1040-5488/06/8303-0166/0 VOL. 83, NO. 3, PP. 166–177
OPTOMETRY AND VISION SCIENCE
Copyright © 2006 *American Academy of Optometry*

ORIGINAL ARTICLE

Low-Vision Reading Speed: Influences of Linguistic Inference and Aging

SARAH M. SASS, BA*, GORDON E. LEGGE, PhD, and HYE-WON LEE, PhD

Department of Psychology, Minnesota Laboratory for Low-Vision Research, University of Minnesota, Minneapolis, Minnesota (SMS, GEL) and Department of Psychology, Ewha Womans University, Seoul, Korea (HWL)

ABSTRACT

Purpose. Reading is a dynamic task involving both linguistic and visual analysis. In this study, we asked how two types of linguistic information—characters used in segmenting words from one another, and sentence context–differ in their usefulness for people with normal and low vision. Given evidence for age-related differences in some forms of cognitive processing, we also investigated the effect of age.

Methods. There were four groups of 10 participants: vision status (normal, low) crossed with age (young, <35 years; old, >65 years). Reading speeds were compared for regularly spaced text and text in which the spaces were removed, a manipulation intended to eliminate local cues for text segmentation and force attention to clusters of letters or whole words. We also evaluated the effect of sentence context by comparing reading speeds for regular sentences and sentences in which word order was scrambled.

Results. Removal of spaces had a greater impact on low vision than normal vision, reducing average speeds to 45% and 66% of speeds for regularly spaced text, respectively. We interpret this to mean that people with low vision have less access to spatially distributed linguistic regularities of text such as prefixes, suffixes, or word length. Removal of sentence context through scrambling had a greater impact on normal vision than low vision, reducing mean reading speed to 53% and 66%, respectively. Finally, comparison of our young and old readers showed no major differences in the use of sentence context or in the impact of removing spaces between words.

Conclusions. People with low vision appear to rely more on spacing information in sentences, whereas people with normal vision appear to make better use of sentence context, irrespective of age.

(Optom Vis Sci 2006;83:166–177)

Key Words: low vision, reading, reading speed, aging

"Low vision" can be defined as an acuity on the letter chart of <20/60 or, more functionally, as the inability to read the newspaper at a normal distance of 40 cm (16 inches) with best correction from glasses or contact lenses. Reading difficulty has been reported to be the most common presenting symptom in low vision clinics.[1]

Three types of visual impairment account for most reading deficits in low vision: low acuity, reduced contrast sensitivity, and visual field loss, particularly central field loss. Recent empirical findings and theoretical analysis in our laboratory provide evidence that all three of these types of impairment contribute to reduction in the size of the visual span, the number of letters that can be recognized without moving the eyes.[2–4] Legge et al.[3] described a method for measuring visual span profiles—plots of percent correct letter recognition as a function of distance (in character spaces) left and right of fixation. The breadth of empirical visual span profiles reveals that people with normal vision recognize relatively few letters with high accuracy on each fixation, roughly 10 letters per fixation under best conditions. Under degraded stimulus conditions (such as low contrast letters or letters near the acuity limit), visual span profiles shrink in size.[4] Visual spans also shrink in normal peripheral vision, even when letter size is increased to compensate for decreased acuity.[3,5] This finding implies that low-vision readers with central field loss, who must use peripheral vision, almost certainly have reduced visual spans. Legge et al.[3] have presented theoretical and empirical evidence showing that narrower visual span profiles are associated with slower reading.

Three sensory mechanisms almost certainly have an impact on the size of the visual span: decreasing letter acuity in peripheral

---

*Ms. Sass' current affiliation is: Department of Psychology, University of Illinois, Urbana-Champaign, Illinois.

vision, crowding between adjacent letters, and decreasing accuracy of position signals in peripheral vision. The roles of these factors in determining the size of the visual span are reviewed by Legge.[6] Crowding, sometimes termed "lateral masking," might be especially relevant to the interpretation of the spacing manipulation in the present study. Crowding refers to the interference of flanking letters on the recognition of target letters, an effect that is quite pronounced in peripheral vision.[7] It is likely that crowding influences the size of the visual span in central vision and the shrinkage of the visual span in peripheral vision. Nonetheless, it has been difficult to demonstrate the direct effects of crowding on reading speed. For example, it is known that increasing the spacing between letters reduces crowding. Accordingly, we would expect that increased letter spacing should result in faster reading, especially in peripheral vision in which crowding is more pronounced. Despite this expectation, extra-wide letter spacing does not increase reading speed in peripheral vision.[8]

For the sake of clarity, we want to distinguish the concept of visual span from the concept of perceptual span. Perceptual span is defined in terms of the functional demands of reading, including oculomotor demands and contextual effects.[9] Operationally, it refers to the region of visual field that influences eye movements and fixation times in reading. It is estimated that the perceptual span extends 15 characters to the right of fixation and leftward to the beginning of the currently fixated word up to a maximum of four characters.[9,10] Unlike perceptual span, visual span characterizes letter recognition in the absence of oculomotor or contextual factors.

We now turn to the main topic of this article. It is likely that nonvisual factors interact with visual constraints in limiting reading speed. Here, we explore how age and linguistic factors interact with vision status (normal or low) in determining reading performance. We focus on two types of linguistic knowledge that support rapid reading in normal vision: lexical knowledge and sentence context. Lexical knowledge refers to our knowledge about individual words and word structure. Sentence context refers to the relations between words in a sentence based on their meanings (semantics) or their grammatical relations (syntax).

LEXICAL KNOWLEDGE AND THE ROLE OF SPACING

Our knowledge of words and word structure (lexical knowledge) is not only necessary for comprehension of text, but can also play an important role in supporting rapid reading. This can be demonstrated by reading text with spaces removed: "Isthissentenceeasytoread?" In the absence of spaces, readers must rely on their knowledge of whole words or word structure (prefixes, suffixes, and so on) to infer the segmentation of the string of characters into separate words. Normal readers are capable of impressive reading speeds under these conditions (often $>$100 words per minute), although they slow down by 30% to 50% compared with regularly spaced text.[11–13] Rayner et al.[13] have distinguished three ways in which removal of spaces from text might cause reading to slow down, two related directly to word recognition and a third to eye movement control: segmenting. Without spaces in the text, it is difficult to determine where one word ends and the next word begins. One must rely on knowledge of words or word structure to identify candidate segmentation points.

LATERAL MASKING (ALSO TERMED "CROWDING")

It is known that initial and final letters of words are more visible than interior letters because they are flanked on one side by a space.[14] When spaces are removed from text, the reader loses this advantage, and lateral masking is likely to reduce the visibility of initial and final letters of words.

EYE GUIDANCE

Saccade planning and execution in reading may rely on targeting a word to the right of fixation, and this process could rely on spaces to delineate the target word.

A recent series of articles from two research groups has debated the importance of these three factors in reading spaced and unspaced text. Both Epelboim et al.[12,15] and Rayner et al.[13,16] agree on the importance of word identification. The debate emerges over the effect of spaces in influencing eye movements. Epelboim et al.[12,15] contend that spaces are unimportant in determining eye movements in reading, whereas Rayner et al.[13,16] argue that removing spaces from text has an important effect on the pattern of eye movements. Rayner et al.[13] present compelling evidence for differences in eye movement patterns for spaced and unspaced text, but they acknowledge that interference with word recognition is probably the dominant effect of removing spaces. They find that removal of spaces results in increased mean gaze duration on words and a greater difference in the gaze duration on low-frequency and high-frequency words. For example, longer gaze times on low-frequency words such as "steward" compared with high-frequency words such as "student" is taken as indicative of differential lexical access.

Although debate exists regarding the controversial role of spaces in guiding reading saccades in normal vision, our primary interest does not concern this debate. Rather, we are concerned with the agreed-on influence of the spacing manipulation on word identification and the resulting impact on reading speed. Our central interest is in regard to how the removal of spaces from text affects low-vision reading speed focusing on the two word-recognition factors identified by Rayner et al.[13]: segmentation and lateral masking. We consider these factors in relation to the visual span in low vision. Low vision typically results in a reduced visual span, that is, fewer characters than normal are recognizable on a single fixation, and in severe cases, as few as one.[2] Three consequences of a reduced visual span for reading are: 1) the inability to see extended clusters of letters that convey whole words or are diagnostic of word structure such as prefixes and suffixes, 2) the need for an increased number of fixations within individual words, and 3) the demand for integrating information from multiple fixations to identify individual words.

We hypothesize that removal of spaces from text will be more deleterious for low vision than normal vision because both segmentation and lateral masking problems will be more severe. Consider first the challenge of segmenting a string of characters into words with a very narrow visual span, presumed to be characteristic of low vision. For example, Asoldierateacherry. A normal visual span, accommodating the first eight or 10 letters, could provide sufficient information to segment the first two words properly "A soldier. . ." A narrower visual span of three or four letters would leave the segmentation ambiguous; is it "A sold. . .," "As old. . .," or what? The sentence has other local segmentation ambiguities (e.g., "at each" or "ate ache"). Although these ambiguities can be resolved after all letters are recognized and sequenced, we expect that the challenge will be disproportionately greater for a person with a narrow visual span who must integrate information over several fixations. Moreover, readers with very narrow visual spans would have less direct access to clusters of letters forming meaningful structural components of words such as suffixes or prefixes, which could help with segmentation. In other words, the narrower the reader's visual span, the more reliant they are likely to be on spatially localized cues for segmentation, particularly spaces between words. Other local cues to segmentation could include punctuation marks and capital letters. Epelboim et al.[12] noted briefly that removal of these features produced a further decrement in normal reading speed beyond the reduction resulting from removing spaces.

We also expect that lateral masking effects, resulting from removal of spaces, will have a greater deleterious effect on low vision than normal vision. As noted here, visual spans are known to be narrower in peripheral vision,[3] probably in part as a result of increased lateral masking. Low-vision readers with central field loss who read with peripheral vision are likely to be adversely affected by the increase in lateral masking in unspaced text. Other low-vision readers whose visual spans are narrow because of reduced contrast sensitivity or because they are reading near their acuity limits may also experience abnormally strong effects of enhanced lateral masking in unspaced text.

Context

Language contains syntactic and semantic relationships between words that make continuous text more predictable than random words. We might expect this increased predictability to result in faster reading of sentences than random sequences of words.

Legge et al.[17] analyzed the effect of this sort of predictability on the performance of an ideal observer model of reading (Mr. Chips). The model exhibited a 25% increase in reading speed associated with context. Morton[18] compared human reading performance for zero- through eighth-order approximations to English.[19] Comparing first-order (analogous to scrambling word order in text) and eighth-order (very similar to English sentences), Morton[18] found a context advantage of 33% in reading speed. Bullimore and Bailey[20] found a similar context advantage for normally sighted readers.

Do low-vision participants also benefit from context in improving reading speed? There are conflicting views and data. One view argues that the added cognitive load of decoding degraded visual input should leave less cognitive resources available for contextual analysis, and hence there should be less advantage of context.[21] In possible support, some studies show a reduced context effect in normal vision under challenging viewing conditions. Both Chung et al.[22] and Latham and Whitaker[23] observed reduced benefit from context when normal participants read with peripheral vision compared with central vision.

Fine et al.[24] found that normally sighted participants showed slightly less benefit from context when reading with simulated cataracts compared with clear vision. However, Fine et al.[25] found no decrease in the benefit of context in normal peripheral vision. In fact, they found a greater advantage of context in the left visual field compared with central vision or the lower visual field.

Stanovich's influential compensatory activation model[26] turns the argument around. According to this model, when stimulus or participant factors lengthen the processing of words, more time is available for compensatory top-down analysis, providing larger context effects. For instance, when visual input is degraded, a reader may rely more heavily on context to infer the identity of words and might exhibit enlarged context effects. In support of this view, Stanovich and West,[27] in their experiment 6, tested normally sighted participants and found increased context effects on naming latencies for visually degraded words in a sentence-priming paradigm. In this study, only the targets were degraded, not the primes. In a later study invoking the Stanovich model, Speranza et al.[28] measured word recognition accuracy for the last word of sentences in which the prior sentence context made the words highly predictable or not predictable. The entire sentences were embedded in visual noise, with the root mean square (RMS) contrast of the noise a parameter of the study. These investigators found that the maximum performance difference between predictable and unpredictable words (i.e., the maximum effect of context) occurred for moderately high noise levels, that is, for degraded visual inputs. These findings would seem to predict larger context effects in low vision than normal vision.

From this literature, low-vision readers would be expected to benefit from context, but it is unclear whether the benefit would be greater or less than context effects for normally sighted readers. Legge et al.[29] found a 15% to 30% reading-speed advantage for sentences over random words in a heterogeneous group of 147 low-vision participants, roughly consistent with findings from normal readers. Fine and Peli[30] found larger context effects overall (roughly a twofold increase in reading speed as a result of context) but equivalent in size for normal participants and a group of low-vision participants with central field loss, many from age-related macular degeneration (ARMD; AMD). However, Bullimore and Bailey[20] found a substantially larger context effect for low-vision readers with AMD compared with normally sighted readers. The latter two studies[20,30] are noteworthy in showing that low-vision participants with central field loss do indeed benefit substantially from context in reading, despite the findings cited here that normally sighted readers show weaker context effects in peripheral vision.[22,23] Given the continuing uncertainty about the relative size of context effects, we obtained data on normal and low-vision reading speeds for both continuous and random word text. We tested the working hypothesis that context effects are larger for low vision than for normal vision, consistent with the findings of Bullimore and Bailey.[20]

Interaction of Age With Vision Status

In a previous study in our laboratory,[31] we found only minor differences in reading speed between a group of young, normally sighted adults and a group of older adults screened to have completely healthy vision. (This study is described in more detail in the "Discussion" section subsequently.)

There is evidence for greater age-related effects in low-vision reading speed.[32–34] In a study of 141 low-vision participants with a wide range of ages and diagnoses, Legge et al.[32] found that age accounted for approximately 20% of the variance in reading speed, substantially more than Snellen acuity. One problem in interpreting this finding is the natural confound between age and differing causes of impaired vision. Legge et al.[32] addressed this problem by comparing reading performance in young and old participants with the same general type of vision loss, i.e., macular degeneration. They found that reading speeds of participants with AMD were approximately a factor of two lower than acuity-matched younger participants with juvenile macular degeneration (JMD), but note that Lovie-Kitchin et al.[35] did not find a similar difference in reading speeds between JMD and AMD participants. They pointed out, however, that their participants were instructed to read for meaning, rather than to maximize speed, and that these instructions might reduce the difference between the two groups in their study.

How would we expect context to interact with age and vision status? There is evidence that semantic priming effects, perhaps a component of context effects, are larger in older adults.[36] The study of context effects for word recognition in visual noise by Speranza et al.,[28] mentioned previously, found larger context effects for older adults than younger adults. This study, however, did not impose any time pressure on participants' responses and may not be predictive of reading speed.

Recent reviews[36,37] have identified two general factors contributing to age-related effects on memory and cognition. First, there is evidence for slower information processing in old age (e.g., longer behavioral response latencies and delayed event-related potentials). Second, evidence from divided attention studies indicate that attentional resources needed in complex tasks diminish in old age. Reading is certainly a complex cognitive task, demanding rapid linguistic analysis. Moreover, reading with low vision may impose an additional cognitive load. These considerations suggest that context effects might be attenuated in older readers, and to the extent that low-vision reading has greater cognitive demands overall, this age-related difference could be greater in low vision. This argument also predicts that removing spaces from text (as discussed previously) would result in a greater reduction in reading speed for old versus young low-vision readers.

Thus, our third manipulation is to assess the impact of age on reading speed in participants with normal and low vision. If older readers are slower or less efficient in using linguistic knowledge to support rapid reading, we would predict 1) older participants should show weaker context effects than younger participants; 2) this difference should be greater in low vision; and 3) older participants with low vision should show a greater impact of removing spaces from text than younger participants with low vision.

Keep in mind that we are not suggesting that older readers are less capable than younger readers of comprehending or enjoying texts. Rather, the possibility exists that use of "top-down" linguistic knowledge at the early stage of transforming visual input to a string of words is measurably slower or less efficient than in younger readers.

We now summarize our experimental manipulations and the working hypotheses that we tested. There were four groups of participants: young/old × normal/low vision. Reading speeds were measured for all participants in four text conditions: spaced/unspaced text by continuous sentences/random word order. The following four hypotheses were tested: 1. There will be a greater difference in reading speed in spaced versus unspaced text for low-vision participants, (i.e., greater slowing of reading speed with removal of spaces in low vision) because people with reduced visual spans are more reliant on local orthographic cues such as spaces for segmentation of one word from the next. 2. There will be a greater difference in reading speed for continuous sentences versus random word sequences for people with low vision than people with normal vision (i.e., greater slowing of reading speed with removal of context in low vision) because of greater reliance on top-down linguistic inference when the visual input is of poorer quality. 3. There will be a greater difference in reading speed for continuous sentences versus random word sequences for young than old participants (i.e., greater increase in reading speed resulting from context for younger participants) because of more efficient cognitive analysis. 4. Older participants with low vision will exhibit a greater spacing effect and a smaller context effect than younger low-vision participants.

METHODS

Participants

Forty participants were divided into four groups of 10 based on visual status and age. Specifically, there were 20 low-vision participants, 10 of which were in the "old" category (65 years and older) and 10 in the "young" category (35 years and younger). The mean logarithm of the minimum angle of resolution (logMAR) acuities of the two low-vision groups were 0.783 (old) and 0.906 (young) and did not differ significantly. The mean contrast sensitivities of the two low-vision groups were identical (1.02). See Table 1 for details of the individual low-vision participants. The same age cutoffs applied to the two groups of normally sighted participants. The logMAR acuities of the two normally sighted groups were 0.07 (old) and −0.17 (young) and differed significantly. The mean contrast sensitivities of 1.64 (old normal) and 1.88 (young normal) also differed significantly.

Table 2 provides descriptive statistics for the four groups.

Because macular degeneration is the most common cause of vision loss in people over the age of 65 in the United States,[38] we differentially recruited people with macular degeneration in our group of 10 older participants with low vision. It should be noted that in our sample as in the low-vision population in general, there is a natural confound between the causes and types of low vision and age. For example, macular degeneration and central field loss are more common in older people with low vision than in younger people with low vision. Although our young and old low-vision groups were fairly well matched for acuity and contrast sensitivity, it is possible that they differed in some other visual characteristic relevant to reading such as size of the visual span. We will return to this possibility in the "Discussion" section in considering the differing effects of removing spaces on young and old participants with low vision.

TABLE 1.
Acuity and diagnostic characteristics of low-vision readers

P	Age	Acuity (logMAR)	Diagnosis	CS[b]	MMSE	RS (wpm)	VD (cm)	PS (deg)
L01	71	1.12	Mac degen	0.75	29	90	25	3.69
L02	62	0.64	RP, cone-rod dystrophy	0.90	30	145	30	2.56
L03	65	0.12	Mac degen	1.95	29	213	30	0.82
L04	61	1.26	Central scotoma[a]	0.30	29	44	30	3.08
L05	80	0.68	Mac degen	1.05	29	68	30	3.08
L06	82	1.12	Mac degen	1.05	29	28	30	2.56
L07	86	0.52	Mac degen	0.90	29	95	30	2.56
L08	87	0.82	Mac degen	1.05	29	178	30	2.56
L09	77	0.99	Mac degen	1.35	30	86	30	2.56
L10	77	0.56	Ischemic optic neuritis	0.90	30	114	40	0.96
L11	22	1.70	Glaucoma	0.45	30	51	20	5.77
L12	32	0.38	Nystagmus	1.80	30	446	40	0.50
L13	31	0.54	RP	0.90	30	240	40	1.38
L14	28	0.78	Glaucoma, Rieger's syndrome	0.45	30	244	10	7.69
L15	33	1.50	RP	0.45	30	24	20	5.19
L16	35	1.52	RP	0.45	30	74	5	18.46
L17	22	1.08	Optic Atrophy	1.35	30	345	40	1.63
L18	23	0.84	Aniridia	1.50	30	213	25	2.22
L19	31	0.14	RP	1.80	30	281	40	0.50
L20	19	0.58	Unknown	1.05	30	210	40	1.38

[a] Childhood onset, etiology unknown.

[b] Pelli-Robson test.

P = participant; CS = contrast sensitivity; MMSE = Mini Mental Status Examination; RS (wpm) = reading speed in words per minute for the normally spaced and continuous sentences, termed the "standard condition"; VD (cm) = viewing distance in cm; PS (deg) = print size of text in degrees; Mac degen = macular degeneration; RP = retinitis pigmentosa.

TABLE 2.
Descriptive statistics for four groups[a]

	Age	VA (logMAR)	CS	MMSE
Young LV	27.6 (5.6)	0.91 (0.53)	1.02 (0.56)	30.0 (0)
Old LV	74.8 (9.6)	0.78 (0.35)	1.02 (0.42)	29.3 (0.48)
Young NV	25 (5.3)	−0.17 (0.09)	1.88 (0.16)	29.8 (0.42)
Old NV	75.8 (5.5)	0.07 (0.16)	1.64 (0.25)	29.5 (0.85)

[a] Means are presented with corresponding standard deviations in parentheses.

NV = normal vision; LV = low vision; VA = visual acuity; CS = contrast sensitivity as measured by Pelli-Robson examination; MMSE = Mini-Mental Status Examination.

All participants were recruited from community and university organizations, and all were fluent in English.

After informed consent was obtained, we measured visual acuity with the Lighthouse Distance Visual Acuity chart (2nd edition) and contrast sensitivity with the Pelli-Robson chart.[39] Participants were screened for normal cognitive status using the Mini-Mental Status Examination (MMSE).[40] All participants had normal cognitive functioning, with a MMSE score exceeding 24.

Materials and Design

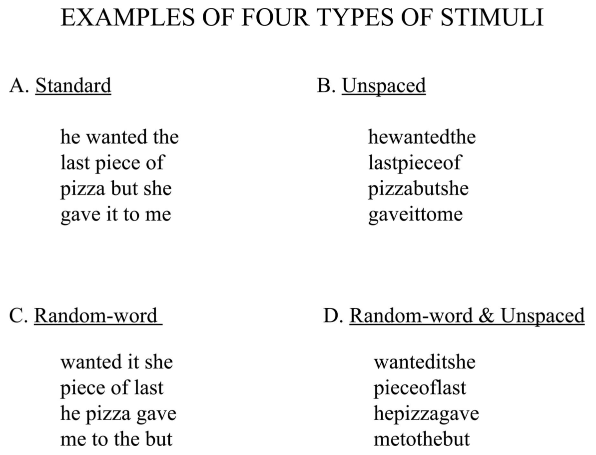
We measured oral reading speeds for four text conditions: normal sentences, unspaced sentences, random word sequences, and unspaced random word sequences. (Note: although the spaced and unspaced random word sequence stimuli are not sentences, for ease, all stimuli are referred to as "sentences" throughout the "Methods" section).

All sentences were in a format similar to the MNREAD format described by Legge et al.[29] Each sentence was comprised of 13 characters on each of four rows, including spaces. Although all the sentences were matched in the number of characters, they varied in the number of words from nine to 14 (average 11.5) and had no punctuation or capitalization. All were in Times New Roman font. The sentences used simple vocabulary and structure and were designed to be simpler than typical magazine or newspaper text. For each regular MNREAD sentence, there were three transformed versions, yielding four sets of test stimuli as follows: 1) normal sentences with spaces and sentence context preserved; 2) random word sequences with contextual information missing, created by scrambling the word order in the corresponding normal sentence[a]; 3) unspaced sentences with preserved sentence context but with spaces deleted between words; and 4) random word and unspaced sequences, lacking both context and spacing information. Figure 1 shows examples of the four types of stimuli.

The set of regular MNREAD sentences was divided into two pools: 109 "practice sentences" and 114 "test sentences." The reason for this distinction is given in the description of the two-step testing procedure subsequently.

---

[a] Instead of scrambling the word order of sentences to remove context, some studies have created "meaningless strings of words" by drawing words at random from word lists. Scrambled sentences may retain some contextual cues not present in random word strings, but we are not aware of any evidence that these two methods for removing context operate differently on reading speed.



EXAMPLES OF FOUR TYPES OF STIMULI

A. Standard

he wanted the
last piece of
pizza but she
gave it to me

B. Unspaced

hewantedthe
lastpieceof
pizzabutshe
gaveittome

C. Random-word

wanted it she
piece of last
he pizza gave
me to the but

D. Random-word & Unspaced

wanteditshe
pieceoflast
hepizzagave
metothebut

FIGURE 1.

Examples of four types of stimuli. (A) An example of an MNREAD sentence used in the study. As illustrated here, the font was Times New Roman and the 56-character sentence was formatted onto four lines of 13 characters (including spaces). Note, however, that the text was rendered as white letters on a black background rather than the black-on-white rendering shown here. (B, C, and D) Examples of the three types of transformed stimuli. (B) Continuous sentence, unspaced. (C) Random sequence (obtained by scrambling word order in A). (D) Random sequence, unspaced. LVO = low vision old; LVY = low vision young; NVO = normal vision old; NVY = normal vision young.

Apparatus and Procedure

The stimuli were presented using an Indy workstation (Silicon Graphics Inc., Mountain View, CA) and a Sony color graphics display monitor (model GDM-17E11, refresh rate = 75 Hz; New York, NY).

For normally sighted participants, the text was composed of 26 point Times Roman letters (x-height = 0.35 cm). At the viewing distance of 40 cm, the corresponding character size subtended 0.5° of visual angle. These participants were encouraged to use their reading correction, if any. None of the participants complained of blur.

For low-vision participants, viewing distance and print size were adjusted to the individual's preference. First, viewing distance was set at 40 cm and the print size enlarged on the screen up to a maximum of 150 points. At larger print sizes, the full 13-character lines would not fit on the screen. If participants required greater magnification, they were permitted to find a shorter viewing distance that they judged to be acceptable. Once the print size and viewing distance were acceptable to the participant, these values were maintained throughout testing. Low-vision participants were also encouraged to use their reading corrections, if any, and typically wore them at their preferred reading distance. None of the low-vision participants complained of blur for the viewing distance and screen magnification used in the reading trials. Values of viewing distance and angular character size for the low-vision participants are given in Table 1.

In all cases, sentences were presented as white characters on a black background with a contrast of approximately 90%. We used "reverse-contrast" text because a substantial subset of low-vision participants read faster with and prefer white text on a black background.[9,41–43] Contrast reversal is known to have little or no effect on normal reading speed.[44] At the beginning of a reading speed trial, a string of ###'s occupying one line of 13 characters appeared at the top left corner of the computer screen and oriented the participant to the location of the upcoming test sentence. The participant triggered the presentation of the test sentence by pressing the space bar on a computer keyboard. The participant read each sentence orally, and the experimenter recorded the number of errors. Participants were permitted to complete their oral reading of the sentence after the screen display terminated and were also permitted to correct misspoken words. Words spoken out of order counted as correct. An error was defined as any omitted word or incorrectly read word in a sentence. Reading speed for the trial was computed as the exposure time divided by the number of words correctly read.

A reading speed measurement for a given stimulus type was conducted in two steps as follows. First, the experimenter used the pool of practice stimuli to find the exposure time for which the participant made a small, nonzero number of errors (the desired performance level was two or three errors). This exposure time was found through a series of reading trials with the practice stimuli in which the experimenter adjusted the exposure time on successive trials. Typically starting with a 2-second exposure time, the experimenter increased or decreased the exposure time (the step size was 0.05 log units, equivalent to increase or decrease in exposure time by a factor of 1.122) depending on whether the participant made too many or two few errors. This adjustment phase terminated when an exposure time yielding the desired performance level was reached. In step 2, using this exposure time, the participant was tested on 10 reading trials. The participant's reading speed for the stimulus type in question was the mean reading speed from these 10 trials.

Each participant contributed two such reading speeds for each of the four stimulus types. There are 24 possible orderings of the four stimulus types. The two repetitions of testing for each of the 10 participants in a group were assigned to two unique orderings of the set of 24 (with each group of 10 participants using only 20 of the 24 orderings). Overall, each participant was tested in eight conditions consisting of two repetitions of the four stimulus types. Ten test stimuli (described in step 2 previously) for each condition were drawn at random without replacement from the pool of 114 test sentences. No participant saw the same sentence more than once.

Analysis of Log Reading Speeds

Our statistical analyses were performed on log reading speeds. Antilogs were taken for reporting values in the manuscript so that numeric reading speeds would be in a more familiar metric, e.g., 200 words per minute rather than 2.3 log words per minute. Log reading speeds have been frequently used in studies of low-vision reading because of the wide range of reading speeds involved, because variability is more nearly constant for log reading values, and because percentage variations (multiplicative changes) seem to be more functionally salient than linear changes in reading speed.

Because a given difference in log reading speed resulting from a stimulus difference (such as presence or absence of spaces) corresponds to a given ratio of the reading speeds, it is conventional practice to plot ratios of reading speeds, rather than differences, when log reading speeds are being analyzed. For example, if a pair of log reading speeds differ by 0.3 log units (logR1 – logR2 = 0.3), the corresponding ratio is approximately 2.0 (R1/R2 = 2.0). Thus, we plot ratios of reading speeds in Figures 2 and 3.

RESULTS

Reading Speeds in the Standard Condition

We refer to sentences with correct word order and normal spacing as the "standard condition." Reading speeds in the standard condition are shown for individual low-vision participants in Table 1 and for the four groups in Table 3. There were statistically significant main effects of vision status (normal versus low) ($F[1,36] = 42.45, p < 0.001$) and age ($F[1,36] = 8.69, p < 0.01$). The interaction of vision status and age was not significant ($F < 1$).

As expected, the low-vision participants read more slowly than the normal participants. The low-vision mean is 36% of the normal mean. This value is undoubtedly dependent on the composition of the low-vision sample but is similar to values in some other studies in our laboratory.[45] Also not surprising, the variability in reading speeds was greater among the low-vision participants.

We also note that the old participants read more slowly than the young participants, averaging 67% of the young reading speeds. We will return to this finding in the "Discussion" section and resolve an apparent discrepancy with previous findings of a lack of aging effects in reading speed.[31]

The mean reading speeds in Table 3 are high compared with commonly cited normative values for college students of approximately 280 words per minute.[46] Two factors account for the higher values for our normal participants. First, our method pushes people to their maximum reading speed rather than measuring their preferred reading speed, a manipulation that can have an impact of up to 50% on reading speed[47]

Second, the MNREAD sentences use mostly short words, tending to inflate the reading speeds. Carver[48] has proposed a metric for measuring reading speed that circumvents the problem of unequal mean word length across texts. He recommends measuring reading speed in characters per second or, equivalently, "standard-length words" per minute, in which one standard length word is equal to six characters. Our MNREAD sentences all had 56 characters, equal to 9.33 standard-length words. Because our test MNREAD sentences averaged 11.5 actual words, conversion to reading speed in standard-length words per minute would involve reducing our measured reading speeds to 81% of the values reported here (9.3 of 11.5 = 0.811). Accordingly, the mean reading speeds in Table 3 would reduce to the following values in standard-length words per minute—413 (young normal), 296 (old normal), 172 (young low vision), and 86 (old low vision).

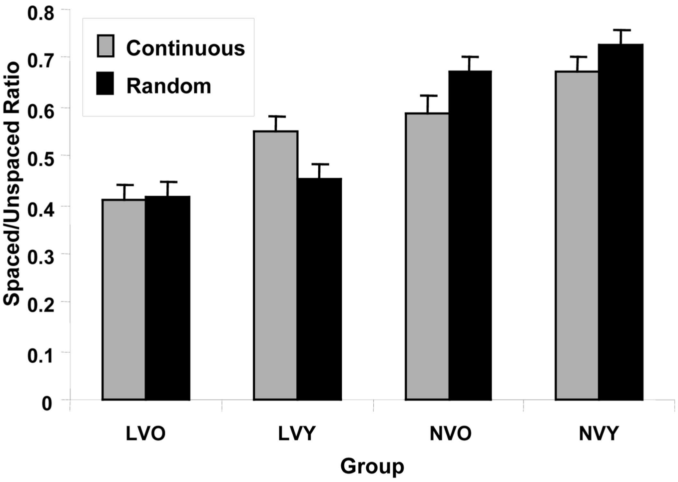


FIGURE 2.

Ratios of reading speeds for unspaced and spaced text for four groups of participants. Each group ratio was found by first computing the mean difference in log reading speeds for unspaced and spaced text across the group and then taking the antilog of the mean (see "Method" section). Error bars show the variations associated with one standard error of the mean. LVO = low vision old; LVY = low vision young; NVO = normal vision old; NVY = normal vision young.

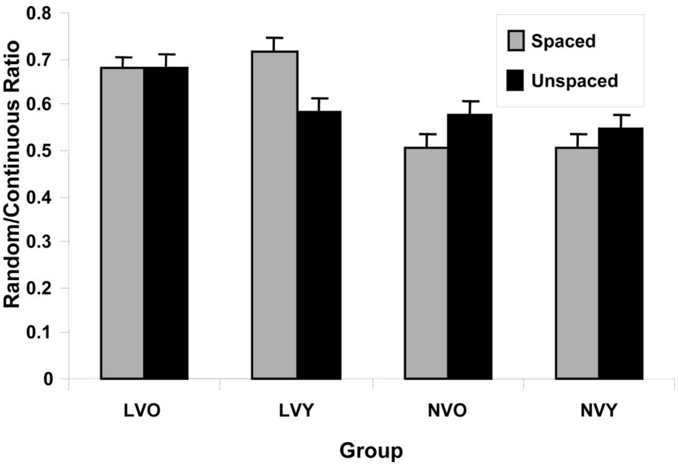


FIGURE 3.

Ratios of reading speeds for random sequences and continuous sentences for four groups of participants. Each group ratio was found by first computing the mean difference in log reading speeds for random sequences and continuous text across the group and then taking the antilog of the mean (see "Method" section). Error bars show the variations associated with one standard error of the mean.

TABLE 3.

Mean reading speeds for four groups[a]

Group	Mean reading speed (wpm)	SD	SD/mean (%)
Young NV	510	180	35
Old NV	365	158	43
Young LV	212	132	62
Old LV	106	58	54

[a] Mean reading speed (words per minute [wpm]) = reading speed in words per minute for the normally spaced and continuous sentences, termed the "standard condition."

NV = normal vision; LV = low vision.

Analysis of Variance

For reasons described at the end of the "Methods" section, statistical analyses were performed on log reading speeds. A 2 (spacing: spaced, unspaced) × 2 (context: continuous, random) × 2 (vision: low, normal) × 2 (age: young, old) repeated-measures analysis of variance was used to analyze the data. Over all conditions, people with normal vision read more quickly than people with low vision ($F[1,36] = 41.83$, $p < 0.01$), younger people read more quickly than older ($F[1,36] = 7.95$, $p < 0.01$), continuous sentences were read more quickly than random sequences ($F[1,36] = 410.63$, $p < 0.01$), and spaced sentences were read more quickly than unspaced sentences ($F[1,36] = 523.24$, $p < 0.01$).

The corresponding mean ratios of reading speeds, collapsed across the other conditions, were: low vision/normal vision = 0.29, old/young = 0.58, random/continuous = 0.59, unspaced/spaced = 0.55. We have adopted the arbitrary convention of expressing such ratios with the lower reading speed in the numerator so that the numbers range from zero to 1.0. These ratios can easily be expressed as percentages by multiplying by 100. For instance, across all groups and across the random and continuous conditions, the unspaced/spaced ratio was 0.55. That is, unspaced text was read 55% as fast as regularly spaced text.

The four-way interaction was not statistically significant. In the following subsections, we address all the significant two- and three-way interactions.

Figures 2 and 3 summarize the group data in bar plots showing ratios that correspond to mean log differences (see "Methods" section). Figure 2 shows ratios of reading speeds for unspaced and spaced text, and Figure 3 shows ratios of reading speeds for random sequences and continuous sentences. This representation of the group results highlights the effects of spacing and context, the two stimulus variables of focus in this article.

Reading Speeds for Spaced and Unspaced Text

Ratios of reading speed for spaced and unspaced text are plotted in Figure 2 for all four groups of subjects for both the random sequences and continuous sentences. As described in the "Methods" section, statistical tests were performed on log reading speeds, and the ratios in Figure 2 correspond closely to group differences in mean log reading speed. Note that ratios are always lower than 1.0 because unspaced text was always read more slowly than spaced text.

Consistent with prediction, there was a space × vision interaction ($F[1,36] = 52.86$, $p < 0.01$) such that people with low vision experienced a greater reading speed reduction (expressed as a ratio) for the unspaced sentences than people with normal vision. The corresponding mean ratios of reading speed for unspaced and spaced text, collapsing across age and context condition were: low vision = 0.45 and normal vision = 0.66. In other words, the low-vision participants read the unspaced text at less than half the speed of regularly spaced text, whereas the normally sighted participants read unspaced text at approximately two-thirds the rate of regularly spaced text.

Within the low-vision group, we predicted a greater spacing effect for the old relative to the young. Consistent with prediction, in a planned comparison we found that the difference between the spaced and unspaced sentences was greater for old low vision than young low vision ($p < 0.01$). The corresponding mean ratios were 0.41 for old low vision and 0.50 for young low vision.

The spacing results confirm two of the hypotheses presented in the "Introduction": the spacing effect is greater for people with low vision, and it is greater for older people with low vision than for younger people with low vision.

Reading Speeds for Continuous versus Random Text

Figure 3 plots ratios of reading speed for the random sequences and continuous sentences for the four groups and two spacing conditions. Note that ratios are always lower than 1.0 because random text was always read more slowly than continuous text.

There was a context × vision interaction ($F[1,36] = 36.73$, $p < 0.0$), but the directionality was contrary to our prediction; there was a greater decrease in reading speed (in ratio terms) in normal vision for random versus continuous text than for low vision. The corresponding mean ratios of reading speeds for random versus continuous text, collapsing across age and spacing, were 0.66 for low vision and 0.53 for normal vision. These results indicate that there is a greater context effect for normal vision. By inverting the mean ratios, we see that normal participants read the continuous text 1.87 times faster than the random sequences, whereas the low-vision subjects read the continuous sentences 1.51 times faster than the random sequences.

Also contrary to prediction, no context × age interaction emerged ($F < 1$). Within the low-vision group, we also predicted a reduced context effect for the old relative to the young. Inconsistent with prediction, in a preplanned comparison, we did not find a significant difference in old versus young reading speed as a function of context ($p = 0.13$).

Contradicting our hypotheses concerning context effects, we found: 1) context effects were larger in normal vision than in low vision; 2) there was no effect of age (young versus old); and 3) there was no evidence of an age-related attenuation of context effects in low vision.

Interactive Effect of Space and Context on Reading Speed

Although there was no two-way space × context interaction, we found a three-way space*context*vision interaction. Specifically, using a post hoc contrast, we found that normally sighted participants showed a greater spacing difference between random sequences and continuous sentences than low-vision participants (Bonferroni corrected, $p < 0.007$).

This result can be understood by inspecting Figure 3. In this figure, the size of the context effect is given by the height of the bars with smaller random/continuous ratios (shorter bars) representing a greater context effect (equivalent to a larger difference in log reading speeds). For the normal subjects, the context effect is slightly larger for the spaced than the unspaced condition. This small effect is consistent with the idea that the context effect diminishes under more difficult stimulus conditions. Here, unspaced text is more difficult than spaced text, *and* there is a slightly reduced context effect for normally sighted subjects. This difference is weaker in the low-vision groups because their context effect is smaller to begin with and the additional influence of spacing is harder to detect. Because this three-way interaction is small and difficult for us to interpret in the context of the hypotheses posed at the end of the "Introduction," we do not address it further in the "Discussion."

DISCUSSION

Our findings confirm the hypothesis presented in the "Introduction" that removing spaces from text is more deleterious for low vision than for normal vision. Because of our focus in this article on linguistic effects, we concentrate our discussion on the impact of removing spaces on text segmentation. Later, we briefly comment on explanations based on lateral masking or eye movement control.

People with low vision may rely more on spatially local cues to text segmentation than people with normal vision. Examples of spatially local cues include spaces between words and punctuation marks; these features typically occupy only one or two character spaces. More spatially distributed features would include whole word identification or clusters of letters marking the beginnings or ends of words (e.g., prefixes such as "pre" or suffixes such as "ment" or "ing"). These spatially extended features typically rely on lexical knowledge and require visual decoding of several adjacent characters. Removal of spaces from text eliminates a key local feature for string segmentation and forces greater reliance on spatially extended features.

As discussed in the "Introduction," people with low vision are likely to have reduced visual spans,[2] that is, on each fixation, they are able to recognize fewer letters. The more severe the reduction in visual span, the less available are spatially distributed cues for text segmentation. In extreme cases, if the visual span is only one or two characters, only local cues would be available for text segmentation within a single fixation. If the local cues are deleted (no punctuation, no spaces), the low-vision reader must revert to the challenge of inferring the beginnings and endings of words from views of one or two letters on a series of fixations. No single fixation would carry an explicit marker for word boundaries.

We predicted that the spacing effect would be larger in old compared with young people with low vision, and this is what we found. The rationale for this prediction was that lexical demands of integrating information for segmenting unspaced text would have more impact on older people with low vision. This may be the correct interpretation, but the lack of an age effect in our context manipulation (see the discussion subsequently) suggests that we consider an alternative explanation. It is possible that the older group had smaller visual spans than our younger group despite the fairly close matching of acuities and contrast sensitivities between the two groups. If so, the larger deleterious impact of removing spaces may be the result of a visual factor rather than age per se. Consistent with this possibility, our group of old low-vision participants read more slowly overall than our young low-vision participants (Table 3).

Our results are consistent with the hypothesis that spatially extended, structural regularities of words and text are less available to low-vision readers who rely more heavily on spatially local features for identifying word boundaries. If this interpretation is correct, we have identified a subtle interaction between linguistic properties of text and vision status that influences low-vision reading speed.

Our findings reinforce the importance of well-specified local indicators of word boundaries in text for people with low vision. Although we did not validate our findings with real-world text, our results suggest that distinctive spacing information is important when individuals with low vision read medicine labels, street signs, and public documents and forms, including U.S. currency bills. In addition to distinctive spacing between words, we speculate that text for low vision would benefit from other local cues for segmenting text such as highly salient punctuation marks. Recently, two fonts have been designed specifically for use by people with low vision—a large-print variant of the Tiresias family of fonts developed at the Royal National Institute of the Blind[49] and APHont developed at the American Printing House for the Blind[50] (both of these font design projects were guided by surveys of low-vision readers, and both fonts include enlarged punctuation symbols in response to the preferences of people with low vision). However, notice that our findings and interpretation do not imply an advantage for extra-wide spacing between words.

We have explained the greater impact on low vision of removing spaces as a problem of text segmentation exacerbated by a reduced visual span. We briefly comment on alternative interpretations based on lateral masking (crowding) and eye movement control. As discussed in the "Introduction," one effect of removing spaces between words would be to increase lateral masking, because the beginning and ending letters of words would no longer have a space on one side. The increased lateral masking would be expected to be more prominent for low-vision participants who rely on peripheral vision because of central scotomas. This account is quite compatible with our explanation based on size of the visual span. As we mentioned in the "Introduction," lateral masking (crowding) is one factor that determines the size of the visual span. Increased lateral masking, as a result of removal of spaces, would probably be accompanied by a smaller visual span. In other words, increased lateral masking resulting from removal of spaces might result in an effectively smaller visual span and corresponding reduction in reading speed.

In the "Introduction," we briefly reviewed the debate over the effect, or lack of effect, of removing spaces on normal reading eye movements.[12,13,15,16] It is well established that reading saccades are shorter than normal in some forms of low vision, including ARMD.[20] These shorter saccades are associated with slower reading. It is possible that the planning of these shorter saccades, or some other aspect of oculomotor control, is more affected by the removal of spaces in low vision than in normal vision. If so, it remains to be discovered why such oculomotor differences should be greater in low vision.

Sentence context is another potential source of information supporting reading speed. A widely used method for assessing sentence context, and the one we used, compares reading speed for continuous sentences and "sentences" with scrambled word order. Our findings indicate a weaker sentence context effect (less advantage for reading regular sentences over scrambled word sequences) for low vision than for normal vision. This finding is consistent with the weaker context effects for normally sighted readers when reading under difficult viewing conditions, e.g., using peripheral vision to read[22,23] or reading with simulated cataracts[24] (the reduced context effect in low vision is consistent with the view, outlined in the "Introduction," that there is an extra cognitive load associated with decoding low-quality visual input; the extra cognitive load would require extra cognitive resources [memory, attention] and would deplete top-down cognitive resources needed for contextual prediction). In our discussion of spacing effects, we briefly mentioned the challenge of integrating information about words from small samples of text encoded with small visual spans. It is possible that low-vision readers trade computational effort at the level of sentence context prediction in favor of computational effort at predicting individual words from recognition of a few letters.

An anonymous reviewer suggested another possible explanation for the reduced context effect in low vision. Perhaps low-vision readers have more experience with scrambled word order because they read text less sequentially than normally sighted readers (i.e., they use more regressive saccades in identifying words and word meaning). Putting this in slightly different terms, perhaps scrambling word order has a reduced effect in low vision because these readers have more practice decoding words in a somewhat scrambled order.

On the other hand, studies of reaction times for naming words after presentation of a sentence[28] have shown a consistent pattern of effects for good and poor readers with normal vision. In the sentence-priming paradigm, the participant reads a sentence aloud with the last word ("target" word) missing. Then the target is presented, and the participant names it as quickly as possible. Three conditions are compared in which targets are semantically predictable ("congruous"), semantically out of place ("incongruous"), or semantically neutral ("neutral"). Comparisons across these conditions reveal both facilitation and inhibition of word recognition times by sentence context. A robust general finding is that overall context effects are smaller in good readers than poor readers (for a review, see Stanovich[51]). Stanovich and West[28] also showed that by degrading the visual quality of the target word, good readers behaved more like poor readers in showing amplified context effects. Stanovich[26] has interpreted the pattern of results across a range of experiments with the sentence-priming paradigm in terms of an interactive compensatory model. The key points are that 1) word recognition uses several sources of information, principally bottom-up visual input and top-down contextual inference; and 2) when the bottom-up visual input is less reliable or is processed less efficiently by perception, greater weight is given to the top-down information. The result is a greater context effect (top-down effect) when visual input is deficient.

A prediction from the Stanovich[26] model is that people with low vision should show greater context effects than people with normal vision, because of lower quality perceptual input. Our results with the scrambled-text paradigm are clear in showing the opposite effect, a stronger context effect for normal vision than low vision. We cannot be sure how to reconcile our findings with Stanovich's[26] findings. A more direct test of the Stanovich[26] model would be to measure low-vision context effects in the sentence-priming paradigm. If low-vision participants showed the predicted increase in context effects in this situation, we could seek reconciliation by looking at key differences between the two paradigms.

Our discussion of the Stanovich[26] work attempts to establish contact between the psychophysical work on context effects in reading, of which the present article is an example, and the substantial educational literature on context effects in good and poor normally sighted readers. It should be noted that "poor reading" in low vision is presumptively the result of sensory deficits from eye disease. In reality, however, it is likely that acquired low vision afflicts adults categorized as both good and poor readers before the onset of low vision. Whatever the factors are that distinguish good and poor reading in people with normal vision, these factors are likely to interact with sensory limitations in determining low-vision reading performance. We expect that such differences in reading ability, predating the onset of low vision, contribute to variability in measurements of low-vision reading performance.

In the "Introduction," we also predicted a greater context effect for young than old participants. The premise of this prediction was that the attentional resources required for contextual inference in reading might be less available for older readers. To the extent that cognitive demands are greater in low vision, we also predicted an interaction effect where the age-related attenuation of context effects would be greater in low vision than in normal vision. Contradicting this view, we found no significant age-related differences in context effects and no significant interaction effect.

Our finding of a difference in context effects between normal and low vision, but a lack of a difference between our young and old groups may reveal an interesting distinction. Whatever attentional or other cognitive resources are used in making use of sentence context are not affected by aging per se, but are affected by difficulties in visual information processing.

As mentioned earlier, we did find a greater deleterious effect of removing spaces for older low-vision readers. We do not attribute this age difference to reduced attentional resources in older participants, because we did not observe a general age by context interaction. Our preferred interpretation is not based on age differences in attentional resources, but that our older low-vision participants probably had smaller visual spans on average.

Before concluding, we turn to a discussion of aging effects on normal reading speed and the resolution of an apparent discrepancy in the literature. In the present study, we found that the old normal participants read more slowly than the young normal participants, averaging 67% of the young reading speeds. This finding appears to differ from a previous study in our laboratory[31] in which groups of young and old participants did not differ significantly in reading speed for a range of medium character sizes (0.3° to 1.0°). (For both larger and smaller characters, Akutsu et al.[31] did find slower reading in the older group and explained the deficits in terms of young-old differences in contrast sensitivity.)

The apparent difference between the Akutsu et al.[31] findings (lack of an age-related decrease in reading speed) and the significant age-related difference in the present study can be understood in terms of the screening and classification of older participants. In both studies, older participants were enrolled in the studies based on self reports of good eye health and laboratory screening tests verifying letter acuity and contrast sensitivity in the normal range. In the Akutsu et al.[31] study, we obtained detailed clinical reports from the 19 participants' optometrists and ophthalmologists. These reports revealed that nine had no signs of eye disease (termed the "old normal" group), five had early signs of eye disease, four with cataract and one with retinal detachment, (termed the "mild disease group"), one had intraocular lenses from cataract surgery, and we were unable to obtain satisfactory clinical reports on four. Accordingly, of the entire group of 19 older participants, we were able to verify completely healthy vision only in nine, the "old normal group." It is this highly screened group that did not show a statistically significant difference from the young normal group for a limited range of print sizes. However, Akutsu et al.[31] also reported that the larger subset of 14 older participants (nine "normal" and five "mild disease") read significantly slower than the young normal group, with differences ranging from 10% to 34%, depending on character size. For 0.5° characters (the same as the character size in the current study), Akutsu et al.'s[31] larger group of 14 older participants had a mean reading speed that was 84.4% of that of the young normal group (295 words per minute for the older group and 349 words per minute for the younger group.)

In the present study, our acceptance criteria for older participants included self-reports of good eye health (no known eye disease) and laboratory measurement of letter acuity and contrast sensitivity in the range for normal vision. (However, as shown in Table 2, the old normal group had significantly poorer visual acuity and contrast sensitivity than the young normal group.) This makes our group comparable to the unscreened larger group of 14 participants in the Akutsu et al.[31] study. (From a practical point of view, such groups represent older participants who read without visual complaint, and such groups are commonly used in psychologic or psychophysical testing.) In agreement with Akutsu et al.,[31] in the present study, we found that older participants with self-reported normal vision read more slowly than young participants, 67% of the young normal rate in the present study compared with 84.4% in the Akutsu et al.[31] study. This small discrepancy might be the result of differences in the method for measuring reading speed (drifting text used by Akutsu et al.,[31] versus static MNREAD sentences in the present study), differences in the ages of the older participants in the two groups (mean 68.7 for Akutsu et al.[31] and 75.8 for the old-normal group in the present study), or differences in acuity or contrast sensitivity of the two groups.

We believe that these comparisons make an important point. Age differences in reading speed may often be attributable to subtle visual deficits, even in participants with no diagnosed eye disease. Strong corroboration for this point comes from a recent large population-based study.[52] Lott et al.[52] obtained reading speeds and many other measures of visual and nonvisual function from 900 participants. Reading speed data were analyzed from a subsample of 544 participants with good acuity (better than 20/32). Their ages ranged from 58 to 102 years. Reading speed was found to decline with age, but multiple regression analysis indicated that when other measures were taken into account (especially low contrast acuity, a measure of motor ability, and a measure of attention), age was no longer an independent predictor of reading speed. An interpretation of these findings is that reading speed declines in old age, even for people with normal visual acuity and self-reported healthy vision. However, it is likely that much of the measurable decline can be traced to subtle visual, motor, or attention deficits, with the prevalence of these subtle deficits increasing with age.

The issue of the relationship among age, sensory deficits, and cognitive deficits is an important and subtle one. The preceding paragraphs take the view that subtle sensory deficits increase in prevalence with age and that age-related declines in reading (or other cognitive tasks) are attributable, at least in part, to these sensory deficits. A useful review of age-related vision deficits and their impact on cognitive function is given by Scialfa.[53] However, there is also persuasive evidence for relatively large, age-related declines in normal cognitive function per se. See, for instance, the recent review by Salthouse.[54] Thus, although sensory aging may play a causal role in affecting reading speed, it may also be the case that other, independent causal factors may result in age-related declines in both sensory and cognitive function.

In this article, we have explored the interactions among linguistic properties of text, vision status, and age in influencing reading speed. We conclude: 1) the reading speeds of people with low vision suffer more from the removal of spaces from text, consistent with a greater reliance on local features of text, especially spaces, for identifying word boundaries, than on larger components of words such as prefixes, suffixes, or whole word identification; 2) people with low vision benefit less from sentence context than people with normal vision; and 3) age (young versus old) does not play a major role in differentiating the usefulness of linguistic cues for text segmentation or in using sentence context.

ACKNOWLEDGMENTS

We thank J. Stephen Mansfield for his help with programming and equipment issues. This research was supported by NIH grant EY02934 to Gordon E. Legge.

Portions of this research were presented at the 14th annual National Conference for Undergraduate Research, April 19–26, 2000, Missoula, Montana.

Received January 20, 2004; accepted November 28, 2005

REFERENCES

1. Leat SJ, Legge GE, Bullimore MA. What is low vision? A reevaluation of definitions. Optom Vis Sci 1999;76:198–211.
2. Legge GE, Ahn SJ, Klitz TS, Luebker A. Psychophysics of reading. XVI. The visual span in normal and low vision. Vision Res 1997;37:1999–2010.
3. Legge GE, Mansfield JS, Chung ST. Psychophysics of reading. XX. Linking letter recognition to reading speed in central and peripheral vision. Vision Res 2001;41:725–43.
4. Legge GE, Lee HW, Owens D, Cheung SH, Chung ST. Visual span: a sensory bottleneck on reading speed. J Vis 2002;2:279a. Available at: http://journalofvision.org/2/7/279/. Accessed December 1, 2005.
5. Chung ST, Legge GE, Cheung SH. Letter-recognition and reading speed in peripheral vision benefit from perceptual learning. Vision Res 2004;44:695–709.
6. Legge GE. Psychophysics of Reading in Normal and Low Vision. Mahwah, NJ: Lawrence Erlbaum Associates Inc. 2006.
7. Bouma H. Interaction effects in parafoveal letter recognition. Nature 1970;226:177–8.
8. Chung ST. The effect of letter spacing on reading speed in central and peripheral vision. Invest Ophthalmol Vis Sci 2002;43:1270–6.
9. McConkie GW, Rayner K. The span of the effective stimulus during a fixation in reading. Percept Psychophys 1975;17:578–86.
10. Rayner K, Well AD, Pollatsek A. Asymmetry of the effective visual field in reading. Percept Psychophys 1980;27:537–44.
11. Spragins AB, Lefton LA, Fisher DF. Eye movements while reading and searching spatially transformed text: a developmental examination. Mem Cognition 1976;4:36–42.
12. Epelboim J, Booth JR, Steinman RM. Reading unspaced text: implications for theories of reading eye movements. Vision Res 1994;34:1735–66.
13. Rayner K, Fischer MH, Pollatsek A. Unspaced text interferes with both word identification and eye movement control. Vision Res 1998;38:1129–44.
14. Bouma H. Visual interference in the parafoveal recognition of initial and final letters of words. Vision Res 1973;13:767–82.
15. Epelboim J, Booth JR, Steinman RM. Much ado about nothing: the place of space in text. Vision Res 1996;36:465–70.
16. Rayner K, Pollatsek A. Reading unspaced text is not easy: comments

on the implications of Epelboim's (1994) study for models of eye movement control in reading. Vision Res 1996;36:461–70.

17. Legge GE, Hooven TA, Klitz TS, Mansfield JS, Tjan BS. Mr. Chips 2002: new insights from an ideal-observer model of reading. Vision Res 2002;42:2219–234.
18. Morton J. The effects of context upon speed of reading, eye movements, and eye–voice span. Q J Exp Psychol 1964;16:340–54.
19. Miller GA, Selfridge JA. Verbal context and the recall of meaningful material. Am J Psychol 1950;63:176–85.
20. Bullimore MA, Bailey IL. Reading and eye movements in age-related maculopathy. Optom Vis Sci 1995;72:125–38.
21. Baldasare J, Watson GR, Whittaker SG, Miller-Shaffer H. The development and evaluation of a reading test for low vision individuals with macular loss. J Visual Impair Blin 1986;80:785–9.
22. Chung ST, Mansfield JS, Legge GE. Psychophysics of reading. XVIII. The effect of print size on reading speed in normal peripheral vision. Vision Res 1998;38:2949–62.
23. Latham K, Whitaker D. A comparison of word recognition and reading performance in foveal and peripheral vision. Vision Res 1996;36: 2665–74.
24. Fine EM, Peli E, Reeves A. Simulated cataract does not reduce the benefit of rapid serial visual presentation. Vision Res 1997;37: 2639–47.
25. Fine EM, Hazel CA, Petre KL, Rubin GS. Are the benefits of sentence context different in central and peripheral vision? Optom Vis Sci 1999;76:764–9.
26. Stanovich KE. Toward an interactive–compensatory model of individual differences in the development of reading fluency. Read Res Q 1980;16:32–71.
27. Stanovich KE, West RF. On priming by a sentence context. J Exp Psychol Gen 1983;112:1–36.
28. Speranza F, Daneman M, Schneider BA. How aging affects the reading of words in noisy backgrounds. Psychol Aging 2000;15:253–8.
29. Legge GE, Ross JA, Luebker A, LaMay JM. Psychophysics of reading. VIII. The Minnesota Low-Vision Reading Test. Optom Vis Sci 1989;66:843–53.
30. Fine EM, Peli E. The role of context in reading with central field loss. Optom Vis Sci 1996;73:533–9.
31. Akutsu H, Legge GE, Ross JA, Schuebel KJ. Psychophysics of reading. X. Effects of age-related changes in vision. J Gerontol 1991;46: 325–31.
32. Legge GE, Ross JA, Isenberg LM, LaMay JM. Psychophysics of reading. XII. Clinical predictors of low-vision reading speed. Invest Ophthalmol Vis Sci 1992;33:677–87.
33. Ahn SJ, Legge GE. Psychophysics of reading. XIII. Predictors of magnifier-aided reading speed in low vision. Vision Res 1995;35: 1931–8.
34. Lovie-Kitchin JE. Reading performance of adults with low vision [PhD dissertation]. Queensland: Queensland University of Technology, 1996.
35. Lovie-Kitchin JE, Bowers AR, Woods RL. Oral and silent reading performance with macular degeneration. Ophthal Physiol Opt 2000; 20:360–70.
36. Anderson ND, Craik FIM. Memory in the aging brain. In: Tulving E, Craik FIM, eds. The Oxford Handbook of Memory. London: Oxford University Press, 2000:411–26.
37. Balota DA, Dolan PO, Duchek JM. Memory changes in healthy older adults. In: Tulving E, Craik FIM, eds. The Oxford Handbook of Memory. Oxford: Oxford University Press, 2000:395–409.
38. Lighthouse International. New York: c 1998–2003. Available at: www.lighthouse.org/vision_impairment_causes.htm#mac. Accessed January 20, 2004.
39. Pelli DG, Robson JG, Wilkins AJ. The design of a new letter chart for measuring contrast sensitivity. Clin Vis Sci 1988;2:187–99.
40. Folstein MF, Folstein SE, McHugh PR. "Mini-Mental State." A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 1975;12:189–98.
41. Sloan LL. Reading Aids for the Partially Sighted: A Systematic Classification and Procedure for Prescribing. Baltimore: Williams & Wilkins, 1977.
42. Rubin GS, Legge GE. Psychophysics of reading. VI. The role of contrast in low vision. Vision Res 1989;29:79–91.
43. Legge GE, Rubin GS, Schleske MM. Contrast-polarity effects in low-vision reading. In: Woo GC, ed. Low Vision: Principles and Applications. Proceedings of the International Symposium on Low Vision, University of Waterloo, June 25–27, 1986. New York: Springer-Verlag, 1986:288–307.
44. Legge GE, Rubin GS, Luebker A. Psychophysics of reading. V. The role of contrast in normal vision. Vision Res 1987;27:1165–77.
45. Bruggeman H, Legge GE. Psychophysics of reading. XIX. Hypertext search and retrieval with low vision. Proc IEEE 2002;90:94–103. Available at: http://gandalf.psych.umn.edu/legge/read19.pdf. Accessed December 1, 2005.
46. Taylor SE. Eye movements in reading: facts and fallacies. Am Educ Res J 1965;2:187–202.
47. Huey EB. The Psychology and Pedagogy of Reading, With a Review of the History of Reading and Writing and of Methods, Texts, and Hygiene in Reading. New York: Macmillan, 1908.
48. Carver RP. Reading Rate: A Review of Research and Theory. San Diego: Academic Press, 1990.
49. Perera S. LPfont: an investigation into the legibility of large print typefaces. Available at: www.tiresias.org/fonts/lpfont/report/index.htm. Accessed October 4, 2004.
50. Kitchel JE. American Printing House for the Blind Educational Research. Large Print: Guidelines for Optimal Readability and APHont™ a font for low vision. Available at: www.aph.org/edresearch/lpguide.htm. Accessed October 4, 2004.
51. Stanovich KE. Progress in Understanding Reading: Scientific Foundations and New Frontiers. New York: Guilford Press, 2000.
52. Lott LA, Schneck ME, Haegerstrom-Portnoy G, Brabyn JA, Gildengorin GL, West CG. Reading performance in older adults with good acuity. Optom Vis Sci 2001;78:316–24.
53. Scialfa CT. The role of sensory factors in cognitive aging research. Can J Exp Psychol 2002;56:153–63.
54. Salthouse TA. What and when of cognitive aging. Curr Dir Psychol Sci 2004;13:140–4.

Gordon E. Legge
N218 Elliott Hall
75 East River Road
Minneapolis, MN 55455
e-mail: legge@umn.edu