Enhancement of text for the visually impaired

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Previous research has established the benefits of image enhancement by spatial filtering for face perception and motion video appreciation among elderly low-vision observers [Invest. Ophthalmol. Vis. Sci. **32,** 2337 (1991); J. Opt. Soc. Am. A **11,** 1929 (1994)]. It has also been reported that similar enhancement could increase reading speeds by a factor of 2–4 in the same population [cf. Ophthalmology **96,** 115 (1989)]. In our experiments we sought to determine what benefit, if any, was derived from spatial filtering of text for low-vision readers. Results from this series of studies indicate that 66% of patients do increase their reading rate with enhancement, but this increase is small. Change in reading rate with spatial filtering ranged from a 100% decrement to a 125% improvement, with an average 13% improvement. Only 10 of 67 subjects increased their reading rates by 50% or more. The clinical information that we gathered does not allow us to predict accurately which patients will benefit from spatial filtering. On the basis of these findings we conclude that enhancement of text by spatial filtering does not substantially increase reading rates for most low-vision patients.

INTRODUCTION

The inability to read is a primary complaint of low-vision patients. The effects of low vision on reading skill have been carefully studied over the past 10 years (cf. Legge *et al.*[1]). For example, Legge[2] reported that reading rates for low-vision patients with central field loss (CFL) are approximately half that of acuity-matched low-vision patients with intact central fields. In a study by Rubin and Legge,[3] the average reading rate at maximum contrast for subjects with CFL was 68 words per minute (wpm), whereas for those without CFL the average reading rate was 112 wpm. In that study, subjects were asked to read text scrolled from right to left across a television screen. This presentation technique has been reported to increase reading rates for low-vision observers.[1] Even so, the rates reported by Rubin and Legge for low-vision readers are substantially slower than reading rates for normally sighted observers, which average approximately 330 wpm for a standard page of text.[4]

Reading rates for normally sighted observers are generally unaffected by small decreases from 100% contrast. Rates do not drop to half maximum until contrast is reduced to 6%.[5] However, for low-vision observers, Rubin and Lugge[3] found that the average contrast at which reading rates decreased to half maximum was 34%. For some of the subjects in that study as little as a 30% decrease in contrast led to a 50% decrease in reading rate. The low-vision subjects in that study were relatively young (mean = 37.5 yr), so it is unlikely that this increased sensitivity to contrast attenuation was due to aging. Rubin and Legge[3] conducted these studies in part to help identify those patients who would benefit from contrast enhancement.

The effectiveness of contrast enhancement by spatial filtering for improving performance of the visually impaired has been well established. For example, Peli *et al.*[6,7] have shown that the contrast-enhancement algorithm designed by Peli and Lim,[8] applied to faces, improves face recognition for low-vision adults in comparison with the use of unenhanced images. This algorithm has been shown to improve perceptibility of details and increase appreciation of motion videos in the same population.[9] The stimuli used in both experiments (faces and natural scenes) include high-spatial-frequency components at contrasts below the threshold of the observers.[10] Therefore it is reasonable to assume that if the contrast of these frequencies is increased, perceptibility and thus performance would improve.

Lawton[11] proposed that enhancing the spatial-frequency components of text to which low-vision observers have lost sensitivity (i.e., at medium and high spatial frequencies) would lead to increased reading rates. She tested this idea by using partially individualized filters that were designed to compensate for the specific sensitivity losses of each patient. She measured the minimum magnification needed to identify words for enhanced and unenhanced presentations. Her results showed that, with enhancement, slightly smaller words could be identified. In subsequent research Lawton[12,13] tested the effects of enhancement on sentence reading. She used a rapid serial visual presentation display in which each word is presented in succession at the same place on a computer screen. Again her subjects were able to reduce the need for magnification and increase their reading rates by a factor of 2–4 when text was enhanced.

The intriguing nature of Lawton's results, along with the proven effectiveness of spatial filtering for other tasks, has led us to test the applicability of the adaptive enhancement algorithm of Peli and Lim[8] to reading in low-vision adults. Unlike in the studies reported by Lawton, we have used the same enhancement for all our subjects. Previous research[7] has shown that subjects in the low-vision population from which our subjects are drawn tend to select similar spatial frequencies and levels of enhancement and that there is little difference in performance on a face recognition task between the application of a stan-

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Fig. 1. Examples of unenhanced (left) and enhanced (right) text. Subjects never saw the two conditions on the same screen. Note the increased size of the enhanced text, which is due to the dark annular region around each character.

dard enhancement and individually tuned enhancement. Thus there is no *a priori* reason to believe that the same would not be true of a reading task. In addition, Rubin and Legge[3] concluded that "general shifts in contrast sensitivity among low-vision subjects have greater effects on reading performance than the relatively small changes in sensitivity at different bands" (p. 88).

EXPERIMENT 1: THE EFFECTS OF SPATIAL FILTERING ON READING RATE

If boosting the contrast of high spatial frequencies increases the perceptibility of letters and therefore words, then reading should be faster for spatially filtered text. We tested this hypothesis by asking low-vision adults to read sentences presented in a standard, unenhanced condition and with the enhancement parameters described below.

Subjects

Subjects were recruited on the basis of visual function and a willingness to participate. Data from 31 subjects are reported here. (Data from several other subjects were eliminated either because their native language was not English or they failed to complete both conditions.) All had acuity between 20/100 and 20/800 in the eye(s) tested [mean log minimum angle of resolution (logMAR) = 1.07 (Snellen equivalent: 20/235); median = 1.00 (20/200)]. In most cases subjects were tested with the better eye if it was in the 20/100–20/800 range; if not, they were tested with the more debilitated eye. (Five subjects with the same acuity in both eyes were tested binocularly.) There were no differences in the effects of enhancement on the basis of the eye tested across subjects. All subsequent analyses have been collapsed across this variable. Twenty-eight subjects had documented CFL in the eye(s) tested. Subjects' ages ranged from 33 to 89 with a mean of 68.4; median age was 71. Informed consent was obtained from all subjects before testing.

Apparatus

Stimuli for the reading tests were presented on a 12-in. Sony monitor connected to a modified Horizon Low Vision Magnifier (Mentor O & O, Norwell, Massachusetts). The stimuli were scanned into the system from text generated in Monaco 18-pt font and laser printed. The fidelity of the scanner was such that the ragged edges produced by the laser printer were visible in the enlarged scanned images (see Fig. 1). The Horizon was modified to allow for precise control of display speed. A DigiVision device (DigiVision, San Diego, California), which implements a version of the adaptive enhancement algorithm of Peli and Lim,[8] was used to provide enhancement. Figure 2 provides a schematic representation of the implemented algorithm. There are three independent controls on the DigiVision corresponding to variables in the algorithm: *detail (W)* determines the size of the averaging window (which is Gaussian in shape) and ranges from 4% to 64% of the image width; *contrast (K)* corresponds to an amplification factor ranging from 1.0 to 3.0 in steps of 0.2; *background (N)* is the fraction of the original mean luminance recombined with the high-pass filtered image. A more detailed description of the algorithm is given by Peli and Peli.[10] The settings that we chose for these experiments (see Table 1) resulted in ~7 cycles/letter (W) and a gray background. This is because none of the original (black) background was added back into the filtered image. (The same settings were used for all subjects.) The resulting characters were visually as similar as possible to Lawton's[12] published examples for which she reported the largest increases in reading rate.

As in Lawton's studies, we presented unenhanced text as white characters on a black background. All testing was done in a darkened room with a 60-W bulb shielded and used only to illuminate a small work space for the experimenter. Neither the bulb nor its reflection was visible to the subjects.

Stimuli

Stimuli were sentences extracted from the MNRead reading test developed by Legge *et al.*[14] Each sentence had 55 characters and between 9 and 13 words. Each sentence was preceded by a string of six Z's and was followed by a string of six X's to demarcate the beginning and the end of the sentence. (This was primarily for the ease of the experimenter.) The same stimuli were used in all subsequent experiments.

Procedure

Before testing, acuity was measured in each eye with a standard Snellen acuity chart. All subjects were seated 16 in. (40 cm) from the monitor. There was no compensation for reduced accommodation. Any detrimental effects of blur were small because of the size of the characters and were equal across conditions.[15,16] At this distance the height of a lowercase "e" without enhancement was 6.0 deg. A lowercase "e" with enhancement subtended ~6.7 deg. Accurate measurements could not be made because of the difficulty in defining the edge of the stimulus with enhancement (see Fig. 1). We based our measurements on the outside edge of the solid dark annulus. The white portion of the character was the same size across conditions. In both display conditions, an average of 4.5 character spaces were present on the screen at any one time. Legge *et al.*[1,17] have shown that 4–5 characters present at one time in a scrolled display allow for maximum reading rates.

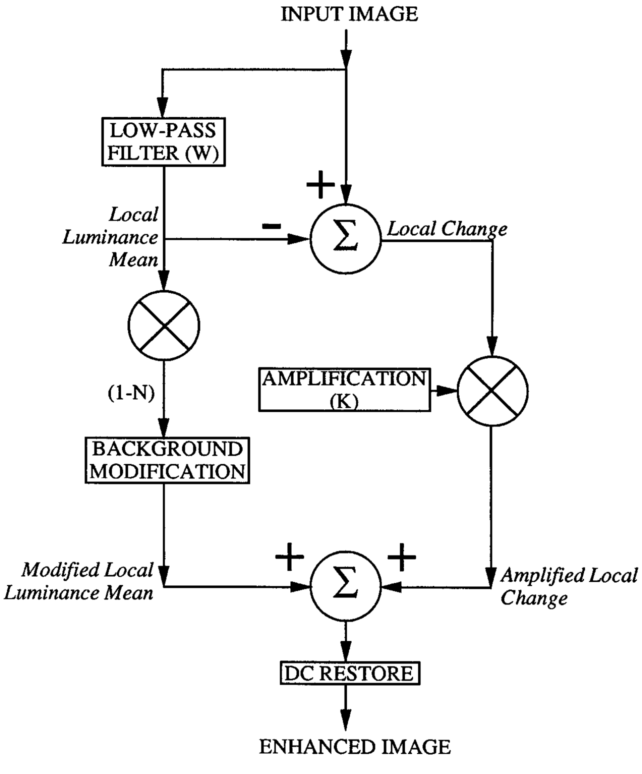

Fig. 2. Schematic of the implementation of the enhancement algorithm of Peli and Lim[8] used in this study.

Table 1. Parameter Settings for the DigiVision Device

Detail, W	20 × 20 pixels
Contrast, K	1.6× original
Background, N	0%

The subjects' task was to read each sentence out loud as it scrolled across the screen from right to left. Subjects were shown at least one sample sentence for each condition. They were also asked to read one sentence out loud before testing began. For each condition the presentation rate of the first sentence was 10.23 wpm, and it was increased in steps of that size until the subject made two or more errors on a single sentence. This rate was then repeated. If two or more errors were again made, the rate one step below was recorded as the maximum reading rate. If fewer than two errors were made, the rate was again increased until two or more errors were made on two consecutive sentences. Following a short break, the procedure was repeated in the other presentation mode. The order of conditions was counterbalanced across subjects, and each sentence was seen only once by a given subject. The order of sentences was the same for all subjects. All condition comparisons are within subject.

In addition to diagnosis, acuity, and reading rate, demographic data were also collected from each subject. These included age, years since diagnosis, reading aids used, and number of hours of reading each day. Subjects who used the Horizon or closed-circuit TV's at home or at work were excluded from the analyses.

Results and Discussion

Table 2 shows results from this and the remaining experiments. A comparison of maximum reading rate for the small unenhanced (SU) and small enhanced (SE) text (this nomenclature has been adopted to facilitate comparisons with the remaining experiments) showed a small (7.6-wpm) but statistically significant increase in reading rate with enhancement [$t(30) = 2.12$, $p = 0.042$]. Reading rates in the SU condition varied widely. Therefore we also looked at the relative change in reading rate with enhancement for each subject. This was done for better representation of important changes in reading rate. That is, for a subject reading 100 wpm, a 10-wpm increase represents only a 10% improvement. However, for a subject reading 10 wpm without enhancement, the same 10 wpm increase represents a 100% improvement.

Subjects showed an average 13.5% increase in reading rate with enhancement. This was significantly greater than zero [$t(30) = 2.30$, $p = 0.029$]. Inspection of the data showed vast differences in relative improvement. One possible explanation of these differences is the relative size of the characters in relation to each subject's acuity. Legge *et al.*[1] have shown a steep increase in reading rate up to 5× threshold character size for low-vision observers. For many of our subjects the 6.0-deg characters that we used were smaller than this 5× threshold. When we look only at our subjects for whom these characters were smaller than 5× threshold (near-acuity group), we see a 33.8% increase in reading rate with enhancement. This result approached significance [$t(8) = 2.16$, $p = 0.063$]. On the other hand, those subjects for whom the characters were larger

Table 2. Reading Rate by Display Format in Words per Minute (SEM)[a]

Experiment	SU	SE	Control Condition	Average Change in Rate (SE − SU)	Average Percent Change [(SE − SU)/SU] × 100
1 ($n = 31$)	112.53	120.12		7.59[b]	13.54[b]
	(9.35)	(9.80)		(3.58)	(5.89)
2 ($n = 23$)	110.31	117.87	104.08	7.12	0.08
	(12.85)	(9.94)	(8.50)	(5.08)	(7.65)
3 ($n = 13$)	92.86	110.17	99.94	17.31[b]	34.63[c]
	(14.16)	(13.96)	(15.33)	(5.84)	(11.41)
Mean across Experiments	107.95	117.26		9.31[c]	13.01[c]
	(6.13)	(6.79)		(2.66)	(4.56)

[a] SEM, standard error of the mean, in parentheses.
[b] Value significantly greater than 0 by *t*-test at 0.05 (or 0.01)[c] level of significance.
[c] 0.01 level of significance.

than 5× threshold (above-acuity group) showed only an average 4.7% increase. This was not statistically different from zero. There was a significant difference between the near- and the above-acuity threshold groups [$t(27) = -2.30$, $p = 0.029$].

We can conclude from these data that those subjects who are relatively more impaired showed improvements in reading with the spatial filtering. It is also possible that the increase in reading rate within this group was due to the increased size of the enhanced characters, which is a by-product of the algorithm. Inspection of Fig. 1 will reveal a dark annular region surrounding each character in the enhanced condition. This increased the relative size of each character in comparison with the unenhanced condition. The asymptote at 5× acuity threshold at which Legge *et al.*[1] reported maximum reading rates is preceded by a steep increase in reading rate up to that character size. Therefore it is possible that the improvements that we see can be explained by the increased size of the enhanced characters and not by the spatial filtering specific to the adaptive enhancement algorithm. Experiment 2 was designed to answer this question.

EXPERIMENT 2: THE EFFECTS OF INCREASED CHARACTER SIZE

To test the effects of increased character size on reading rate, we decreased the size of the unenhanced text so that when the enhancement was applied, the enhanced text would be approximately the same size (within the discrete magnification steps available with the Horizon) as the unenhanced text in experiment 1. We chose to decrease the size of the small unenhanced text in order to maintain the number of characters available per screen across conditions and experiments. In addition, we included larger unenhanced (LU) text that was the same size as the unenhanced text in experiment 1 and about the same size as the enhanced text in this experiment. If the increased size alone were responsible for the increased reading rate seen in the previous experiment, then characters magnified to be the same size should be read at the same rate as enhanced text, and both of these should be read faster than the smaller unenhanced text.

Subjects

Twenty-three subjects were recruited from the same low-vision population as in experiment 1. Their average acuity was 20/208 (MDN = 20/200), and their average age was 67.1 (MDN = 70). Seventeen were tested monocularly.

Apparatus

In addition to the apparatus used in experiment 1, we also used a Mentor B-VAT II Video Acuity Tester (Mentor O & O, Norwell, Massachusetts).

Procedure

Acuity was tested with the B-VAT II system. With this system, single Snellen acuity letters can be presented in sizes corresponding to 20/15–20/300. The system can present each letter individually, and it randomly selects letters for each presentation. Therefore problems of crowding and chart memorization have been eliminated. For each eye, subjects were asked to name letters that appeared individually on the screen. Subjects stood 10 ft from the monitor, which was adjusted for testing from 20 ft, and testing began at a letter size corresponding to 10/300. Letter size was decreased until the subjects could no longer correctly identify four of five characters. The size was then increased one step. If four of the five characters at that size were named correctly, that size was recorded as the acuity in that eye. If not, the size was increased until that standard was attained. Subjects who were unable to identify letters at the 10/300 size were moved closer to the screen (5 ft), thus increasing the relative character size, and testing continued as described.

The reading test was the same in this experiment with the addition of the LU condition. The SU stimuli subtended 4.9 deg, SE ~5.5 deg, and LU 6.0 deg. Each subject read sentences in all three presentation modes in counterbalanced order. As before, each sentence was seen only once.

Results and Discussion

The results are shown in Table 2. A one-way repeated-measures analysis of variance (ANOVA) showed a significant effect of presentation condition on reading rate [$F(2, 44) = 3.65$, $p = 0.034$]. LU text was read most slowly, followed by SU and SE. The only significant pairwise comparison was between the LU and SE text (Scheffe's protected least significant difference, $p < 0.05$). The significant difference in reading rate between SE and LU text is counter to the hypothesis that the increased size of the enhanced characters was responsible for the increases in reading rate found in experiment 1.

We also looked at the relative improvement with enhancement. For the 23 subjects in this experiment there was less than 1.0% improvement with enhancement. Neither the near- (-12.2%) nor the above-acuity (4.7%) groups showed improvements statistically different from zero. There was also no difference between the groups. It is unclear why the near-threshold group showed no improvement in this experiment (in fact, they showed a nonsignificant decrease). It is possible that the reduced size of the characters is responsible, but if this were the case, the LU text should have been read faster. However, among the near-threshold group, LU text was read 4.5% more slowly than SU text.

The absolute difference in reading rate between SU and SE text found in this experiment (7.6 wpm) is the same as was found in experiment 1. The lack of a relative change with enhancement might be due to the increased variability within the sample for the SE condition (experiment 1, SEM = 9.8; experiment 2, SEM = 12.9). Although the increases are not statistically different, we continue to see increases in reading rate when the text is filtered. Another by-product of the enhancement device is an increase in the luminance output of the monitor. It is possible that this is responsible for the increases that we see. Experiment 3 explored this possibility.

EXPERIMENT 3: THE EFFECTS OF INCREASED LUMINANCE

The application of the enhancement algorithm through the DigiVision device increases the voltage input to the display screen. This in turn increases the brightness of the screen. As seen in Fig. 1, the background is gray in the enhanced condition and black in the unenhanced condition. In addition to the increase in background luminance, there is an increase in the maximum luminance of the enhanced characters relative to the unenhanced characters. This experiment was designed to determine whether it is, in fact, the increased voltage (and therefore the luminance) present in the enhanced condition that leads to the increases in reading rate that we have seen. It has been shown, for example, that increasing the ambient light leads to faster reading of printed text by low-vision patients.[18] It is therefore possible that simply increasing the luminance of the text (the stimulus of interest) may lead to increases in reading rate among low-vision patients.

We tested this possibility by presenting unenhanced text for which the maximum voltage input to the monitor was adjusted to be at the same level as in the enhanced condition but without spatial filtering. We chose to equate the voltage input instead of the luminance output because of the difficulties involved in measuring the maximum luminance of the enhanced display. This was again due to the lack of precision in defining the character boundaries, as well as to the limits of the measuring instrument. It was difficult to obtain accurate measurement of the luminance of the characters in the enhanced condition because of the increase in scatter from the surround and the 1.1-deg test spot from which the Minolta 200 integrates light.

Matching voltage is equivalent to equating the numerical representation in a computerized device. However, because the display is operating outside the linear range in all but the unenhanced conditions, luminance is monotonically, though not linearly, related to the voltage. Therefore when the voltage was increased without spatial filtering, the luminance also increased. We call this the boosted-luminance condition.

The apparatus and procedures were the same as in experiment 2. Thirteen subjects (mean acuity 20/286, mean age 59.4) completed the experiment. Six were tested monocularly.

Results and Discussion

A one-way repeated-measures ANOVA again showed a significant effect of presentation condition on reading rate [$F(2, 24) = 4.59$, $p = 0.021$] (see Table 2). SE text was read fastest, followed by boosted luminance and SU. Pairwise comparisons showed a statistically significant difference between SU and SE text (Scheffe's PLSD, $p < 0.05$). The boosted-luminance condition was not different from either the SU or the SE condition.

The 34.6% average increase in reading rate with enhancement was significant in this sample. When we looked at our near- and above-acuity groups separately, only the near-acuity group showed an average change different from zero (50.5%; $t(5) = 3.09$, $p = 0.027$]. The relative change in rate for the above-threshold group was substantial (21.1%) but did not differ significantly from zero. This overall relative improvement, along with the slower reading rates, may be due to the slightly decreased acuity of this group of subjects. However, neither the difference in acuity nor the differences in reading rate in comparison with the other experiments were statistically reliable.

We can conclude from these data that the increased luminance of the spatially filtered text does not fully account for the increases in reading rate found with this display. However, it is possible that at least some of the improvement can be accounted for by luminance alone, without spatial filtering. An answer to this question is left for future research.

GENERAL DISCUSSION

A three (experiment) by two (SU versus SE) ANOVA showed neither an effect of experiment nor an interaction between the experiment and the effects of enhancement on reading rate [$F(2, 64) = 0.38$, nonsignificant (n.s.) and $F(2, 64) = 1.09$, n.s., respectively]. Therefore we have collapsed our data across experiments for these two conditions.

Overall, we found an average 9.3-wpm increase in reading rate when the adaptive enhancement algorithm[8] was applied to scrolled text. This corresponds to a 13.01% average increase; both increases are different from zero [$t(66) = 3.5$, $p = 0.0008$ and $t(66) = 2.85$, $p = 0.006$]. We separated subjects from all three experiments into two acuity groups based on the 5× threshold criterion. Our above-threshold group showed a 7.2% increase, and our near-threshold group increased an average of 24.5%. Only a change in the near-threshold group was different from zero [$t(21) = 2.44$, $p = 0.024$].

Figure 3 shows each subject's relative change in reading rate with enhancement. As can been seen, and was

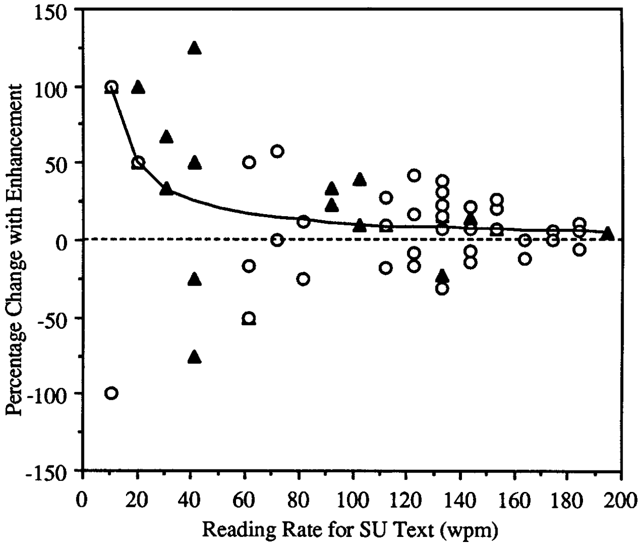

Fig. 3. Relationship between reading rate for SU and SE text for all subjects. Note the number of subjects who read *more slowly* with enhancement. Filled triangles, near-acuity threshold group; open circles, above-acuity threshold group. Solid curve, relative increase in reading rate with one 10.23-wpm step.

indicated above, there are large individual differences in both reading rate and change with enhancement. What this figure clearly shows is, first and foremost, that many of our subjects (34%) actually read enhanced text more slowly than unenhanced text. This cannot be explained by order of presentation. The large relative increases shown by some of our subjects correspond to an increase of only one or two steps in our ascending paradigm. Although it has been shown that maximum reading rates derived from this method are stable,[19] it is possible that these one- or two-step increases are simply due to random error. However, we believe that these results represent the actual reading abilities of these few subjects.

Legge *et al.*[20] have shown that the presence of central field loss (CFL) is the best predictor of reading rate in low-vision subjects. Therefore we also separated our subjects on the basis of the presence or absence of a central scotoma. Of the 67 subjects tested in the three experiments, 52 had documented CFL. Unlike in previous experiments, we found no difference in reading performance based on the status of the central field [$F(1, 65) = 0.74$, n.s.]. Our CFL subjects read SU text at a rate of 104.7 wpm; those subjects with no documented CFL read at 119.4 wpm. These reading rates are substantially higher than those reported by Legge *et al.*,[20] which may account for the lack of difference that we have found. In addition, there was no interaction between status of the central field and change in rate with enhancement [$F(1, 65) = 0.25$, n.s.]. Therefore there was no differential effect of enhancement across these two subsamples. When relative change in reading rate was analyzed, both the CFL and the no-CFL subjects showed significant improvement with enhancement (13.8% and 10.4%, respectively).

Several questions remain regarding these data. It is still unclear why some of our subjects showed substantial improvement while others showed decreased performance with enhancement. It is possible that we have simply not divided our sample appropriately to find the important subject differences that can predict which subjects will improve. We performed a backward stepwise multiple regression analysis to see if we could predict both reading rate for scrolled text and the relative change with enhancement for our subjects. Acuity (in logMAR), age, years since diagnosis, and number of hours of reading each day were included as independent variables in both analyses. Reading rate for SU text was also included in the analysis of relative change. Table 3 shows the results of the analysis in words per minute and Table 4 the results based on relative change. As before, we divided our subjects into groups based on status of the central field and acuity.

For our subjects as a group, less than 20% of the variance in reading rate for scrolled text can be accounted for with the variables that we have included in our model. We have even less ability to predict reading rate within our near- and above-acuity threshold groups. Within our near-acuity group, age was the best (although nonsignificant) predictor. This result is in accordance with the finding by Legge *et al.*[20] that age is one of the best predictors of reading rate among low-vision adults. For our remaining subjects, the inclusion of acuity in the model increased the predictive power.

As mentioned above, relative change with enhancement is likely to be a better metric of improvement than absolute change. However, on the basis of these

Table 3. Prediction of Reading Rate for Scrolled Text

Group	Variance Accounted for (%)	p	Model
All Subjects ($n = 63$)	19.4	0.001	$Y' = 258.38 - 88.24$ (logMAR) $- 0.87$ (age)
CFL ($n = 49$)	20.6	0.002	$Y' = 268.63 - 98.33$ (logMAR) $- 0.86$ (age)
Above threshold ($n = 42$)	15.0	0.016	$Y' = 243.69 - 134.08$ (logMAR)
Near threshold ($n = 21$)	11.1	0.077	$Y' = 163.33 - 1.28$ (age)

Table 4. Prediction of Relative Change with Enhancement

Group	Variance Accounted for (%)	p	Model
All Subjects ($n = 63$)	5.1	0.041	$Y' = 34.04 - 0.20$ (SU rate)
CFL ($n = 49$)	4.1	0.087	$Y' = 33.77 - 0.19$ (SU rate)
Above threshold ($n = 42$)	6.7	0.054	$Y' = 79.03 - 78.74$ (logMAR)
Near threshold ($n = 21$)	39.3	0.004	$Y' = 57.80 - 0.49$ (SU rate) $+ 11.48$ (h)

analyses we are unable to predict relative changes in reading rate with enhancement. Only within our near-acuity threshold group can we account for a substantial amount of the variance. It is interesting to note that the inclusion of a self-report measure of average daily reading time increases the power of the model. If this variable is excluded, significant predictability remains, but only 25.8% of the variance is accounted for. Even within this subgroup, however, it is difficult to predict change with enhancement. The problem is even more pronounced because we are unable to predict reading rate for scrolled text without enhancement.

The second key question is why our results are so different from those reported by Lawton[11–13] and Lawton *et al.*[21] Although we do find improvements in reading rate with enhancement, they are both inconsistent (34% of our subjects read *more slowly* with enhancement) and small. Two important procedural differences between the present study and those reported by Lawton are the number of times each stimulus was seen by a given subject and the order of presentation of the enhanced and the unenhanced text. For example, in her initial report[11] only 22 five-letter words were used in a word identification task, and each word was presented multiple times. In addition, the order of presentation for filtered and unfiltered words is unclear. Similar issues are evident in her 1989 (Ref. 12) and 1992 (Ref. 13) reports. In these studies, designed to investigate the role of spatial filtering on reading rate, only 20 different sentences were used. Again, these stimuli were seen by each subject many times. Thus it is possible, in fact likely, that the improvements that Lawton reports are due at least in part to practice effects. In our study each subject saw any given sentence once, and the order of presentation of the various display formats was counterbalanced across subjects.

Another key difference remains between these two sets of experiments—specifically, the exact nature of the enhancement applied to the text. Lawton individualized her filters on the basis of the contrast sensitivity functions (CSF's) of her subjects. She maintains that the individualized filters that "enhance the spatial frequency amplitudes in proportion to each observer's losses in contrast sensitivity, and not in proportion to an arbitrary enhancement function" (Ref. 12, p. 125) are essential for obtaining the improvements that she reports. We applied a different high-pass filter, and the same enhancement was applied to the text presented to all our subjects. If carefully tuned individualized filters are indeed necessary to improve reading performance, and if small deviations from the ideal filter would result in large changes in performance, then that difference could account for the difference in results between the studies. This, however, is not the case.

Examination of Lawton's reports reveals that, although her filters are based on each patient's CSF, various arbitrary modifications to the filter shapes were applied. For example, Lawton[13] tested the effects of (among other filters) enhancement filters that were based on the CSF of an age-matched or a young normal observer, as well as the effects of a monotonic filter, which follows the test subject's CSF only at frequencies that resulted in an increase in the filter's magnitude. Such changes in filter design were independent of the patients' CSF's. Although the two subjects for whom data are reported both showed a greater increase in reading rate with the filter that was based on the young normal observer than for the filter based on the age-matched observer, maximum reading rates were not different from the rates obtained with the monotonic filter (see Lawton,[13] Fig. 7). The fact that a monotonic filter, which does not compensate for individual losses in contrast sensitivity over the range tested, permits the same reading rates as a filter specifically tuned to each subject at each spatial frequency indicates that strict individualization is not necessary for the improvements reported. Furthermore, the fact that the filters designed with the use of a young observer's CSF for normalization resulted in better performance for all subjects indicates that stronger enhancement of the intermediate spatial frequencies (at which the young and the age-matched normals varied most) improved performance independently of the patients' exact CSF's.

On the basis of the same data[13] it is also clear that similar improvement can be attained without spatial filters. Inspection of Lawton's Fig. 7 reveals that simply by a decrease in the distance between the observer and the display, the same or greater magnitude of improvement is attained. For her atrophic age-related-maculopathy observer, sitting 40 cm closer to the screen (168 cm versus 128 cm) led to an over 100% increase in reading rate *with no filter*. For her disciform age-related-maculopathy observer, the same 40-cm change (from 84 to 44 cm) produced an almost 350% increase in rate. Thus moving the subjects closer to the screen achieved the same or greater benefit. This is not surprising considering that Lawton presented text of approximately 1.1 deg[22] to a patient with 20/200 acuity. This is less than 2× threshold character size (50 min per letter). Therefore as the character size increased (by a decrease in the seating distance), reading rates should increase substantially. At Lawton's closest seating distance (which is closest to the reading distance in this study), her atrophic and disciform subjects showed improvements of 29% and 54%, respectively, with the enhancement filter based on the young normal observer. This was the best relative improvement and was well within the small range of improvement seen in our patients.

The unenhanced text in our experiments was presented at the maximum contrast possible on our display. This raises the question of why any filtration of that text would lead to improved visibility and therefore to an increased reading rate. Letter recognition is possible when the stimuli are low-pass filtered to 1.5–3 cycles/letter.[23,24] We also know that reading rate increases when higher spatial frequencies are included. For example, Legge *et al.*[17] found that a sampling density of approximately 8×8 per character is needed for maximum reading rate. This translates to approximately 4 cycles/letter. This finding suggests that the availability of higher spatial frequencies is needed for faster reading. If we consider the luminance profile across letters as a square-wave grating, for a five-stroke letter the fundamental frequency of the square wave (SW) corresponds to approximately 2.5 cycles/letter. The findings of Ginsberg[23] and Parish and Sperling[24] suggest that letters become recognizable when at least the fundamental frequency of the underlying SW is available. However, as noted, higher frequencies may be needed for maximum reading speed. Sensitivity to these high spatial frequencies is reduced in our patient population.

Increasing letter size up to 5× acuity threshold has also been found to increase reading speed.[17] This increase in size brings the higher frequencies of the SW into lower retinal frequencies, and thus in letters 5× threshold size, the third or the fifth harmonics of the SW (corresponding to 7.5 and 12.5 cycles/letter, respectively) may become suprathreshold and visible.

We know that square-wave gratings of low spatial frequency are detectable when the contrast of the third harmonic becomes suprathreshold.[25] García-Pérez and Sierra-Vázquez[26] have recently presented a model that explains this and other results on the detection of the SW without the fundamental frequency. They show that for a SW without its first few harmonics, detection will occur at a fixed level of contrast for the underlying SW.

It is important to realize that for a SW, the amplitudes of the third and the fifth harmonics are limited to $4/2(3\pi) = 0.21$ and $4/2(5\pi) = 0.13$ of the amplitude of the SW, respectively. Thus their contrast is limited. When the first harmonic is removed from the stimulus, higher harmonics can be increased in amplitude within the limited dynamic range of the display. If this makes these harmonics more visible and they are important for attaining maximum reading rate, then this could explain the modest increases that we have found.

CONCLUSIONS

On the basis of the data presented here, we conclude that spatial filtering of high-contrast text leads to increased reading rates for some low-vision patients. This increased rate is not due to the larger characters in the enhanced condition but may be due in part to their increased luminance. We are exploring this possibility. The increases that we do see may be due to the increased visibility of the higher harmonics of the fundamental square wave of the characters displayed.

It is possible that the differences between our data and those reported by Lawton[12,13] and Lawton *et al.*[21] result from the character size used. That is, the enhancement of smaller text (approximately 2× acuity) may provide the same benefit as larger letters with or without enhancement. If this proves to be the case, it may benefit those low-vision readers for whom particularly large letters are required, by allowing more letters to be displayed simultaneously.

We have also found, as have others, that reading rate cannot be predicted by acuity alone. More importantly, neither acuity nor reading rate for unenhanced text predicts which patients will read spatially filtered text faster. Therefore individual assessment is critical.

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