PSYCHOPHYSICS OF READING: IX. THE STABILITY OF EYE POSITION IN NORMAL AND LOW VISION

DAVID H. PARISH and GORDON E. LEGGE

Note: This paper was written in 1989, but never published in a journal. The version presented in this book is the first publication of this paper. Viewed from the perspective of the year 2002, it is noteworthy that several key inferences about the properties of the visual span in reading have been borne out in subsequent papers in the series. The forward references to these papers in the text below were, of course, not present in the original 1989 manuscript.

Abstract-Slow reading rates are characteristic of people with low vision, particularly those with central-field loss. Fixational inaccuracy may play a role in limiting reading speed. We used a psychophysical method to infer the accuracy of eye placement during reading by people with normal and low vision. Reading speed was measured by timing subjects as they read standardized sentences displayed on a video screen. By measuring reading speed in the presence of controlled amounts of isotropic stimulus jitter (i.e., Gaussian-random horizontal and vertical rigid displacements of the text every video frame), we inferred the tolerance of reading to erratic changes in stimulus position. Using an "equivalent noise" analysis, we estimated the *internal jitter*, representing stochastic variation of eye placement during reading. Reading rates of subjects with normal vision were little affected by substantial amounts of stimulus jitter, implying a considerable amount of imprecision in the placement of eyes during reading. We estimate a position error equivalent to the area of about 5 characters, independent of angular character size, for readers with normal vision. Subjects with low vision showed a more rapid decline in reading rate as stimulus jitter increased. Surprisingly, the low-vision data indicate greater precision in eye placement during reading. For these subjects we estimate a position error of about 2 characters. When normal subjects were tested with low-contrast text, the precision of eye placement increased significantly. These findings indicate a requirement for greater accuracy in eye placement when reading in reduced visual conditions. We interpret our results in the context of models that attribute slow reading in low vision to prolonged fixations or shortened saccades: We infer from our results that shorter, more precise saccades are characteristic of low-vision reading and account for reduced reading rates.

INTRODUCTION

The single most important factor limiting reading speed in low vision is the presence or absence of central vision (Legge *et al.*, 1985b). People with central scotomas usually read more slowly than people with other forms of low vision. As many as 75% of the patients that receive treatment from low-vision clinics have diseases that affect the central field (Faye, 1976). Understanding why these people read slowly is important if we are to develop useful reading aids or methods for training peripheral vision to compensate for central loss.

People with central loss must use peripheral vision. Their reading difficulties cannot be attributed solely to the lower resolution of the periphery because magnification (increased character size) does not result in normal reading speed (Legge *et al.*, 1985b). Several explanations might account for their reading difficulties, including: a) concomitant pathology in peripheral vision; b) physiological properties of normal peripheral vision, such as reduced contrast sensitivity or photoreceptor under-sampling; c) attentional deficits; and d) problems with eye-movement control. The present paper focuses on the role of eye movements in reading, particularly fixation stability.

Central and Peripheral Fixation Stability. The term fixation stability refers to the degree to which the line of sight wanders while a person tries to fixate. Fixation stability is usually characterized by a bivariate normal distribution of eye positions centered on the line of sight to the target. The area containing the line of sight 68% of the time, A(68), is often used as an index of fixation stability (Nachmias, 1959; Steinman *et al.,* 1973). Because the vertical and horizontal standard deviations of eye position are usually unequal, A(68) is contained within an ellipse centered on the target. Typical values of A(68) for people with normal vision range between 40 to 70 square minutes of arc for small circular fixation targets (Rattle, 1968).

People with central scotomas often develop peripheral fixation (Whittaker & Cummings, 1985; White & Bedell, 1985; Timberlake *et al*., 1986). Well-adapted central-loss-subjects consistently use a single, preferred location, outside the scotoma, as a pseudofovea for reading. But how stable is peripheral fixation?

Whittaker et al. (1988) asked subjects to fixate a single letter at twice the acuity limit. They found that fixation stability decreased with eccentricity for normal eyes with simulated central scotomas and for eyes with naturally occurring central scotomas. They suggested that for scotomas of 20º diameter or less, the accuracy of peripheral fixation was sufficient for identifying letters at the corresponding peripheral acuity limit. Timberlake *et al*. (1986) used a scanning laser ophthalmoscope to map the retinal locations of scotomas and to measure the size of the areas used to fixate. For three patients with dense macular scotomas, fixational areas were approximately nine times as large as those for normal foveal fixation. We do not know, however, whether the decrease in fixation stability for isolated targets is associated with reduced reading speed.

Determinants of Reading Speed. The pattern of eye movements in normal reading consists of fixational pauses separated by saccades. Reading time is determined principally by fixation duration and saccade length, and, to a lesser extent, by saccade duration (which is small compared with fixation duration), occasional regressive saccades, and return sweeps from the end of one line to the beginning of the next. Ignoring the lesser factors, reading rate R in words/min, is related to fixation duration D in minutes, and saccade length L in words by:

$$R = L/D \qquad (1).$$

It will prove convenient to define reading time T in minutes/word as the reciprocal of reading rate R:

$$T = 1/R = D/L \qquad (2).$$

If we assume that the pattern of eye movements in reading has the same qualitative form in low vision[1], reduced reading speed can be attributed to either prolonged fixation duration D, reduced saccade length L or a combination of the two.

Prolonged Fixation Duration. If fixation stability decreases due to peripheral viewing or other reasons, fixational pauses in reading may be prolonged because the target's image spends a smaller proportion of its time centered on the pseudofovea. The simplest assumption is that fixation duration D is proportional to fixation area A:

$$D = kA \qquad (3).$$

where k is a constant of proportionality.

One way of evaluating this proposal is to examine the effects of stimulus instability (jitter) on reading speed. We can create stimulus jitter by randomly displacing text on a TV screen on each video frame according to a bivariate normal distribution. When this is done, the text appears to jitter and jump around like reading in a car traveling on a bumpy road. If the stimulus instability is small compared to eye jitter, we expect relatively little effect on reading performance -- a highly unstable eye should be relatively tolerant to stimulus instability. On the other hand, if the stimulus jitter is large compared with eye jitter, fixational pauses may be prolonged and reading speed should decrease. Assuming statistical independence of eye jitter and text jitter, the corresponding bivariate areas add and any given stimulus feature falls within a larger bivariate normal area on the retina. Designating the bivariate area associated with eye (internal) jitter A_i and the bivariate area of stimulus jitter A, the overall bivariate area of fixation is equal to $A + A_i$. Substituting in Equation 3 and combining with Equation 2, reading time T is given by

$$T = k(A + A_i)/L \qquad (4).$$

By plotting reading time T as a function of stimulus jitter area, we can infer A_i from the x-axis intercept. This is shown schematically in Figure 1A.

Three empirical predictions follow from this formulation: 1) There should be a linear relationship between reading time and the bivariate area of the stimulus jitter; 2) For people with low vision the x-axis intercept should be displaced to the left, reflecting increased fixational instability, but the slope should remain normal; 3) Assuming that fixational stability is determined by hardwired properties of oculomotor control, we expect A_i to be independent of character size. If A_i is of fixed angular size, it should play a greater role in limiting reading rate for characters of small angular size.

Shortened Saccades. Slower reading in low vision might be due to shortened saccades rather than prolonged fixations. This is plausible because average saccade length in normal reading decreases when text is degraded (cf. Kowler and Anton, 1987; O'Regan *et al*., 1983).

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[1] In cases of nystagmus, the foregoing assumption is implausible. There may also be cases in which D and L are normal but in which one or more of the minor determinants of reading speed play an exaggerated role.

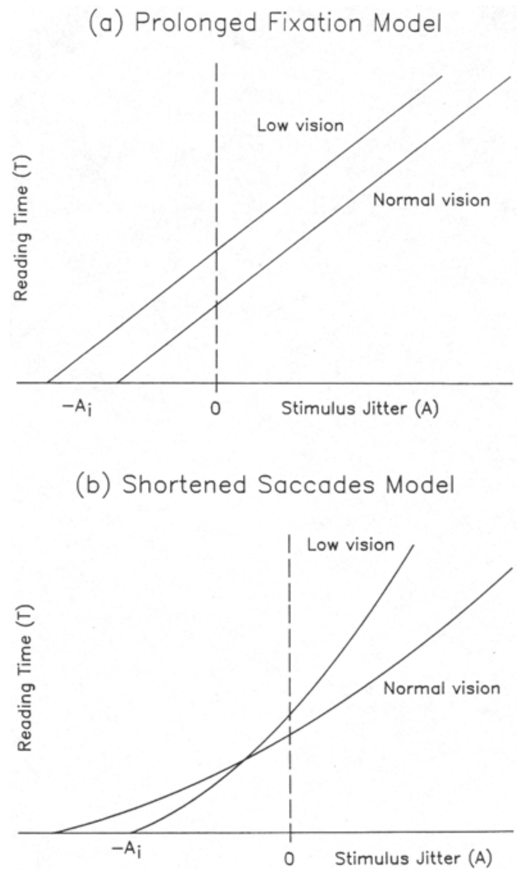

Fig. 1 -- Schematic plot of reading time as a function of stimulus jitter for the prolonged-fixation model (a) and the shortened-saccade model (b). Internal jitter (Ai) is defined as the negative of the X-axis intercept, found by extrapolating the line to the left of the vertical axis.

Average saccade length in reading is undoubtedly tied to the size of the “visual span” i.e. the number of letter spaces left or right of fixation in which letters can be recognized. In the case of normal reading, we can picture the visual span as a circular region surrounding the center of the fovea whose size is determined by angular character size and retinal resolution[2]. Saccade length will determine the overlap of the resolvable regions associated with successive fixations. If saccades are too long, there will be no overlap and text will be lost between successive fixations. If saccades are too short, the overlap will be excessive and reading unnecessarily slow. A good reader will employ saccades of some optimal length, determined, at least in part, by the size of the visual span. Any shrinkage of the visual span should be accompanied by a reduction in saccade length.

There is evidence that variability in saccade length increases with mean saccade length (McConkie *et al*., 1988; Coeffe & O'Regan, 1987; Jacobs, 1986). McConkie *et al*. (1988) have shown that the horizontal dispersion of saccade landing sites is well fit by a normal distribution. The variation is due to the combined influences of local cognitive control of eye movements in reading and to errors in the oculomotor system.

[2] The concept of “visual span” was developed in much greater detail in two subsequent papers in this series (R16, 1997; R20, 2001). This is a sensory definition of visual span and should be "visual span" as asymmetric

We can use the jittered-text method as a psychophysical probe to study saccade length. To begin, we construct a model linking saccade length to stimulus-jitter area. We assume that there is a bivariate normal distribution of landing sites having area A_L functionally dependent on mean saccade length $_L$. Taking-the simplest case, suppose that A_L is proportional to $_L$:

$$A_L = kL \qquad (5)$$

where k is a constant[3]. AL is a measure of the variability in saccade landing sites that is tolerated in reading. If additional variability is introduced by stimulus jitter, text will be lost between saccades unless overall landing-site variability is somehow reduced to the tolerable level. The reader can compensate for the added text jitter and can continue to read every word accurately, but only by reducing mean saccade length and its associated variability. As a result, reading slows down.

We can express this argument mathematically. Assuming that the stimulus jitter and distribution of saccadic landing sites can be represented by statistically independent bivariate normals with areas of A and A_L respectively, overall eye-position variability can be represented by a bivariate normal with area $A + A_L$. We define At as a tolerance value on this overall bivariate area beyond which reading becomes inaccurate:

$$A+A_L=A_t$$

Replacing A_L with kL (from Eq. 5) and rearranging:

$$L = (1/k)\ (A_t-A) - (A_t/k)\ (1-A/A_t)$$

Substituting for L in Equation 2:

$$T = (kD/A_t)(1/[1-A/A_t]) \qquad (6).$$

For very small amounts of stimulus jitter where $A/A_t << 1$:

$$T = (kD/A_t)\ (1+A/A_t) = (kD/A^2{}_t)\ (A+A_t) \qquad (7).$$

Three empirical predictions follow from this formulation. 1) For small values of stimulus jitter, there is a linear relationship between reading time T and stimulus-jitter area A. For large values of A, the relationship becomes curvilinear (see Fig. 1b). When the stimulus jitter becomes large enough, shortened saccades can no longer compensate for the overall jitter and the model breaks down. Either reading accuracy deteriorates (as well as speed) or some alternative reading strategy is adopted (e.g., extended fixational pauses as in the first model). 2) The negative of the x-axis intercept is the area A_t of the bivariate normal distribution of eye positions. When

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[3] This assumption is consistent with a form of Fitt's law (1954) in which horizontal position error is proportional to saccade length, so long as the vertical position error is unaffected by saccade length. It is quite possible that a much weaker dependence exists between bivariate area and saccade length. This should not affect the qualitative result of our argument.

visibility is reduced, At gets smaller, a consequence of shorter mean saccade length. This is reflected as an x-axis intercept nearer the origin. 3) Because A_t appears in the denominator in equation 6, a reduction in its value is accompanied by an increased slope.

Figure 1b shows schematically this model's predictions for curves of low-vision and normal reading in the presence of stimulus jitter. Unlike the model based on prolonged fixations, this model predicts smaller intercepts and steeper slopes for low vision compared with normal subjects.

METHOD

Reading Speed Measurements. Reading speed was measured using the MNread procedure (Legge *et al.*, 1989). Briefly, subjects were required to read aloud a single sentence of text, termed a flashcard, displayed on a high-resolution monochrome monitor (Conrac SNA 17/Y) with P4 phosphor. The monitor was driven by an Imaging Technology Inc. (ITI) frame buffer installed in an IBM AT computer. The frame buffer had resolution of 512 x 480 pixels and 256 gray levels. Text was displayed at full contrast (.98), as black characters on a white background (200 cd/m²). There were 170 different sentences available for presentation. Each sentence had 13 characters, including spaces, on each of four lines. The font was a standard serif font known as Zip-a-Tone Century Schoolbook. Sentences were constructed using high frequency, non-technical words and were declarative in nature. Figure 2 shows a typical flashcard.

Fig. 2 -- An example of a typical "flashcard" used to measure reading speed. All flashcards were formatted into 13 characters on each of 4 lines.

Subjects were instructed to read each flashcard aloud as fast as possible without skipping words. The presentation time was adjusted between trials until subjects could no longer read an entire sentence. Reading rate was computed for each sentence as the number of words correctly read divided by the stimulus duration. Recent data indicate that silent and oral reading rates obtained with this method are almost identical (Legge *et al.*, 1989).

The reading rate for a given condition was the mean of all "good" trials. For a trial to be considered "good", more than half the words had to be correct. The lower bound on performance was set at 50% to prevent the inclusion of trials in which a subject "stumbled" on the first word or two and gave up on the rest of the sentence. Such "bad" trials occurred between five and ten percent of the time. For subjects with normal vision, two or three "good" trials were gathered for each condition, in each session, so that over the course of the experiment between 8 and 12 trials were used to compute the mean reading rate of each condition. Because subjects with low-vision participated in only a single session, four or five "good" trials were gathered in each condition.

Text Jitter. Text jitter was created by rigidly displacing an entire flashcard in both horizontal and vertical directions on every video frame (i.e. 30 Hz. jitter). This was accomplished by panning the video cursor on the-frame buffer. The displacements in each direction are characterized by independent zero-mean normal distributions with specified standard deviations. The resulting bivariate normal distribution of positions is characterized by an ellipse which has an area equal-to

$$A(P) = 2KpS_HS_V(1-r^2)^{1/2}$$

where S_H and S_V are the horizontal and vertical standard deviations of position and r is the product moment correlation of the two marginal distributions (r = 0 in our studies). kp is taken from the relation

$$P = 100(1-e^{-K})$$

where P is a percentage which expresses the probability of a displacement falling within the ellipse of area A(P). In the present study, $S_H = S_V$, so that the dispersion actually fell within a circle. In keeping with established convention, P was set equal to 0.68. A complete discussion of the use of the bivariate area measure of eye movements appears in Ditchburn (1973).

Stimulus jitter was varied by adjusting the standard deviations of the horizontal and vertical distributions. The stimulus jitter area A(68) can be expressed as the number of characters fitting within A(68) or as a solid angle. The characters used in the present study were 28 (rows) x 24 (cols) pixel images. Accordingly, 0, .437, 1.72 and 3.8 characters had collective areas that could fit into the four values of A(68). This is shown schematically in Figure 3.

Table 1. Bivariate area of text jitter (deg^2)

	Viewing Distance (cm)				
	6.3	12.6	42	84	420
Jitter (chars)					
0	0	0	0	0	0
0.44	5216.5	1299.5	112.1	29.1	1.17
1.72	20581.9	5113.1	460.7	114.9	4.65
3.80	46968.2	11309.0	1063.7	261.5	10.5

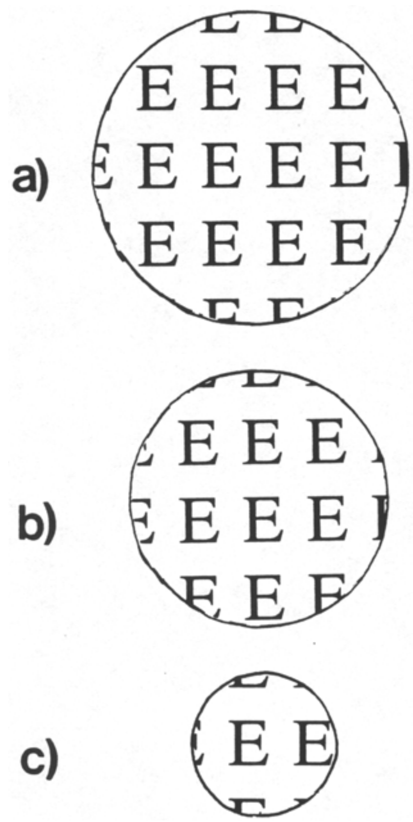

Fig. 3 -- Schematic demonstration of how the magnitude of a bivariate area is measured in terms of the number of characters that could fit into the area. Three distributions, of different sizes, are shown. The largest subtends about 15 characters, the middle distribution subtends about 10 characters and the smallest subtends about 3 characters.

We measured reading speed as a function of jitter area for five angular character sizes (center-to center spacing)--10, 5, 1.5, 0.75 and 0.15 deg. Angular character size was varied by changing viewing distance from 6.3 to 420 cm, leaving the stimulus display unchanged. Table 1 shows the stimulus jitter areas, measured in deg^2 for each of the five angular character sizes.

Procedure for subjects with normal vision. Four psychology students with normal or corrected-to-normal vision participated. All combinations of viewing distances and jitter values were tested in each of four sessions, which typically took between 1 and 1.5 hours each.

Procedure for Low-vision subjects. The visual characteristics of our 12 low-vision subjects are shown in Table 2. The main experiment focused on the eight low-vision subjects (A-H) with central field loss. The diagnosis, field and media classifications were provided by each subject's ophthalmologist. Acuity and some field measurements were conducted in our laboratory.

Table 2. Low-vision subjects

subject	decimal acuity	media	central-loss	diagnosis
A	.042	clear	yes	macular degeneration
B	.083	clear	yes	retinopathic lesions
C	.250	clear	yes	ocular histoplasmosis
D	.063	cloudy	yes	myopic degeneration, aphakia
E	.033	clear	yes	macular degeneration
F	.143	clear	yes	optic nerve atrophy
G	.083	cloudy	yes	cong. rod vision
H	.167	clear	yes	macular hemorrhage
I	.250	clear	no	optic neuritis
J	.167	cloudy	no	cong. cataracts
K	.100	clear	no	macular pucker
L	.167	cloudy	no	cong. cataracts

Each low-vision subject participated in one session. The set of viewing distances and range of jitter values was determined individually. Before the first trial, a sample flashcard was displayed and the subject was asked to move to the distance that was most comfortable for reading. Reading rate was then measured across a range of jitter values, after which the experiment was repeated at another viewing distance: Although a few subjects became fatigued quickly, almost all were able to complete the experiment at two viewing distances, several gave data at three distances, and one subject ran at four viewing distances.

RESULTS

Normal vision

Figure 4 shows reading time (the reciprocal of reading rate) as a function of stimulus jitter area. Area is measured as the number of characters that fit into A(68) for the bivariate normal distribution of jitter (see METHOD). The five panels, one for each of the five character sizes, show data for all four normal subjects. For each subject and character size, we tested the hypothesis that a nonlinear function provides a better fit to the data than a linear fit (Hays, 1981, Sec. 14.8). For all subjects, normal and low vision, the hypothesis was rejected, meaning that linear fits adequately describe the data. Linear regressions typically accounted for 60 - 90% of the variance.

The data from Fig. 5a are replotted in Fig. 5b with internal jitter expressed as the number of characters fitting into A(68). Expressed in these units, internal jitter is roughly independent of character size for two subjects and has a peak at intermediate character sizes for two others. Overall, there is a tendency for internal jitter to be greatest for characters of intermediate size and least for large and small characters. An ANOVA revealed a significant effect for character size ($F = 13.58$, $p < .05$). Apparently, subjects tolerate greater positional instability when reading text composed of characters of intermediate size, roughly the range of character sizes for which reading speed is fastest (Legge *et al.*, 1985a). We return to this somewhat paradoxical result in the DISCUSSION.

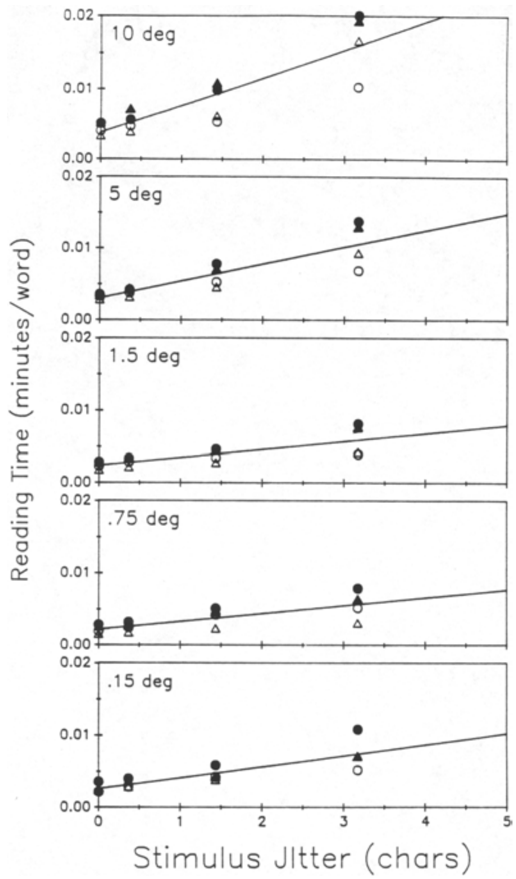

Fig. 4 -- Reading time for subjects with normal vision is shown as a function of stimulus jitter area, measured in characters, for each of five character sizes. The data from all four subjects are shown on each panel.

Averaged across all character sizes and normal subjects, the internal jitter area was 4.9 characters. The implication of this rather large value for reading speed is quite remarkable. Because reading time is proportional to the sum of stimulus jitter area and internal jitter (Fig. 4), reading time is doubled when stimulus jitter increases from 0 to equal internal jitter. In other words, the internal jitter is a measure of the stimulus jitter that halves reading rate. It seems remarkable that additive eye-position variability extending over an area equivalent to about five characters reduces reading rate by only a factor of two.

Low Vision

Again, plots of reading time T as a function of stimulus jitter area are well fit by straight lines and can be used to estimate internal jitter. The intercepts and slopes characterizing these lines are shown for all low-vision subjects in Table 3.

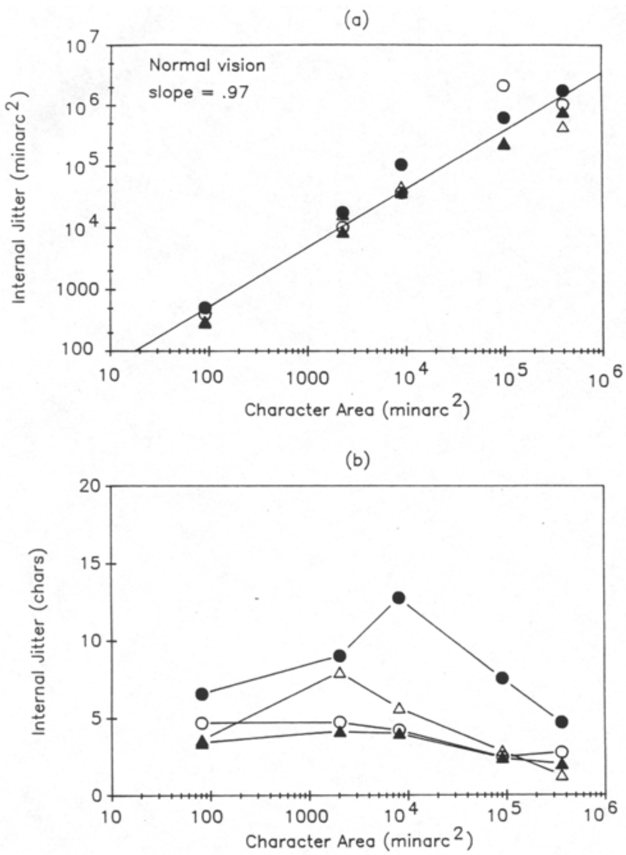

Fig. 5 -- (a) Internal jitter (A_i) is shown for subjects with normal vision as a function of character area. Both are measured in minarc². The best-fitting line is drawn through the grouped data. (b) The data from Fig. 5a are replotted on a scale where A_i is measured in characters.

Fig. 6a shows internal jitter as a function of angular character size on log-log coordinates. Both variables are expressed as areas, measured in minarc². Each point is an intercept from one experiment with a low-vision subject. As with normal-vision subjects, the set of points is well fit by a straight line with a slope close to one (slope = 1.01, r = .910). Clearly, internal jitter area scales with angular character size. Fig. 6b shows the same data, but with internal jitter expressed as the number of characters fitting in A(68). In these units, internal jitter does not vary systematically with angular character size ($F = 2.087$, $p = .28$). Averaged across low-vision subjects and character sizes, internal jitter had a mean value of 2.0 characters. Surprisingly, the mean internal jitter for low-vision subjects is less than half the mean value for normal subjects. A between-groups one-way ANOVA showed a highly significant difference ($F = 16.61$; $p < .01$) between the two sets of internal jitter values.

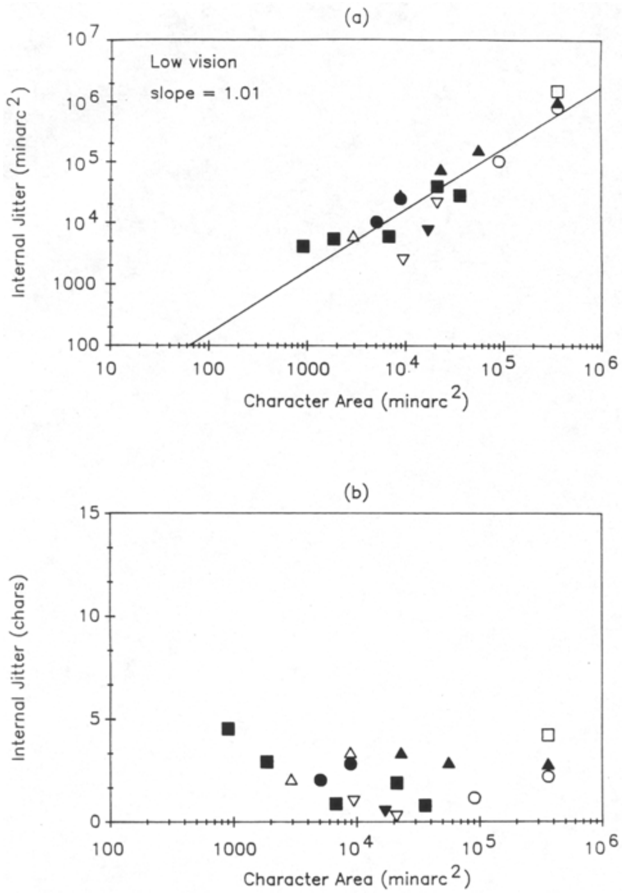

Fig. 6 -- (a) Equivalent jitter for eight central-loss subjects is shown as a function of character area. Both variables are measured in minarc². The best-fitting line is drawn through the grouped data. (b) The data from Fig. 6a are replotted on a scale where Ai is measured in characters.

Slope

Both models presented in the Introduction make predictions about the slopes of the lines that describe reading time as a function of stimulus jitter. For comparison, the slopes of the regression lines for all subjects and conditions are plotted in Figure 7. Reading time T is measured in minutes/word and stimulus jitter is measured in the number of characters that fit into the area of dispersion; the slope describes how reading time changes per unit change in the size of A(68). It is clear that at all character sizes, the slopes for the low-vision subjects are higher than those for subjects with normal vision.

Table 3. Low-vision data.

Data are shown for all subjects with low-vision. For each subject, the correlation coefficient (r) and the slope ($= m \times 10^{-6}$) of the best linear fits are reported, along with the x-axis intercept (A_i), measured in characters.

Subject	Char Width (deg)	r	m	A_i
A				
	10.0	0.836	22.363	2.20
	5.0	0.999	44.963	1.17
B				
	3.15	0.997	49.375	0.80
	1.57	0.992	32.110	2.83
	1.18	0.801	39.338	2.04
C				
	1.57	0.988	13.373	3.38
	0.90	0.970	51.259	2.07
D				
	10.0	0.938	11.640	2.82
	3.93	0.753	10.168	2.89
	2.52	0.919	7.683	3.37
E				
	10.0	0.899	12.228	4.22
	3.15	0.995	45.531	0.79
F				
	2.42	0.991	23.652	1.91
	1.37	0.984	39.390	0.89
	0.72	0.996	9.958	2.93
	0.50	0.870	13.202	4.54
G				
	2.42	0.925	41.112	0.26
	1.62	0.998	173.95	1.01
H				
	2.17	0.881	79.998	0.52
I				
	2.10	.989	11.689	0.77
	1.43	.981	56.478	0.12
J				
	1.97	.984	2.766	2.15
	1.23	.984	3.921	1.31
	0.73	.969	7.807	0.90
K				
	1.91	.937	15.615	0.57
	1.14	.975	26.297	0.34
L				
	1.02	.982	8.711	1.95

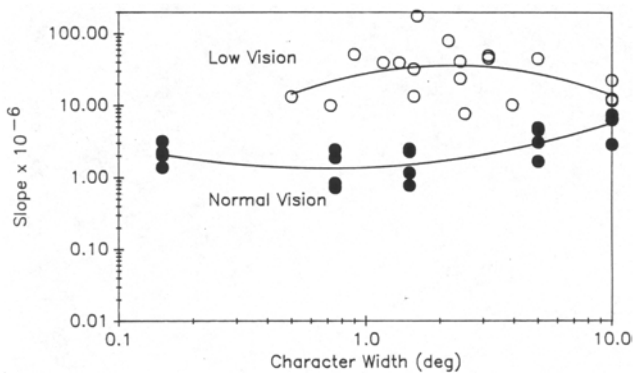

Fig. 7 -- The slopes of the lines that describe reading time as a function of stimulus jitter are plotted as a function of character size for normal and low-vision subjects. Reading time is measured in minutes/word and jitter is measured in characters (e.g., the number of characters that fit into A(68)). The slope therefore reflects how reading time changes per unit change in A(68).

DISCUSSION

In this paper we have tested two models that may account for slow reading in low vision. Both models assume the presence of an internal noise source, termed internal jitter, that results in some form of positional instability of the stimulus. Using an "equivalent noise" analysis (Pelli, 1981; Legge, Kersten & Burgess, 1987), we estimated the magnitude of the internal jitter and tested the predictions of the two models.

The prolonged-fixation model can be rejected because two of its three predictions were contradicted by the data. According to this model, internal jitter is identified with fixational instability. The model predicts a linear relation between reading time and stimulus jitter as observed. However, the model predicts that internal jitter (i.e. fixational instability) is greater in low vision than in normal vision. This was not true; internal jitter was smaller for subjects with low vision. In addition, the model predicts that subjects with normal and low vision would be equally affected by stimulus jitter, that is, they would have equal slopes when reading time is plotted against stimulus jitter. Instead, we found that subjects with low vision had steeper slopes, indicating relatively greater effects of stimulus jitter.

The shortened-saccade model receives more support because two of its three predictions are confirmed and the third is partially confirmed. According to this model, internal jitter is identified with the variability of saccade lengths. The model asserts that this variability can be reduced by shortening saccades, and that people with low vision reduce saccade length to compensate for a shrinkage of the visual span. This model predicts smaller estimates of internal jitter in low vision than in normal vision, and this is what we found. The model also predicts the steeper slopes observed in low vision. Finally, this model predicts a linear relation between reading time and stimulus jitter for small, but not large, values of stimulus jitter. Our data indicate that straight lines fit the data across the entire range of stimulus jitter.

According to the shortened-saccade model, people with low vision have a reduced visual span, that is, they can identify fewer letters around the point of fixation. To compensate, they execute shorter saccades. These saccades are more precise (i.e. exhibit less stochastic variability) and are less tolerant to external instability.

The notion of an adaptive oculomotor system in normal reading is not new. It is known that as character size changes, saccade length also changes, so that saccade length, measured in characters, remains roughly constant (Morrison & Rayner, 1981). In addition, McConkie *et al*. (1988) recently showed the adaptive control of fixation locations during reading. An adaptive strategy may account for the increase in internal jitter over the middle range of character sizes that was noted in Fig. 5b. It is known that reading rates decline for very small or very large characters. Perhaps this is related to a shrinkage in the size of the visual span (measured in characters.)[4] If so, subjects might adapt by executing shorter saccades and by exhibiting smaller values of internal jitter (Fig. 5b).

According to this argument, readers with normal vision compensate for "difficult reading" by resorting to shorter saccades. To test this idea, we measured internal jitter for four subjects with normal vision, as a function of text contrast. Character size was held constant at .75 deg. and the Michelson contrast of the text was set equal to .98, .08 or .04. Legge, Rubin and Luebker (1987) showed that in normal vision, there is very little decrease in reading rate as contrast drops from 1.0 to about .10, but that reading rate declines rapidly below .10. One subject (AMO) had participated in the previous experiments and three were new. The testing procedures and stimuli were otherwise exactly as previously described. The estimates of internal jitter are displayed in Figure 8.

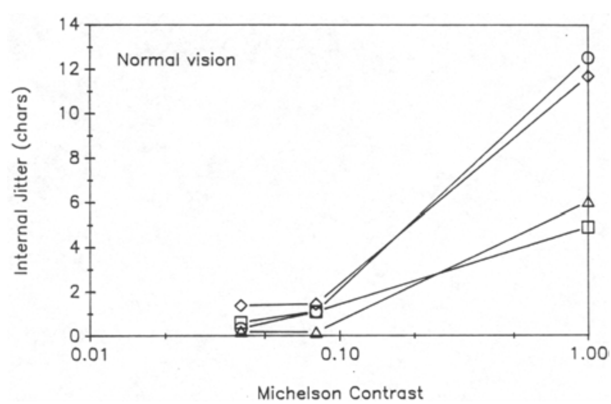

Fig. 8 -- Internal jitter is plotted as a function of Michelson contrast for four subjects with normal vision. Contrast values were 1.0, .08 and .04.

Although there is considerable individual variation, the four subjects show the same pattern of results -- as the contrast of the text is lowered, internal jitter gets smaller. Whereas the estimates of internal jitter for full-contrast text fall in the typical range for normal vision (Fig. 5b), the area of internal jitter is reduced to about one character for each subject in the low-contrast conditions. In the framework of the shortened-saccade model, the subjects compensated for the degraded viewing conditions by programming shorter saccades.

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[4] Legge, Lee, *et al*. (2002) presented data confirming this possibility. Their data indicate that visual spans are largest for a range of intermediate character sizes and decline for larger or smaller character sizes.

We began by asking whether fixation instability might account for the particularly slow reading of many subjects with central-field loss. We proposed a prolonged-fixation model. However, data from our jittered-text experiment suggested that shortened saccades provide a better account of slow reading in low vision. Shortened saccades may be an adaptive response to a reduced visual span in reading. Future research must determine whether the visual span is especially small for subjects who must read with peripheral vision (in our later study (R20, 2001), we did indeed observe that the visual span shrinks in peripheral vision.). However, our contrast experiment with normal subjects implies that conditions exist in which the visual span shrinks in foveal vision. It is likely that such an effect plays a role in limiting reading speed for low-vision subjects with residual central vision. To confirm this expectation, we tested four low-vision subjects with residual central vision (I-L in Table 2). As expected, values of internal jitter fell within the same range as previously described for the eight subjects with central-field loss. These data appear as the last four subjects (I-L)-listed in Table 3.

This paper does not explain why people with central-field loss tend to read more slowly than people with other forms of low vision. It raises the possibility, however, that the difference is due to shorter saccades. The shorter saccades in turn may be a consequence of a smaller visual span in reading. More generally, slow reading in low vision seems to be tied to shortened saccades rather than to prolonged fixations. Low-vision readers respond to degraded sensory input much like normal readers, not by dwelling excessively on each fixation but by marching through the text in shorter, more precise steps.

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