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# Psychophysics of Reading—XVI. The Visual Span in Normal and Low Vision

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**The visual span in reading is the number of characters that can be recognized at a glance. The shrinking visual span hypothesis attributes reading speed deficits in low vision, and slow reading in normal vision at low contrast, to a reduction in the visual span. This hypothesis predicts that reading time (msec/word) becomes increasingly dependent on word length as text contrast decreases. We tested and confirmed this prediction using the rapid serial visual presentation (RSVP) method. Estimates of the visual span ranged from about 10 characters for high-contrast text to less than two characters for low-contrast text. Eye-movement recordings showed that longer reading times at low contrast are partitioned about equally between prolonged fixation times and an increased number of saccades (presumably related to a reduced visual span). RSVP measurements for six out of seven low-vision subjects revealed a strong dependence of reading time on word length, as expected from reduced visual spans. © 1997 Elsevier Science Ltd.**

Reading Low vision Visual span Contrast Eye movements

## INTRODUCTION

The "visual span" in reading is the number of characters that are recognized on each glance. We will provide an operational definition below. In this paper, we ask two main questions: Does shrinkage in the size of the visual span explain (1) slow reading in low vision; and (2) reduced reading speed for normal subjects when the text contrast is low?

Our use of the term "visual span" is similar to O'Regan's usage (O'Regan, 1990, 1991). He defined the visual span as the distance on either side of the point of fixation within which characters of a given size can be recognized. Because letters flanked by other letters are more difficult to identify in peripheral vision, the visual span for reading is smaller than the visual span for isolated letters.

Our notion of "visual span" differs from the concept of "perceptual span" (McConkie & Rayner, 1975; Rayner & McConkie, 1976). "Perceptual span" is defined in terms of the functional demands of reading, including detection of word length and spacing, in addition to letter recognition. Rayner & McConkie (1976) estimated that the perceptual span extends 15 characters to the right of fixation and four characters to the left. For a review of theory and data on the perceptual span, see Rayner & Pollatsek (1989).

Legge *et al.* (1987) showed that normal reading speed slows down when text contrast falls below 10%. One possible explanation is that the number of letters recognized in each glance is reduced at low contrast—"the shrinking visual span hypothesis". It should take longer to recognize words whose lengths exceed the size of the visual span because two or more glances would be necessary. An indicator of a shrinking visual span would be an increased dependence of word-recognition time on word length.

According to a second explanation, the number of letters in the visual span remains constant, but a longer viewing time is needed to recognize them at low contrast—"the prolonged viewing hypothesis". This explanation is analogous to the use of slower film in photography. According to this second account, slower reading at low contrast would not show a stronger dependence of word-recognition time on word length because recognition of all words would slow down by the same amount.

We examined the interaction of contrast and word length on reading times using a "rapid-serial-visual presentation" (RSVP) method. A significant interaction would support the shrinking visual span hypothesis. A significant effect of contrast with no interaction would support prolonged viewing. Our approach is similar to one used by Farah & Wallace (1991) in studying word recognition and letter recognition in acquired dyslexia.

Low vision is often defined as best-corrected letter acuity less than 20/60 in the better eye, or the inability to read regular newsprint with optimal refractive correction. Most people with low vision read slowly, even when the

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text has high contrast and is suitably magnified (Legge *et al.*, 1992). Rubin & Legge (1989) showed that the reduced reading speeds of some people with low vision can be modeled by contrast attenuation; these people behave like normal readers except for an early stage of contrast loss. This model applies best to people with cloudy ocular media (e.g., those with cataracts).

Why does a loss of effective contrast in low vision cause slower reading? Is it due to either shrinkage of the visual span or a need for prolonged viewing of letters? We addressed this question by measuring RSVP reading performance as a function of word length for seven low-vision subjects.

TABLE 1. Subjects with normal vision

| Subject | Gender | Age (yr) | logMAR acuity | Experiments |
|---|---|---|---|---|
| AA | F | 24 | −0.1 | 3 |
| CM | F | 28 | 0.0 | 3 |
| DS | M | 35 | 0.0 | 1 |
| GS | M | 22 | 0.0 | 3 |
| JC | F | 25 | −0.2 | 3 |
| PB | M | 40 | −0.3 | 1,2 |
| RC | M | 18 | 0.0 | 1 |
| SA | F | 27 | 0.0 | 1,2 |
| TK | M | 22 | −0.3 | 1,2,3 |
| WB | F | 23 | −0.3 | 1,2 |

## EXPERIMENT 1: EFFECTS OF CONTRAST AND WORD LENGTH IN NORMAL VISION

The purpose of this experiment was to distinguish between two explanations for slow reading when the text contrast is low. Does reading speed show a greater dependence on word length at low contrast (shrinking visual span), or is there no interaction between contrast and word length (prolonged viewing)?

### *Method*

*Apparatus and stimuli.* The words were presented on a Conrac 7241C19 color monitor driven by an IBM AT computer containing three Imaging Technology frame buffers (FG-100-AT-512/2). The screen resolution was 512 × 480 pixels, with 256 gray levels. All stimuli were achromatic.

The background luminance was constant at 100 cd/m$^2$. The letters were darker than the background. Text contrast was defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where $L_{max}$ is the luminance of the background and $L_{min}$ is the luminance of the letters. Contrast reduction was achieved by increasing the luminance of the letters while holding the luminance of the background constant. Display luminance was calibrated with a Minolta CS-100 photometer before each session.

The display screen was covered with a matte-black paper mask except for a window 40 cm wide by 2.5 cm high. Sequences of four unrelated words were presented in this window in rapid succession, one word at a time. The words were rendered in a fixed-width font, similar to Courier, with each letter in a box 24 pixels wide and 38 pixels high.

We used pools of 100 words at each of four lengths—3, 6, 9, and 12 letters. First, we selected the 100 most common 12-letter words (Carroll *et al.*, 1971). For the other word lengths, we found the 100 words most closely matched in frequency to the 12-letter words. The words were printed in lower case, except for a few proper nouns (6.5% of the words), such as Philadelphia, that began with a capital. Within a trial, the four words had equal length and were chosen randomly (without replacement) from the appropriate pool.* The trial began with a string of "0"s on the screen to indicate word length and position. Following the RSVP sequence, a masking string of "X"s appeared on the screen.

*Subjects.* Table 1 lists characteristics of the normal subjects and the experiments in which they participated. All were graduate students or members of our laboratory staff, and were highly skilled readers. All subjects were native English speakers, except SA (one of the authors) who was a fluent English speaker. Each subject was informed about the experimental purpose and procedures and gave written consent for participation. Six of the 10 subjects participated in Experiment 1.

*Procedure.* All tests were conducted with binocular viewing, with room lights off. The subject was seated either 12.5 or 75 cm from the screen, projecting 6 or 1 deg characters (center-to-center horizontal letter spacing). (The corresponding $x$-heights were 5 or 0.83 deg.) The subject was instructed to read aloud the four words in the trial sequence as accurately as possible. Exposure time was the same for each of the four words and there was no blank time between words.

We refer to the "exposure duration" as the time to show all four words in the RSVP sequence. The first two trials were practice, with the exposure duration set long enough for the subject to read the words without errors. An error was defined as any word not read verbatim. A word was scored as right or wrong, so the maximum number of errors in a trial was four. In subsequent trials, the experimenter adjusted exposure duration to meet the following error criteria at a fixed duration: at least one but no more than four errors in four trials, and no more than two errors on any single trial. This rule yielded an exposure duration in which the subject scored between 75 and 94% correct across four trials and at least 50% correct in each individual trial. If the number of errors exceeded the criteria, the exposure duration for subsequent trials was increased until the criteria were met. When the criteria were satisfied, reading speed was computed (words/min) as the number of words read

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*When the words of a given pool were depleted, they were "shuffled" and recycled. Subjects who participated in all of the conditions undoubtedly encountered the same words more than once. If subjects learned the words in the pools, they might have used this information to guess the longer words from glimpses of only a few letters. The result would be to shorten reading times for the longer words relative to the shorter words, flattening the curves in Figs. 1 and 2. If this occurred, our values of visual span in Tables 2 and 3 are overestimates.

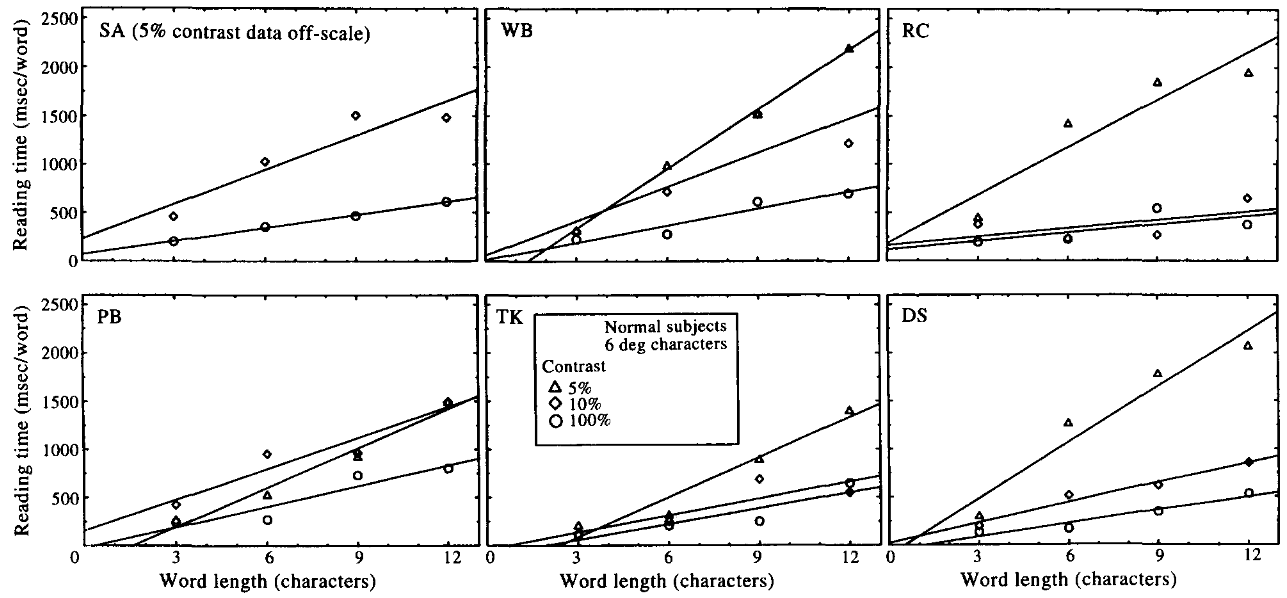

FIGURE 1. Reading time as a function of word length for 6-deg characters. Reading time is the reciprocal of reading speed. The six panels show data for six normal subjects. The three sets of data in each panel show results for three contrast levels. Table 2 lists parameters of the regression lines.

correctly divided by the exposure duration, averaged across the four trials. Reading time in msec/word was computed as the reciprocal of the reading speed.

### *Results*

The panels of Fig. 1 show reading time (msec/word) as a function of word length. The character size was 6 deg. The three sets of data in each panel show results for text contrasts of 100, 10 and 5%. In most cases, the regression lines fit the data quite well. Table 2 lists slopes, intercepts, $r^2$ values and visual spans (see below) for each subject. Subject SA's 5%-contrast data are not shown in Fig. 1 because they lie off scale, but the regression parameters appear in Table 2.

TABLE 2. Regression parameters and visual spans for six normal subjects: 6-deg characters

| Subject | %Contrast | $A_c$ | $B_c$ | $r^2$ | $V_{span}$ |
|---|---|---|---|---|---|
| SA | 100 | 70.7 | 45.0 | 0.997 | 5.56 |
| | 10 | 228 | 119 | 0.868 | 2.10 |
| | 5 | 2541 | 305 | 0.807 | 0.820 |
| WB | 100 | 12.2 | 58.3 | 0.915 | 4.29 |
| | 10 | 57.3 | 118 | 0.721 | 2.12 |
| | 5 | −286 | 206 | 0.998 | 1.21 |
| PB | 100 | −22.6 | 71.3 | 0.871 | 3.51 |
| | 10 | 155 | 107 | 0.904 | 2.34 |
| | 5 | −215 | 136 | 0.973 | 1.84 |
| TK | 100 | −103 | 54.4 | 0.811 | 4.60 |
| | 10 | −34.9 | 58.0 | 0.728 | 4.31 |
| | 5 | −326 | 138 | 0.941 | 1.81 |
| RC | 100 | 118 | 28.6 | 0.476 | 8.74 |
| | 10 | 163 | 28.7 | 0.347 | 8.71 |
| | 5 | 183 | 165 | 0.864 | 1.52 |
| DS | 100 | −53.8 | 46.2 | 0.932 | 5.41 |
| | 10 | 23.5 | 69.4 | 0.967 | 3.60 |
| | 5 | −102 | 194 | 0.937 | 1.29 |
| Mean | 100 | 3.58 | 50.6 | | 5.35 |
| | 10 | 98.7 | 83.4 | | 3.86 |
| | 5 | 299 | 191 | | 1.42 |

$A_c$ and $B_c$ are intercepts and slopes for the linear regression fit $T = A_c + B_cL$, where $T$ is reading time in msec/word, and $L$ is word length in characters. $V_{span} = 250/B_c$ is the visual span, in letters.

A repeated-measures analysis of variance (ANOVA) showed a significant main effect of word length ($P < 0.001$). The main effect of contrast just failed to reach significance at the 0.05 level ($P = 0.052$). We also found a significant interaction between contrast and word length ($P < 0.001$); the sets of lines in Fig. 1 tend to diverge for longer word lengths, indicating that contrast has a much greater effect on the reading time for long than for short words.

The regression lines in Fig. 1 show the relationship between reading time, $T$, and word length, $L$:

$$T = A_c + B_cL \tag{1}$$

where $A_c$ and $B_c$ are contrast-dependent intercept and slope parameters (Table 2).

According to the prolonged viewing hypothesis, the primary determinant of slower reading at low contrast is an increase in overall viewing time. In Eq. (1), this corresponds to growth in the intercept parameter $A_c$ with no change in $B_c$ (i.e., vertical shifts of the curves.) Subject SA's regression lines all have positive intercepts whose values grow substantially with decreasing contrast, consistent with prolonged viewing. RC also shows monotonic growth of the intercept with decreasing contrast, but the change is very small (from 118 to 183 msec/word). The other four subjects do not show consistent growth of the intercept with decreasing contrast and, in several cases, the intercept values are negative. As shown at the bottom of Table 2, mean

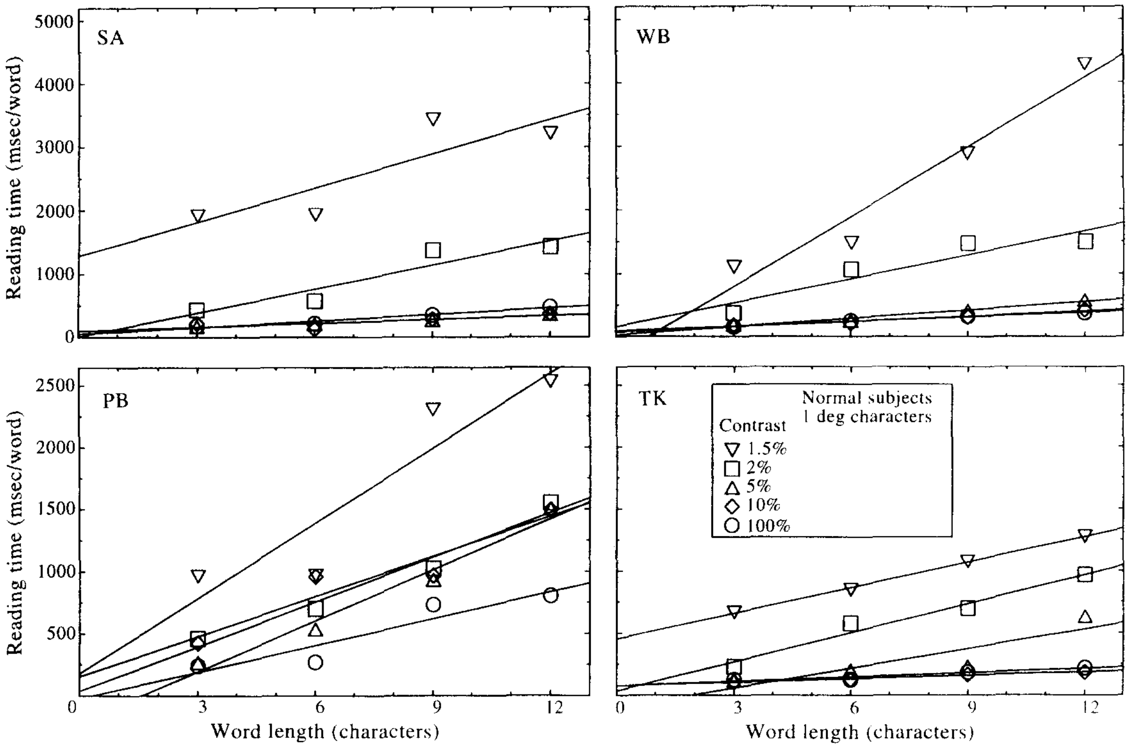

FIGURE 2. Reading time as a function of word length for 1-deg characters. Data are shown for four normal subjects and five contrast levels. Regression parameters are given in Table 3. Other details as in Fig. 1.

intercept values grow with decreasing contrast, but the effect is primarily due to SA's unusually high intercept values. Excluding SA, the mean intercept values are −9.8 msec/word (100% contrast), 72.9 msec/word (10% contrast), and −149.6 msec/word (5% contrast). SA's data leave open the possibility that prolonged viewing contributes to slow reading at low contrast, at least for some subjects.

The shrinking visual span hypothesis predicts the observed interaction between word length and contrast. If the visual span at high contrast is wide enough for 12 or more characters to be identified in parallel, curves of reading time vs word length should be flat; the slope $B_c$ in Eq. (1) should be zero (or very small). If the visual span is much narrower for low-contrast text, the reader must proceed in smaller steps, recognizing only a few letters at a time. If this is the case, the stronger dependence of reading time on word length will be manifest in an increase in the slope $B_c$. All six subjects in Fig. 1 have slopes consistent with this hypothesis, that is, monotonic growth of the slope with decreasing contrast (see Table 2).

We can estimate the size of the visual span as follows. The slopes of the regression lines in Fig. 1 have units of time per letter (i.e., time/word divided by the number of letters per word). The reciprocal slope is the number of letters identified per unit time. If we assume that the reading task consists of a series of glances (fixations) of approximately equal duration, the reciprocal slope can be used to estimate the number of letters identified per glance. The average fixation time in reading is about 250 msec (Rayner & McConkie, 1976).

We operationally define visual span to be the reciprocal of the slope from regression lines of reading time vs word length (as in Fig. 1) in units of letters/msec, multiplied by 250 msec. Correction of these estimates of the visual span are necessary when fixations differ substantially from 250 msec (see Experiment 3).

The visual span entries in Table 2 give values corresponding to the curves in Fig. 1. Mean values across the six subjects are also shown: 5.35 letters at 100% contrast, 3.86 letters at 10%, and 1.42 letters at 5%.

Figure 2 shows corresponding results for 1-deg characters. Data are shown for four subjects and five contrast levels ranging from 1.5 to 100%. There was little effect on reading time until contrast dropped to about 5%. This shows that RSVP reading is more tolerant to contrast reduction for 1-deg letters than for 6-deg letters, consistent with other types of reading (Legge *et al.*, 1987, 1990).

For the data in Fig. 2, a repeated-measures ANOVA showed significant main effects of both word length ($P < 0.01$) and contrast ($P < 0.001$), and a significant word length×contrast interaction ($P < 0.001$). This pattern of results is what is expected from a shrinking visual span.

Parameters of the regression lines and estimates of visual spans are given in Table 3. The mean visual span exceeds 10 characters at high contrast, but drops to 1.74 for the lowest contrast. We attach no importance to the higher value of the visual span at 10% (12.7) than at

TABLE 3. Regression parameters and visual spans for four normal subjects: 1-deg characters

| Subject | %Contrast | $A_c$ | $B_c$ | $r^2$ | $V_{span}$ |
|---|---|---|---|---|---|
| SA | 100 | 50.0 | 34.4 | 0.954 | 7.27 |
| | 10 | 97.5 | 20.3 | 0.597 | 12.3 |
| | 5 | 95.2 | 20.6 | 0.972 | 12.1 |
| | 2 | 7.50 | 126 | 0.878 | 1.98 |
| | 1.5 | 1287 | 178 | 0.732 | 1.40 |
| WB | 100 | 88.0 | 24.9 | 0.984 | 10.0 |
| | 10 | 69.5 | 28.0 | 0.948 | 8.93 |
| | 5 | 21.4 | 44.6 | 0.966 | 5.61 |
| | 2 | 154 | 126 | 0.865 | 1.98 |
| | 1.5 | −307 | 366 | 0.950 | 0.683 |
| PB | 100 | −22.6 | 71.3 | 0.871 | 3.51 |
| | 10 | 155 | 107 | 0.904 | 2.34 |
| | 5 | −215 | 136 | 0.973 | 1.84 |
| | 2 | 36.8 | 120 | 0.967 | 2.08 |
| | 1.5 | 179 | 202 | 0.854 | 1.24 |
| TK | 100 | 78.0 | 11.5 | 0.885 | 21.7 |
| | 10 | 77.1 | 9.20 | 0.977 | 27.2 |
| | 5 | −101 | 52.9 | 0.784 | 4.73 |
| | 2 | 35.8 | 77.7 | 0.970 | 3.22 |
| | 1.5 | 453 | 68.6 | 0.998 | 3.64 |
| Mean | 100 | 48.4 | 35.5 | | 10.6 |
| | 10 | 99.8 | 41.1 | | 12.7 |
| | 5 | −49.9 | 63.5 | | 6.07 |
| | 2 | 58.5 | 112 | | 2.32 |
| | 1.5 | 403 | 204 | | 1.74 |

$A_c$ and $B_c$ are intercepts and slopes for the linear regression fit $T = A_c + B_c L$, where $T$ is reading time in msec/word, and $L$ is word length in characters. $V_{span} = 250/B_c$ is the visual span, in letters.

100% (10.6). In fact, the mean slope values do not show this nonmonotonicity.

### *Discussion*

There is strong evidence at both character sizes for the shrinking visual span hypothesis. There is only weak evidence for the prolonged viewing hypothesis.

What determines the size of the visual span? According to O'Regan (1990, 1991), the number of adjacent letters recognizable in central vision is determined by three factors: the size of the critical features in the letters, the fall-off in the eye's spatial resolution away from the fixation point, and the geometry of the display surface. Using values of parameters suggested by O'Regan, his model predicts that the maximum size of the visual span is 15.6 letters,* occurring for a letter size near 1 deg. For letters subtending 6 deg, the model's visual span drops to 10.4 letters. Our empirical estimates of visual span for high-contrast 1-deg and 6-deg letters were 10.6 and 5.3 letters, lower than O'Regan's theoretical values. A better match to our empirical values could probably be found by a different choice of parameters. Despite the numerical discrepancy, O'Regan's analysis provides a plausible approach to explaining the size of the visual span and its dependence on character size.

O'Regan *et al.* (1983) measured the recognition of letters (flanked by numerals) as a function of retinal eccentricity. They defined visual span in terms of the eccentricity within which letters could be recognized above some criterion level. When the criterion was 50% correct, the maximum visual span was 22 letters, but when the criterion was 90% correct, the visual span was 10 letters.

Rayner & Bertera (1979) used an eye-tracking method to mask letters (each subtending about 0.33 deg) surrounding the point of fixation during reading. When the mask covered the central seven letters, reading speed was very low, about 12 words/min. When the mask covered 11 letters, reading was essentially impossible. These results imply that readers have a visual span of 7–11 letters.

The empirical estimates of the present paper, and those just cited, point to a visual span in reading of about ten letters for normal text (~0.3–1.0 deg), and somewhat smaller for magnified text (6 deg).

Two caveats should be kept in mind while evaluating our interpretation. First, we might expect the shrinking visual span to yield curves in Figs. 1 and 2 that are stair steps, rather than straight lines, with the distance between steps being related to the size of the visual span. For instance, if the visual span were 6 characters wide, we would expect the reading time $T$ to be constant (flat curve) for word lengths up to six letters, constant at $2T$ for word lengths from 7 to 12 letters, etc. Our finding of straight lines rather than stair steps may indicate that we did not sample word length finely enough, or that there is some degree of serial processing within each glance. Even if the visual span does encompass six letters, the recognition time for three-letter words may be a little shorter than six-letter words. This would be the case if letters near the point of fixation are recognized faster than slightly more peripheral letters, or if statistical variability in letter-recognition times makes it faster, on average, to recognize three letters than six letters. There is evidence that word-recognition times depend on word length, even when word frequency is taken into account (McGinnies *et al.*, 1952).

Second, rather than considering "prolonged viewing" and "shrinking visual span" as unrelated alternatives, it is possible that one causes the other. Kowler & Anton (1987) showed that the duration of fixations between saccades in reading tends to increase for short saccades (less than about 1 deg). They attributed the increased time, at least in part, to requirements of oculomotor programming of saccades. It is possible that a shrinking visual span would necessitate short saccades. If the angular size of these short saccades fell below about 1 deg, prolonged viewing might result.

## EXPERIMENT 2: COMPARING READING SPEEDS FOR RSVP AND STATIC TEXT

Previous studies with drifting text and static text have shown that reading speed is fairly constant for contrasts above about 10% (Legge *et al.*, 1987, 1990). Rubin &

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*O'Regan's equations express the size of the visual span as the number of letters rightward from fixation. This is a half-width measure. We express visual span as a full width, doubling the numerical values generated by O'Regan's equations.

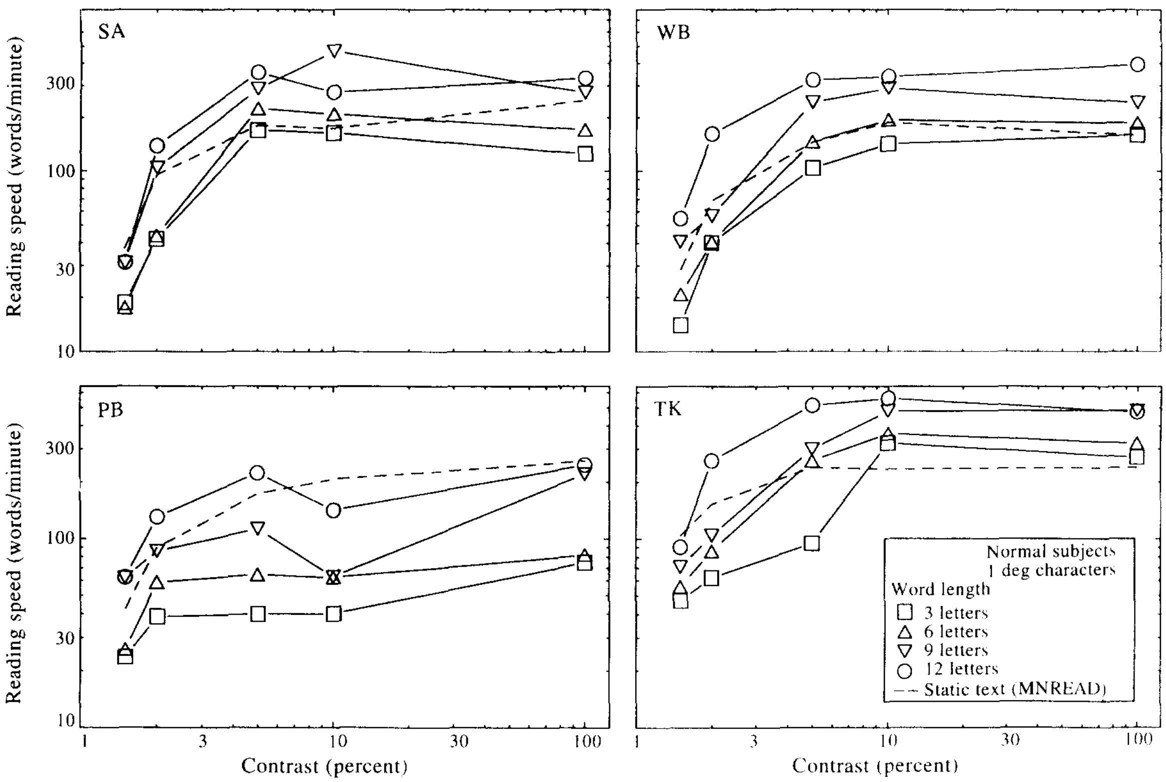

FIGURE 3. Reading speed as a function of text contrast for 1-deg characters. Each panel shows data for one normal subject—dashed curve for static text (MNREAD test) and data symbols for RSVP text of four word lengths.

Turano (1992) have speculated that a ceiling on speed is imposed by the need for eye movements, and accounts for this contrast invariance of reading speed. If so, reading speed should be more dependent on contrast for RSVP, where there is a reduced need for eye movements.

Legge *et al.* (1987) offered a different explanation; the weak dependence of reading speed on text contrast might be due to the compressive coding of contrast in the visual cortex. If so, reading speeds for RSVP and static text should show the same contrast dependence. We examined these alternatives by comparing reading speeds from RSVP (data from Experiment 1) and static text.

### *Methods*

Four normally sighted subjects participated (Table 1). Reading speed for static text was measured with the MNREAD computer test, described by Legge *et al.* (1989). We used a variant of the test in which the text was composed of unrelated words, for closest comparison with our RSVP measurements.

A brief description of the MNREAD procedure follows. In a trial, 11 unrelated words of different lengths were selected randomly from a pool of 302 words. The 11 words were formatted as four lines of 13 character spaces. They were rendered as black letters on a white background and displayed with the same font and monitor as the RSVP text in Experiment 1. The subject was asked to read the text aloud as rapidly as possible. In a series of trials, the exposure time was reduced until the subject could no longer read all 11 words without error. Three trials were conducted at this exposure time. For each trial, reading speed was computed as the number of words read correctly divided by the exposure time.

### *Results and discussion*

Each panel of Fig. 3 shows reading speed vs contrast for one normal subject—dashed curve for static text, and data symbols for RSVP text at four word lengths. The character size was 1 deg.

Despite some individual differences, the static and RSVP curves are qualitatively similar: flat at high contrast, with a steep descent at low contrast. This finding is consistent with an explanation for the high-contrast behavior in terms of compressive coding of contrast, and is inconsistent with a ceiling on speed imposed by eye movements.

We also observed that the contrast dependence of the RSVP curves did not vary with word length. The proportional decline in reading speed from highest to lowest contrast was about the same for 3-, 6-, 9-, and 12-letter words.

Other researchers have reported very high speeds for RSVP text compared with static text. For example, Rubin & Turano (1992) reported an average reading speed of 1171 words/min for RSVP text (for characters eight times larger than acuity characters) and 303 words/min for static text. We obtained lower reading speeds, and a smaller difference between RSVP and static text. The mean speed for static text at 100% contrast was 226 words/min. The mean speeds for the 3-, 6-, 9-, and 12-

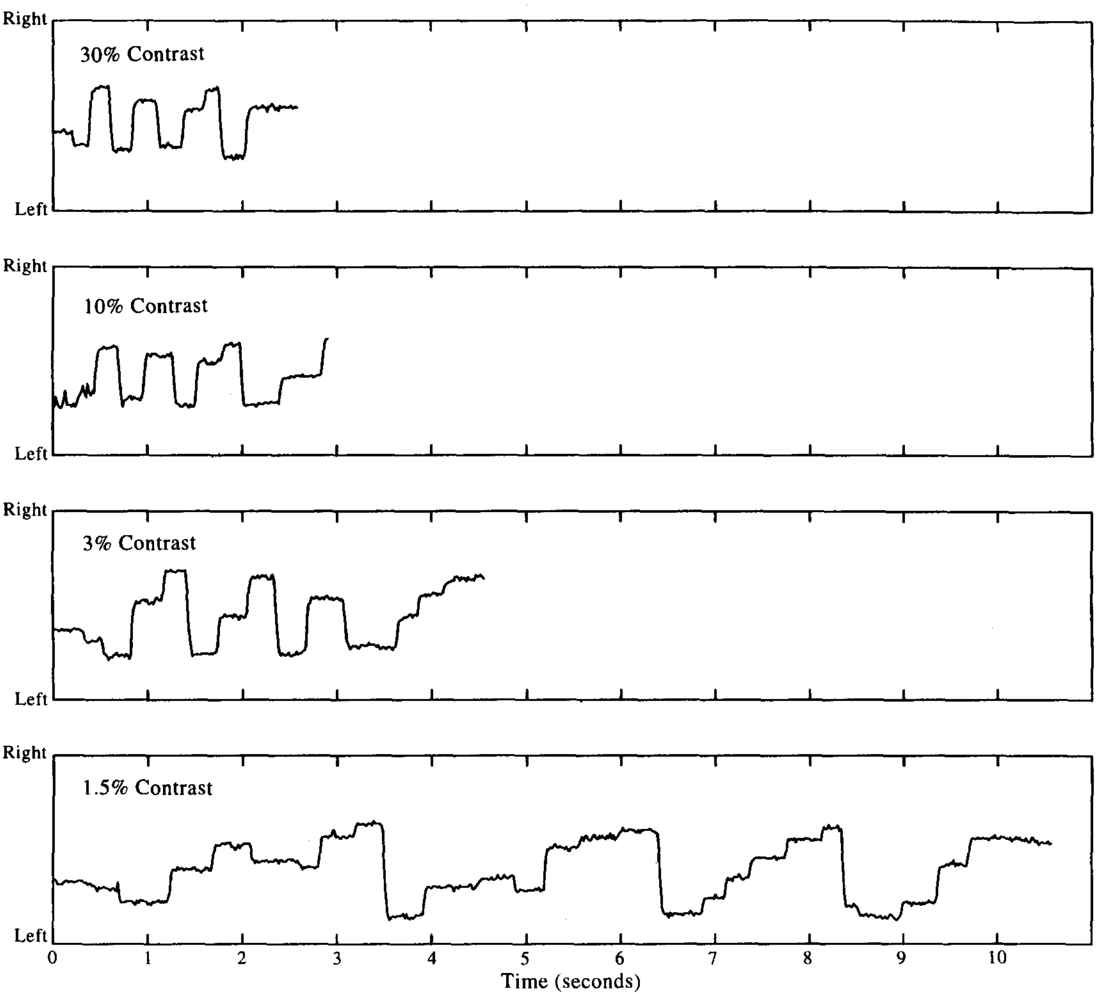

FIGURE 4. Sample eye-movement traces for one subject. Each panel shows horizontal eye position (corresponding to left-to-right position in the text) as a function of time while the subject read one sentence. The four peaks correspond to the four short lines of text in the MNREAD sentence. The four panels show results for text contrasts of 30, 10, 3 and 1.5%.

letter RSVP conditions were 403, 324, 234 and 173 words/min.

A possible reason for the discrepancy between our speeds and those of Rubin & Turano (1992) is that our text was composed of unrelated words rather than sentences. The predictability of the words in sentences may yield an increased reading speed. This possibility was supported by unpublished results of G.S. Rubin (personal communication, 1991). He measured reading speeds for a normal subject with the following results: static-text sentences = 250 words/min, RSVP sentences = 1000 words/min, static-text unrelated words = 190 words/min, and RSVP unrelated words = 380 words/min. Rubin's speeds for static and RSVP unrelated words were very close to ours, and substantially lower than speeds obtained with sentences. We conclude that our use of unrelated words accounts for the lower RSVP speeds we obtained.

Finally, we also compared static-text and RSVP speeds for 6-deg characters (data not shown). Like the 1-deg data, there was no systematic difference in the contrast dependence.

## EXPERIMENT 3: EYE-MOVEMENT MEASUREMENTS AS A FUNCTION OF TEXT CONTRAST

Legge *et al.* (1997) have analyzed the linkage between the size of the visual span and mean saccade size in the context of an ideal-observer model of reading. Their analysis indicates that a reduction in the size of the visual span should result in shorter, more numerous saccades. It follows that if the visual span is smaller for low-contrast text, there should be more saccades in reading. We tested this prediction by measuring eye movements.

Our estimates of visual span (Tables 2 and 3) assumed constant mean fixation times at different contrast levels. The weak evidence we found for prolonged viewing at the lowest contrasts raises the possibility of increased fixation times. We also addressed this issue with direct eye-movement measurements.

### *Method*

Five normally sighted subjects participated (Table 1). Viewing was monocular (right eye) with the other eye occluded. The head was stabilized with a bite bar. Eye movements were measured with an ISCAN RK-416 video eye tracker. This device specifies eye position by locating the center of the pupil in video images captured at a 60 Hz rate.

In a pre-trial calibration procedure, subjects fixated on nine dots in a 3-by-3 grid covering the area of the text. A post-trial calibration followed each three to five reading trials. The accuracy of the eye tracker was sufficient to identify saccades of less than one letter.

The stimuli were MNREAD sentences (Legge *et al.*, 1989) with 1.63-deg characters. As in Experiment 1, contrast was reduced by increasing the luminance of the letters toward the constant luminance of the background (100 cd/m$^2$). The subject was instructed to read the sentence silently, but quickly and carefully. The subject pressed a button after finishing a sentence. Each subject read 9–15 sentences at each contrast in blocks of between three and five sentences. Four of the subjects were tested at six contrast levels—90, 60, 30, 10, 3 and 1.5%. CM was tested only at 30, 10, 3 and 1.5%. In order to include CM's data in the averaged data, normalization (see below) was based on performance at 30% contrast.

Apart from the use of an eye tracker and a bite bar, there were two noteworthy differences between the reading tasks in Experiments 2 and 3. Subjects read aloud in Experiment 2 and the text was composed of unrelated words. In Experiment 3, subjects read silently and the text consisted of sentences. Previous research has shown that reading speed is highly correlated for silent and "out-loud" reading, and for sentences and unrelated words (Legge *et al.*, 1989).

For data analysis, the frame-by-frame $X$ and $Y$ coordinates of the center of the pupil were plotted as "strip charts" on the computer screen. We scored these strip charts by hand. We could identify forward and regressive saccades, and distinguish them from long return sweeps at the end of each line of text. Return sweeps were not included in the saccade counts.

### *Results and discussion*

Sample data are shown for one subject in Fig. 4. Each of the four panels shows the eye-movement trace associated with one MNREAD sentence at one contrast level. The horizontal axis is time in seconds. The vertical scale is left-to-right distance across the text. Each trace has four prominent peaks corresponding to the four short lines of text in the MNREAD sentence. The horizontal extent of the traces increases, representing more time, from the 30%-contrast panel at the top to the 1.5%-contrast panel at the bottom. It is clear that there are more saccades in the lower-contrast panels (i.e., more stair steps to reach the peaks). An increasing number of saccades at low contrast is consistent with a shrinking visual span.

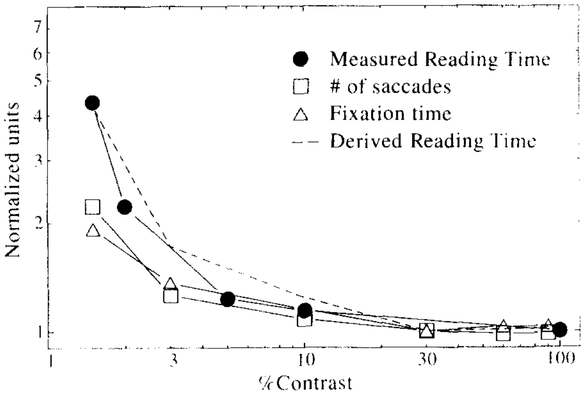

FIGURE 5. Comparison of verbal reading performance and eye-movement measures at several text contrasts. All measures have been normalized to have a value of 1.0 at 30% contrast. The Measured Reading Times are based on the verbal reading speeds, from the MNREAD test, reported in Experiment 2 (Fig. 3). Data points for the number of saccades and fixation times are averaged, normalized values from five subjects, obtained in Experiment 3. The dashed curve, labeled Derived Reading Time, shows the product of the number of saccades and fixation times.

Using eye-movement data like these, we asked how the longer reading times at low contrast are partitioned between an increase in the number of saccades and growth in fixation time per saccade. For each subject, we computed the mean number of saccades per sentence (including both forward and regressive saccades) at each contrast level. We normalized via each subject's mean number of saccades at 30% contrast (see Method), and averaged these normalized values across subjects. Similarly, we computed the average normalized fixation times. For comparison with verbal reading, we converted the MNREAD reading speeds from Experiment 2 to reading times (reciprocal of reading speed), normalized by the value at 100% contrast*, and averaged across the four subjects.

Figure 5 compares the normalized verbal measures and eye-movement measures of reading performance. The curve for the verbal data, labeled Measured Reading Time, is almost flat from 10 to 100% contrast, but rises sharply at low contrasts. At the lowest contrast (1.5%), the time to read the sentence has increased more than four-fold.

The open squares show the average number of saccades, also normalized. The number of saccades also grows at low contrast, but not as rapidly as the measured reading time. Normalized fixation times are shown by the open triangles. They show a similar pattern of growth with contrast. Finally, the dashed line, labeled Derived Reading Time, is the product of the number of saccades and average fixation time, a simple model for overall reading time. Given that the Derived Reading Times were based on one set of data in which we measured eye movements (Experiment 3) and the Measured Reading Times were based on a set of verbal reading speed trials (Experiment 2), the match is surprisingly good. It is clear that the reduction in reading speed at low contrast is

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*For consistency with the eye-movement data, it would have been preferable to normalize reading speed by the value at 30% contrast. Unfortunately, we did not measure reading speed at this contrast level in Experiment 2.

TABLE 4. Subjects with low vision

| Subject | Gender | Age | logMAR acuity | Cloudy media | Central loss | Clinical diagnosis | $A_c$ | $B_c$ | $r^2$ | $V_{span}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| A | F | 44 | 1.00 | Y | N | Congenital cataract | −206 | 208 | 0.997 | 1.20 |
| B | F | 32 | 1.20 | Y | Y | Cataract and degenerative myopia | 581 | 22.7 | 0.577 | 11.0 |
| C | M | 36 | 1.00 | Y | N | Congenital cataract | −377 | 223 | 0.916 | 1.12 |
| D | F | 64 | 1.20 | N | Y | Myopic retinal degeneration | −187 | 232 | 0.998 | 1.08 |
| E | M | 41 | 0.70 | Y | N | Cataract and RP | 2668 | 261 | 0.866 | 0.958 |
| F | F | 59 | 1.18 | Y | Y | Myopic retinal degeneration | 720 | 232 | 0.828 | 1.08 |
| G | F | 61 | 1.30 | Y | N | Congenital cataract and glaucoma | −2126 | 2176 | 0.945 | 0.115 |

$A_c$ and $B_c$ are intercepts and slopes for the linear regression fit $T = A_c + B_c L$, where $T$ is reading time in msec/word, and $L$ is word length in characters. $V_{span} = 250/B_c$ is the visual span, in letters.

caused by both an increase in the number of saccades and an increase in fixation times.

The increased number of saccades is what we would expect to accompany a shrinking visual span. The growth in fixation time is indicative of prolonged viewing at low contrast. The longer fixation times also indicate that a correction is in order for the visual span estimates from Experiment 1. We assumed constant fixation times of 250 msec. Our eye-movement records show that mean fixation time for the five subjects was 220 msec at 90% contrast, remaining nearly constant down to 30% contrast. Mean fixation time rose for lower contrasts, reaching 406 msec at 1.5% contrast. When we use these figures instead of 250 msec to compute the mean visual span values for the highest and lowest contrasts in Table 3, we obtain the following modified values: at 100% contrast, the visual span drops from 10.6 letters to 9.33 letters, and at 1.5% contrast, the visual span rises from 1.74 to 2.83 letters.

The eye-movement recordings provide evidence that slow reading at low contrast results from both shrinkage of the visual span and prolonged viewing.

## EXPERIMENT 4: EFFECTS OF WORD LENGTH IN LOW VISION

Slow reading in low vision can sometimes be explained as a loss of effective stimulus contrast (Rubin & Legge, 1989). This suggests a link between slow reading in low vision and a reduced visual span, analogous to the reduced visual span in normal vision at low contrast. We asked whether low-vision subjects would show a strong dependence of RSVP reading time on word length, indicative of a reduced visual span.

### *Method*

*Subjects.* We studied seven low-vision subjects with a mean age of 48 years. They were referred to us from the Minneapolis Society for the Blind or were selected from our lab's roster of subjects. Cloudy media was the primary selection criterion because we wanted to evaluate the putative link between visual span and loss of retinal-image contrast. All low-vision subjects were native English speakers with reading fluency and had no known cognitive deficits. Characteristics of the low-vision subjects are listed in Table 4.

Acuities in Table 4 were measured with the Lighthouse Distance Visual Acuity chart (2nd edition) and pertain to the higher acuity eye. Diagnosis, central visual field, and ocular media designations were obtained from each subject's ophthalmologist or optometrist. A binary classification was used to describe the status of central fields (loss or intact) and media (cloudy or clear). The visual field was designated as having "Loss" if an absolute scotoma covered all or part of the central 5 deg (diameter) and as "Intact" otherwise. Ocular media were designated as "Cloudy" if corneal scarring, cataracts, vitreous debris or other obstructions occurred within the ocular media and designated as "Clear" in the absence of such obstructions.

*Procedure.* We used the same apparatus and RSVP procedure described in Experiment 1. The low-vision subjects were tested only with 100%-contrast 6-deg characters.

### *Results and discussion*

Figure 6 shows data for seven low-vision subjects, one per panel. Notice that three different vertical scales are used to accommodate the wide range of reading times. The solid line in each panel is a regression line for the low-vision subject. The dashed lines are average regression lines for six normal subjects, at three values of text contrast (5, 10 and 100%). Parameters of the regression lines and the derived values of visual span are listed in Table 4.

Most of the low-vision subjects have steeper slopes than the normal 100%-contrast slope, indicative of a reduced visual span. Some of them also have vertically shifted curves, indicative of prolonged viewing.

The regression lines of subjects A, C, and D fall within the cluster of lines obtained in Experiment 1 for normally sighted subjects. Their data are consistent with a shrunken visual span.

Subject G has an extremely steep slope, and correspondingly tiny visual span of about 0.12 letters. This subject is a 61-year-old woman with congenital cataract and advanced glaucoma. She has a small island of residual central vision. Her data reveal the extreme difficulty she encountered in piecing together long words.

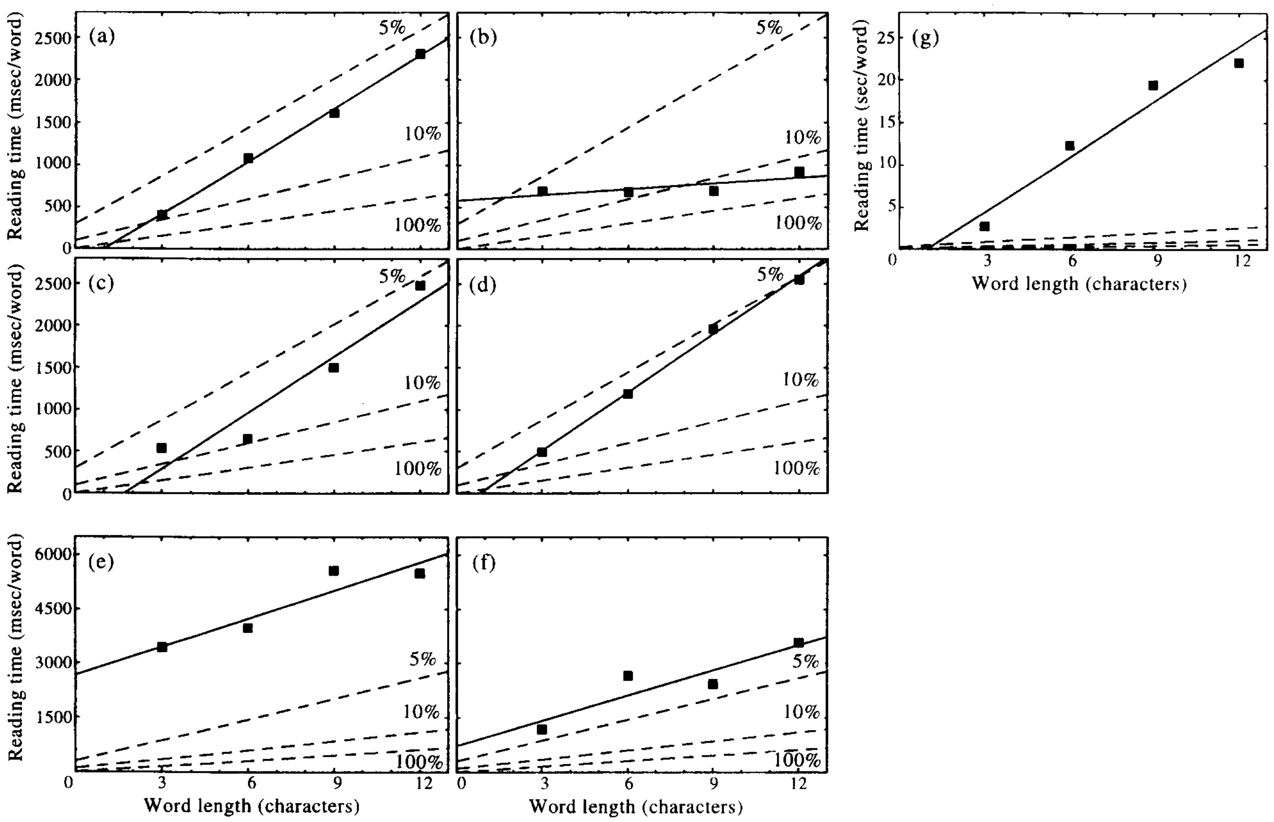

FIGURE 6. Reading time as a function of word length for seven low-vision subjects. Three different vertical scales are used to accommodate the wide range of reading times. The character size was 6 deg. The data points and solid regression line in each panel show performance of one low-vision subject for high-contrast text. The regression parameters are given in Table 4. The dashed lines are average regression lines at three contrast levels for normal subjects at 6 deg, based on data from Experiment 1.

In her case, part of the difficulty may have stemmed from losing her place between fixations.

Subjects A and C have congenital cataracts. Although their fields are clinically intact, their visual spans are small, close to one letter. Presumably, diminished retinal-image contrast has resulted in a reduced visual span. Although a person's clinical field may be intact, low contrast sensitivity may restrict the functional field severely.

Subject B's regression line is quite flat and has a correspondingly high visual span. The line, however, has a vertical shift, compared with the normal 100%-contrast line. This pattern is consistent with slower reading due to the need for prolonged viewing.

Finally, subject E's line has a very large vertical shift (prolonged viewing) and a somewhat elevated slope (shrunken visual span) This pattern is consistent with slow reading resulting from both causes.

The effects of reduced visual span may extend to other forms of low vision. Bullimore & Bailey (1995) measured eye movements in reading for a group of patients with age-related macular degeneration. They attributed most of the reduction in reading speed to shortened saccades from which they inferred a reduced visual span.

RSVP may have practical benefits for low-vision reading. Rubin & Turano (1994) compared low-vision reading performance for static and RSVP text. They found that RSVP speeds were 1.5 times faster for patients with central scotomas, and 2.1 times faster for low-vision patients without central scotomas. However, Fine & Peli (1995) found no reading speed advantage in low vision for RSVP over drifting text.

Normally, RSVP text is presented with equal exposure time for each word. When recognition times are strongly dependent on word length, there may be an advantage in increasing the exposure time for longer words. In a limited test of this notion with four normally sighted subjects (reading low-contrast text) and one low-vision subject (reading high-contrast text), we found no significant increase in reading speed when RSVP exposure time was proportional to word length. It is unlikely that modifying RSVP in this manner would be of practical benefit in a low-vision aid.

The principal finding of Experiment 4 is that some low-vision subjects show a pattern of results consistent with a reduced visual span. This reduced span can help to account for their reading speed deficits.

Our low-vision results differ in an interesting way from findings with reading-disabled (dyslexic) readers. Whereas reduced contrast results in poorer performance for low vision, Williams *et al.* (1995) have reported that contrast reduction improves performance in a search task by reading-disabled subjects. Their explanation for this effect is that low contrast restores the proper temporal sequence of signals in a deficient transient (magnocellular) pathway and signals in a normal sustained (parvocellular) pathway.

We have a different, speculative interpretation of the Williams *et al.* (1995) result. In a series of studies, Geiger and colleagues (cf., Geiger *et al.*, 1994) have provided evidence that dyslexics have an abnormally wide visual span and abnormal spatial interactions within the enlarged span (but see also Klein *et al.*, 1990, for countering evidence). Geiger *et al.* (1994) artificially restricted the visual span of dyslexic subjects by having them read text through a narrow slit. They reported that this training regimen was successful in improving reading performance of dyslexic readers. By our account, contrast reduction results in a smaller visual span in reading. It is possible, therefore, that reduction of text contrast, as per Williams *et al.* (1995), reduces the visual span for dyslexic readers, but the reduction improves reading performance.

## SUMMARY AND CONCLUSIONS

In Experiment 1, we found evidence for interacting effects of text contrast and word length in an RSVP reading task. These results are consistent with a shrinking visual span hypothesis, according to which the number of letters recognizable at a glance shrinks at low contrast. From the data, we estimated the size of the visual span at high contrast to be about ten letters for 1-deg characters, and about five letters for 6-deg characters. At very low contrast, the visual spans shrink to less than two characters.

Experiment 1 provided weak support for a prolonged viewing hypothesis, according to which more time is required to recognize letters within each glance at low contrast.

In Experiment 2, we showed that reading speed has the same qualitative dependence on contrast for RSVP and static-text presentation. This makes it unlikely that the contrast independence of normal reading speed is due to a ceiling imposed by eye movements.

In Experiment 3, we measured eye movements. We observed an increased number of saccades at low contrast, supportive of the shrinking visual span hypothesis. However, we also observed growth in fixation times, supportive of the prolonged viewing hypothesis. The increased reading time at low contrast is partitioned about equally between an increase in the number of saccades and an increase in fixation times.

In Experiment 4, we found that low-vision subjects with cloudy ocular media show a strong dependence of reading time on word length. We interpreted the findings as indicating that these subjects read with a reduced visual span.

The results help us understand why reading slows down when text contrast is very low (normal vision), or when effective text contrast is low (low vision). The visual span shrinks. The reader recognizes fewer characters at a glance, and is compelled to advance in smaller steps through the text. Our findings also indicate that the glances between these steps increase in duration, further reducing reading speed.

## REFERENCES

Bullimore, M. A. & Bailey, I. (1995). Reading and eye movements in age-related maculopathy. *Optometry and Vision Science, 72*, 125–138.

Carroll, J. B., Davies, P. & Richman, B. (1971). *Word frequency book.* New York: American Heritage.

Farah, M. J. & Wallace, M. A. (1991). Pure alexia as a visual impairment: a reconsideration. *Cognitive Neuropsychology, 8*, 313–334.

Fine, E. & Peli, E. (1995). Scrolled and rapid serial visual presentation texts are read at similar rates by the visually impaired. *Journal of the Optical Society of America A, 12*, 2286–2292.

Geiger, G., Lettvin, J. & Fahle, M. (1994). Dyslexic children learn a new visual strategy for reading: a controlled experiment. *Vision Research, 34*, 1223–1233.

Klein, R., Berry, G., Briand, K., d'Entremont, B. & Farmer, M. (1990). Letter identification declines with increasing retinal eccentricity at the same rate for normal and dyslexic readers. *Perception and Psychophysics, 47*, 601–606.

Kowler, E. & Anton, S. (1987). Reading twisted text: implications for the role of saccades. *Vision Research, 27*, 45–60.

Legge, G. E., Klitz, T. S., and Tjan, B. S. (1997). Mr. Chips: an ideal-observer model of reading. *Psychological Review*, in press.

Legge, G. E., Parish, D. H., Luebker, A. & Wurm, L. H. (1990). Psychophysics of reading–XI. Comparing color contrast and luminance contrast. *Journal of the Optical Society of America A, 7*, 2002–2010.

Legge, G. E., Ross, J. A., Isenberg, L. M. & LaMay, J. M. (1992). Psychophysics of reading–XII. Clinical predictors of low-vision reading speed. *Investigative Ophthalmology and Visual Science, 33*, 677–687.

Legge, G. E., Ross, J., Luebker, A. & LaMay, J. M. (1989). Psychophysics of reading—VIII. The Minnesota low-vision reading test. *Optometry and Vision Science, 66*, 843–853.

Legge, G. E., Rubin, G. S. & Luebker, A. (1987). Psychophysics of reading—V. The role of contrast in normal vision. *Vision Research, 27*, 1165–1177.

McConkie, G. W. & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception and Psychophysics, 17*, 578–586.

McGinnies, E., Comer, P. B. & Lacey, O. L. (1952). Visual recognition thresholds as a function of word length and word frequency. *Journal of Experimental Psychology, 44*, 65–69.

O'Regan, J. K. (1990). Eye movements and reading. In Kowler, E. (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395–453). New York: Elsevier.

O'Regan, J. K. (1991). Understanding visual search and reading using the concept of stimulus "grain". *IPO Annual Progress Report, 26*, 96–108.

O'Regan, J. K., Levy-Schoen, A. & Jacobs, A. M. (1983). The effect of visibility on eye-movement parameters in reading. *Perception and Psychophysics, 34*, 457–464.

Rayner, K. & Bertera, J. H. (1979). Reading without a fovea. *Science, 206*, 468–469.

Rayner, K. & McConkie, G. (1976). What guides a reader's eye movements? *Vision Research, 16*, 829–837.

Rayner, K. & Pollatsek, A. (1989). *The psychology of reading.* Englewood Cliffs, NJ: Prentice-Hall.

Rubin, G. S. & Legge, G. E. (1989). Psychophysics of reading—VI. The role of contrast in low vision. *Vision Research, 29*, 79–91.

Rubin, G. S. & Turano, K. (1992). Reading without saccadic eye movements. *Vision Research, 32*, 895–902.

Rubin, G. S. & Turano, K. (1994). Low-vision reading with sequential word presentation. *Vision Research, 34*, 1723–1733.

Williams, M., May, J., Soman, R. & Zhou, H. (1995). The effects of spatial filtering and contrast reduction on visual search times in good and poor readers. *Vision Research, 35*, 285–291.

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