

ECENTRIC VIEWING TRAINING IN MACULAR DEGENERATION USING

AUDITORY OCULAR MOTOR BIOFEEDBACK

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Abstract

Ocular motor-based auditory biofeedback, in which an individual "hears their eyes move," has been used successfully in patients with ocular motor dysfunction, as well as in visually-normal adults to increase awareness of and control over their eye movements. The present study used auditory ocular motor biofeedback to improve reading in adults with central scotomas due to macular degeneration (MD). Experimental group members had MD ($N=10$); control group members had normal vision ($N=5$). Observers read text and performed fixation, saccadic, and pursuit tracking during presentation of auditory biofeedback related to horizontal eye position. All received 15 min. of biofeedback training during each of six sessions over a two-week period. The primary pre- and post-training assessment included objective measurement of reading rate. The MD group showed a significant increase in reading rate (percent change mean = 21.88%, $SD = 24.82$), whereas the control group did not (mean = 4.13%, $SD = 22.01$). Nine of the ten observers with MD exhibited varying degrees of improvement in overall reading performance. Improvements were evidenced by one or more of the following: a decreased number of fixations, regressions or number of saccades per re-

turn-sweep, and increased reading accuracy, speed, or ease. These results were consistent with MD observers' reports of faster and more automatic reading ability attributed to the training. Control group results were mixed and lacked a consistent trend. Adults with central field loss can use auditory ocular motor biofeedback to learn to read faster and more efficiently. The biofeedback may initially heighten the attention paid to eye movements, leading to improved eccentric viewing through associative learning; that is, the eye movement strategies ultimately become conditioned and hence automatic. Such rapid retraining of ocular motor abilities, i.e., 1.5 total hours of biofeedback, merits further experimentation, with longer training periods where possible.

Key Words

eye movements, reading, macular degeneration, central field loss, biofeedback

INTRODUCTION

Reading and Macular Degeneration

The most significant problem reported by patients with central scotoma, such as those with macular degeneration (MD), is its interference with reading.¹ Readers with MD typically produce eye movement patterns which compromise their visual input.

Their patterns may evidence: (1) a relatively high number of progressive saccades, leading to fixations of abnormally long and variable duration as each line of text is read, (2) frequent instances of multiple saccades, rather than a single accurate saccade, comprising the return-sweep movement after each line has been read, and (3) a tendency to "lose their place" horizontally and/or vertically while reading, resulting in more re-reading, as evidenced by a higher number of regressions.²⁻⁵ Each of these factors reduces reading speed.

Thus, reading with macular degeneration is problematic due largely to a lack of basic ocular motor tracking skills in the presence of central vision loss. The effect of inefficient eye movements is compounded in readers with central field loss because only images falling on eccentric, relatively low-acuity retina can be processed as meaningful visual input.

Auditory Ocular Motor Biofeedback

Ocular motor-based auditory biofeedback refers most commonly to pitch-varied tonal feedback related to change in horizontal eye position.⁶ By drawing attention to and/or heightening awareness of one's eye movements, auditory ocular motor biofeedback can lead to an increase in intentional control of the eyes, which, over time, becomes increasingly reflexive.⁷ Experimentally, this technique has

Table 1. Clinical Data
AMD = Age-related macular degeneration, JMD = Stargardt's macular degeneration

Clinical Code	Age (yrs)	Visual Status/ Related Conditions	Pre Near VA OU		Post Near VA OU		Pre Distance VA OU		Post Distance VA OU	
			Snellen	LogMar	Snellen	LogMar	Snellen	LogMar	Snellen	LogMar
MAI1	84	AMD	20/125	0.8	20/100	0.7	20/160	0.9	20/125	0.8
MWB1	82	wet AMD	20/160	0.9	20/160	0.9	20/250	1.1	20/200	1.0
MNW1	76	AMD, macular drusen	20/40	0.3	20/32	0.2	20/50	0.4	20/63	0.5
MRF1	74	wet AMD, macular scars	20/100	0.7	20/160	0.9	20/320	1.2	20/200	1.0
MAM3	74	wet AMD	20/63	0.5	20/40	0.3	20/100	0.7	20/160	0.9
MJT1	64	JMD, macular scars, vitrectomy	20/125	0.8	20/160	0.9	20/250	1.1	20/250	1.1
MCG1	62	AMD, macular drusen	20/160	0.9	20/160	0.9	20/200	1.0	20/200	1.0
MJD3	47	JMD	20/250	1.1	20/125	0.8	20/320	1.2	20/250	1.1
MMS2	47	JMD, peripheral retinal holes	20/250	1.1	20/160	0.9	20/400	1.3	20/250	1.1
MDA2	43	JMD, macular scars, lattice degeneration	20/160	0.9	20/100	0.7	20/200	1.0	20/160	0.9
SJB1	81	Control	20/32	0.2	20/40	0.3	20/100	0.7	20/40	0.3
SEK2	81	Control	20/20	0	20/12.5	-0.2	20/40	0.3	20/40	0.3
SMV2	71	Control	20/50	0.4	20/25	0.1	20/40	0.3	20/63	0.5
SRR1	62	Control	20/20	0.0	20/20	0.0	20/32	0.2	20/25	0.1
SFG1	62	Control	20/16	-0.1	20/16	-0.1	20/25	0.1	20/20	0.0

demonstrated that individuals with poor central vision or in the absence of specific visual cues can maintain relatively accurate vergence,⁸ and fixation.^{6,9} Clinically, auditory biofeedback has been used to limit or reduce deleterious visual effects of eye movement abnormalities including nystagmus and abnormal saccadic intrusions.¹⁰⁻¹³ Recently, in research with visually-normal young adults, Fayos and Ciuffreda confirmed and extended the hypothesis that the rhythm produced by the hearing of one's eye movements can be a powerful conditioning tool to train individuals to move the eyes more efficiently under conscious control during reading.⁷ It has been known for some time that reading by individuals with reading deficiencies can improve using ocular motor-based, visual feedback techniques; examples include vergence training, and reading-related saccadic eye movement conditioning using a rate-controlled moveable text-limiting aperture (e.g., the Guided Reader).¹²⁻¹⁶ It should be noted that "reading performance" is not used here as a formulaic variable but rather as a general term (whose improvement is evidenced by, e.g., decreased number of fixations and regressions, decreased number of saccades per return-sweep, and/or increased speed, accuracy, and subjective ease of reading).

Rationale and Design of Study

The present study tested the hypothesis that auditory ocular motor biofeedback

can facilitate more efficient control of eye movements during reading, and that therefore such feedback presented to readers with MD can improve reading. The investigation used auditory ocular motor biofeedback to improve reading in a group of adults with central scotomas due to macular degeneration. The goal was to enable these observers to read more easily and efficiently following the eye movement training. As is critical in this type of clinical study, a control group with normal vision (age-matched insofar as was feasible) was included, which received the same training and the same pre- and post-training evaluation as the experimental group. This design precluded several common confounds, for example, that an effect was brought about simply from the individuals' practicing reading during the six training sessions. A description of the training, its effects on reading and other variables, and the implications of the results are presented in the remainder of this paper. Because the vision loss in MD is due to central scotoma, any reading improvements attributable to the change in ocular motor control can be inferred to have come about through a simultaneous improvement in eccentric viewing.

METHODS

All procedures were approved by the appropriate institutional review board and conformed to the tenets of the Declaration of Helsinki. Signed informed consent was

obtained from all observers prior to any testing.

Groups

Data were gathered from adults with MD (N=10) assigned to the experimental group, and those of similar age with normal vision (N=5), who formed the control group (see Table 1). The experimental group members ranged from 43-84 years of age (median = 69). The control group members ranged in age from 62-81 years (median = 71). All observers reported being in good general health. Records of previous vision examinations for each observer were obtained via written consent (see Table 1 for clinical characteristics). In addition, visuoscopy examination (without dilation) was performed by one of the authors (KC, who is an optometrist); this confirmed the presence of macular degeneration in the experimental group members. No control group members showed ocular pathologies that would be expected to affect reading or other measures in this study.

Pre-training Assessment Apparatus and Procedures

A pre-training assessment battery was administered consisting of the following tests and procedures:

- * A brief history of each observer's reading ability was obtained to identify individuals who might have had processing-related reading problems.

Table 2. Reading rates before and after the auditory biofeedback training sessions			
Clinical Code	Pre-training Reading Rate (wds/min)	Post-training Reading Rate (wds/min)	Reading Rate % change
Experimental Group			
MAI1	55.00	62.00	12.73
MWB1	44.00	69.00	56.82
MNW1	207.00	258.00	24.64
MRF1	56.00	82.00	46.43
MAM3	242.00	249.00	2.89
MJT1	22.00	23.00	4.55
MCG1	55.00	58.00	5.45
MJD3	79.00	74.00	-6.33
MMS2	30.00	49.00	63.33
MDA2	36.00	39.00	8.33
Experimental Group (N=10)		Mean % change 21.88 (sd 24.82)	
Control Group			
SJB1	228.00	205.00	-10.09
SEK2	321.00	386.00	20.25
SMV2	220.00	182.00	-17.27
SRR1	193.00	163.00	-15.54
SFG1	175.00	160.00	-8.57
Control Group (N=5)		Mean % change 4.13 (sd 22.01)	

- * Distance and near visual acuity were measured using Lighthouse Distance and Near Visual Acuity Tests.^a
- * Global visual search was evaluated using a timed "embedded figures" task, in which the participant was asked to find eight items hidden in a complex drawing within a maximum of three minutes.^b
- * The Developmental Eye Movement (DEM) test was administered to assess global saccadic tracking ability.^c
- * A maze tracing task was used as a measure of eye-hand coordination.^d
- * Lastly, the Ober2:Visagraph recording and automated computer analysis system and reading tests^e were used to assess reading performance.¹² This system has a resolution of 0.25 degrees, a linearity of +/-15 degrees, and a bandwidth of 50 HZ. Infrared emitters and sensors embedded in a pair of goggles worn by the observer permitted simultaneous recording of the horizontal eye movements of the left and right eyes as a standardized 100 word (Ober2:Visagraph) paragraph was read. The goggles fit comfortably and were used over the customary near

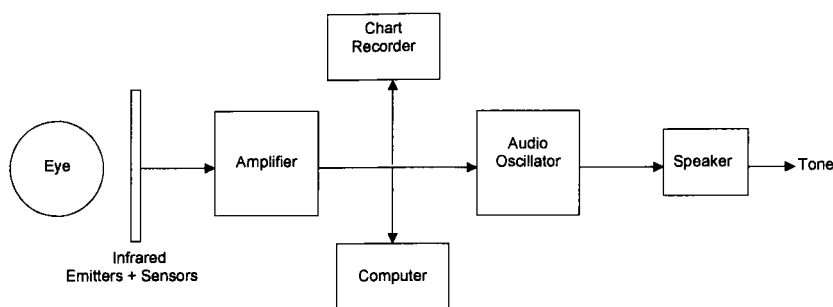


Figure 1. Schematic representation of auditory ocular motor biofeedback system.

spectacle correction. Individuals read passages of the highest available standardized comprehension level (Ober2:Visagraph adult "Level 10"). Each held the text independently and read at their own comfortable reading distance, which ranged from 7 to 40 cm in MD, and from 30 to 50 cm in the control group. All were seated in an ophthalmic examination chair (equipped with a headrest) and were instructed to keep both the head and text stable (excessive head and/or text movement would not have yielded data scorable by the Ober2:Visagraph). Ten "yes or no" questions (Ober2: Visagraph) then were administered to assess the level of reading comprehension. Per the instructions, a minimum of 70% comprehension was required for the eye movement results to be considered valid. Most observers scored at the 80% criterion or higher; in the event that the minimum 70% comprehension criterion was not attained, the test was re-administered (per the Ober2: Visagraph instructions) until that level was achieved. Automated Ober2: Visagraph data analyses were performed using the standard software provided.

Some of the pre-training tests in the assessment battery included brief practice pre-tests prior to collection of experimental data, e.g., this was true for the embedded figures and maze tracing tasks, and the Ober2:Visagraph reading test.

Auditory Ocular Motor Biofeedback Training Apparatus and Procedures

The horizontal eye position was recorded based on the infrared limbal reflection technique.¹² The eye movements were recorded by the Ober2 Research Model system;⁸ the resolution and linearity were similar to that of the Ober2:Visagraph, but the sampling rate was 120 HZ. The recorded eye movement signal was transmitted also to an audio oscillator which produced a tone that changed continuously and systematically with variation in horizontal eye position; this signal in turn was fed to a speaker positioned behind the observer to produce the correlated audio information. In a small number of the training sessions the Ober2 Research Model system was unavailable; an Eye Tone system⁸ with similar relevant characteristics was substituted. The audio tone was set so that it increased progressively from a low to high pitch as the eyes shifted from left-to-right across a line of text.¹⁰

Each observer was seated with the head positioned in a chin/forehead rest to minimize head movement (see Figure 1). The custom-made eye movement system frames (with infrared emitters and sensors) were fastened snugly into place using Velcro straps. Trial frame lenses, which were matched to the habitual spectacle correction for near as determined by lensometry, were used with most of the individuals affected by MD. These were attached to the eye movement system using Halberg clips.

Training consisted of six 15 minute sessions over a period of two to three weeks; most frequently only one session per day was conducted per person. Half

(7.5 minutes) of each session was devoted to reading training and the other half to other related visual tasks, including saccadic, fixation, and pursuit tracking (see below).

Before beginning the biofeedback training, the pitch changes characteristic of normal reading, e.g., consisting of progressive saccades and return sweeps, were demonstrated to the individual by playing a prerecorded audiotape. Observers then were instructed to “make their eyes move rhythmically and consistently” and to “try to move their eyes from word to word, without going back to look at a previous word,” and to “move their eyes to the beginning of each new line in one continuous sweep.” Control and experimental group members received identical training.

Individuals read from several American short stories, such as “Big Two-Hearted River” by Ernest Hemingway. The original text pages had been scanned into a desktop computer and, using a word processor, re-printed in a standard font (black letters on white background) at sizes ranging from 12 to 24 point, appropriate to the individual’s visual acuity. Pages were placed on a manuscript stand for easy removal by a research assistant. Within each story, the text on each page had the same horizontal starting position. Whenever possible, the text was placed at a standard 40 cm. If this was not close enough, the distance was decreased until the material could first be clearly seen by each observer (ranging from 10 to 30 cm for the MD, and 28 to 40 cm for the control group). This resulted in the reading material subtending angles which differed (horizontally and vertically) from one observer to another (ranging from 6 to 15 degrees left or right of center and 10 to 22 degrees vertically from the midpoint of the page). The smallest angle subtended by a single character was 0.29 deg, and the largest 2 deg either horizontally or vertically.

The fixation, saccadic, and pursuit training was as follows. The prerecorded audiotape was played to demonstrate the desired feedback sounds associated with each task. During fixation training, the observer was presented with a stationary 0.5 degree circular target (a bright spot) displayed on a computer monitor placed at a distance of 40 cm. The instruction was to maintain gaze on the target, while trying

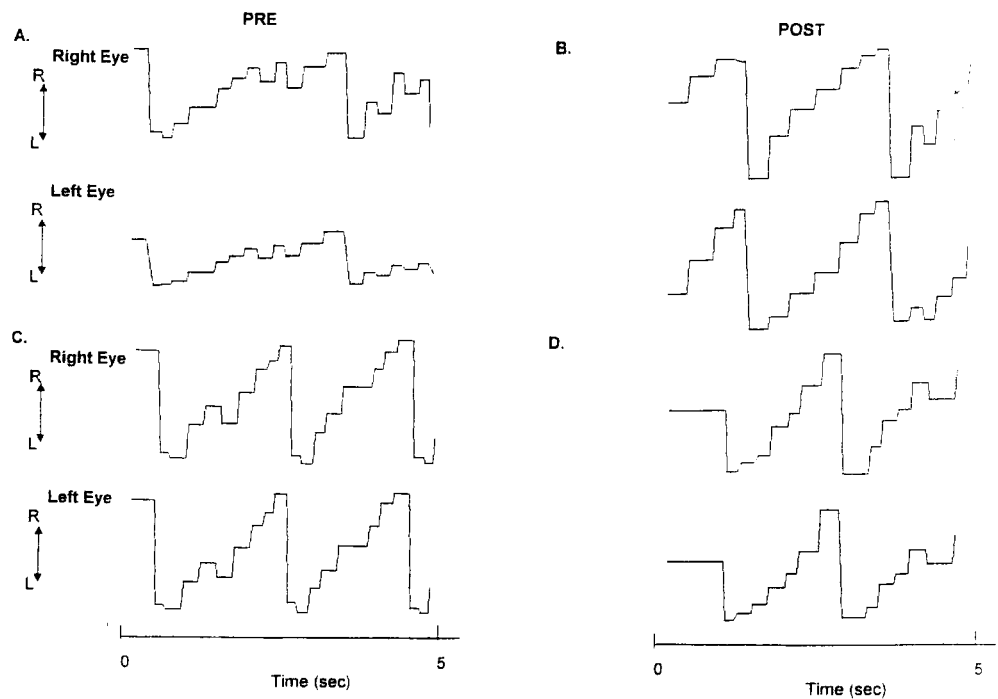


Figure 2. Pre-training and post-training Visagraph system reading eye movement recordings, from one observer (MNWI) with MD, who showed a substantial increase in reading rate after training (panels A-B), and one control (SJB1) group member, whose reading rate did not increase (panels C-D).

to keep the tone as steady as possible. The individual was advised that a tone with a wavering or jerky quality would indicate unsteadiness of the eyes. During saccadic training, observers were asked to follow displacement of a step target as the target moved from 8 deg left of center to 8 deg right of center, at 0.2 Hz, using eye movements which would produce a single and abrupt change in tonal pitch with every displacement of the target. Smooth pursuit training involved the observers’ being asked to follow a target moving smoothly left and right (+/-8 degrees, 0.2 Hz, constant velocity triangle wave) on the screen, while trying to move their eyes to produce a continuously smooth change in pitch. For reference, each was told that the desired pursuit “sound” might remind them of a slide trombone. Individuals were reminded frequently to try to use the tone to help them control their eye movements.

Post-training: Following the final training session, the assessment battery that had been administered before the training was repeated.

RESULTS

Pre- Versus Post-training Reading Assessment

The (standardized) Ober2:Visagraph eye movement recording reading test was used to assess change in reading rate, as well as change in fixation and regression number attributable to the training. Figure 2A-D shows pre-training and post-training Visagraph system reading eye movement recordings from one individual with MD, who exhibited a substantial increase in reading rate after training (panels A-B), and one control group member, whose increase was comparatively small (panels C-D). A comparison of pre-versus post-training data showed that reading rate increased in 9 out of 10 individuals with MD (sign test, $p = 0.011$), as compared with 1 out of 5 control group members (sign test, $p = 0.188$). Table 2 summarizes reading rates before and after the six biofeedback training sessions. The MD group showed a significant increase in reading rate (percent change mean = 21.88%, SD = 24.82, $p < 0.01$, one-tailed t-test), whereas the control group did not (mean = 4.13%, SD = 22.01, $p > 0.05$, one-tailed t-test). A Fisher exact test was applied to determine the significance of

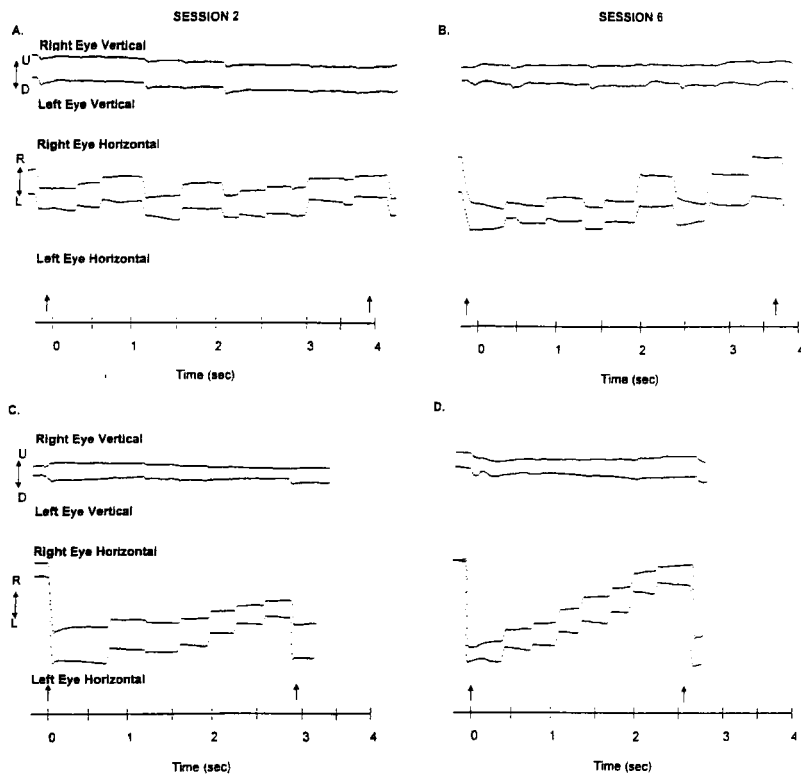


Figure 3. Ober2 Research Model system reading eye movement recordings. Panels A-D present eye movement recordings from one experimental (MNW1) and one control (SJB1) group member during reading in each of two biofeedback training sessions, showing the tendency for fixations per 100 words and regressions per 100 words to decrease following training by a larger amount in the experimental than in the control group. Single-headed Arrows = return-sweep saccades; U = up, D = down, R = right, L = left; Horizontal extent of Double-headed Arrows in Panel A = 6 deg, in Panel B = 8 deg, and in Panels C and D = 4 deg.

the reading rate improvements (based on the outcomes observed in the two groups) and found a significant difference ($p < 0.02$). These results are consistent with MD observers' subjective reports of faster and more automatic reading ability attributed to the training.

Nine of the ten experimental group members (sign test, $p = 0.011$), and one of the five normal observers (sign test, $p = 0.188$), exhibited varying degrees of improvement in overall reading performance. That is, results showed a faster reading rate, a reduced number of saccades per return-sweep, fewer fixations, and/or fewer regressions in the experimental group. For example, the number of fixations decreased in six individuals with MD, and in three without. The number of regressions decreased in seven observers with MD, and in three without. Figure 3A-D shows eye movement recordings from one experimental and one control group member during reading in each of two biofeedback training sessions. This figure exemplifies the tendency during

training (that was discernible clearly after training) for fixations per 100 words and regressions per 100 words to decrease by a larger amount in the experimental than in the control group.

Near and Distance VA Chart Reading Changes

A comparison of pre- versus post-training data showed that measured (Snellen) distance VA improved in six out of the ten individuals with MD, whereas two stayed the same, and two performed less well (see Table 1). This result reached statistical significance ($p < 0.05$, one-tailed t-test). The remaining trends did not reach significance, but were as follows: In the control group, measured distance VA improved in three out of five, was unchanged in one, and was poorer in the fifth individual. Measured near VA improved in seven out of the ten observers with MD, whereas one was unchanged, and two performed more poorly. Measured near VA improved in two out of the five control group members, whereas two were unchanged, and one performed less well.

Visual Search Changes

Data from the embedded figures task were evaluated by measuring the time required to complete the task (to a limit of three minutes), and by counting the number of figures identified. A comparison of pre- versus post-training data showed that while none of the ten observers with MD identified all eight figures prior to training, six did so after training. In the control group, three out of the five identified all eight embedded figures prior to training, and four out of five did so after training. All of the members of the experimental group performed the task more quickly after training than before, whereas the control group results were mixed.

Developmental Eye Movement (DEM) Test Changes

The DEM assessment uses a standard formula which takes into account errors and total time to complete the test. The data from one individual each from the experimental and control groups were corrupted due to technical difficulties during testing. Data from these individuals therefore were excluded from this analysis. A comparison of the available pre- versus post-training data revealed that five of the nine experimental sub-group members improved, and two did less well (as evaluated using the standard formula). This result reached statistical significance ($p = 0.02$, one-tailed t-test). The remaining two individuals in the experimental sub-group improved, in that after training they were able to complete the DEM test, whereas this had not been true previously. In the control subgroup, three improved and one did less well.

Maze Tracing Task Changes

Maze performance was evaluated by counting the number of errors made during the task, and the time taken to complete the task. A comparison of pre- versus post-training data showed that in the MD group, five of the ten made fewer errors, two were unchanged, and three made more errors. In the control group, two made fewer errors, one was unchanged, and two made more errors. Time to completion was shorter in six of the ten observers with MD, and four took longer to complete the task. Time to completion was faster in three control group members, was unchanged in one, and was slower in one.

DISCUSSION

This study demonstrates that individuals with macular degeneration can use auditory ocular motor biofeedback rapidly and efficiently to improve overall reading rate and performance. These results are consistent with successful previous therapeutic intervention using auditory eye movement biofeedback in a variety of abnormal static and dynamic ocular motor conditions,¹¹ and in slow normal reading.⁷ Because the vision loss in MD is due to central scotoma, the reading improvements attributable to the change in eye movement control can be inferred to have come about through a simultaneous improvement in eccentric viewing. That is, it is reasonable to assume that the training facilitated increasingly optimal placement of text upon useable eccentric retina; if a scanning laser ophthalmoscope had been available, this could have been confirmed directly. Tonal and rhythmic quality related to relative horizontal eye position are two likely direct sources of information for such improved eye control, and the preponderance of evidence from previous research (both from normal and clinical samples) clearly demonstrates that auditory ocular motor biofeedback augments visual functioning (see Introduction, and Visual-Auditory Interactive Process, below).

It is possible that the reduction in reading rate shown by some of the observers with normal vision, who were viewing foveally, reflects a minor interference, distraction or effect of the auditory biofeedback, or it may simply be normal variance in measurement (see below). The former would be consistent with a finding by Smith, in which performance in a small sample of visually-normal adults was compromised slightly when auditory ocular motor feedback was coupled with normal, foveal, visual feedback.⁹ Perhaps in that instance, when fixation already was optimal (based on normal visual input), the tonal information served as a distraction. In the present study, a few of the individuals from each group reported that the auditory biofeedback initially was distracting, although such reports usually subsided by the second session. This was also true of the reading eye movement study of Fayos and Ciuffreda,⁷ in which a few of the observers initially felt the tonal

change to be very distracting, yet ultimately performed better.

Alternatively, the normal test-retest variability of visually-normal readers measured using the Visagraph system⁷ may, in adults with macular degeneration, be artificially damped by the temporal resolution of the system (no finer than "words per minute"). Because many of the individuals with MD read extremely slowly (e.g., 20 WPM), the temporal resolution of the Visagraph might not be adequate to assess problems with test-retest variability that are easily discerned among faster, visually-normal, readers. In an effort to minimize such variability, a practice run and at least one test Visagraph run (to fulfill the comprehension criterion) were administered in the present study. Although this issue merits further investigation, it must be emphasized that among the individuals with MD, the present results show an overwhelmingly positive effect of auditory biofeedback on reading eye movements.

The visual acuity data measured pre- and post-training in the present research may be viewed as encouraging but inconclusive, in that results were mixed in each group. Surprisingly, however, at least two of the observers with macular degeneration (MCG1 and MWB1) reported visual acuity improvements as measured by their own eye doctors during examinations performed within several weeks after the training. According to the clinical examination records, the visual acuities of these patients had either been stable or had been declining, but were not improving, prior to the training.

The most likely explanation of the measured visual acuity gains is not that the vision *per se* improved; rather, the ocular motor skill required for eccentric viewing improved as a result of the auditory biofeedback training. That is, no visual system structures were treated or enhanced, but the opportunity to process images increased due to improved eye movement control. In the two individuals who anecdotally reported subsequent visual acuity improvement, it can be inferred that these ocular motor and putative eccentric viewing skills were maintained and continued to improve after the study ended. Probably the latter improvement can be attributed to patients' practice.

Two individuals with MD (MNW1 and MAM3) had unusually high reading

rates of over 200 words per minute. This may be explained by the fact that the former had the best visual acuity (approximately 20/40), although she reported being severely limited by her vision loss and was therefore highly motivated to participate in this research. The latter had amblyopia in the fellow eye and felt that sometimes she used that eye preferentially during reading, although this could not be confirmed.

Visual-Auditory Interactive Process

These results support the suggestion that for individuals with macular degeneration, using meaningful auditory information to supplement the compromised visual feedback inherent to central field loss can enhance the efficacy of conventional eccentric viewing training. As stated in the introduction, auditory ocular motor biofeedback draws attention to and/or heightens awareness of one's eye movements. This leads initially to intentionally improved control of the eyes, which, over time, becomes increasingly reflexive.⁷ In the present study, it is possible that selective attention to images falling on peripheral retina was increased, to use the available visual information maximally and thus more efficiently. Conversely, attention to foveal input may have been reduced, thereby minimizing distraction.

It is interesting to note that all of the observers in the experimental group, and many of those in the control group, reported subjectively having benefited from the training; in particular, the biofeedback during reading, fixation, saccadic tracking, and smooth pursuit training appeared to be most useful, respectively (separate analyses of results from the latter three training tasks are beyond the scope of this paper). Practical constraints prohibited long-term follow-up, via repeated post-training assessment, in this investigation, although this would be desirable for future similar studies. In addition to long-term assessment of reading variables and visual acuity, future research might profitably include use of scanning laser ophthalmoscopic and neural imaging techniques to track task-related activity on the retina and in the brain, respectively, before, during, and after ocular motor training.

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