-vision subjects was 39.8 years (SD = 9.0). The mean age of the 7 normal subjects was 19.9 years (SD = 2.6). We have no reason to believe that the performance of this young normal group would differ in important ways from a normal group matched in age to our low-vision sample. Visual acuities were measured using the Lighthouse Distance Visual Acuity Test. Acuities in Table 1 represent the subject's best monocular acuity with usual refractive correction in place. Subject CFL7's acuity was estimated to be >1.6 logMAR because she was unable to read any letters on the top line of the Lighthouse chart from a distance of 1 m. Subjects CFL1 and CFI1 had acuities of 0.3 (logMAR). Subject CFL1 was included as a low-vision subject because he has CFL. Subject CFI1 is a borderline case.

CFL was defined as an absolute scotoma within all or part of the central 5° region of the visual field as measured using a tangent screen (12-mm target at a viewing distance of 1 m). The tangent screen test revealed that subjects CFL2, CFL3, CFL5, and CFL6 had dense central scotomas, and that subject CFL1 had numerous pinpoint scotomas in the central 5° region of his visual field. Although subject CFL4 had a large scotoma in his peripheral field which appeared to extend into a very small area of his central field, the tangent screen test was not accurate enough to determine with certainty if he met the CFL criterion.

Table 1 also contains information about subjects' reading habits. Subjects were classified as frequent readers if they reported that they read printed materials every day (with or without a magnifier). Subjects were classified as CCTV users if they reported that they currently use a CCTV for reading. Subjects were classified as computer mouse users if they reported that they had regularly used a computer mouse for at least 6 months. All the normal subjects were frequent readers and mouse users.

Materials and apparatus

Carver[10] and Whittaker and Lovie-Kitchin[8] have recommended that reading researchers use text materials that are graded at least 3

A.

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Educated persons of course
know that other places have
much that is worthwhile.  They
appreciate the fact that few
things broaden one so much as
travel, because it acquaints
one with strange people, var-
ied scenery, and other cus-
toms.  By contact with those
whose methods of working and
living differ from ours, much
can be learned.  We are fre-
quently surprised to note that
*
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B.

According to the text, travel can be
(a) dangerous
(b) a good learning experience
(c) a good way to learn a foreign language
(d) difficult if you do not speak English

FIGURE 1.

A: An example of one of the passages that was used in an experimental trial. The format shown here was used in the CCTV and MOUSE conditions, and consisted of 13 lines of text, with a maximum of 30 characters per line. The * symbol on the 14th line served as an end-of-passage marker. The same passages were used in the DRIFT and RSVP conditions, and displayed as described in the text. B: Example of a comprehension question for the passage in A.

grade levels below the ability level of the subjects. The reading materials used in this study were all of 6th grade level. All the subjects had completed at least the 11th grade. In total, 43 passages were selected from the 5th book of the McCall and Crabbs[11] series of reading primers; a subset of 16 of these passages was used for the experimental trials, and the remaining passages were used for practice trials. Approximately the first 70 words from each passage were used in the experiment. No passage was presented more than once to any subject in the experimental trials.

The texts were printed on an Apple Laserwriter printer. Fig. 1A shows an example of one of the experimental passages, and illustrates how the passages were formatted for the CCTV and MOUSE conditions. The format consisted of 13 lines of text with a maximum length of 30 characters per line. We used a Courier 10-point font with exact 10-point baseline spacing. An asterisk was placed at the start of the 14th line to mark the end of a passage. This formatting was used to produce the type of text that a low-vision person might encounter on an everyday reading task, such as reading a book or a magazine article. In the CCTV condition, the printed passages were placed on the X-Y platform for use by the subject. For the MOUSE and DRIFT conditions, the passages were converted to digital images by an HP ScanJet IIcx scanner, and used as described below. For RSVP, text files were saved in the computer and were displayed one word at a time on the screen.

One multiple-choice comprehension question was prepared for each passage. Fig. 1B shows an example. Care was taken to ensure that the questions could not be answered using general knowledge.

A VTEK Voyager XL CCTV magnifier was used in the CCTV condition. The VTEK display (M-19 19-inch monochrome monitor) was also used in the MOUSE, DRIFT, and RSVP conditions. Stimuli in the latter three conditions were generated on a Compaq Presario CDS-924 computer with M-S28 mouse and converted to video on the VTEK monitor by an AVerKey PC to TV converter. It was important to use the same video screen to equate for video characteristics across all four conditions.

VisAbility software (version 1.10, AI-Squared, Manchester Center, VT, 1993–94) was used on the Compaq computer for the MOUSE condition. This software reads the position of a mouse-controlled cursor. Instead of displaying the normal screen image, the software magnifies a portion of the screen image at the location of the cursor and presents the magnified portion on the computer screen. The user moves this magnified "window" through the image of a block of text by moving the mouse. In the MOUSE condition, subjects read scanned passages having the same format as shown in Fig. 1A.

We note two differences in page navigation with a computer mouse and the CCTV. First, when observers moved the computer mouse from left to right, the displayed text moved from right to left because they were moving a window over the scanned image. In the CCTV condition, when observers moved the X-Y platform from right to left, the displayed text also moved from right to left because the printed page was being moved under the lens of a video camera. Second, a movement of the computer mouse of approximately 3 cm in a straight left to right direction corresponded to a movement of 30 character spaces on the VTEK monitor at the level of magnification used. This mouse gain was selected after pilot trials showed that it was the most comfortable setting for both low-vision and normal observers. A movement of the X-Y platform in the CCTV condition of approximately 6 cm in a straight left to right direction corresponded to a movement of 30 character spaces on the VTEK monitor. This comparison indicates that the hand and arm movements required to read text in the CCTV condition were greater than those required to read text in the MOUSE condition; or, conversely, the mouse condition required better fine motor control.

VisAbility software was also used to display text in the DRIFT condition. In this mode, the software automatically navigates through a scanned text image at a selected speed. The observer can view magnified text as it drifts from right to left across the monitor screen. There are 16 possible speed settings that corresponded to reading speeds between 23 and 365 words per minute for the level of magnification used in this experiment. From the observer's point of view, the entire passage consisted of a single line of drifting text. The ends of the passages were again marked with asterisks. Subjects could "pause" and "restart" the drift at will by pressing a key on the keyboard. In the absence of any subject-initiated pauses, reading speeds were determined by the subjects' selections of comfortable speeds, which occurred during the speed-adjustment phase of the experiment as described below.

The RSVP text was generated with a custom Turbo Pascal program running on the Compaq computer. The program used bitmaps of a digital Courier font from an SGI workstation, scaled to match the printed Courier font used in the other three conditions. The words from each passage were preloaded into memory and were displayed at a 60 Hz frame rate. The possible word-display rates were 3600/N words per minute, where N was the number of video frames per word. Speeds were adjusted by entering a value in words per minute; the program then selected the nearest available speed and displayed the text at that rate. Subjects were able to pause and restart the RSVP text by pressing a key on the keyboard. As in the DRIFT condition, the speeds selected by the observers during the speed-adjustment phase of the experiment determined reading speeds in the absence of any pauses. An asterisk was again used to mark the end of a passage.

The angular character sizes (magnification) were approximately equal across the four conditions for each subject. All normal subjects read text at a viewing distance of 40 cm. In the CCTV condition, the character size was 3.0° (x-height) with center-to-center character spacing of 4.3°. The character size for the MOUSE and DRIFT conditions was 3.3° and for the RSVP condition 3.2°.

Black construction paper was used to limit the visible portion of the VTEK monitor screen to 34.8° wide by 26.2° high for the CCTV and MOUSE conditions. This window allowed subjects to view 8 characters per line on approximately 3 lines of text at any given time. The window size for the DRIFT condition was also 8 characters wide (34.8°) by 1 line high (7.6°). These window sizes were large enough to yield maximum or near-maximum reading speeds.[1, 2] In the RSVP condition, the window size was 53° wide by 7.6° high. The window width was made large enough to display the longest words in the passages (13 characters). All normal subjects read black letters displayed on a white background.

Low-vision subjects were tested with the same window sizes, but they were allowed to select the contrast polarity and viewing distance (see Table 1). All the low-vision subjects were consistent in their choice of viewing distance (within 2 cm) across all four conditions. Table 1 shows the corresponding angular character sizes expressed as an acuity reserve; that is, as a multiple of the subject's acuity letters. Most of the low-vision subjects selected a reading distance close to the "standard" distance of 40 cm. Those who sat closer apparently did so to maintain an adequate acuity reserve.

The luminance of the VTEK monitor was measured with a Minolta CS100 Chroma Meter. Small, nonsystematic variations in luminance occurred when the monitor was switched between the computer (MOUSE, DRIFT, and RSVP conditions) and the CCTV camera. The mean luminance across all subjects and conditions was 109 cd/m^2, with an SD of 8.5 cd/m^2. Analysis of all luminance measurements showed that contrast never fell below 90% (Michelson definition), except for subject CFL1's CCTV trials, where it fell to 86%.

Procedure

Carver[10] operationally defined five different reading strategies. He coined the term rauding in reference to the strategy commonly used in reading a novel or news article. According to Carver's definition, the goal of rauding is to "understand the complete thoughts the writer intended to communicate," (p. 20). Among Carver's examples of instructions that are likely to produce rauding is the following: "Read carefully because there will be a few questions on what you read later" (p. 18). In our study, observers were instructed to read the passages as they would normally read a magazine article but without skipping or skimming. They were also told that they would be asked a multiple-choice question about the main ideas in the passage. These instructions were intended to produce rauding as defined by Carver. During testing, all subjects were asked periodically if they were reading the passages as they would normally read a magazine article. All affirmed that they were reading the passages in this way.

In addition to practice trials, each subject read four different passages in each of the four text-display conditions. The passage order was counterbalanced so that, as far as possible, each passage was read approximately the same number of times in each display condition. The condition order was also counterbalanced. Reading trials were conducted with the room lights extinguished.

After practice reading on a given display condition, a stopwatch was used to time subjects as they silently read four separate passages. At the start of CCTV, MOUSE, and DRIFT trials, the first letter of the first word of a passage was visible at the right edge of the screen. After a warning signal from the experimenter, the subject was instructed to start reading. (In the RSVP condition, passage numbers were visible at the start of trials.) Subjects called out when they reached the asterisk at the end of each passage, and the experimenter ceased timing. All subjects were asked multiple-choice questions. At the conclusion of testing, all subjects were asked to rank-order the four text-display methods in terms of personal preference for reading a general magazine article.

Because the DRIFT and RSVP methods involve automatic presentation of text, the practice period included a procedure to identify appropriate rates of automatic presentation. First, subjects were shown the DRIFT and RSVP displays at default speeds (about 50 words per minute in the DRIFT condition and 80 words per minute in the RSVP condition for low-vision subjects; about 100 words per minute in the DRIFT condition and about 180 words per minute in the RSVP condition for normal subjects). Subjects were trained in the use of the "Pause" key to start and pause texts. They were then asked if the default speed seemed too fast or too slow for magazine reading. Based on the subjects' responses, the speeds were adjusted using practice passages until the subjects confirmed that they could read the passages as they would normally read a magazine article. Finally, each subject read additional practice passages to confirm that the speed they had chosen was comfortable for reading. If a subject decided that this speed was too fast or too slow after the additional practice, the speed adjustment process was repeated until the subject found a comfortable reading speed. This speed was used for the experimental trials. Across the low-vision subjects, the adjustment phase ranged from 2 to 9 practice trials (mean = 4.4) on 1 to 6 passages (mean = 2.6) for RSVP, and 1 to 6 practice trials (mean = 3.3) on 1 to 3 passages (mean = 2) for DRIFT.

All reading speeds were calculated as the number of standard-length words read per minute. The number of "standard-length words" in a passage is defined to be the total number of characters (including spaces and punctuation) divided by 6.[10]

RESULTS

Table 2 summarizes all of the reading-speed data in standard-length words per minute (wpm). Geometric means and standard deviations are given for each subject and for the groups. It should be noted that subject CFL7 was only tested on one passage per condition because of her very low reading speed. This subject was excluded from all further reading-rate analysis. Subject CFL4 was excluded from the field-loss analysis because it proved difficult to classify him using the tangent screen test.

The standard deviations were often very low in the individual reading speeds for the DRIFT and RSVP conditions because the only source of variability was the subjects' use of the Pause key;

TABLE 2.
Mean reading speeds (standard-length words per minute) and preferences

	Subject	CCTV			MOUSE			DRIFT			RSVP		
		M_G	%SD	Pref.	M_G	%SD	Pref.	M_G	%SD	Pref.	M_G	%SD	Pref.
Central field loss	CFL 1	50	5	2	44	5	4	24	2	1	64	6	3
	CFL 2	34	8	1	23	19	4	47	0	2	38	27	3
	CFL 3	65	10	1	54	7	2	70	2	3	73	6	4
	CFL 4	109	5	1	100	11	2	172	2	3	103	7	4
	CFL 5	28	10	4	27	11	1	35	7	2	18	9	3
	CFL 6	19	17	2	13	22	4	19	4	1	16	5	3
	CFL 7[a]	4	—	4	3	—	3	8	—	2	7	—	1
	Mean[b]	36	62	2.00	29	75	3.00	35	68	1.80	35	102	3.20
Central field intact	CFI 1	76	6	4	72	4	3	69	1	1	72	3	2
	CFI 2	62	5	4	51	13	3	90	1	1	85	6	2
	CFI 3	34	4	2	48	6	3	68	5	1	55	5	4
	CFI 4	75	9	2	73	19	1	69	1	3	62	10	4
	CFI 5	35	7	1	46	11	4	89	3	2	98	1	3
	Mean[b]	53	49	2.60	57	25	2.80	76	16	1.60	73	26	3.00
Low vision	Mean[a]	47	69	2.18	44	79	2.82	58	88	1.82	54	88	3.18
Normal vision	N 1	64	9	3	71	5	2	92	1	1	180	3	4
	N 2	83	3	1	81	13	3	91	2	2	169	5	4
	N 3	90	3	1	88	2	3	226	4	2	358	4	4
	N 4	64	3	3	50	14	4	134	1	1	171	5	2
	N 5	96	8	1	90	8	2	238	2	3	307	8	4
	N 6	71	7	2	66	2	1	176	3	3	219	7	4
	N 7	96	7	3	98	9	4	149	4	1	169	5	2
	Mean	80	19	2.00	76	26	2.71	148	48	1.86	215	37	3.43

[a] Subject CFL 7 was excluded from the low-vision group analysis because it was only possible to obtain one reading rate for each of the text-presentation conditions because of her very low acuity.

[b] CFL (central-field loss) means are based on the reading rates of subjects CFL 1, CFL 2, CFL 3, CFL 5, and CFL 6. Subject CFL 7 was excluded from the central-field status analysis for the reasons described above. Subject CFL 4 also was excluded from the central-field status analysis because the status of his central field was difficult to evaluate with the techniques used in this experiment. CFI (central field intact) means are based on the reading rates of subjects CFI 1 to CFI 5.

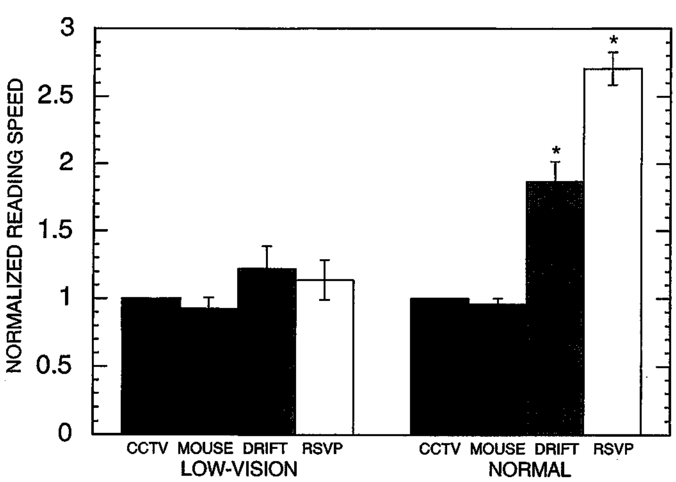

FIGURE 2.
Normalized reading speeds. Mean reading speeds for the four display conditions (see Table 2) were normalized by the mean value for CCTV reading. The bars show the normalized speeds for low-vision and normal groups. Error bars show ±1.0 SEM. Asterisks (*) designate those conditions that differed significantly from CCTV at the 0.01 level.

otherwise, the text was presented automatically at the speed selected by the subject in the adjustment phase. Low-vision subjects paused occasionally on RSVP trials, but rarely paused on DRIFT trials.

Analysis of responses to multiple-choice questions revealed that only 17 of 292 questions were answered incorrectly. Low-vision subjects were 96% correct and normal subjects were 92% correct. The 17 incorrect responses were distributed across 9 different passages, with no more than 4 incorrect responses recorded for any single passage.

A two-way analysis of variance (ANOVA) of low-vision and normal-vision reading speeds showed a significant main effect for group ($F = 280.3$, $p < 0.001$), a significant main effect for text-presentation condition ($F = 48.9$, $p < 0.001$), and a significant group × text-presentation condition interaction ($F = 49.1$, $p < 0.001$).

Fig. 2 shows mean reading speeds of the groups (normal and low vision) normalized by mean CCTV reading speed. In comparison with their reading speeds in the CCTV condition, low-vision observers read 6% slower in the MOUSE condition, 23% faster in the DRIFT condition, and 15% faster in the RSVP condition. No

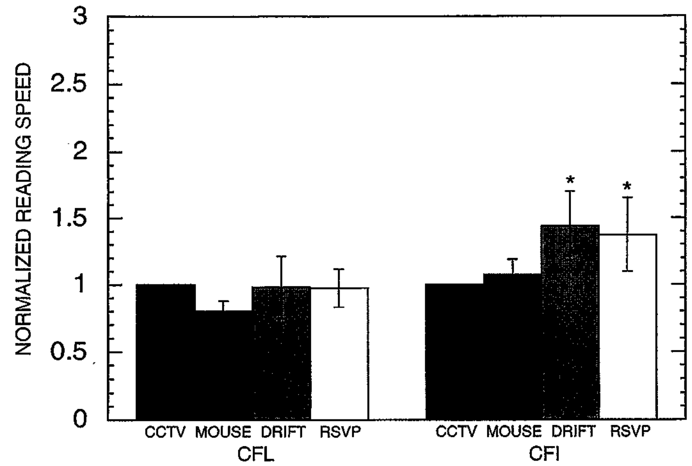

FIGURE 3.
Normalized reading speeds for low vision groups with CFL and CFI. Other details as in Fig. 2.

pairwise comparison between text-presentation conditions was significant (0.01 criterion) for this group. In comparison with their reading speeds in the CCTV condition, normal subjects read 5% slower in the MOUSE condition, 85% faster in the DRIFT condition, and 169% faster in the RSVP condition. Both the CCTV-DRIFT difference ($t = 6.27$, $p < 0.01$) and the CCTV-RSVP difference ($t = 9.53$, $p < 0.01$) were significant. In addition, the normal-vision group read significantly faster in the DRIFT condition compared with the MOUSE condition ($t = 6.56$, $p < 0.01$), significantly faster in the RSVP condition compared with the MOUSE condition ($t = 9.74$, $p < 0.01$), and significantly faster in the RSVP condition compared with the DRIFT condition ($t = 3.84$, $p < 0.01$). The CCTV-MOUSE difference did not reach significance.

Next, we compared the reading speeds for the CFL and CFI groups. A two-way ANOVA showed a significant main effect for group, CFL vs. CFI ($F = 106.3$, $p < 0.001$), a significant main effect and for text-presentation condition ($F = 5.9$, $p < 0.01$). Fig. 3 shows the CFL and CFI group means, normalized by the mean CCTV rates. In comparison with their reading speeds in the CCTV condition, the CFL group read 19% slower in the MOUSE condition and 3% slower in the DRIFT and RSVP conditions, although no text-presentation condition pairwise comparison was significant (0.01 criterion) for this group.

In comparison with their reading speeds in the CCTV condition, the CFI group read 8% faster in the MOUSE condition, 43% faster in the DRIFT condition, and 38% faster in the RSVP condition. For the CFI group, there were significant differences for DRIFT vs. CCTV ($t = 4.60$, $p < 0.01$), RSVP vs. CCTV ($t = 3.51$, $p < 0.01$), DRIFT vs. MOUSE ($t = 4.78$, $p < 0.01$), and RSVP vs. MOUSE ($t = 3.32$, $p < 0.01$). The CCTV-MOUSE and DRIFT-RSVP differences did not reach significance.

How do our results compare with those of previous studies? Consistent with Beckmann and Legge,[1] our low-vision group showed no significant differences in reading speed between DRIFT and CCTV (although our CFI sub-group did show a significant difference). Consistent with Rubin and Turano,[5] our CFI group benefited more than our CFL group from RSVP, although our baseline was CCTV reading speed, whereas theirs was static text. Finally, our results are consistent with Fine and Peli,[9] who also found that low-vision subjects read RSVP and drifting text at similar speeds.

We examined the possibility that slow readers are little affected by the mode of text presentation, whereas fast readers show a greater influence. For each subject, we computed the mean and standard deviations of the log reading speeds across the four text presentation conditions. Considering all subjects (normal and low vision), there was a correlation of 0.49 ($p < 0.05$) between the means and the standard deviations; people who read faster tended to have a wider dispersion of speeds across the text-presentation conditions. The correlation was not significant within either the low-vision or normal groups on their own.

Subjects' preference rankings for the four types of text displays are also shown in Table 2 from 1 "most preferred" to 4 "least preferred." The order of mean preference scores is the same for normal and low vision, with DRIFT preferred most, followed by CCTV, MOUSE, and RSVP in descending order. Five low-vision subjects selected DRIFT as their top choice, and none ranked it last. CCTV, MOUSE, and RSVP all received four last-place rankings from low-vision subjects.

Because RSVP was read fastest, but preferred least, there is not a tight link between speed and preference. Subjects' comments revealed at least two factors, other than speed, that influenced their preference rankings. First, even though DRIFT and RSVP reading relieve one from doing page navigation, they also remove a sense of autonomy—like the difference between being a passenger in a car and being the driver. Evidently, some low-vision readers prefer manual control over automatic in reading. Second, there is a difference in the degree to which the four display methods allow the reader to maintain a cognitive representation of the physical page. CCTV reading uses a physical page and provides the reader with some motor feedback concerning the page position of the word being read. In MOUSE reading, one can easily lose track of position on the page. In RSVP reading, the concepts of both page and line are replaced by an endless stream of words. DRIFT retains the sense of a line of text, but page layout is lost.

CONCLUSIONS

Clinicians, rehabilitation professionals, designers of adaptive technology, and low-vision readers are all interested in learning whether reading performance is greatly influenced by the method of text presentation. The method may vary in both the nature of the visual display and in the means for navigating through the text. We compared reading speeds for four widely used types of text presentation–CCTV, MOUSE, DRIFT, and RSVP. Key visual parameters were held constant across the four conditions by presenting all reading material at the same luminance, contrast, and character size on a single video monitor. The subjects performed a simple, everyday reading task and maintained good comprehension across all conditions. We can now answer the three questions raised at the beginning of this article.

1. Does the reduction in navigational demands across the CCTV, MOUSE, DRIFT, and RSVP text-presentation conditions result in corresponding increases in the reading speeds of low-vision subjects? Low-vision subjects showed relatively small effects

of the type of text presentation. The largest pairwise difference in mean reading speeds was 43% (DRIFT vs. CCTV for the CFI group). We found evidence that the automatic display methods (DRIFT and RSVP) yield faster reading speeds (approximately 40%) than the manual methods (CCTV and MOUSE) for CFI subjects, but there were no significant differences for the CFL subjects.

Why is there so little influence of the method of navigation on low-vision reading speed? We believe that visual factors are the bottleneck in most cases of low vision. Although the cost in time for navigation may vary somewhat across the four modes of text presentation, most of the time in reading is taken up with visual decoding. Hence, reading speed is primarily limited by visual factors, not navigational factors.

2. Do the variations in reading speeds of the low-vision subjects across the four text-presentation conditions show the same pattern as the normal subjects? As expected, normal subjects read much faster for DRIFT and RSVP where manual navigation was not required. Also, as expected, RSVP was faster than DRIFT. For low-vision subjects, the differences were smaller, and they did not read faster with RSVP than DRIFT. There was very little difference between the two manual navigation methods, MOUSE vs. CCTV, for normal or low-vision subjects.

3. Does central-field status make a difference? The group with CFL read more slowly overall, and showed less effect of the method of text presentation, than the group with intact central vision. This observation is consistent with our view that visual decoding, not page navigation, plays the primary role in limiting low-vision reading speed.

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