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Psychophysics of Reading—X. Effects of Age-Related Changes in Vision

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This study examined the influence of age-related changes in vision on reading performance. Maximum reading speed was measured in groups of young (n = 16, mean age 21.6 years) and old (n = 14, mean age 68.3 years) subjects, all with acuities of 20/32 or better. A psychophysical procedure was used for measuring reading speed that has proven reliable and sensitive to visual factors in previous research. Data were collected for character sizes ranging from .15° to 12°. Research revealed that old subjects who were free of eye disease read as fast as the young subjects for character sizes ranging from .3° to 1.0°. This is the range in which reading speed is maximum for young subjects. Research also revealed that old subjects showed a deficit when reading text composed of very small or very large characters. Their speeds dropped to about 70% of the young adult speeds. These deficits may be due to age-related losses in visual contrast sensitivity.

READING is crucial to full participation in most vocational, social, and recreational activities. Quality of life suffers for anyone who experiences difficulty in reading. The popular belief exists that in old age vision fails and reading becomes difficult or impossible. But is reading difficulty really an inevitable consequence of old age? There are two aspects to the question of age-related vision loss and reading.

First, the leading causes of low vision are eye diseases that afflict the elderly (e.g., macular degeneration, cataract, glaucoma). (Low vision refers to any chronic visual disability, not correctable by spectacles or contact lenses, that impairs everyday function. A Snellen acuity less than 20/60 is often taken as a criterion for low vision.) Seventy-one percent of all people with low vision are over 65 years of age (Kirchner & Peterson, 1979). In a series of studies, Legge and colleagues have asked how different forms of low vision affect reading performance (citations to these works are given as appropriate below). In these studies, Legge and colleagues evaluated the effects on reading of text variables likely to be important in low vision, such as character size and field size (Legge, Pelli, Rubin, & Schleske, 1985), and contrast (Legge, Rubin, & Luebker, 1987). They also revealed the importance of central-field loss and cloudiness of the ocular media in accounting for reading deficits (Legge, Rubin, Pelli, & Schleske, 1985).

Second, there is accumulating evidence that healthy aging eyes exhibit subtle visual deficits. For example, after 40 to 50 years of age, there are measurable losses in high-spatial-frequency contrast sensitivity (Derefeldt, Lennerstrand, & Lundh, 1979; Owsley, Sekuler, & Siemsen, 1983; Wright & Drasdo, 1985). Such losses might adversely affect performance on visual tasks involving fine detail, such as reading very small print. There is also evidence that the low-spatial-frequency enhancement of contrast sensitivity due to temporal modulation is diminished in people over 60 years of age (Sloane, Owsley, & Jackson, 1988; Wright & Drasdo, 1985). An age-related reduction in contrast sensitivity for moving gratings has also been reported (Owsley et al., 1983; Sekuler, Hutman, & Owsley, 1980; Wright & Drasdo, 1985). Together, these findings raise the possibility of age-related deficits in visual processing of large, moving targets. Since images of letters move across the retina during reading, we might anticipate age-related deficits in reading text composed of very large characters.

Evidence already exists for a link between contrast sensitivity and reading. Legge et al. (1987) measured reading rate (in words/minute) as a function of character size for text having a wide range of contrast values. They were able to relate their results to contrast-sensitivity functions measured with sine-wave gratings. This result suggested that spatiotemporal contrast sensitivity plays a role in limiting reading speed. Rubin and Legge (1989) showed that deficits in contrast sensitivity could be used to predict part (and sometimes all) of the deficits in reading speed of a group of low-vision subjects.

It is possible, therefore, that deterioration in contrast sensitivity or other age-related vision changes might affect reading performance. The purpose of this research is to ask whether deficits in reading performance accompany aging, even for people with healthy eyes.

Reading rate was measured as a function of angular character size for groups of young and old subjects. (Angular character size in degrees of visual angle depends on linear character size and viewing distance. Doubling the viewing distance decreases angular character size by about a factor of two. Retinal-image size of a target is proportional to its angular size.) Previous studies have shown that reading rates for normally sighted subjects are greatest for a range of intermediate character sizes ranging from about .3° to 2° (Legge, Pelli, Rubin, & Schleske, 1985; Legge, Ross, Leubker, & LaMay, 1989). Reading speed declines for smaller or larger characters. If contrast sensitivity plays a role in limiting reading speed, then age-related changes in low- and high-spatial-frequency contrast sensitivity will result in reading deficits for large and small characters, respectively. There should be relatively less effect for characters of an intermediate size, the range in which young people have maximum reading rates.

It is possible that visual changes in old age other than contrast sensitivity might cause a different pattern of results. For example, smaller pupil size and increasing density of the crystalline lens both contribute to lower retinal illuminance and might reduce reading speeds at all character sizes. Light levels were not varied in this study, but have shown elsewhere that reading rate in normal vision is little affected by large changes in photopic luminance (Legge & Rubin, 1986). There might also be nonvisual factors affecting reading performance in the elderly. It is expected that any deficit associated with age-related changes in cognitive function would appear as a reduction in maximum reading speed, occurring for characters of intermediate size.

One purpose of our character-size manipulation was to separate visual from other factors influencing reading, but we had a practical motivation as well. It is important to know whether the range of optimal character sizes is different for young and old readers. If the optimal range for old readers is narrower (or shifted to larger character sizes), the options for appropriate type fonts would be different.

Our measure of performance is *reading rate in words/minute*. A drifting-text method is used. A subject reads aloud a line of text that drifts across the face of a TV monitor. At low drift rates, the subject reads the text perfectly. The drift rate is adjusted upward until the subject makes a small number of errors. By this means, we find the drift rate at which oral reading departs from 100% accuracy. There is a sharp transition from perfect reading (no errors) to ineffective reading (many errors). This sharp transition can be used to give a good estimate of maximum reading speed (Legge et al., 1985).

The drifting-text method is an objective psychophysical means for evaluating the visual component of reading. It was designed to be insensitive to nonvisual factors that influence everyday reading, such as text complexity, cognitive or linguistic ability, reading strategy (skimming, etc.), motivation, and skill in manipulating magnifiers. It is a "forced-march" method in which subjects are pushed to their limits. It permits easy, computer-based control of stimulus parameters and objective scoring of reading performance. Our experience has shown that it yields highly reproducible data.

Everyday reading usually involves static text. We have used the drifting-text procedure in much of our previous work because it is particularly appropriate for work on low vision. Drifting text is convenient for work with very large character sizes, and it resembles text that is scanned through the field of high-power magnifiers. We have developed a new procedure for measuring reading rates with static text (Legge, Ross, Luebker, & LaMay, 1989). This study has shown that reading rates for drifting and static text have a very similar dependence on character size.

METHODS

Subjects. — Nineteen elderly subjects participated in the study (mean age 68.7, range 60–74 years) (see Table 1). All had acuities of 20/32 or better, and all were recruited based on self-reports of good ocular health. Follow-up reports from ophthalmologists and optometrists confirmed that nine subjects had completely healthy eyes (no identifiable pathology). These nine were termed the "old-normal" subgroup. Five subjects had early signs of eye disease; four with cataracts and one with retinal detachment. These five were termed the "mild-disease" subgroup. The remaining five subjects were excluded from the data analysis, four because

Table 1. Eye Condition/Acuity and Educational Level of Subjects ($N = 19$)

Subject	Age	Eye Condition	Eye Tested	Acuity[a]	Educational Level	Reading (hours/day)
A	68	Normal	L	1.25	High school graduate	2
B	71	Normal	R	.80	High school graduate	2
C	75	Normal	L	1.00	College graduate	1
D	65	Normal	R	.80	12th grade	1
E	67	Normal	R	.63	High school graduate	2
F	67	Normal	R	1.00	College graduate	2
G	67	Normal	R	1.00	3 yrs college	1
H	67	Normal	R	1.00	12th grade	1
I	63	Normal	R	.80	3 yrs college	2
J	69	Retinal detachment	R	.80	High school graduate	2
K	66	Cataract	R	.80	High school graduate	1
L	65	Cataract	R	.80	GED	2
M	77	Cataract	R	1.00	High school graduate	2
N	69	Cataract	R	1.00	2 yrs college	2
O	72	IOL[b] implant	R	.63	BBA	2
P	75	No report	R	1.00	MS	2
Q	60	No report	L	.80	College graduate	1
R	69	No report	L	.63	High school graduate	2
S	74	No report	R	1.00	High school graduate	1

[a]Acuity is decimal acuity in which 20/20 is 1.00 and 20/40 is .5, etc.
[b]IOL, intraocular lens.

recent reports were unavailable, and one because of an intraocular lens implant (i.e., Subjects O, P, Q, R, and S in Table 1).

All of the old subjects were native English speakers, and all lived independently. Most were recruited from the Honeywell Retiree Volunteer Project or the People's Center of Minneapolis, and were identified because they appeared to be in good ocular and mental health. Each subject filled out a brief questionnaire, including information on current reading habits and educational level (Table 1). All reported that they read one to two hours daily at the time of testing. Five had more than two years of college education, and the remaining nine were high school graduates.

The group of old subjects is representative of well-educated, independently living, retired people (aged near 70), who read on a daily basis without effort or need of special aids. They have normal visual acuity and no visual complaints.

The young group consisted of 16 subjects with normal vision and corrected acuities of 20/20 or better (mean age 21.6, range 19–30 years). All were University of Minnesota undergraduates. All were native English speakers.

The two groups differed significantly in visual acuity ($p <$ .05). When expressed in decimal notation (where 20/20 = 1, 20/200 = .1, etc.), the young group had a mean of 1.02 (*SD* .10). The old group had a mean decimal acuity of .91 (*SD* .16).

Apparatus. — For a more complete description of the apparatus, see Legge, Rubin, and Luebker (1987). Text was displayed on a Conrac SNA 17/Y monochrome monitor driven by a Grinnell GMR274 frame buffer and LSI-11/23 computer. To eliminate glare, room lights were extinguished during testing, and the monitor's screen was black except for a horizontal strip (25 cm wide × 1.8 cm high) through which a single line of text drifted (see Figure 1). The rectangular strip contained 22 character spaces. Legge, Pelli, Rubin, and Schleske (1985) and Legge, Rubin, Pelli, and Schleske (1985) have shown that a window width of five characters or more permits maximum reading rates for drifting text. The letters were displayed as black characters on a white background (110 candelas/m²). The Michelson contrast of the text (difference in luminance between letters and background divided by their sum) was .96. The type font was fixed-width, with serifs and descenders, similar to Courier.

Figure 1. An example of the text display.

Angular character size (defined as center-to-center character spacing) was controlled by changing viewing distance. It ranged from .15° (445 cm viewing distance) to 12° (11 cm viewing distance). (For the 12° condition, characters on the screen were zoomed up by a factor of 2. This meant that the rectangular strip contained 11 rather than 22 characters, and its height was 3.6 rather than 1.8 cm. This was done so that subjects would not have to be placed closer than 11 cm to the screen.) During testing, subjects wore their normal distance-lens correction (glasses or contacts). For each viewing distance, supplementary lens power was used (using a clip-on lens holder for subjects with glasses) so that the subject could focus clearly. The appropriate lens was chosen by placing static text on the screen and introducing lenses in small steps of dioptric power around the nominal correction for that distance. The added lens for which the subject said the text was clearest was then used.

The text material was selected from the passage "Plants that eat insects: a look at carnivorous plants" (Dean, 1977) [the text was slightly modified by Peter Eisenberg (1981)].

Procedure. — After informed consent was obtained, each subject completed a brief questionnaire on their medical history, education, and reading habits. Visual acuity was measured for each eye using the Lighthouse Distance Visual Acuity Test (second edition).

The reading test was conducted monocularly for two reasons. First, for the near viewing distances (i.e., large character sizes), it was difficult to converge the eyes to fuse binocularly. Second, several of the old subjects had marked differences between the left and right eyes. The subject's "better" eye was used in the reading experiment (i.e., the eye free from pathology or with higher acuity). When the two eyes were equal in these respects, the subject chose which eye to use. The other eye was covered with an eye patch. As shown in Table 1, the right eye was tested for 12 of 14 old subjects and for 13 of 16 young subjects. It is unlikely that there was a difference in ocular dominance between the two groups. Ocular dominance does not correlate highly with monocular performance on everyday tasks, including reading (Sheedy, Bailey, Buri, & Bass, 1986).

Before formal data collection, each subject was shown examples of drifting text and was given several practice trials. The practice trials used .2° characters (334 cm viewing distance). Stable performance occurred very quickly (typically within a few minutes), and formal data collection did not begin until this had occurred. At each new viewing distance, initial trials were conducted with low drift rates and acted as additional practice. Reading rates at different character sizes were collected in random order. A regression analysis indicated that position in the order did not have significant effect on reading speed. There was no evidence of effects due to fatigue.

Prior to a trial, the first character of an 80-character line of text was visible at the right margin of the screen. After giving a warning signal, the experimenter initiated the drift of the line of text across the screen. The subject read the text aloud. If no errors were made, the experimenter increased the drift rate and tested the subject on a new line. This procedure continued until the subject began to make errors. Then, a bracketing process quickly located the drift rate for which the subject made a small proportion of errors. Once this drift rate was established, a single measurement of reading rate was based on at least two lines of text. *Reading rate* in words/minute is equal to the corresponding drift rate in words/minute, multiplied by the proportion of words correctly read.

RESULTS

Our method for measuring reading speed relies on a sharp transition from perfect reading (no errors) to ineffective reading (many errors) as drift rate increases. Previous research has shown that a sharp transition exists for young readers (Legge, Pelli, Rubin, & Schleske, 1985), but does it exist for old readers as well? In Figure 2, data are shown for 14 old subjects (open triangles) and 16 young subjects (open circles). The horizontal axis is *Normalized Drift Rate* and refers to drift rates divided by the rate for which subjects were 90% correct. The vertical scale gives the percentage of words correctly read. The data were collected from the individual trials used to establish reading rates for these subjects. As Figure 2 shows, the transition from perfect reading to many errors is sharp, and follows the same pattern for young and old subjects. The transition from 100% correct to 50% correct occurs for a change in drift rate of only 20%. These results are consistent with the previous findings of Legge, Pelli, Rubin, and Schleske (1985), and confirm that this method for testing reading speed is equally applicable to young and old subjects.

In Figures 3 and 4, we present the data in two ways. Figure 3 compares mean results for the young group with mean results for all 14 old subjects. Nominally, all 14 had normal vision (by self-report), and their acuities were within the normal range (20/32 or better). From a practical point of view, they are representative of old subjects who read without visual complaint. Follow-up reports from ophthalmologists and optometrists indicated that only nine of these subjects were free from any sign of ocular pathology (see "Methods" and Table 1). In Figure 4, reading performance of the young group is compared with the subgroup of old subjects confirmed to be in good ocular health. From a theoretical point of view, Figure 4 best addresses whether normal, age-related changes in vision contribute to reading deficits.

Figure 3 shows mean reading rate as a function of angular character size for the young (open circles) and old (closed circles) groups. (Reading rate is plotted on a log scale because previous work has shown that standard errors are more nearly constant in log units. In addition, some experimental manipulations result in reading rates that range over more than a log unit, e.g., reading rate as a function of text

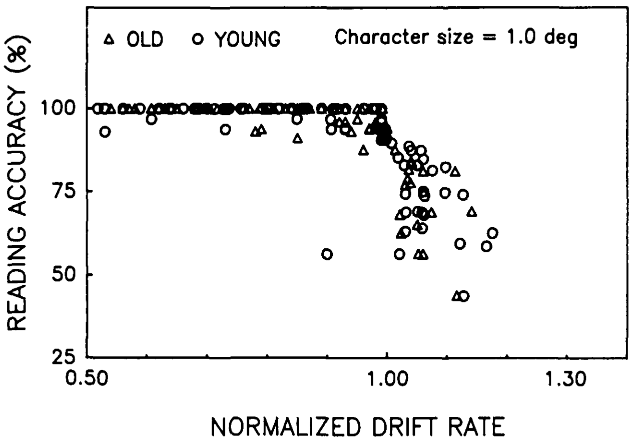

Figure 2. Reading accuracy as a function of drift rate. Percentage of words correctly read is plotted as a function of normalized drift rate for young (open circles) and old (open triangles). Normalized drift rate refers to the actual drift rate divided by the drift rate for which subjects were 90% correct.

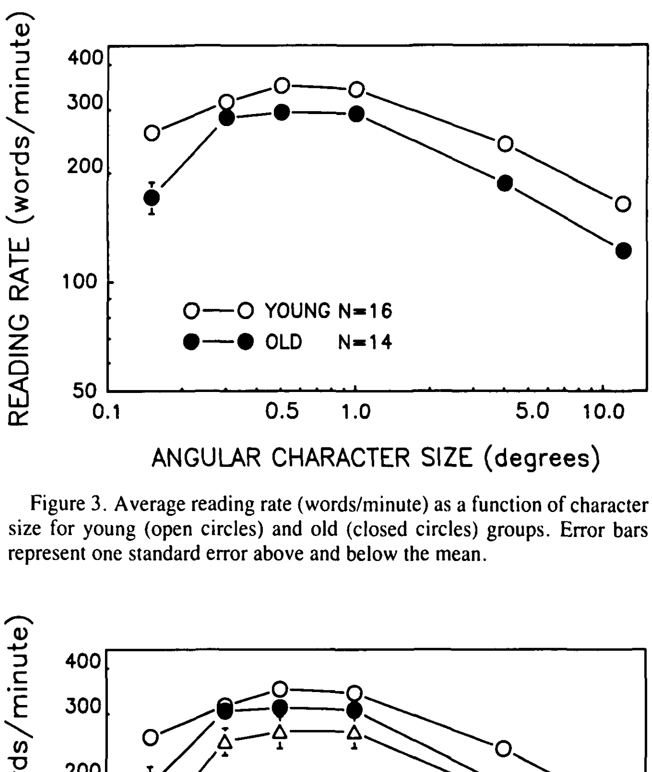

Figure 3. Average reading rate (words/minute) as a function of character size for young (open circles) and old (closed circles) groups. Error bars represent one standard error above and below the mean.

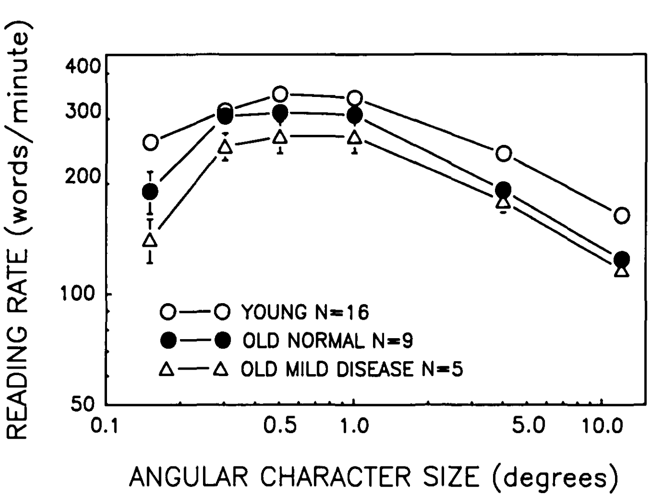

Figure 4. Average reading rates (words/minute) as a function of character size are shown for three groups. Data for the young group (open circles) have been replotted from Figure 3. The old-normal group (closed circles) is the subgroup of old subjects with completely healthy eyes. The old-mild disease group (open triangles) is the subgroup of old subjects with early signs of eye disease. Error bars represent one standard error above and below the mean.

contrast.) Standard errors were less than 5%. Curve shape is qualitatively similar for the two groups. Maximum reading rates occur for a range of intermediate character sizes (.3°–1°) and decline for larger and smaller character sizes. A two-way analysis of variance (ANOVA) with repeated measures on the log reading rates showed significant main effects for character size ($F = 160.73, p < .01$), age ($F = 34.50, p < .01$), and a significant age by character-size interaction ($F = 5.08, p < .01$).

Three points are important in comparing the data from the young and old groups. First, reading rates are significantly lower for the old group, ranging from 10 to 34% less. Post-hoc comparisons (Howell, 1982, p. 322) indicated that the group differences are significant at each character size ($p < .05$), except .3° and 1.0°. [The test described by Howell is similar to the Neuman-Keuls test and Tukey's HSD test. It is an analysis of simple effects, that is, the effect of one variable at one level on a second variable. We were interested in the effect of the age variable (young vs old) at each of six character sizes.] Table 2 summarizes average rates and percentage differences at each character size.

Second, differences between young and old groups are greater for very small characters (.15°) and for large characters (4° and 12°) than for characters of an intermediate size. As shown in Table 2, the greatest performance difference occurs at .15°, where the old group mean is 66.1% of the mean for the young group. Even this difference is quite small, amounting to about the same percentage difference in reading rates found at 1° and 4° for the young group on its own.

Third, the range of optimal character sizes is the same for young and old subjects. Both groups read with maximum speed for characters ranging in size from about .3° to 1°.

The young group had significantly better visual acuity than the old group (see "Subjects"). It is possible that this difference contributed to the difference in reading speeds between the two groups, especially for the smallest characters. However, no evidence was found for a strong link between reading rate and decimal acuity. Within the old group, correlations between reading rate and decimal acuity at different character sizes ranged from .58 (at .5°) to −.37 (at 12°). Only the correlations at .5° and 1.0° were significant ($p < .05$).

In Figure 4, the reading rates of the young group are compared with those of the old-normal subgroup (i.e., those with no signs of ocular pathology). While the mean reading rates of the old-normal subgroup lie a little closer to the rates of the young group, the pattern of results is the same as in Figure 3. A two-way ANOVA of log reading rates showed significant main effects for age ($F = 21.98, p < .01$) and character size ($F = 146.60, p < .01$), and a significant interaction ($F = 3.97, p < .01$). Post-hoc comparisons for the individual character sizes revealed no significant differences between young and old-normal subjects in the range .3° to 1°. This is the range of maximum reading speeds for both groups. Apparently, maximum reading speeds are little affected by age-related changes in normal vision.

Figure 4 also shows mean rates for the five subjects with mild forms of eye disease (Table 1). Their performance is slightly depressed compared with the young and old-normal groups. In the case of more severe disease, performance characteristic of low vision would be observed.

Table 2. Average Reading Rates (words/minute)

Character Size (deg)	Young ($n = 16$) Rate	Old ($n = 14$) Rate	Old ($n = 14$) (%)[a]	Old-Normal ($n = 9$) Rate	Old-Normal ($n = 9$) (%)[a]
.15	258.59	170.87	66.1	190.32	73.6
.30	314.47	284.68	90.5	304.60	96.9
.50	349.18	294.84	84.4	310.95	89.1
1.00	343.21	291.90	85.0	306.38	89.3
4.00	240.34	186.69	77.7	191.31	79.6
12.00	163.51	121.28	74.2	124.13	75.9

[a]Percentage of the young group's rate.

Discussion

There are small differences in the reading rates of our young and old subjects, but these occur for very small or large character sizes. For the intermediate range of character sizes for which reading is fastest (.3° to 1.0°), the old-normal subgroup (no eye disease) had reading speeds that did not differ significantly from the young group. This study concludes that advancing age per se has little or no effect on maximum reading speed.

Everyday reading distances range from about 25 to 40 cm (10–16 inches). At 25 cm, the title letters of this article have an average size of about .70° and the text itself about .34°, both within the optimal range. Newspaper characters subtend about .3° at 25 cm, also within the optimal range. When yet smaller print is encountered, angular character size can be increased by holding the text closer to the eye. The nearer viewing distance may require added lens power for focusing.

The near equality of young and old reading rates in the optimal range argues against a cognitive explanation for the deficits we observed. One would expect a general cognitive deficit to manifest itself as a reduction in maximum reading speed. It is possible, of course, that reading speed is normal but reading comprehension is reduced. Legge, Ross, Luebker, and LaMay (1989) studied the relationship between maximum reading speed and comprehension in normal and low vision. They found that comprehension was normal in all cases when reading speed was 70% or less of a person's maximum rate. Their findings suggest a reasonably tight link between comprehension and reading rate. In addition, they examined their data for age-related differences in comprehension and found none.

The old group shows greater deficits for large and small characters than for characters of intermediate size. Age-related losses in contrast sensitivity can provide one explanation for these deficits. Previous research has shown that reading rate is invariant across character size (and for color- and luminance-contrast conditions) when letter contrast is expressed as a multiple of threshold contrast (Legge et al., 1987, 1990). This means that a subject's reading rate declines by the same amount for a reduction by a given factor in text contrast or a loss in contrast sensitivity by the same factor. High-spatial-frequency contrast sensitivity is typically lower in old age and may contribute to reduced reading speed for .15° characters. Based on a calculation provided by Legge et al. (1987), the spatial-frequency resolution required for reading .15° characters is about 13 cycles/degree (c/deg). [The "fundamental" spatial-frequency of a letter is the reciprocal of its character size, in this case 1/.15 = 6.7 c/deg. Reading requires spatial frequencies extending to at least twice the fundamental frequency (i.e., to about 13.4 c/deg).] Owsley et al. (1983) and Wright and Drasdo (1985) have shown that 13 c/deg contrast sensitivity in old age is reduced by about a factor of 3 from young normal values. Legge et al. (1987) showed that a reduction in text contrast by a factor of 3 for a character size of .15° results in reading rates that are 50 to 70% of maximum values. At this character size, the old group reads at 66% of the rate of the young group. Therefore, losses in contrast sensitivity can account quantitatively for the age-related reduction in reading rate at .15°.

Contrast sensitivity may also explain age-related deficits in reading very large characters. In the "Introduction," evidence was cited for an age-related reduction in low-spatial-frequency sensitivity at moderate temporal frequencies. When people read drifting text, their eyes fixate on a character at the right of the screen and then track it as it drifts across the screen. After tracking for four or five letter spaces, the eyes saccade back to the right edge of the screen to pick up a new letter and repeat the cycle (Buettner, Krischer, & Meissen, 1985; Legge, Pelli, Rubin, & Schleske, 1985). This pattern results in retinal images having temporal transients about 4 times/second (4 Hz). Reading of static text also involves temporal transients, because the eyes move roughly 4 times/second. Legge et al. (1987) have argued that contrast sensitivity with 4-Hz flicker provides the best comparison for reading. To predict reading deficits for 4° and 12° characters, we require age-comparative 4-Hz contrast sensitivities at .5 and .16 c/deg, respectively. Such data are available for .5 c/deg and 7.5 Hz from Sloane et al. (1988). They found a contrast-sensitivity reduction by about a factor of 3 for their older subjects. Legge et al. (1987) showed that a threefold loss in text contrast reduced reading rates at 4° to about 85% of maximum rates. Our old subjects read text composed of 4° characters at 78% of the young rate. Once again, the contrast-sensitivity prediction is in good agreement with the observed results.

Oculomotor limitations provide an alternative qualitative explanation for the age-related reading deficits for small and large characters. Smooth-pursuit eye tracking is required to read drifting text, and there is evidence for age-related deficits in this form of eye-movement control (Sharpe & Sylvester, 1978; Spooner, Sakala, & Baloh, 1980). There is evidence that dynamic visual acuity (i.e., acuity for moving targets) declines more rapidly with age than conventional static acuity (Scialfa et al., 1988), presumably due to failures of eye tracking. Such an effect could result in slower reading of .15° letters by old subjects. These characters (slightly smaller than the 20/40 letters on a conventional eye chart) were close to the acuity limit of all our subjects. For this explanation to hold, there must be a statistical decoupling between dynamic-visual acuity and static-visual acuity, because we found a low correlation between reading rate and static visual acuity within our group of old subjects (see "Results"). The slower reading of very large characters may also be related to smooth-pursuit eye tracking. All subjects, young and old alike, have decreased reading speeds for very large characters. Legge, Pelli, Rubin, and Schleske (1985) suggested that this general slowdown might be related to smooth-pursuit tracking. But this is unlikely because a slowdown also occurs for static text where smooth-pursuit eye movements are not used (Legge, Ross, Luebker, & LaMay, 1989).

Prolonged visual persistence provides another explanation for the large-character deficit. A defective transient system in older subjects might result in longer lasting neural images at low-spatial frequency, effectively smearing large letters and reducing reading rate. However, the existence of age-related differences in persistence or transient response remains uncertain (Kline & Schieber, 1981; Sloane et al., 1988; Sturr, Church, Nuding, Van Orden, & Taub, 1986; Sturr, Church, & Taub, 1988; Tyler, Ryu, & Stamper, 1984).

This study shows that old subjects have difficulty reading very large text. For our largest two character sizes (4° and 12°) mean reading rates for the old group are 78 and 73%, respectively, of the mean rates for young subjects. Such large characters are rarely encountered, except with the use of magnifiers. Our data indicate that it may be unwise to enlarge characters beyond 1° for old readers because their reading speed may drop, relative to younger readers. We conclude that old subjects with normal vision do not require magnification for reading (unless the letters are tiny) and that magnification of print size beyond 1° or 2° is likely to be deleterious.

While old readers with normal vision may be hampered by magnification, those old readers with low vision will usually require magnification (Legge, Rubin, Pelli & Schleske, 1985). Unfortunately, there can be no simple recommendation regarding print size for material aimed at older readers. If those readers are free from pathology, the print size should be in the range that is optimal for young adults. But if the older readers have low vision, they will require much larger characters, usually necessitating the use of a magnifying aid (cf. Sloan, 1977).

In summary, our results indicate that old subjects with normal acuity read almost as fast as young adults when the text is of optimal size. Equality is almost exact for the subgroup of old subjects verified to be in good ocular health. Even for old subjects with early signs of eye disease, maximum reading speeds were about 80% of the rates for young adults. However, old subjects are less tolerant to deviations from the optimal range. For very small or very large characters, they experience more noticeable deficits. The problem of tiny characters can usually be solved by bringing the text closer to the eye, but this may require lens correction. Characters large enough to pose a problem are rarely encountered. On the whole, our results lead us to believe that essentially normal, rapid reading is characteristic of old age.

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REFERENCES

Buettner, M., Krischer, C. C., & Meissen, R. (1985). Characterization of gliding text as a reading stimulus. *Bulletin of the Psychonomic Society, 23,* 479–482.

Dean, A. (1977). *Plants that eat insects: a look at carnivorous plants.* Minneapolis, MN: Lerner Publication.

Derefelt, G., Lennerstrand, G., & Lundh, B. (1979). Age variations in normal human contrast sensitivity. *Acta Ophthalmologica, 57,* 679–690.

Eisenberg, P. (1981). *Word expectations in reading: the effect of text-constraints on error detection and eye movements during real-time reading.* Unpublished doctoral dissertation, University of Minnesota.

Howell, D. (1982). *Statistical methods for psychology.* Boston, MA: Duxbury Press.

Kirchner, C., & Peterson, R. (1979). The latest data on visual disability from NCHS. *Journal of Visual Impairment and Blindness, 73,* 151–157.

Kline, D. W., & Schieber, F. (1981). Visual aging: a transient/sustained shift? *Perception and Psychophysics, 29,* 181–182.

Legge, G. E., Parish, D. H., Luebker, A., & Wurm, L. (1990). Psychophysics of reading. XI. Comparing color contrast and luminance contrast. *Journal of the Optical Society of America, A7,* 2002–2010.

Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading. I. Normal vision. *Vision Research, 25,* 239–252.

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

Legge, G. E., Ross, J. A., Maxwell, K. T., & Luebker, A. (1989). Psychophysics of reading. VII. Comprehension in normal and low vision. *Clinical Vision Sciences, 4,* 51–60.

Legge, G. E., & Rubin, G. S. (1986). Psychophysics of reading. IV. Wavelength effects in normal and low vision. *Journal of the Optical Society of America, A3,* 40–51.

Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading. V. The role of contrast in normal vision. *Vision Research, 27,* 1165–1171.

Legge, G. E., Rubin, G. S., Pelli, D. G., & Schleske, M. M. (1985). Psychophysics of reading. II. Low vision. *Vision Research, 25,* 253–266.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research, 12,* 689–699.

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

Scialfa, C. T., Garvey, P. M., Gish, K. W., Deering, L. M., Leibowitz, H. W., & Goebel, C. C. (1988). Relationship among measures of static and dynamic visual sensitivity. *Human Factors, 30,* 677–687.

Sekuler, R., Hutman, L. P., & Owsley, C. (1980). Human aging and spatial vision. *Science, 209,* 1255–1256.

Sharpe, J. A., & Sylvester, T. O. (1978). Effect of aging on horizontal smooth pursuit. *Investigative Ophthalmology & Visual Science, 17,* 465–468.

Sheedy, J. E., Bailey, I. L., Buri, M., & Bass, E. (1986). Binocular vs. monocular task performance. *American Journal of Optometry and Physiological Optics, 63,* 839–846.

Sloan, L. L. (1977). *Reading aids for the partially sighted: A systematic classification and procedure for prescribing.* Baltimore, MD: Williams & Wilkins.

Sloane, M. E., Owsley, C., & Jackson, C. A. (1988). Aging and luminance adaptation effects in spatial contrast sensitivity. *Journal of the Optical Society of America, A5,* 2181–2190.

Spooner, J. W., Sakala, S. M., & Baloh, R. W. (1980). Effect of aging on eye tracking. *Archives of Neurology, 37,* 575–576.

Sturr, J. F., Church, K. L., Nuding, S. C., Van Orden, K., & Taub, H. A. (1986). Older observers have attenuated increment thresholds upon transient backgrounds. *Journal of Gerontology, 41,* 743–747.

Sturr, J. F., Church, K. L., & Taub, H. A. (1988). Temporal summation functions for detection of sine-wave gratings in young and older adults. *Vision Research, 28,* 1247–1253.

Tyler, C. W., Ryu, S., & Stamper, R. (1984). The relation between visual sensitivity and intraocular pressure in normal eyes. *Investigative Ophthalmology & Visual Science, 20,* 204–212.

Wright, C. E., & Drasdo, N. (1985). The influence of age on the spatial and temporal contrast sensitivity function. *Documenta Ophthalmologica, 59,* 385–395.

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