Eye-Movement Training for Reading in Patients with Age-Related Macular Degeneration

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PURPOSE. To determine whether training oculomotor control, without direct practice in reading sentences, could increase reading speed in patients with age-related macular degeneration (AMD).

METHODS. Sixteen patients with AMD participated in the study (age range, 65–87 years; mean, 77). The training program consisted of a series of exercises that were designed to allow the patients to practice eye movements. At the beginning of training, the subjects practiced small horizontal saccades in response to cognitively easy stimuli (e.g., dots). The training then progressed to practicing larger eye movements and then to practicing saccades with single letters, pairs of letters, and three-letter words. Reading of sentences was practiced in only one exercise, during the last session of the 8-week training.

RESULTS. The difference between average reading speeds before and after training was 24.7 wpm (difference between medians, 17.9 wpm). The increase in speed was statistically significant (Wilcoxon signed rank test = 124.0, $P < 0.001$). There was no significant relationship between change in maximum reading speed and ETDRS (Early Treatment Diabetic Retinopathy Study) acuity ($r = -0.14$, $P = 0.76$) or between change in maximum reading speed and age ($r = 0.25$, $P = 0.45$).

CONCLUSIONS. The results indicate that a training curriculum that concentrates on eye-movement control can increase reading speed in patients with AMD. This finding is especially interesting, because the training involved little direct practice in reading sentences but instead concentrated on having subjects practice control of eye positions and eye movements. (*Invest Ophthalmol Vis Sci.* 2005;46:2886–2896) DOI: 10.1167/iovs.04-1296

Among the most common visual impairments in persons more than 50 years of age is a progressive loss of central visual function as a result of age-related macular degeneration (AMD). It has been estimated that one in three individuals older than 75 years and one in 30 individuals older 52 years were affected by AMD.[1] As central acuity becomes progressively more impaired, a parafoveal locus for fixation, also called a preferred retinal locus (PRL), may be chosen, because it provides better visual acuity and may accommodate a larger span of characters for reading than the diseased fovea. However, reading speed using a PRL is considerably slower than that of normal foveal reading.[2–5] Reading rates of patients with central scotomas can be 20 to 50 words per minute (wpm) or fewer,[6,7] or from one fifth to one third the rate of normally sighted subjects.[8]

Slow reading in patients with central vision loss is due to a combination of sensory,[9,10] oculomotor,[6,11–15] and perceptual[16,17] deficits of the peripheral visual system. Sensory losses in the periphery, such as decreased acuity and contrast sensitivity,[9,18] may be compensated for by altering the text's characteristics and by using magnification aids.[8,19–22] Although easily accomplished, scaling the text characteristics alone does not return reading performance to normal speeds.

Failure to align the PRL properly with the text to be read, coupled with inaccuracy of saccades, also has a deleterious effect on reading speed.[6,11–15,23–28] Fixation stability decreases[29,30] and the number of saccades increases with eccentricity.[14] In addition, use of eccentric vision may decrease localization performance.[31]

It has been reported that providing auditory feedback about eye movements to patients while they read increases reading speed.[21,32–35] It also has been reported that eye-movement training transfers to performance of other tasks. Younger control subjects showed improvement in game playing after being trained to use efficient tracking strategies.[36] Because of the numerous deficits in the control of eye movements as a result of using a PRL, we hypothesized that a rehabilitation program designed to practice control of eye position and relative movements in response to simple tasks would result in a transfer of skills to parafoveal reading. In the present study, we examined whether training oculomotor control, without direct practice reading sentences, could increase reading speed in patients with AMD.

MATERIALS AND METHODS

Patients

Sixteen patients with AMD participated in the study (age range, 65–87 years; mean, 77). Disease characteristics and phenotypes were graded from fundus photographs by one of the authors (GAF). Visual acuity was measured with ETDRS (Early Treatment Diabetic Retinopathy Study) acuity charts, and letter contrast sensitivity was measured with Pelli-Robson contrast sensitivity charts. The patients' clinical characteristics are presented in Table 1. Their visual acuities in the trained eyes ranged from 0.44 to 1.28 logMAR (mean, 0.75 logMAR [logarithm of the minimum angle of resolution], approximately 20/110). Patients

TABLE 1. Patient's Clinical Characteristics

Patient	Age (y)	Sex	Trained Eye	Visual Acuity	Contrast Sensitivity	Refraction (40 cm)	Phenotype*
1	78	M	OS	0.84	1.30	+2.00 + 1.00 × 30°	1, 2
2	75	F	OD	0.44	1.20	+0.25 + 1.50 × 10°	1, 4
3	82	F	OD	0.56	0.88	Plano	1, 3
4	66	F	OD	0.44	1.65	+1.75 +0.75 × 180°	1, 2
5	81	F	OD	0.84	1.30	+2.00	1, 3
6	76	F	OD	0.78	1.40	−3.00 +1.75 × 60°	3
7	75	F	OS	0.54	1.25	Plano	1, 3
8	80	F	OS	1.28	0.60	+1.25 +2.00 × 140°	1, 4
9	82	F	OD	0.78	1.25	+1.50 +0.75 × 60°	1, 4
10	77	M	OS	0.96	1.45	+0.75 +0.75 × 180°	1, 4
11	72	F	OS	0.84	1.30	−2.75 +0.75 × 155°	2, 3
12	87	F	OS	0.90	1.20	−3.25 +2.00 × 95°	1, 3
13	74	M	OD	0.70	0.85	+2.50	1, 2, 4
14	80	F	OD	1.00	0.85	+2.25	1, 2, 5
15	76	M	OS	1.20	0.80	+6.50	2, 4, 5
16	65	F	OD	0.96	1.05	−3.50 +1.00 × 90°	1, 2, 5

*Phenotypes based on macular changes: (1) drusen; (2) pigment mottling or clumping, patchy hypopigmentation; (3) geographic atrophy; (4) fluid, hemorrhage, exudates; and (5) fibrotic scarring.

with relatively good acuity were chosen for this study to maximize compliance with our training program. Each patient's cognitive status was also assessed with the Mini-Mental Status Examination. Patients with a score below 25, which indicates cognitive impairment that could negatively affect learning performance, were excluded. All of our patients passed the Mini-Mental Status Examination.

The research complied with the tenets of the Declaration of Helsinki, and informed written consent was obtained from the subjects after explanation of the nature and possible consequences of the study. The research was approved by the University of Illinois Institutional Review Board.

PRL Identification

PRL location was estimated for each patient based on three fundus fixation photographs. Because the disease may obscure the fovea, the approximate retinal locus of the fovea was estimated in each patient by using the optic nerve head as a landmark. This technique has been used in several studies.[6,25,27,37,38] The location of each patient's PRL was then calculated relative to the estimated location of the fovea for each of the photographs. The PRL was then estimated to be the average of these positions.

Psychophysical Acuity Visual Field Mapping

Letter acuity field maps were measured in each patient, with a fundus-imaging system (FIS) developed in our laboratory. The system is an adaptation of a slit lamp (G2 Ultra Slit Lamp; Marco Technologies, Jacksonville, FL). One accessory arm of the slit lamp was used to project the image of an external 5-in. CRT (80 Hz noninterlaced frame rate and a resolution of 1600 × 1200 pixels; Moraine Displays, Inc., Big Bend, WI) through a 60-mm lens (AF Micronikkor; Nikon, Tokyo, Japan). The 25× magnification setting of the slit lamp, coupled with a 60-D lens, projected the CRT image to a 30° field of view. Illumination for fundus viewing was provided by filtering the light source of the slit lamp using an infrared pass filter (Wratten 89B; Eastman Kodak, Rochester, NY). An infrared sensitive charge-coupled device (CCD) camera (IR-1000; Dage-MTI, Michigan City, IN) was mounted on the other arm of the slit lamp. The images collected by the camera were further processed by an enhancement board (Dage-MTI) that allowed contrast and luminance adjustment. The fundus image was then displayed on a 9-in., black-and-white monitor in real time. The experimenter viewed the patient's fundus image and the letter target overlaid on the fundus at the location of stimulation (BOB II Video OSD; On Screen Display Module; Decade Engineering, Turner, OR; Fig. 1A). The experimenter

ensured that the letters were imaged on the intended retina areas by presenting stimuli only when the eye was stable and fixation was at the PRL (determined by viewing the locations of landmarks on the fundus images).
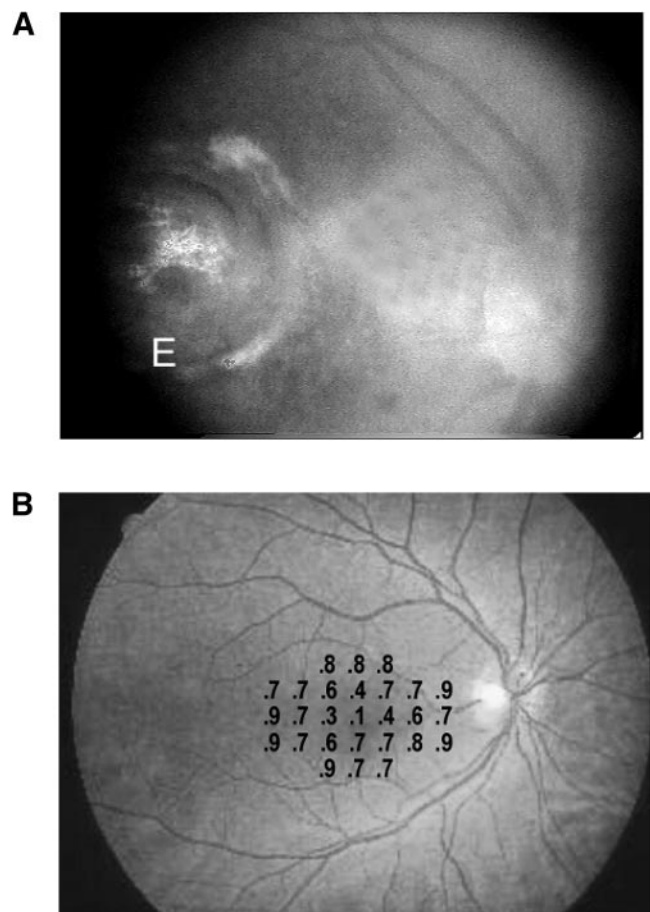
FIGURE 1. (A) Photograph of a fundus image viewed through the FIS with infrared illumination. The stimulus letter and its position on the retina can be observed in real time. (B) A map of the average FIS acuity (in logMAR) in a young, normally sighted group. The acuities are overlaid on an image of a normal fundus.

The acuity field area extended 18° horizontally and 12° vertically. During a trial, a letter randomly chosen from a set of eight letters was presented at one of the testing locations (randomly chosen from 27 possible testing locations; positions shown in Fig. 1B). Letter stroke widths ranged between 0.8 (−0.09 logMAR) and 16.4 minarc (1.21 logMAR; Snellen equivalent of ~20/16–20/328), and the minimum step size was 0.8 minarc. Twenty-seven threshold algorithms were run simultaneously to obtain a letter acuity threshold value for each of the locations.

Training

During training, the subject was comfortably seated at a viewing distance of 40 cm from the screen, and head position was maintained with a forehead and chin support. Training was performed monocularly, using the eye with the better visual acuity. The other eye was patched. Each subject was given new reading glasses with appropriate refraction for the training viewing distance (Table 1), and these were worn throughout the training. At the beginning of the 8-week training, a "reference" letter acuity threshold was measured by showing letters at the center of the monitor screen (21-in. CRT, 1600 × 1200 resolution). Letter acuity thresholds were estimated by using a method of adjustment. A font size that was 0.3 log units above each patient's reference letter acuity threshold was used for all of his or her training exercises. Reference acuity was remeasured at the beginning of each of the training sessions, to check for possible disease progression and/or change in the location of the PRL to a more eccentric position during the course of training. No patient had a decrease in reference letter acuity during the course of training, suggesting no enlargement of the central scotoma and/or no shift in PRL to a more eccentric location.

Eye Tracking

We monitored eye movements using an eye-tracking system (Model 504 Pan/Tilt; Applied Science Laboratories [ASL], Bedford, MA) with a "flock-of-birds" magnetic head tracker. The sampling and output rate of this system was 60 Hz, with a spatial resolution of 0.25° of visual angle. This remote eye-tracking system tracks the pupil and the first Purkinje image (cornea reflection), using the bright pupil-illumination technique. The model used also compensates for head position. All methods of assessing eye movement and eye position in patients with macular disease are complicated by unsteady fixation and uncertainty about fixation locus. To calibrate the eye tracker, we asked each patient to fixate and identify letter optotypes placed at nine positions on the monitor (three on the top row, three on the center row, and three on the bottom row). The size of the letters was set at the patient's reference acuity size, to increase the probability that the patient viewed these stimuli with his or her PRL. The assumption was that acuity in other areas of the retina was more impaired than that at the PRL because of the central locus of the disease and the poorer acuity at more eccentric retinal locations. Therefore, it is likely that these size letters were identified by using the same PRL as that used for viewing the reference acuity task and for viewing the FIS acuity task. We used the eye tracker to monitor saccade direction and magnitude, as well as fixation durations; we did not use it to identify the location of the PRL.

The patterns of fixations on this calibration screen, measured immediately after the initial registration of eye movements, are shown for a normally sighted subject (age, 56 years) and a patient with AMD in Figure 2. The subjects were asked to fixate sequentially on the nine targets (positions shown as X's). The circles mark the locations of fixations, and the diameters of the circles represent fixation durations. The normally sighted subject made few, accurate, and relatively long fixations near the locations of the targets, whereas the patient made a larger number of shorter and inaccurate fixations, documenting the difficulty in eye-movement control. However, the clustering of many of the patient's fixations around the position of the targets confirms the accuracy of the calibration procedure.

The eye movements of a normally sighted subject while reading are shown in Figure 3A. We recorded eye movements while the subject
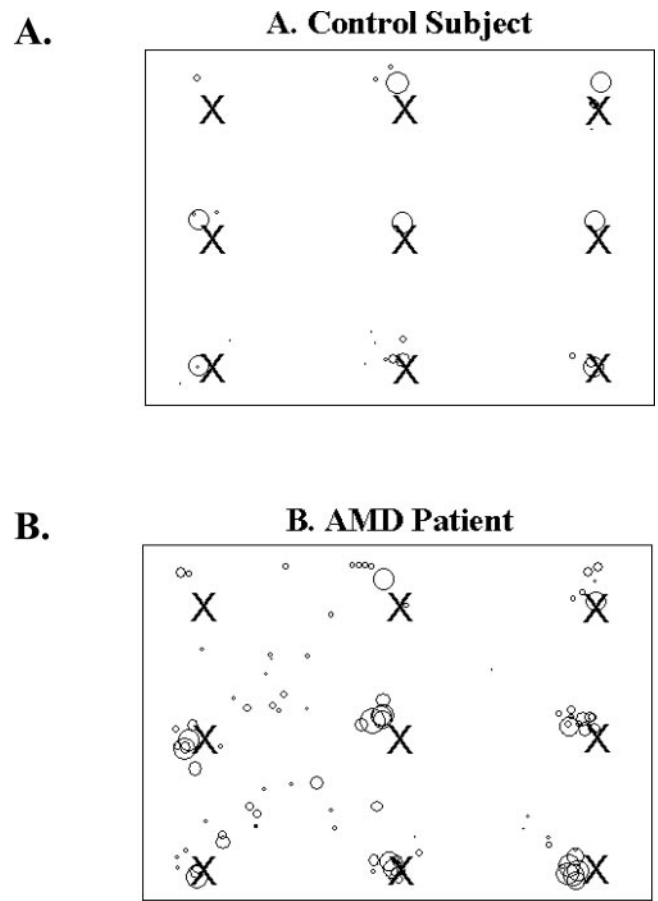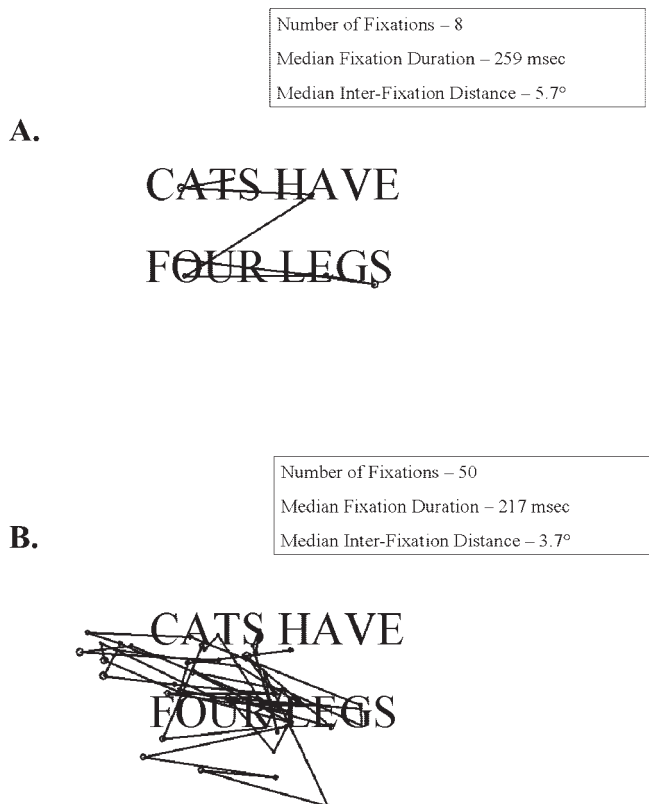

FIGURE 2. Fixation locations are shown for a normally sighted subject (**A**) and a patient with AMD (**B**). The subjects were asked to fixate sequentially on the nine targets (Xs), beginning at the upper right. *Circles*: locations of fixations; diameters of the *circles* represent the fixation duration.

read and then calculated the number of fixations, median duration of fixations, and median interfixation distances. The circles mark the locations of fixations, the diameters of the circles represent fixation durations, and the lines connecting the circles represent the saccades. This subject made a low number of saccades and fixations when reading. An example of the eye-movement patterns of a patient with AMD reading the same text during the pretraining assessment is presented in Figure 3B. The patient had a greater number of short-duration fixations and shorter interfixation distances. This patient could read only the last two words of the larger-text sentence. The greater number of fixations and inappropriate saccades reflect the difficulty that this patient had in controlling eye movement while reading.

Training Exercises

The training program consisted of a series of exercises that were designed to allow the patients to practice eye movements. At the beginning of training, we had the subjects practice small horizontal saccades in response to cognitively easy stimuli (e.g., dots). The training then progressed to practicing larger eye movements and then to practicing saccades with single letters, pairs of letters, and three-letter words. The logic was to focus on eye movement control and gradually increase the information content of the stimulus. Reading of sentences was practiced in only one exercise during the last session of the 8-week training. During our training program, the experimenter monitored relative eye movements and extents and provided verbal feedback to the patient concerning the appropriateness of his or her movements.

A.

> Number of Fixations – 8
> Median Fixation Duration – 259 msec
> Median Inter-Fixation Distance – 5.7°

CATS HAVE

FOUR LEGS

B.

> Number of Fixations – 50
> Median Fixation Duration – 217 msec
> Median Inter-Fixation Distance – 3.7°

CATS HAVE

FOUR LEGS

FIGURE 3. The patterns of eye movements are shown for a normally sighted subject (**A**) and a patient with AMD (**B**) while reading the text. *Circles*: locations of fixations; diameters of the *circles* represent fixation durations, and the *lines* connecting the *circles* represent the saccades.

The training exercises were labeled: Saccade; Dot Saccade; Letter Saccade; Letter-Matching Saccade; Saccade: Word Identification, Preset Search; Random Search; Serial Presentation: Matching; Serial Presentation: Word Identification; Moving Window: Letter Identification; Moving Window, Word Identification; and Moving Window: Sentences. Complete descriptions of the training exercises and the schedule of training are described in the Appendix.

Outcome Measure

We quantified the effects of eye-movement training on reading by using a sentence-reading task. Two lines of text were presented on the monitor screen (Fig. 3). The sentences were adapted from the Woodcock Johnson III Exercises of Achievement, Reading Fluency.[39] Sentences were presented at 0.1, 0.2, 0.3, 0.4, and 0.5 log unit above the reference threshold acuity. The patient read a sentence aloud and then reported whether the sentence made sense. Speed of reading (in words per minute [wpm]) was measured as a function of font size (logMAR). Baseline reading rates were measured during the first session before any training and again during the last session of training after the final training exercise.

RESULTS

Many of the measures collected during the present study document the clinical characteristics of the patients with AMD and difficulties that they had controlling eye movements. These data will be presented first, followed by the results of the eye-movement training program.
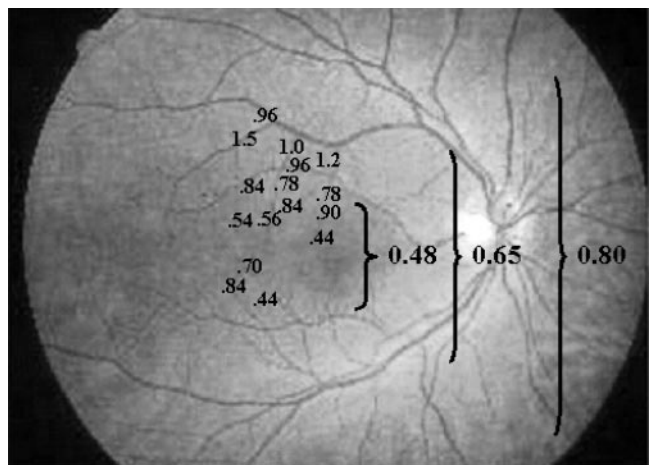
Clinical Characteristics of the Patients with AMD

Locations of PRLs. The locations of the 16 patients' PRLs, as determined from fundus fixation photographs, are mapped onto an image of a normal fundus in Figure 4. At each PRL, the patient's ETDRS acuity is indicated. The three brackets drawn on this image designate regions within which visual acuities of 0.48 logMAR (20/60) or better (inner area), 0.65 logMAR (20/89) or better (mid area), and 0.80 logMAR (20/126) or better (outer area) were observed in normally sighted subjects.[18] This allows for an assessment of the relative normalcy of the acuities measured at the patients' PRLs. In general, the patients' ETDRS acuities were more impaired than those of visually normal subjects at equivalent eccentricities.

Fundus-Imaging System. Because we used a new instrument to assess visual acuity fields, we initially validated these maps by comparing the changes in acuity as a function of eccentricity obtained with the FIS in a group of normally sighted subjects to those obtained during free viewing in a separate group of highly trained subjects.[18] The mean change in acuity on the FIS for eight younger, normally sighted subjects (five women, three men; age range, 20–40 years; mean, 27; visual acuity, 20/20 or better) was 0.04 logMAR per degree (equivalent to two letters on the ETDRS chart); the data from Seiple et al.[18] for an age-similar group of normally sighted subjects (two women, two men; mean age, 35 years; visual acuity, 20/20) showed an average slope of 0.03 logMAR per degree over the same range of eccentricity. Similar rates of decrease for the two methods of measuring parafoveal function suggest that the FIS can be used for accurate assessment of local acuity.

Average visual acuity fields, as measured with the FIS, of a group of nine older normally sighted subjects (four women, five men; age range, 47–84 years; mean, 61; visual acuity, 20/30 or better) and of patient 15 are shown in Figures 1B and 5, respectively. In 13 of the 16 patients, the location of best acuity corresponded to the retinal locus of fixation observed in the fundus photographs. In the other three patients, the location of best acuity, as measured with the FIS, was immediately lateral (±3°) to the locus of fixation observed in the fundus photographs. In these three patients, the differences between the acuity at the location of best acuity and that at fixation averaged 0.23 logMAR.

Initial Performance on Training Exercises. Average response delays for the Letter Saccade training exercise are plotted in Figure 6A for the 16 patients and for three normally

FIGURE 4. The locations of the 16 patients' PRLs, as determined from fundus fixation photographs, are mapped onto an image of a normal fundus.
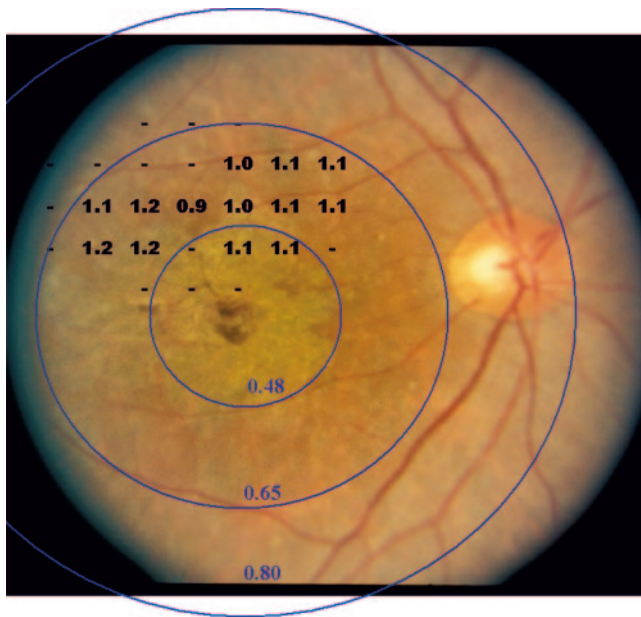
FIGURE 5. The visual acuity field of patient 15 is mapped onto a photograph of his fundus.

sighted subjects (one woman, two men; ages 28, 56, and 66 years; visual acuity, 20/20) on the first training trial. The data from the normally sighted subjects were obtained over the same period as the patients' training sessions. As this group was small and not age matched, their data are presented only to give the reader a benchmark by which to judge qualitatively the magnitude of the patients' responses. The delays of the normally sighted subjects were shorter than those of the patients with AMD and were not related to age, as the youngest subject had the longest delays of the three subjects. Average response delays for the Word-Saccade task (Fig. 6B) and the Preset-Search task (Fig. 6C) were also longer in the patients with AMD than in the three normally sighted subjects. Average accuracy in the Moving-Window Word-Identification task (Fig. 6D) was higher in the three normally sighted subjects than in the patients. These data document the difficulties that the patients had in performing the training tasks.

Effects of Eye-Movement Training

Effects of Training on Performance of the Exercises. We examined the changes in performance as a function of practice for each of the training exercises (Table 2). For the Dot Saccade task, delays to saccades averaged 1040 ms on the first trial and 888 ms on the last trial (F = 84.9, $P \leq 0.001$). Response times to letter saccades decreased from an average of 2153 ms for the initial trial to 1620 ms on the last trial (F = 14.3, $P = 0.004$). For the Letter-Matching Saccade task, response times averaged 2056 ms on the first trial and 1800 ms on the last trial (F = 3.6, $P = 0.09$). There was essentially no change in performance as a function of training for the Word-Identification Saccade task. Response times averaged 2185 ms on the first trial and 2056 ms on the last (F = 0.01, $P = 0.97$). For the Preset-Search task, the patients had an average response time of 1640 ms on the first trial and 1347 ms on the last (F = 10.1, $P = 0.01$). For the Letter-Matching Serial Presentation task, response times averaged 2900 ms on the first trial and 1985 ms on the last (F = 16.0, $P = 0.04$). The accuracy of performance in the Moving-Window Word-Identification task averaged 86% in the first trial and increased to an average of 96% on the last (F = 6.12, $P = 0.04$).

Effects of Training on Acuity. We measured reference acuity for letters at the beginning of each training session. In this group of patients, mean reference acuity improved over the 8 weeks of training (Fig. 7A). The main effect of training session, however, was not significant (F = 0.30; $P = 0.95$). When the patients' data were examined individually, there was a significant relationship between reference acuity in session 1 and the extent of improvement in acuity at session 8 ($r = .65$, F = 10.16, $P = 0.007$). Patients with poorer acuity showed a greater improvement in acuity over the course of training (Fig. 7B).

Effects of Training on Reading. Although patients demonstrated significant improvements in performance on some of the training tasks, we also wanted to know whether training eye movements generalizes to improvement in reading. To assess this, we compared reading performance before and after training. Reading speeds were plotted as a function of text sizes and best fitted with a sigmoid equation of the form $y = a/1 + \exp(-[x - b]/c)$, where a quantifies the horizontal position of the curve, b is the maximum reading speed, and c is the slope of the function. In Figure 8, the speeds of reading sentences are plotted against font sizes for two (one woman, one man; ages, 29 and 55 years; visual acuity, 20/20) normally sighted subjects (filled circles and triangles) and for patient 6 before (open squares) and after (filled squares) training. Legge et al.[40] reported that reading speeds for drifting text decreased in observers with normal vision as character size increased above an angular size of 4° (equivalent to 1.7 logMAR). We did not observe this decline in reading speed when using letter stroke widths smaller than 1.5 logMAR (2.6° character size).

For each patient with AMD, the differences in maximum speed (log b in wpm) before and after training are plotted as a function of the differences in font size (a in logMAR) in Figure 9. Data points falling on the y-axis indicate a gain in reading speed after training, and points falling on the x-axis indicate a gain in sentence acuity. The difference between average reading speed before and after training was 24.7 wpm (0.1 log unit; difference between medians, 17.9 wpm; 0.08 log unit). The increase in speed was statistically significant (Wilcoxon signed rank test = 124.0, $P < 0.001$). For the 11 of the 16 patients with AMD who increased their maximum reading speed by greater than 10 wpm, the average increase was 35.5 wpm (median, 21.5 wpm). There were no significant relationships between change in maximum reading speed and ETDRS acuity ($r = -0.14$, $P = 0.76$) or between change in maximum reading speed and age ($r = 0.25$, $P = 0.45$).

The average values of a were 0.76 logMAR (20/115) before and 0.67 logMAR (20/93) after training. The data were normally distributed, and the decrease in font size was statistically significant (paired $t = 5.01$, $P < 0.001$).

DISCUSSION

Our results indicate that eye-movement training increases reading speed in patients with AMD. The finding of significantly increased reading speed is especially interesting because our training involved little direct practice in reading sentences, but instead concentrated on training the patients in controlling their eye positions and movements. The improvements we found after training in this group of patients averaged approximately 25 wpm (27.5%), which represents an improvement to near normal speed for this reading task. Our patients had relatively high reading speeds before training (range, 51–121 wpm; average, 91 wpm), whereas reading rates of 20 wpm or slower have been observed in other patients with AMD.[7,20,22,41] This was probably due to the relatively good acuity of the patients in our group. Although the reading speed increases that we observed were modest, they are of the same
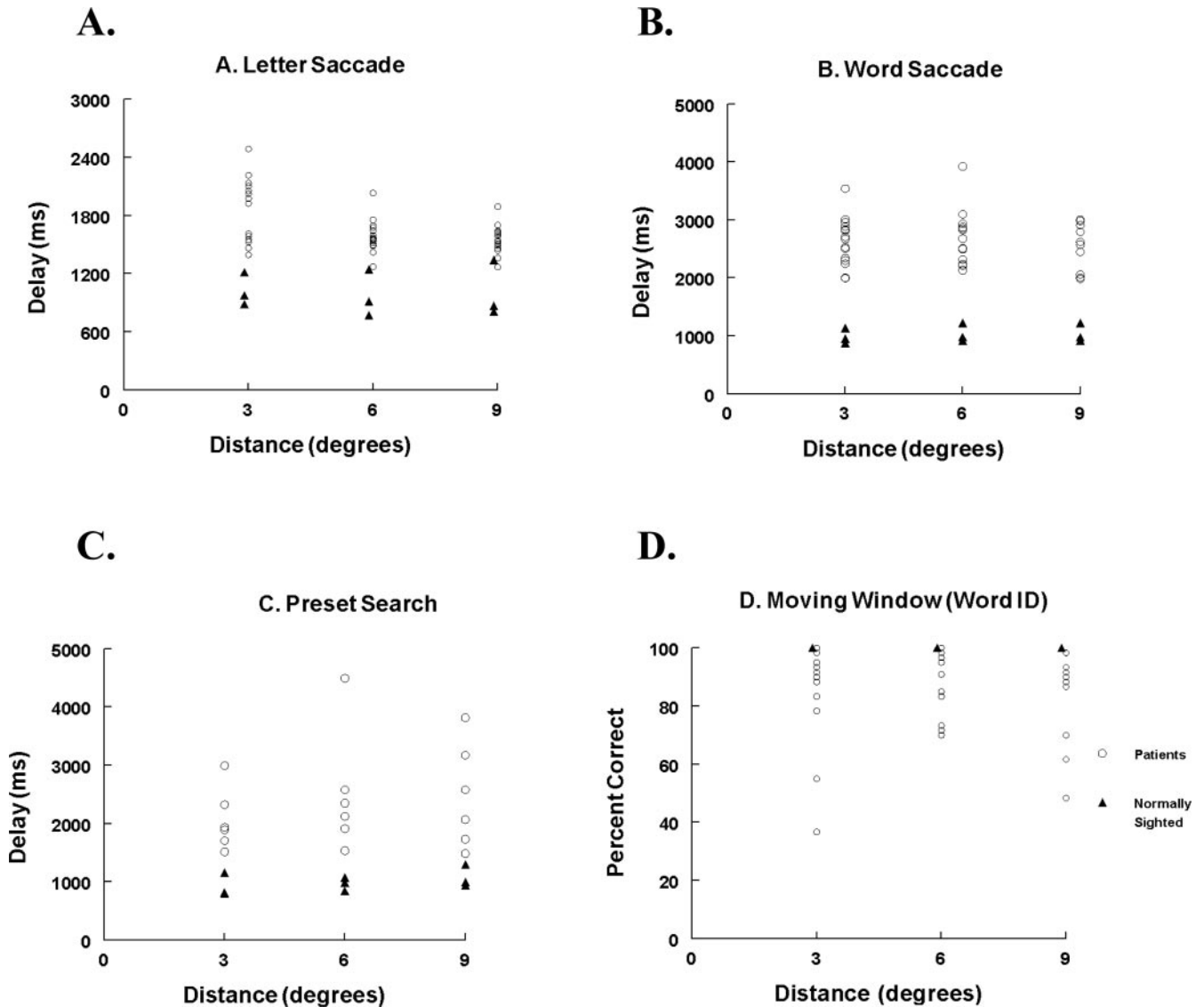
FIGURE 6. (A–C) Average response delays and (D) accuracy of word identification in the Moving-Window exercise in the first trial of the patients with AMD (○) and of three normally sighted subjects (▲) at each intertarget distance.

order of magnitude as those reported in the literature. Hall and Ciuffreda[21] found an increase of 12 wpm, and Solan et al.[34] reported an increase of 36 wpm when using training programs that provided feedback about eye movements during reading. In contrast, Nilsson[20] reported an increase of 50 wpm, and Frennesson et al.[22] reported an increase of 46 wpm, when comparing reading speeds before training and with no magnification to speeds after training and with magnification devices.

**TABLE 2.** Changes in Performance of Training Exercises

Training Exercise	Pretraining	Posttraining	*P*
Dot saccade (ms)	1,040	888	<0.001
Letter saccade (ms)	2,153	1620	0.004
Letter-matching saccade (ms)	2,056	1,800	0.09
Word-identification saccade (ms)	2,185	2,056	0.97
Preset search (ms)	1,640	1,347	0.01
Serial matching: letters (ms)	2,900	1,985	0.04
Moving window: words (%)	86	96	0.04

Eye Movements with a PRL

The eye-movement system is a mechanism that normally places an object on the fovea for inspection of fine details (foveation). When the fovea is diseased and a PRL is used for inspection, new oculomotor strategies must be adopted. This is not easily accomplished by adult patients. White and Bedell[13] reported that 6 of 11 patients with juvenile macular degeneration, but only 1 of 10 patients with AMD, shifted the reference point of eye movements to a PRL without training. The single patient with AMD who accomplished this had a disease duration of 17 years, the longest of any patient in the study. The difficulty in adopting new scanning behavior relative to the new fixation location may have its origins in the decreased spatial representation and increased positional uncertainty associated with the parafoveal retina.[16,17]

The sensory deficits of the parafoveal retina may also have secondary effects on reading by influencing eye movements. For example, the decreased contrast sensitivity of the peripheral locations in the visual field may also account for decreased reading speeds at these eccentric locations. Others[42–44] have
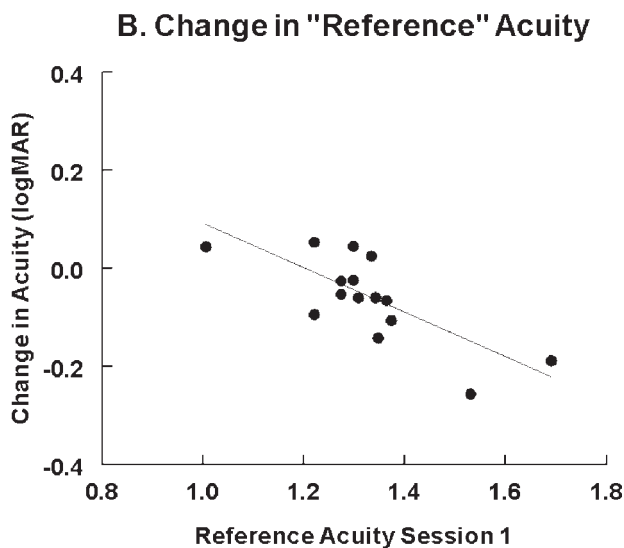
A.

A. Average "Reference" Acuity

B.

B. Change in "Reference" Acuity
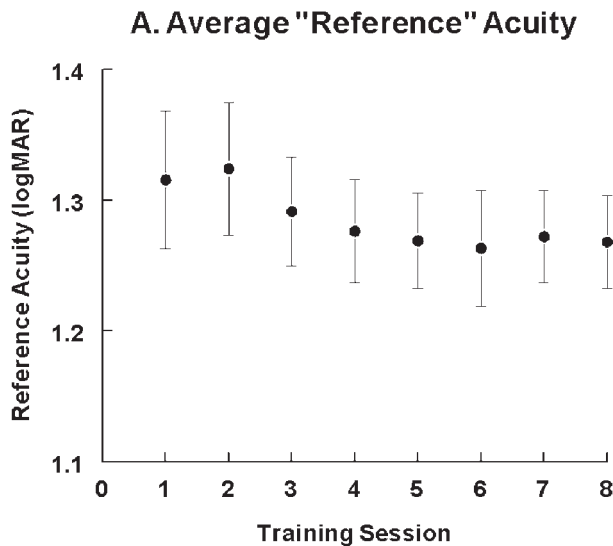
FIGURE 7. (**A**) The average reference acuities for 16 patients with AMD are plotted as a function of testing day. (**B**) For each patient, the difference in reference acuity in session 8 minus that in session 1 is plotted against his or her reference acuity in session 1.

shown that, as contrast sensitivity decreases, the number of saccades and duration of fixations increase. Legge et al.[45] hypothesized that visual span and information acquisition speed may be reduced as a function of decreased contrast.

It also has been hypothesized that shifts of covert spatial attention precede and serve to trigger the next saccade.[46] Because the magnitude of allocation of covert attention decreases with increasing eccentricity[47,48] and with increasing age,[49] generation of the next saccade may be delayed. In agreement, Legge et al.[2] found that age is a better predictor of the reading speed of patients with AMD than are clinical measures.

The role of eye movements in determining reading speed is emphasized by the results of experiments in which text was
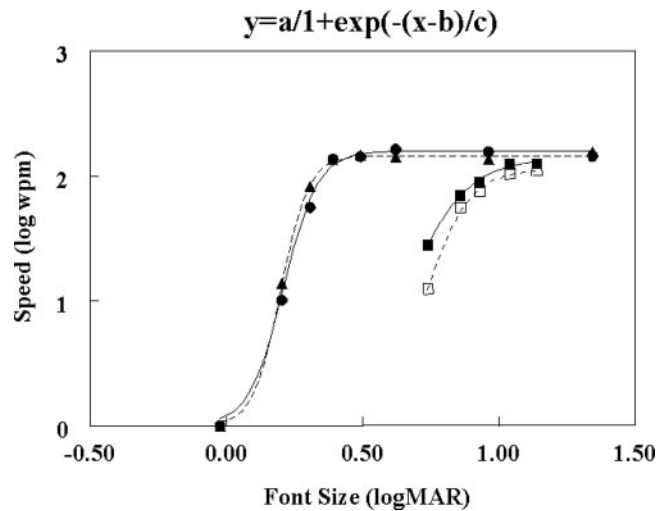
$$y = a/1 + \exp(-(x-b)/c)$$

FIGURE 8. Speed of reading sentences plotted against font sizes for two normally sighted subjects (● and ▲) and for patient 6 before (□) and after (■) training.

scrolled or rapidly and sequentially presented. Reading rates are much higher when eye movements are not required.[38,50-52] Rubin and Turano[38] reported that patients with central vision loss read rapid serially presented text at an average rate of 120 wpm but read text that requires eye movements at an average rate of only 81 wpm.

Eccentric Viewing Training

There are reports that patients with AMD can benefit from low-vision aids and reading rehabilitation training.[19-22,53] Many of these vision-rehabilitation programs have been designed to improve reading ability with training techniques that enhance the patient's awareness of the location of his/her

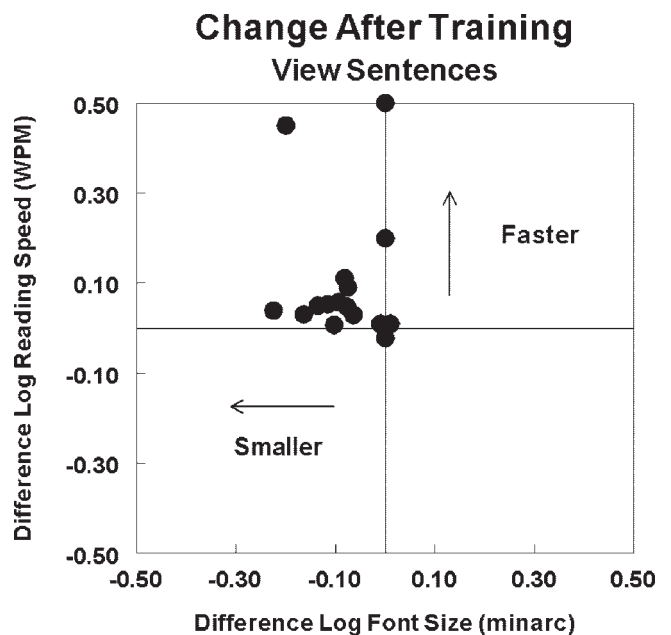## Change After Training
View Sentences

FIGURE 9. Effects of training. Differences in maximum speed (log *b* in words per minute) before and after training are plotted for each patient as a function of the differences in font size (*a* in logMAR) before and after training.

PRL.[20,54–57] Cognitive training has also been shown to improve reading comprehension of patients with macular disease.[58]

A second approach to reading rehabilitation emphasizes the training of eye movements while reading.[21,34,59] Hall and Ciuffreda[21] reported that providing auditory feedback about the appropriateness of reading eye movements increased reading rates by 21% ± 25%. Contestabile et al.[59] used auditory feedback to train fixation stability in a group of patients with eye disease. After training, the visual acuities significantly improved from a pretraining level of 0.12 ± 0.12 to a posttraining level of 0.28 ± 0.17, and reading speed improved by an average of 21.7 ± 16.9 wpm (see Fig. 3 in Ref. 59). In our study, we observed a significant shift in the reading speed versus letter size function to smaller text and an improvement in reference acuity, although the latter finding was not statistically significant. Solan et al.[34] also reported an average increase of 17% (36 wpm) for patients who were given eye movement and reading training.

Recently, Han et al.[35] described a program of eye-movement training for patients with brain injuries. Similar to the logic of our training program, these investigators trained reading-related eye movement skills using nontext stimuli and simulated-reading eye movements. They[35] reported improvements, using a subjective reading-rating scale questionnaire, including an increase in the time that patients reported they could read comfortably and an increase in comprehension.

Multiple PRLs

Training reading, without simultaneously viewing the fundus, raises the question of where the patients were viewing. Patients can use one or more PRLs, depending on the size of the scotoma, the size of the stimuli, and the conditions of the task.[30,60–64] However, Guez et al.[63] reported that the PRLs were stable in 20 of 24 patients when they fixated on digits of different sizes. The remaining four patients used two PRLs: one for large and another for small stimuli. Duret et al.[62] reported that, in their two patients with AMD, a single PRL was used 13 of 14 times for reading words of 4 or fewer letters and 19 of 24 times for words of 10 or fewer letters. Based on these reports, it appears reasonable to assume that our subjects used a single PRL for our training tasks involving stimuli of one, two, or three letters. In support, we found that most patients used the same single retinal location for fixation in fundus photographs and for viewing in the letter acuity task presented in the FIS. In addition, we observed no consistent changes in fixation position when we tracked eye movements during training. However, the possible use of multiple PRLs does not invalidate the conclusions of our study. We trained eye movement control and its effects on reading; we did not train PRLs.

Locus of Training Effects

Questions remain about the locus of the increased reading speeds observed in our study. It is important to parse out the improvements that were directly attributable to the training program from the relative contributions of ancillary effects, such as elapsed time (i.e., did the patients adapt on their own over the training period as a function of living with the disease), repeated assessments, and providing a social situation in which the patients expected training and improvements. These are questions that are relevant to all treatment interventions, and in future research we will address each of them as they relate to reading rehabilitation.

Summary

The improvements in speed that we observed were modest, but they may translate to a better quality of life for these patients. For example, if one assumes an average of 2000 words per page in a newspaper, at a reading speed of 91 wpm, a patient would require approximately 22 minutes to read the page. At 116 wpm, it would take the patient approximately 17 minutes, or a savings of 5 minutes per page. Our results indicate that a curriculum that concentrates on training eye-movement skill, without direct reading practice, has the potential to increase reading speeds in patients with AMD.

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APPENDIX

Exercises

Dot Saccade. In this exercise, a dot was alternately presented at one of two locations on the monitor (3°, 6°, or 9° apart). The subject's task was to saccade between the dots as they were presented. The rate of alternation (0.5 or 1 Hz) and/or distance between dots was increased as the training progressed.

Letter Saccade. This exercise was similar to the dot saccade, except that letters were presented instead of dots. On randomly chosen alternations, the letter changed, and the subject reported when the letter changed to a different letter; the subject was not required to identify the letter. Response delay and accuracy were recorded.

Letter-Matching Saccade. In this exercise, pairs of letters were alternately presented 3°, 6°, or 9° apart. The pairs were either the same letter or different letters. The pairs changed on randomly selected alternations. The patient was required to report "same" or "different" when the pairs changed. Response delay and accuracy were recorded.

Saccade: Word Identification. Two- or three-letter words were alternatively presented 3°, 6°, or 9° apart (spacing between words). On randomly chosen alternations, the word changed, and the subject was required to identify the new word. Response delay and accuracy were recorded.

Preset Search. The patient fixated a central cross, and then a letter was presented elsewhere on the monitor. Letters were presented sequentially in a clockwise pattern, beginning at the 10 o'clock position at 3° from the center of the screen. The patient was asked to find and name the letter. Response delay and accuracy were recorded. As performance increased, the letters were presented at 6° and then 9° eccentricity.

Random Search. This exercise was similar to the Preset Search, except that the letters appeared at random positions on the screen.

Serial Presentation: Matching. In this exercise, two- or three-letter combinations were presented in the center of the screen. On each trial, the patient fixated a central dot that then disappeared and was replaced by the letter. The patient's task was to report whether the letters were identical or different. Response delay and accuracy were recorded. The rate of presentation was altered as a function of the response of the patient. This task allowed the patients to practice maintaining fixation and to practice pattern recognition with the parafoveal retina.

Serial Presentation: Word Identification. This exercise was similar the Matching exercise, except that two- or three-letter words were presented. The patient's task was to identify the words. Response delay and accuracy were recorded.

Moving Window: Letter Identification. Letters were presented sequentially across the screen from left to right. In separate trials, the distances between letters were 3°, 6°, and 9°. On each redraw, the preceding letter disappeared. The letters changed on randomly selected redraws, and the subject was required to name the letters when they changed. Response delay and accuracy were recorded.

Moving Window: Word Identification. In separate exercises, two- or three-letter words were presented sequentially across the screen from left to right. In separate trials, the distances between words were 3°, 6°, and 9°. On each redraw, the preceding word disappeared. The words changed on randomly chosen presentations, and the subject reported the word when it changed. Response delay and accuracy were recorded.

TABLE A1. Tasks for Each Session

	Interstimulus Interval (sec)	Interstimulus Distance (deg)	Time (min)	Total (min)	Comments
Day 1					
Static acuity			5		
Baseline reading			15		
Dot saccade	2	3, 6, 9	46		
Dot saccade	1	3, 6, 9	31		
Letter saccade	2	3	15	112	
Day 2					
Static acuity			5		
Letter saccade	2	3, 6, 9	46		
Letter saccade	1	3, 6, 9	31		
Letter-matching saccade	2	3	15	97	
Day 3					
Static acuity			5		
Letter-matching saccade	2	3, 6, 9	46		
Letter-matching saccade	1	3, 6, 9	31		
Word saccade	2	3, 6	30	112	
Day 4					
Static acuity			5		
Word saccade	2	6, 9	30		
Word saccade	1	3, 6, 9	31		
Preset search	2	3, 6, 9	39	105	
Day 5					
Static acuity			5		
Preset search	2	9	13		
Preset search	1	3, 6, 9	35		
Random search	2	3, 6, 9	41		
Random search	1	3, 6	22	116	
Day 6					
Static acuity			5		
Random search	1	3, 9	22		
Serial matching: letters	1		28		2 letters
Serial matching: letters	1		28		3 letters
Serial matching: words	1		28	111	2 letters
Day 7					
Static acuity			5		
Serial matching: words	1		14		2 letters
Serial matching: words	1	1	28		3 letters
Moving window: letters	2	3, 6, 9	39		1 letter
Moving window: words	2	3, 6	26		2 letters
Day 8					
Static acuity			5		
Moving window: words	2	9	13		2 letters
Moving window: words	1	3, 6, 9	39		3 letters
Moving window: sentences	2	3, 6, 9	32		
Outcome reading			15	104	

Moving Window: Sentences. Words that formed sentences were presented sequentially horizontally across the screen from left to right. In separate trials, the distances between letters were 3°, 6°, and 9°. On each redraw, the preceding word disappeared. The patient read each word aloud. Once all the words in the sentence were presented, the subject reported whether the sentence made sense or was nonsensical.

Schedule of Training

Each of the training exercises was practiced for a series of 10 trials, and each trial consisted of 30 repetitions of the task for each of the three intertarget distance conditions. To design the training schedule, the time taken to complete each training task was calculated. For example, for the dot-saccade task, the first trials were conducted with a 2-second delay between target alternations. With 30 alternations per trial, each trial lasted 60 seconds. We allowed for a 30-second rest period between trials. The total time for the 10 trials for one condition (3°, 6°, or 9°) was calculated at 870 seconds. We then allowed a 1-minute rest between conditions, for a total of 45.5 minutes for the three intertarget distance conditions. This task was also practiced with a 1-second delay between alternations, for a total 31.5 minutes of testing. Similar calculations were performed for each of the tasks. The training consisted of eight weekly sessions. The tasks for each session are shown in Table A1. Each session was scheduled to last for 2 hours but occasionally lasted longer, because of more extended rests.