Vision Res. Vol. 32, No. 5, pp. 895–902, 1992
Printed in Great Britain

0042-6989/92 $5.00 + 0.00
Pergamon Press plc

Reading Without Saccadic Eye Movements

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Received 22 May 1991; in revised form 11 September 1991

To assess the limitation on reading speed imposed by saccadic eye movements, we measured reading speed in 13 normally-sighted observers using two modes of text presentations: PAGE text which presents an entire passage conventionally in static, paragraph format, and rapid serial visual presentation (RSVP) which presents text sequentially, one word at a time at the same location in the visual field. In Expt 1, subjects read PAGE and RSVP text orally across a wide range of letter sizes (2X to 32X single-letter acuity) and reading speed was computed from the number of correct words read per minute. Reading speeds were consistently faster for RSVP compared to PAGE text at all letter sizes tested. The average speeds for text of an intermediate letter size (8X acuity) were 1171 words/min for RSVP and 303 words/min for PAGE text. In Expt 2 subjects read PAGE and RSVP text silently and a multiple-choice comprehension test was administered after each passage. All subjects continued to read RSVP text faster, and 6 subjects read at the maximum testable rate (1652 words/min) with at least 75% correct on the comprehension tests. Experiment 3 assessed the minimum word exposure time required for decoding text using RSVP to minimize potential delays due to saccadic eye movement control. Successive words were presented for a fixed duration (word duration) with a blank interval (ISI) between words. The minimum word duration required for accurate oral reading averaged 69.4 msec and was not reduced by increasing ISI. We interpret these results as an indication that the programming and execution of saccadic eye movements impose an upper limit on conventional reading speed.

Reading Eye movements Saccades

INTRODUCTION

Skilled readers with normal vision typically read less than 400 words/min. What determines this upper limit on reading speed? There are several obvious possibilities such as the time it takes to decode the visual stimulus and perform the complex lexical, syntactic, semantic and contextual processing required for comprehension of meaningful text. A less obvious constraint is the limit imposed by the programming and execution of saccadic eye movements during normal reading.

When reading conventional stationary text, the eyes move in a saccadic fashion with an average latency of about 250 msec between saccades (Rayner, 1978). Each saccade tends to place fixation near the beginning of the next word (McConkie, 1988). Ignoring regressive eye movements and words skipped in the saccadic sequence, these average latencies translate to a reading rate of 240 words/min. Only about 10% of the time between saccades is consumed by the eye movement itself, leaving a fixation interval of about 220 msec. Only a small portion of the fixation interval is required to decode the visual stimulus. Rayner, Inhoff, Morrison, Slowiaczek and Bertera (1981) demonstrated that the visual information required for near-asymptotic reading speed is available within 50 msec after word exposure.

It has been hypothesized that the fixation interval is extended by saccadic suppression which reduces the visibility of stimuli immediately before, during, and for 80–100 msec after a saccadic eye movement (Volkmann, 1976). However, saccadic suppression has generally been observed in tasks where the stimuli are near the threshold of visibility. Salthouse, Ellis, Diener and Somberg (1981) found no evidence for saccadic suppression in a suprathreshold letter identification task at any time during fixation.

Various investigators have tried to determine the contribution of eye movement control factors and cognitive processing to the fixation duration. To isolate eye movement control factors, Salthouse and Ellis (1980) had subjects make a two-step saccade from an asterisk to a 2- or 4-letter target string and on to a second asterisk. The minimum time to fixate the target and initiate a saccade to the second asterisk 5.4° to the right of it was about 200 msec even when no further perceptual or cognitive processing of the target was required. Rayner (1978) reported that it takes about 175 msec to execute an eye movement to a word 2° from fixation (about the equivalent of a 5-letter word in 12-point type). Experiments such as these have led to the view that the programming and execution of saccadic eye movements accounts for most of the fixation duration in reading.

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However, several studies reviewed by O'Regan (1990) challenge the assumption that there is an incompressible latency for programming saccadic eye movements that contributes significantly to fixation duration. O'Regan noted that saccade latencies could be reduced below 100 msec by extinguishing the central fixation target before the saccade. He concluded that most of the saccadic latency is attributable to visual factors involved in localizing stimuli and decision processes involved in selecting the saccade target. But whether the limiting factors are oculo-motor or visuo-motor, saccadic eye movement control seems to play an important role in determining fixation duration.

A second approach to investigating the role of eye movements in limiting reading speed has been to measure reading speed using a task that minimizes eye movements. One such method is to present text sequentially at a fixed location in the visual field. Gilbert (1959a,b) was the first to use this technique which has since been labeled "rapid serial visual presentation" or RSVP (Forster, 1970). Gilbert used a cine loop to present short sentences a pair of words at a time. He reported 92% accuracy in word identification when pairs of words were exposed for 83 msec followed by an 83 msec blank interval between words (equivalent to a reading rate of 720 words/min).

Many variants of RSVP have been used since Gilbert's original studies. The text has been presented one word at a time or with groups of two or more words simultaneously visible (Juola, Ward & McNamara, 1982; Cocklin, Ward, Chen & Juola, 1984). The words have been presented at a constant rate or at a variable rate related to the latency of processing words of varying difficulty (Ward & Juola, 1982). Several studies (Potter, Kroll, Yachzel, Carpenter & Sherman, 1986; Ward & Juola, 1982; Cocklin *et al.*, 1984) have shown that RSVP reading speed can be increased to about 720 words/min (83 msec/word) with comprehension at least as good as that obtained with rapid skimming of static text. However, Potter, Kroll and Harris (1980) reported that retention of information was worse for RSVP than for rapid skimming at 600 words/min (100 msec/word), and Masson (1983) found that a pause had to be inserted between sentences presented with RSVP to maintain comprehension at a level comparable to static reading. None of the RSVP studies has demonstrated that word duration can be reduced below about 170 msec/word (350 words/min) without reducing word recall or comprehension below that achieved with conventional static reading.

In sum, the previous literature suggests that the latency of eye movements is well matched to the latency for cognitive processing of text, both being about 175 msec/word. In fact, if one adds the minimum saccade latency from the non-reading tasks to the minimum word exposure duration from the RSVP experiments, one would arrive at a maximum reading speed of only 170 words/min (350 msec/word). This implies that the control of eye movements occurs in parallel with visual decoding and cognitive processing during reading. However, in informal observations of RSVP reading in our laboratory, we were surprised to find some subjects reading more than 1600 words/min with excellent recall and comprehension. This led us to reexamine the limitation on reading speed imposed by eye movements.

EXPERIMENT 1

The primary purpose of this experiment is to determine how fast a person can read RSVP text compared to conventional static text presented one page at a time. Previous investigations have generally treated reading rate as the independent variable and used a measure of accuracy (word recognition, recall, comprehension, etc.) as the dependent variable. To meet our stated objective, we use reading rate itself as the dependent variable. Since reading rate can vary dramatically depending on the reading task confronting the subject (e.g. proofreading vs skimming) we needed to define a reading task that could be administered in a standardized fashion across all subjects and conditions. Legge, Pelli, Rubin and Schleske (1985) and Legge, Ross, Maxwell and Luebker (1989) demonstrated that oral reading provides an efficient, reliable measure of reading performance. Reading rates measured with oral reading vary in the same fashion as silent reading with stimulus variables such as letter size and color. Oral reading is also particularly well suited to psychophysical studies because it can be objectively scored by computing the number of words read correctly per unit of time.

For our first experiment we measured oral reading speed for RSVP and static text over a range of letter sizes.

Methods

Stimuli. Text was displayed on a 19″ US Pixel monochrome monitor (P-104 phosphor) under control of an IBM AT computer with an Imagraph IP1010-8 graphics controller. The display system had a resolution of 1024 × 1024 pixels at a 60 Hz noninterlaced frame rate. Individual letters were digitized with a Panasonic CCD camera and Imaging Technology PCVision frame grabber. The letters were taken from a proportionally-spaced Times Roman font, printed on an HP Laserjet. The height of a digitized uppercase letter was 32 pixels and the "x-height" (height of a lowercase "x") was 15 pixels. The angular subtence of the letters was adjusted by varying the viewing distance and changing the magnification (zoom) on the display with pixel replication. Viewing distance ranged from 25 to 217 cm and the maximum zoom magnification was 6X. Letters had a minimum luminance of 5.5 cd/m^2 and were displayed as dark letters on a bright background with a luminance of 181 cd/m^2. For RSVP reading, the rate of text presentation was calibrated with a photodiode and oscilloscope. The maximum rate was 1800 words/min (one new word every other frame or 30 words/sec). Text was selected from standardized reading materials with sixth through ninth grade difficulty, and the various passages were presented in random order. No subject saw the same passage of text more than once.

Procedure. Two modes of text presentation were tested in random order. *PAGE* text was displayed single spaced with the entire page of 200 or more words visible on the screen at the same time. The experimenter gave the subject a ready signal, then the text was presented for a fixed duration, usually 10 sec. The subject read the text aloud and was given credit for each word read correctly. If the subject read the entire page, the duration of the succeeding trial was reduced to 5 sec. Reading rate was computed as the number of words read correctly per minute.

RSVP text was displayed one word at a time in the center of the screen. A black fixation dot indicated the center of each word's location. At the beginning of a trial there was a brief tone and the fixation dot was replaced by the first word of the sentence. The word was displayed for a fixed period of time (word duration) then was immediately replaced by the next word. This procedure continued until a complete sentence had been presented. The observer read the sentence, and if all of the words were read correctly, the word duration in the next sentence decreased by 50%. Conversely, word duration increased by 50% if the observer did not read the words correctly. The step size was reduced to 25% after the second reversal. A trial ended after three decreasing sequences and the final word duration was converted to reading rate in words per minute.

Subjects were allowed to continue responding after the text disappeared from the screen, and in the RSVP condition many chose to recite the sentence after it had been viewed in its entirety. For both text modes we adopted a very strict criterion for scoring reading performance. Each word had to be read verbatim for the sentence to be counted as correct.

Prior to testing, each subject's visual acuity was measured with a trans-illuminated Lighthouse ETDRS acuity chart at 3 m. Text was presented at 2, 4, 8, 16 and 32 times the subject's single-letter acuity limit, in random order. All viewing was binocular with natural pupils. Each subject had a practice session for both reading modes before actual testing began.

Subjects. Thirteen normally-sighted subjects participated in this experiment. Their ages ranged from 20.7 to 85.2 yr (mean 52.2 ± 19.0) and binocular acuities ranged from -0.19 to 0.20 logMAR (20/12 to 20/32 Snellen, mean -0.03 ± 0.14 logMAR or $20/19 \pm 1.4$ lines Snellen). Three subjects had acuities worse than 20/20, all of whom were over 60 yr of age. None of the subjects were aware of the specific purposes of the experiment nor had they seen any of the text previously.

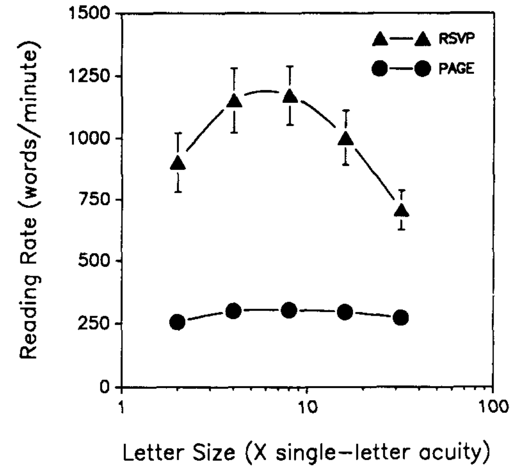

FIGURE 1. Reading rate in words per minute is plotted for RSVP and static PAGE modes of text presentation. Letter size has been normalized by each subject's letter acuity. Solid symbols are arithmetic means for 13 subjects. Error bars on the RSVP data plot $\pm$ 1 SEM. Standard errors for PAGE data are smaller than the symbols.

RESULTS

Figure 1 plots reading rate vs letter size for PAGE reading and RSVP reading. Letter size has been normalized by each subject's visual acuity. Connected symbols represent the mean reading rates. Error bars representing ± 1 SEM are shown for RSVP reading. Error bars were less than the symbol size for PAGE reading. PAGE reading rates varied little over the range of letter sizes used and reached a maximum of 303 words/min. RSVP reading was more sensitive to letter size than PAGE reading (repeated measures ANOVA, letter size $\times$ presentation mode interaction significant, $P < 0.002$). Average RSVP rates varied from 704 words/min for letters 32 times single-letter acuity (160 minarc for 20/20 acuity) to 1171 words/min for letters 8 times letter threshold (40 minarc for 20/20 acuity). Four observers read without error at the maximum rate we could display (1800 words/min) for one or two letter sizes. Thus, the average RSVP reading rates in Fig. 1 are probably an underestimate of average reading performance.

The flat letter-size function for PAGE reading is consistent with previous reports. For normally-sighted readers, reading speed is weakly dependent on letter size over the range from 12 to 360 minarc (equivalent to 2.4–72 times normal single-letter acuity (Legge *et al.*, 1985). The effect of letter size on RSVP reading rates has not previously been investigated. We find that reading speed is much more strongly dependent on letter size for RSVP text than for PAGE text. We discuss the possible reasons for this difference in the General Discussion.

RSVP reading rates were consistently higher than PAGE reading rates for all subjects and at all letter sizes tested. Figure 2 compares reading rates for PAGE and RSVP conditions for each subject. Data are shown for the smallest letter size (2X single-letter acuity) and for an intermediate size (8X single-letter acuity). All data fall well above the solid diagonal line indicating that reading rates were substantially faster for RSVP reading compared to PAGE reading. Most of the data lie between the dashed line (2-fold increase) and the dotted line (4-fold increase).

The most striking result in Expt 1 is that people who read PAGE text at 250–300 words/min can read RSVP text accurately at rates in excess of 1000 words/min

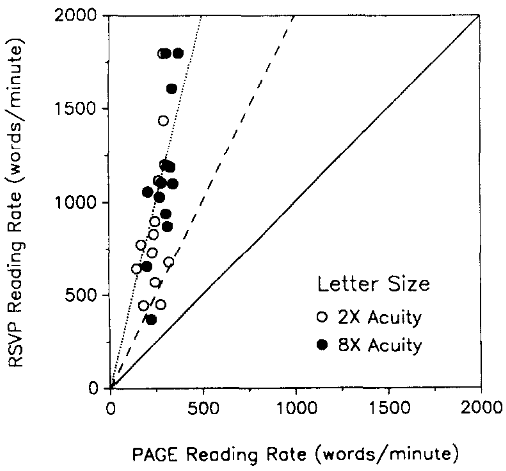

FIGURE 2. Reading rate for RSVP text is plotted vs reading rate for PAGE text for two letter-size conditions. Each point represents data for a single observer. Data falling above the solid diagonal line indicate that reading rate was faster for RSVP compared to PAGE text. The dashed and dotted lines designate 2- and 4-fold improvements, respectively, for RSVP reading speed.

(60 msec/word). None of the subjects had extensive practice with RSVP prior to the experiment. Can we conclude that 60 msec/word is all that is necessary for reading, and that the remaining 140 msec is required to program and execute saccadic eye movements? First, we must consider the limitations of our reading measurements.

In the PAGE conditions, subjects read as much of a passage as they could finish in a single 10 sec trial. In the RSVP condition one sentence was read at a time. We did not present the entire passage at one time with RSVP because subjects would clearly have been limited by the speed of verbalization. But since we tested only single sentences in the RSVP condition, we are confronted by the possibility that subjects may have buffered the visual information in some partially processed representation and completed processing during the interval between sentences. Although verbalization speed would not have affected RSVP reading, it could be argued that reading rate for our static PAGE condition was limited by the speed of pronouncing words. Finally, while subjects were confident that they understood the meaning of both RSVP and PAGE passages, we did not assess comprehension in Expt 1. We address these issues in Expt 2.

EXPERIMENT 2

Much of the previous research on RSVP has investigated the extent to which processing of RSVP text is "on line" vs delayed until the end of the sentence or phrase. In support of the on-line hypothesis, several investigators including Forster (1970) and Potter (1984) have shown that recall of scrambled RSVP sentences is much worse than recall of normal-order sentences. Fischler and Bloom (1984) and Potter (1984) found that RSVP sentences caused priming effects on subsequent lexical decision tasks, indicating that the rapidly presented sentences could provide immediate contextual information.

In support of the delayed-processing hypothesis, some of our subjects in Expt 1 reported difficulty with sentences longer than about 10 words. However, this may have been due to short-term memory limitations since subjects were required to recite the sentences verbatim. Potter *et al.* (1986) reported that the latency to determine the plausibility of a sentence increased and accuracy decreased for sentences longer than 8 words presented with RSVP. But latencies did not continue to increase for sentences longer than 10 words, as would be expected if processing were delayed. Perhaps the strongest support for the delayed-processing hypothesis is Masson's (1983) finding that comprehension of RSVP text was inferior to conventional text unless a pause was inserted between sentences in RSVP. But readers of conventional text also pause between sentences (Just & Carpenter, 1980), so RSVP may be no different in the proportion of on-line vs delayed processing.

In order to reduce the opportunity for delayed processing of RSVP text, we presented the entire passage in a single trial for Expt 2. In addition, we switched to silent reading and tested comprehension for both RSVP and PAGE text.

Methods

Stimuli. The test used for silent reading was taken from the Gates–MacGinity Reading Tests, Second Edition, Level D (grades 4–6) and Third Edition, Levels 4, 5/6 and 7/9. Twenty passages were chosen that ranged from 95 to 125 words in length. Multiple choice questions were selected from among those provided by the authors. Each question was pilot tested to insure that the question could not be answered at better than a chance level prior to reading the passage and could be answered after reading the passage without referring back to the original story. Some of the questions had to be modified and several new questions were added so that we ended up with 4 questions per passage, each with 4 possible answers. All other aspects of the stimuli were the same as in Expt 1.

Procedure. PAGE and RSVP reading were first tested using the same oral reading procedure and text used in Expt 1. The oral reading rates were used to give the experimenter an idea of where to start the silent reading tests.

For the silent PAGE condition, the entire passage was displayed for a period (trial duration) that was judged to be just long enough for the subject to complete the story. The subject was informed that the text would be visible for a limited time and that she/he should read as fast as possible while maintaining adequate comprehension to answer questions at the end of the trial. The experimenter used the computer's internal clock to time how long it took the subject to read the passage (reading duration) to the nearest 0.1 sec. If the subject completed the story by the time it was erased from the screen, the experimenter asked the 4 comprehension questions. If the subject failed to complete the story or answered fewer than 3 of the 4 questions correctly, then the duration of the subsequent trial was increased by a factor of 1.26 (0.1 log unit). If the subject answered three or more questions correctly, trial duration was decreased by the same factor. This procedure continued until the subject failed two trials in a row, and the reading rate was computed for the last successful trial.

For the silent RSVP reading, the entire passage was displayed sequentially at a fixed rate (word duration). A pause equal to one word duration was inserted between sentences. The same staircase procedure was used for silent RSVP reading as for silent PAGE reading, with the same scoring criterion. Reading rate was then adjusted to reflect the added pauses between sentences.

Practice sessions were given prior to both the silent PAGE and silent RSVP runs. Passages were assigned randomly to PAGE and RSVP conditions for each subject. All testing was done with letters four times the subject's single-letter acuity.

Subjects

Nine subjects were tested in Expt 2. The subjects ranged from 32 to 65 yr of age. Two of the subjects had previously participated in Expt 1. None were aware of the specific purposes of the experiment, nor did they see any passage of text more than once.

Results

Reading rates for silent and oral reading are shown in Fig. 3. Since the distribution of silent RSVP reading rates was strongly skewed on both linear and logarithmic scales, we elected to use medians rather than means to represent average performance.

Median reading rates for the oral PAGE and RSVP conditions are comparable to those obtained in Expt 1. The median RSVP reading rate (991 words/min) was 3.6 times faster than the median PAGE reading rate (278 words/min). One subject read RSVP text accurately at 1800 words/min, the fastest rate we could test.

Silent reading rates were generally higher than oral rates and much more variable. The median silent RSVP rate (1652 words/min) was 2.1 times faster than the median silent PAGE rate (790 words/min), but this comparison is somewhat misleading since there was a strong ceiling effect for RSVP reading. Six of the nine subjects read silent RSVP text at the maximum rate with adequate comprehension. Each of these subjects achieved at least 75% correct on the comprehension test for two passages at 1652 words/min (1800 words/min presentation rate adjusted for pauses between sentences).

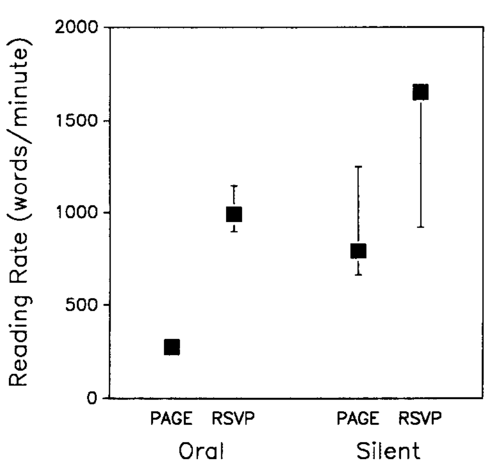

FIGURE 3. PAGE and RSVP reading rates are compared for both oral and silent reading. Reading rates for oral reading are based on verbatim recitation of the text. Reading rates for silent reading are based on 75% correct responses to comprehension questions following each passage. The symbols plot median reading rates and error bars indicate inter-quartile ranges.

EXPERIMENT 3

The results of Expts 1 and 2 indicate that normal subjects can accurately read and comprehend text when the words are presented for as little as 67 msec. These times are comparable to those reported by Rayner *et al.* (1981) as the minimum exposure time required for decoding the visual information used in reading. In Rayner's experiment, subjects read static text at their normal rates, but the fixated word was masked at various delays after fixation. They still had to make saccadic eye movements, and the control of these movements may have interfered with or delayed visual processing. In Expt 3 we investigated the minimum word exposure time required for decoding text using RSVP to minimize potential delays due to saccadic eye movements.

Methods

Stimuli. The text and display apparatus were the same as in Expt 1. RSVP text was displayed at four times the subject's single-letter acuity. For each sentence, successive words were presented for a fixed period of time (word duration) with a fixed number of blank frames between words (inter-stimulus interval or ISI). As in Expt 1, word duration decreased on the subsequent trial if the subject read the sentence correctly and increased if the sentence was read incorrectly. ISIs of 0, 33, 83 and 117 msec were tested in ascending order. Word duration threshold plus ISI was converted to reading rate in words per minute.

Subjects. Ten of the original thirteen subjects participated in this experiment.

Results

Figure 4 plots average reading rates (± 1 SEM) vs ISI. Reading rate declined with increasing ISI. These data are replotted in Fig. 5 with reading rate converted to the duration of text presentation.

The open symbols plot the entire word-to-word interval (word duration + ISI duration) which is inversely proportional to reading rate. The solid symbols plot word duration only, which averaged 69.4 msec over the range of ISIs tested.

The introduction of a blank ISI between words did not reduce the word duration threshold. If anything, word duration increased slightly for ISIs of 33 and 83 msec, but the differences are not statistically significant. These results are consistent with data reported by Rayner *et al.* (1981) for a page reading task in which the subjects had

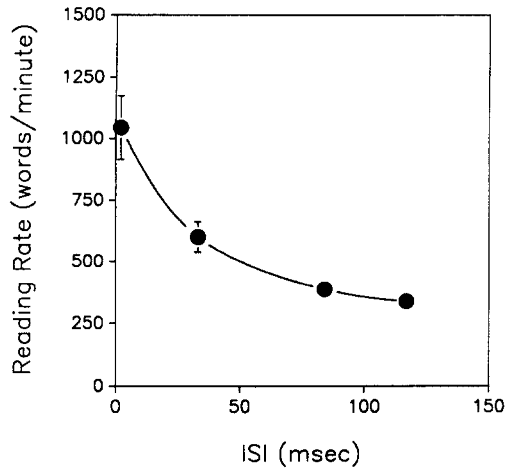

FIGURE 4. Mean reading rate (+1 SEM) is plotted for RSVP text presented with blank intervals between successive words (ISI). Text size was scaled to four times the subject's letter acuity.

to make saccadic eye movements. Thus, it doesn't matter whether the text is presented in a fixed location or the reader has to scan the text in the conventional manner: the visual information required for decoding and comprehending text can be acquired in less than 70 msec.

GENERAL DISCUSSION

Our subjects, who require about 250 msec/word to read static pages of text, can read and understand RSVP text exposed for less than 70 msec/word. The RSVP results appear to be at odds with numerous previous studies, none of which reported high levels of comprehension for less than about 170 msec/word. What accounts for this apparent discrepancy?

One possibility is that the text we used was easier to read than that used in previous experiments. For the oral reading we used reading materials from grade levels 6–9. For the comprehension tests we used text from grade levels 4–9. Previous investigators have used text from a variety of sources including *Reader's Digest* and standardized reading materials similar to ours. Juola *et al.* (1982) compared RSVP reading of 7th–8th grade text to 9th–10th grade text. They found that reading comprehension scores declined from 70% correct to 55% correct as the difficulty of the text increased. However, their testing was conducted at much slower reading rates, about 320 words/min in the RSVP condition most similar to ours.

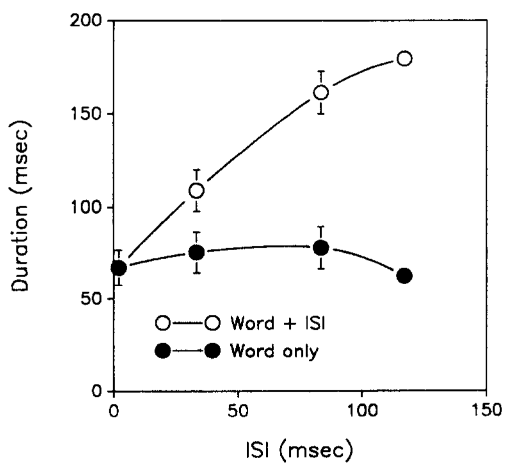

FIGURE 5. The data in Fig. 4 are replotted with reading rate converted to the duration of text presentation. Open symbols plot the entire word-to-word duration, including blank ISI, if any. Solid symbols plot the duration of the word only, ignoring any blank ISI between words.

We also considered whether some aspect of the visual stimulus could have contributed to the high RSVP reading rates. We were careful to use high contrast text with luminances well into the photopic range, and selected letter sizes to cover the range of optimal sizes for each reader. While RSVP shows a much greater dependence on letter size than PAGE reading, we would have had to use letters smaller than two times the acuity limit (< 10 minarc for 20/20 vision) or greater than 16 times the acuity limit (> 80 minarc) to reduce reading speed to previously reported levels. It seems unlikely that differences in the visual characteristics of the stimuli were an important factor.

Given our primary interest in determining the maximum reading rate for a criterion level of performance (verbatim oral reading or 75% comprehension), we used reading rate as the dependent variable. Previous investigations of RSVP have used performance level as the dependent variable, measuring comprehension, recall, etc. at a series of predetermined reading rates. We believe that this change in test procedure may have led to a higher estimate of maximum RSVP reading rates. Figure 6 plots RSVP reading data for two observers who participated in Expt 2. Open symbols plot reading comprehension score (proportion correct) as a function of the reading rate. The solid line graphs the average comprehension score for multiple trials at the same rate and the dotted line indicates chance performance.

The reading comprehension function in the left panel is quite flat, typical of most of our data. The observer answered all comprehension questions correctly for reading speeds up to about 400 words/min. At higher rates the function becomes somewhat more variable but levels out at 75% correct for all rates tested up to the maximum of 1652 words/min. The comprehension function in the right panel is steeper, but there is still a broad plateau over which reading comprehension remains nearly constant at about 75% correct. Had we tested these observers at only two reading rates such as 350 and 700 words/min, as has been done in most of the previous work, we might have inferred from the drop in comprehension scores from 100 to 75% correct that 700 words/min is near the upper limit for RSVP reading speed. The vertical arrows on the x-axis indicate RSVP thresholds for the two subjects as we defined them, 1652 words/min for the left panel and 920 words/min for the right panel. Legge *et al.* (1989) also reported that reading rate functions are shallow and quite variable when comprehension score is used as the dependent variable.

Despite impressive improvements in reading speed with only a little practice using RSVP, few of our

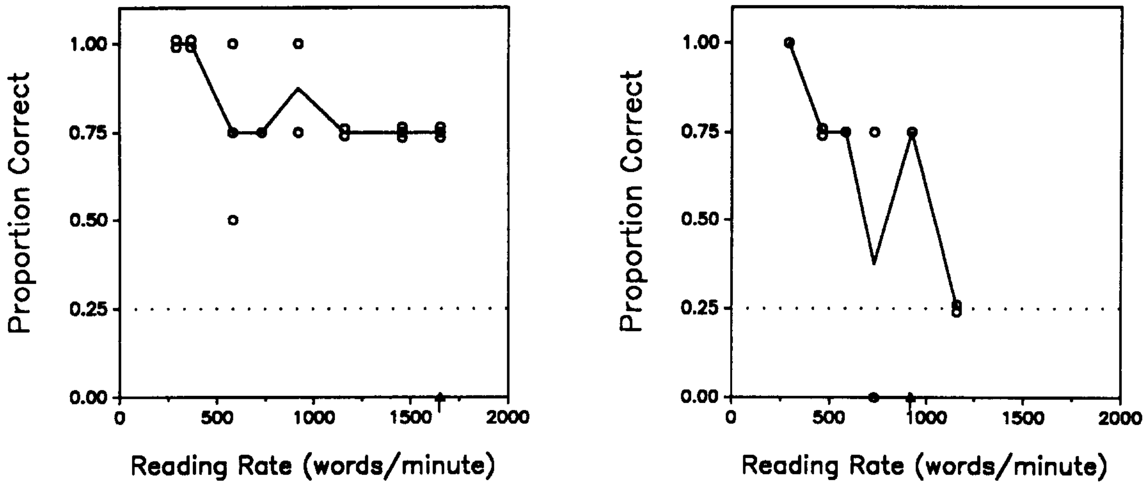

FIGURE 6. Proportion of correct responses to comprehension questions are plotted as a function of reading rate for two observers in Expt 2. Each symbol represents performance for a single passage. The solid line connects average proportions correct, and the small arrow on the horizontal axis indicates the reading rate threshold as defined by our 75% correct criterion. The subject in the left panel did not drop below an average of 75% correct so the maximum rate of 1652 words/min was used for her threshold. The subject in the right panel dropped to 37.5% correct at 730 words/min but returned to 75% correct at 920 words/min before failing again at higher rates.

observers felt comfortable reading at such high rates. With conventional text presentation the reader is free to glance back at an earlier part of the passage, to pause or skip ahead. With RSVP the reader has no control over test presentation. Complete concentration is required throughout, and even a momentary blink can disrupt an entire passage. Perhaps RSVP could be made less taxing on the observer if she/he were given control over text presentation and allowed to pause or back up the sequence.

Just, Carpenter and Woolley (1982) suggested that RSVP, like speed reading and skimming, may limit the level to which test is processed. Major themes and important points may be available to the reader, but lower level detail could be lost. Multiple-choice questions such as the type we and previous investigators have used, do not probe for detailed information. However, the oral reading task used in Expt 1 demonstrates that observers can recite complete sentences verbatim when presented with RSVP at rates up to 1800 words/min. While it could be argued that some of the words were reconstructed from the text, they would still have to be processed in sufficient detail to make that context available to the reader.

Despite these limitations, if normal readers can read RSVP text at rates faster than 1000 words/min, then the implications for our understanding of conventional reading are far-reaching. One consequence is that conventional reading may be relatively insensitive to visual factors such as letter size because conventional reading is limited by eye movements rather than the visual quality of the text. This would explain why RSVP reading is much more dependent on letter size than PAGE text, as shown in Fig. 1. The reading rate vs letter size function for PAGE text may be flat because eye movements impose a ceiling on reading rate. When this ceiling is eliminated through the use of RSVP, the underlying letter-size effect is revealed. The same argument would apply to contrast and blur (low-pass filtering), both of which have been shown to exert weak effects on conventional reading rate unless the text is severely degraded (Legge *et al.*, 1985; Legge, Rubin & Luebker, 1987). Another way of putting it is that the normal reader can tolerate substantial reductions in image quality without exceeding the limitations imposed by saccadic eye movement control.

Another implication of the present findings is that abnormal eye movements in visually impaired readers may seriously degrade reading performance even if visual processing of the text is only minimally affected. McMahon, Hansen and Viana (1991) studied saccadic eye movements in patients with bilateral macular disease. He found that patients made almost twice as many saccades as normal controls in scanning a 5-letter sequence. Furthermore, refixation errors were highly predictive of reading speed for continuous text ($r = 0.8$). Timberlake, Pelli, Essock and Augliere (1987) also reported errors in scanning eye movements during reading for two of three patients with macular scotomas. RSVP would provide a means of assessing the extent to which low-vision reading is limited by eye movement characteristics and may be useful as a reading aid for the partially sighted.

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Acknowledgements—We would like to thank Robert Massof and Gordon Legge for their insightful comments, Constance Morrison, Katrina Van Valen, Sue Blair and Jodi Grossman for their help with data collection, and Susan Vitale for assistance with data analysis. This grant was supported by Public Health Service Grant EY06380 to GSR and National Research Service Award EY05936 to KT.