OCULOMOTOR AUDITORY BIOFEEDBACK TRAINING

TO IMPROVE READING EFFICIENCY

Barbara Fayos, Ph.D.
Kenneth J. Ciuffreda, O.D., Ph.D.

Abstract

Oculomotor-based auditory biofeedback, in which an individual "hears their eyes move," has been successfully used in both visually-normal and -abnormal individuals to increase awareness and control of their eye movements. This study examines the effect of oculomotor auditory biofeedback on reading efficiency in normal individuals. Twelve subjects read with auditory biofeedback during four one-half-hour training sessions over a two-week period, and their eye movements were recorded during the first and last sessions. In addition, three control subjects followed the same protocol, but did not receive any auditory information. Reading efficiency was monitored using two types of standardized reading tests: the subjective Nelson-Denny and the objective Ober2:Visagraph eye movement reading tests. Eleven of the 12 subjects who received auditory feedback exhibited varying degrees of improvement in overall reading efficiency, as evidenced by a decreased number of fixations and regressions, a decreased number of saccades per return-sweep, and an increased reading rate. Improvement in reading efficiency was primarily found in those subjects who initially read at the low normal reading level as determined objectively by the Ober2:Visagraph. In the control subjects, the findings were mixed, which suggested lack of any consistent trend. These results clearly demonstrate that oculomotor-based auditory biofeedback can be an effective training tool, especially in low normal readers.

Key Words

auditory biofeedback, eye movements, oculomotor training, reading, vision training

Reading involves linguistic, perceptual, and cognitive processes that are dependent on the oculomotor system for its input.[1] The skilled reader must be mechanically efficient and must be able to comprehend the text material.[2]

The fundamental oculomotor components of reading are the fixations, in which the eye pauses or fixes on a word or some part thereof, and the saccades or rapid eye movements, which are executed to shift the eyes across a line of print.[3] Fixations can be progressive from left-to-right along the line of text, or regressive as the eyes backtrack from right-to-left, perhaps in response to reader confusion, the encounter of uncommon text, or confirmation of some word or phrase. The fixation duration refers to the time that the eye remains fixed on a word, specified in fractions of a second or in milliseconds.

There are other oculomotor parameters and factors that are also important for an understanding of the reading process.[3] Reading rate refers to the speed, usually specified in words per minute, at which a person can read while maintaining an appropriate level of comprehension. The amount of text which is perceived and directly processed during a fixation is called the span of recognition, specified in units of letters or words. And, when the end of a line is reached, a large eye movement (or series of movements) called the return-sweep saccade is required to shift the eyes back to the beginning of the next line. All of the above oculomotor-based parameters constitute an individual's reading profile.[3] Ideally, a reader would make brief but limited fixations with no regressions, while maintaining adequate comprehension. Readers respond to more difficult material by increasing the number of fixations and regressions, and in some cases the fixation duration, thereby resulting in a decreased reading rate.[4]

Although efficient reading is dependent upon controlled eye movements, few individuals are aware of and consciously control their eye movements during reading.[2] In fact, Carmichael and Dearborn[5] suggested that readers have no knowledge of the types of eye movements they make during reading, and thus would be unable to modify their eye movement pattern volitionally. However, more recent studies have shown that reading efficiency can be improved in individuals with reading deficiencies through a variety of techniques including vergence training and reading-related saccadic eye movement conditioning (e.g., the Guided Reader)[2] using a rate-controlled moveable text-limiting aperture.[2,3,6-8] We investigated the proposal that visually-normal individuals may be able to improve their reading efficiency simply by becoming aware of their eye movements, and thereby being able to exercise better control over them.

Oculomotor-based auditory biofeedback has been successfully used to increase awareness and exert control over one's eye movements, thus reducing or limiting the deleterious effects of oculomotor abnormalities, such as nystagmus and saccadic intrusions, on vision.[3,8-10] Auditory biofeedback allows the individual to "hear their eyes move." In fact, auditory biofeedback has been used to demonstrate that subjects either with poor central vision or in the absence of specific visual cues can still maintain relatively accurate vergence[11] and fixation.[12,13] However, in the presence of normal visual feedback, Smith[12] found that auditory feedback was slightly deleterious to fixational ability in his small sample of visually-normal adults. It remains unclear what impact auditory feedback may have on normal subjects during reading.

Rayner and Pollatsek[4] described the reading eye movement pattern as being directly linked to the cognitive process. It has been suggested that a rhythmic pattern exists in the cognitive processing of text, and that this rhythm represents a fundamental organizational principle in reading.[14] Furthermore, it has been found that readers with comprehension problems had rhythms, processed and transcribed from their objective reading eye movement pattern, which were more variable and unpredictable than the rhythms of normal readers.[15] Thus, we hypothesize that the rhythm produced by the hearing of one's eye movements may not only be an effective indicator of reading ability, but also a powerful conditioning tool to train individuals to move their eyes more efficiently under conscious control during reading. This study examines the effect of oculomotor-based auditory biofeedback on reading efficiency in visually-normal individuals.

SUBJECTS AND METHODS

Subjects

Fifteen graduate, optometry, and accelerated high school students were used as subjects. They ranged from 18-38 years of age, with a mean of 23.5 years. A case history was taken, and no subjects reported ocular, systemic or neurological problems. A detailed screening eye examination was performed to ensure that all subjects were normal with regard to best corrected distance and near visual acuity, amplitude of accommodation, stereoacuity, vergence ranges, and phorias. Twelve subjects served as experimental subjects, and three additional as control subjects.

Apparatus

Subjective reading efficiency determination: The Nelson-Denny standardized reading test was used to assess reading rate and comprehension.[16] The test consisted of seven paragraphs with a total of 38 multiple-choice questions. As per instructions, the test was limited to 20 minutes, with the first minute used to determine reading rate.

Objective reading efficiency determination: The Ober2:Visagraph eye movement recording and computer analysis system was used to assess reading efficiency.[3] Resolution was 0.25 degrees with linearity of approximately ±15 degrees; bandwidth was dc to 50 Hz. Infrared sensors and emitters embedded into a special pair of goggles worn by the subjects recorded the horizontal eye movements of the left and right eyes as a standardized 100-word paragraph was read. Subjects read from level 10 adult passages, with this being the highest level. The subjects' heads were maintained steady as they read the standardized text material which was held in their hands at their normal reading distance. Average span of recognition was calculated by dividing the number of fixations into 100. Relative efficiency was calculated from reading rate, number of fixations, and number of regressions, with additional emphasis on regressions as they too were included in the total number of fixations. Grade level correlated with relative efficiency levels. Ten accompanying "yes or no" questions were then administered to each subject to assess the level of reading comprehension. A minimum of 70% comprehension was required for valid eye movement results. All data analysis was completed using the standard software provided.

Auditory biofeedback training: Subjects were positioned in a chin and headrest to ensure minimal head movement. Custom-made frames with infrared sensors and emitters were worn by the subjects. Horizontal eye position was recorded on the basis of limbal reflection.[3] Only eye movements of the right eye were recorded during binocular reading. The eye movements were recorded on a three-channel strip chart recorder (dc to 60 Hz bandwidth). Resolution and linearity were similar to that of the Visagraph. Additionally, the eye movement signal was sent to an audio oscillator which produced a tone dependent on the horizontal position of the eye. This signal was then sent to a speaker positioned behind and to the right of the subject.

Procedure

Pre-training: Subjects were administered the Nelson-Denny standardized reading test (version H) followed by the vision examination. Two Ober2:Visagraph reading tests were then administered, with the first serving as a practice. In the event the minimal 70% comprehension was not attained, the test was readministered until that level was achieved. However, two subjects could not attain more than the 60% level, and were included in this study. The subject was then seated, with the head and chin in the rest. The special spectacle frames with infrared sensors and emitters incorporated were fastened snugly into place using Velcro straps. Most subjects wore contact lenses or had 20/20 visual acuity at near. Three subjects (subjects 2, 3, and 15) did not wear contact lenses and required the incorporation of trial frame lenses which were attached over the eye movement system using Halberg clips. Before the first auditory biofeedback training session was initiated, smooth pursuit, saccadic, and fixational eye movements were recorded to ensure that no subjects had any obvious eye movement abnormality, such as subtle nystagmus or high frequency saccadic intrusions.

Auditory biofeedback training: Subjects read from several short stories: "The Overcoat" and "The Nose" by Nikolai Gogol, and "The Black Monk" and "Peasants" by Anton Chekhov, which were published as part of the Penguin 60 series. Pages were carefully photocopied, enlarged by 10%, and bound at the top such that they could easily be advanced manually by the subject. It was important for each page to have the same horizontal starting position. The text, placed 40 cm in front of the subject and 20 degrees below primary position, subtended an angle of 26 degrees horizontally and 32 degrees vertically. The tone was zeroed 2 cm to the left of the text, so that it progressively increased from a low to high pitch as the eyes shifted from left-to-right across a line of text. Before beginning the biofeedback training, the pitch changes made by progressive and regressive saccades were demonstrated to the subject. Subjects were then instructed to "make their eyes move rhythmically and consistently" and to "try to decrease the number of regressions and fixations per line and saccades per return-sweep." Control subjects wore the eye movement system and were provided the same set of instructions as the experimental subjects; however, they did not receive any auditory biofeedback. Training consisted of four one-half-hour sessions over a period of two weeks, with sessions spaced at least two days apart. For the first and fourth sessions, the subjects read from Gogol. Eye movements were recorded at times 1, 10, 20 and 30 minutes of training

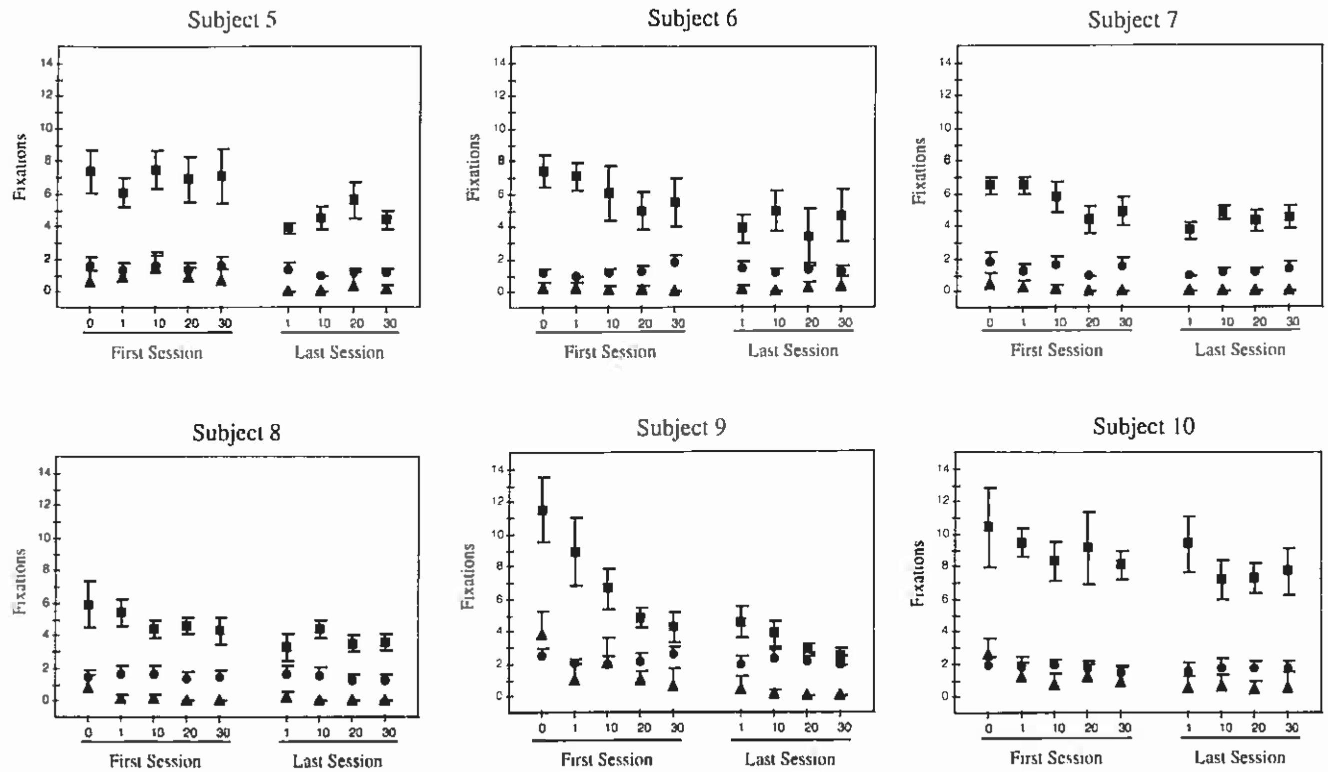

Figure 1. Progressive and regressive fixations, and return-sweep saccades, recorded on the 3 channel strip chart recorder during the first and fourth sessions of training. Experimental subjects receiving auditory biofeedback who demonstrated clear improvement. Symbols: progressive fixations (■), regressions (▲), and return-sweep saccades (●).

during these sessions. Additionally, before the first training session, the eye movements of experimental subjects five through 12 were recorded during normal reading just prior to the introduction of auditory biofeedback. The subjects read from Chekhov at the second and third training sessions during which time their eye movements were not recorded.

Post-training: Following the fourth and final training session, the Ober2:Visagraph reading test was repeated using new level 10 passages, and version G of the Nelson-Denny standardized reading test was administered.

RESULTS

The number of progressive and regressive movements, and the number of saccades per return-sweep, were manually counted from the eye movement records obtained during the first and fourth training sessions. The mean and standard deviation from 10 representative lines of text were calculated (Figures 1-12). In experimental subjects five to 12, eye movements were also recorded at the first session just prior to introduction of the auditory biofeedback (first session, 0 time point).

Figure 1 presents the results from those experimental subjects (six out of 12) who clearly demonstrated improved eye movements across the training process, with improvement reflecting a decrease in the number of fixations, regressions, and saccades per return-sweep. Most of these subjects exhibited substantial improvement within the first training session. The other six experimental subjects demonstrated very little obvious change in eye movements between the first and last training sessions (Figure 2). The control subjects are presented in Figure 3. Two of the three control subjects (#13 and 15) appeared to exhibit a slight oculomotor-based reading efficiency improvement.

Two types of standardized reading tests, the Nelson-Denny reading test and the Ober2:Visagraph eye-movement recording reading test, were used to determine the change in overall reading efficiency as a result of the auditory biofeedback training. All but two of the experimental subjects showed increased reading rate on the Nelson-Denny test after auditory biofeedback training as compared to only one of the three control subjects exhibiting such a change (Figure 4A,B). One half of the experimental subjects showed increased comprehension, and the other half showed slightly decreased comprehension, on the Nelson-Denny test; in contrast, in the control group, one increased, one decreased, and one remained the same (Figure 5A,B), thus suggesting a chance phenomenon in this group. The Ober2:Visagraph eye movement system recorded the total number of fixations, regressions, and reading rate while subjects read a standardized paragraph. Comparing the pre- and post-training data, the number of fixations decreased for all subjects except subject 12 (Figure 6A), the number of regressions decreased for all subjects except subject six who remained constant (Figure 7A), and the reading rate increased for all subjects except subject 12 (Figure 8A). Interestingly, reading comprehension tended to decrease somewhat for most of the experimental subjects (nine out of 12) (Figure 9A). Control subjects exhibited a similar trend (two out of three) (Figure 9B). Other than for subject 12, the average span of recognition (Figure 10A), relative efficiency (Figure 11A), and grade level (Figure 12A) increased in the experimental subjects. Thus, reading efficiency im-

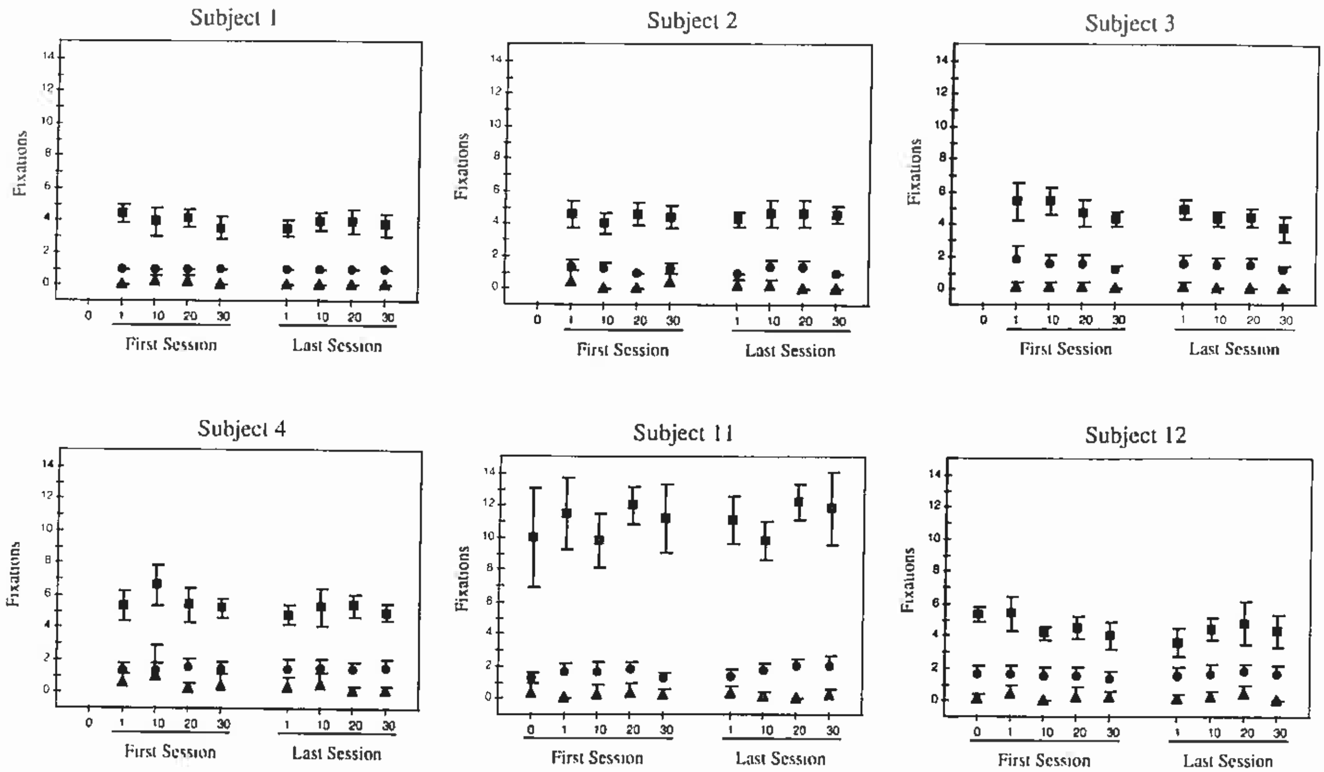

Figure 2. Same as Figure 1, except for experimental subjects who demonstrated no clear improvement.

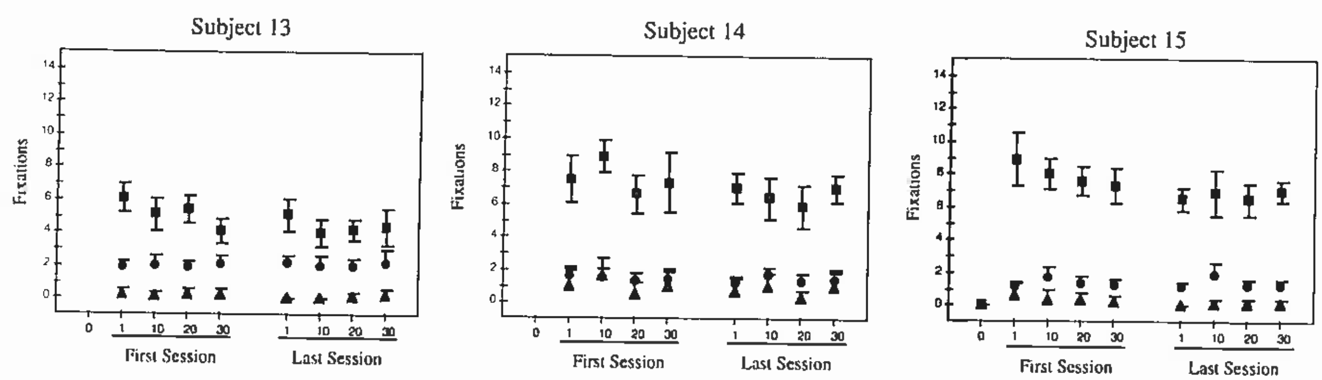

Figure 3. Same as Figure 1, except for control subjects.

proved to varying degrees for all but one of the experimental subjects.

As an additional analysis, experimental subjects were divided into two subgroups based on their level of reading efficiency (per the Taylor table[2]) prior to receiving the auditory biofeedback (Figures 4-12, C and D). Grade level 12 pertains to eye movements representative of a high school senior/college student. Subjects were grouped into the "high normal" subgroup if their reading efficiency grade level was 12 or higher, and they were grouped into the "low normal" subgroup if their reading efficiency grade level was below 12. Those individuals in the high normal subgroup exhibited only slight or no improvement in reading efficiency following the auditory biofeedback training (Figures 4-12C). In contrast, the low normal subgroup demonstrated considerable improvement in reading efficiency, as evidenced by the large decrease in number of fixations and regressions, as well as increase in reading rate (Figures 4-12D).

DISCUSSION

The effect of auditory biofeedback on reading eye movements was investigated by testing a novel training paradigm to improve reading efficiency in individuals who read over a range of normal levels. Previously, oculomotor biofeedback therapy had been used effectively in treating a variety of abnormal static and dynamic oculomotor conditions.[10] However, auditory biofeedback has been shown to be slightly deleterious in a small sample of visually-normal individuals when foveal information was present;[12] under normal viewing conditions (i.e., with normal visual feedback), subjects were unable to fixate as well on a foveal target when

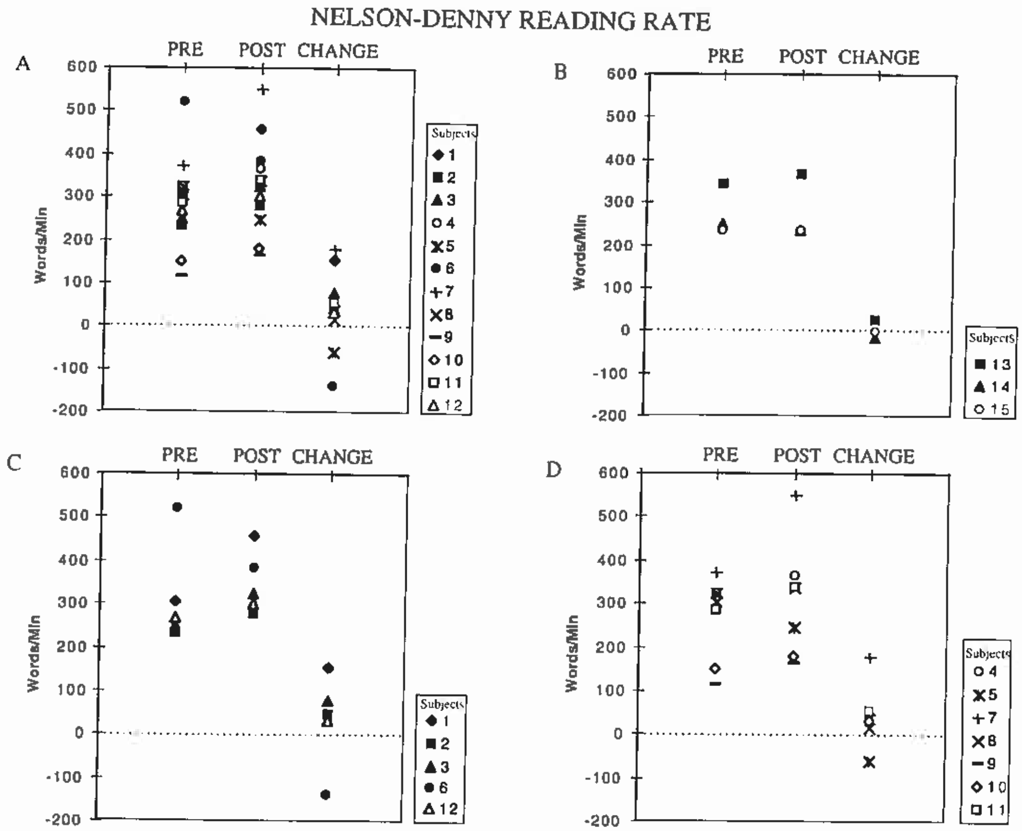

Figure 4. Reading rate determined from the Nelson-Denny standardized reading test prior to training (PRE) and after training (POST). The changes in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2: Visagraph grade level 12 or higher (C), or below grade level 12 (D).

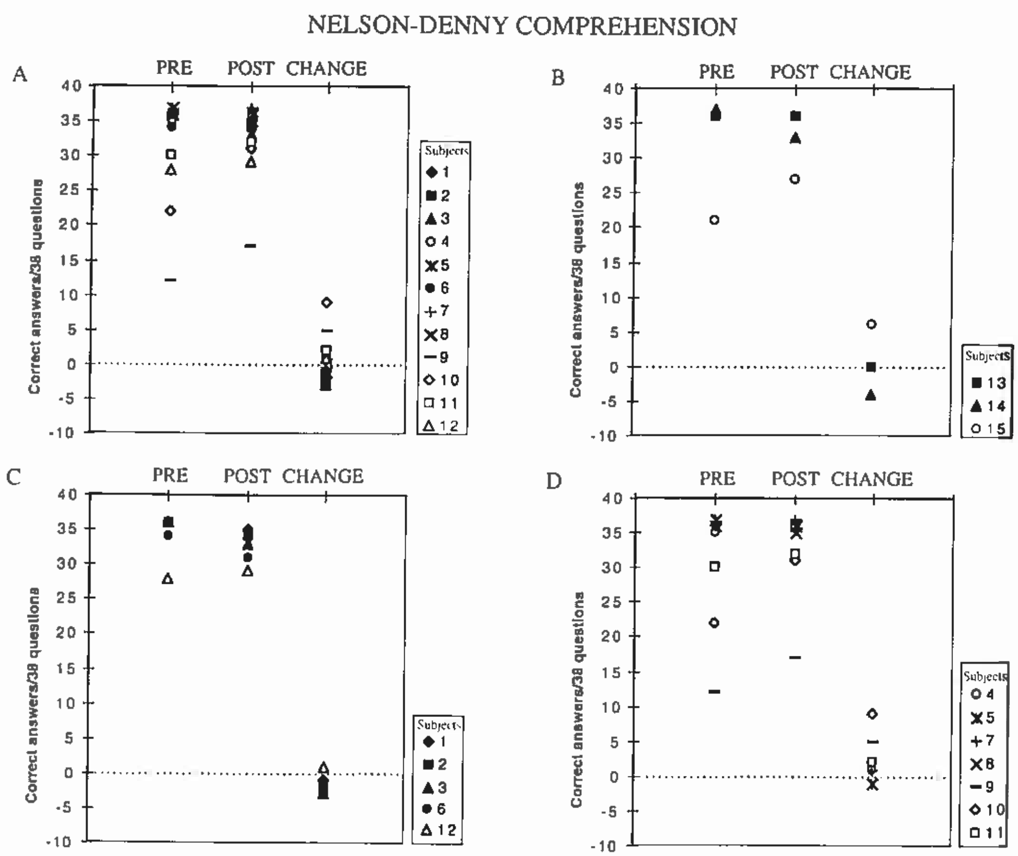

Figure 5. Reading comprehension from the Nelson-Denny standardized reading test prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2: Visagraph grade level 12 or higher (C), or below grade level 12 (D).

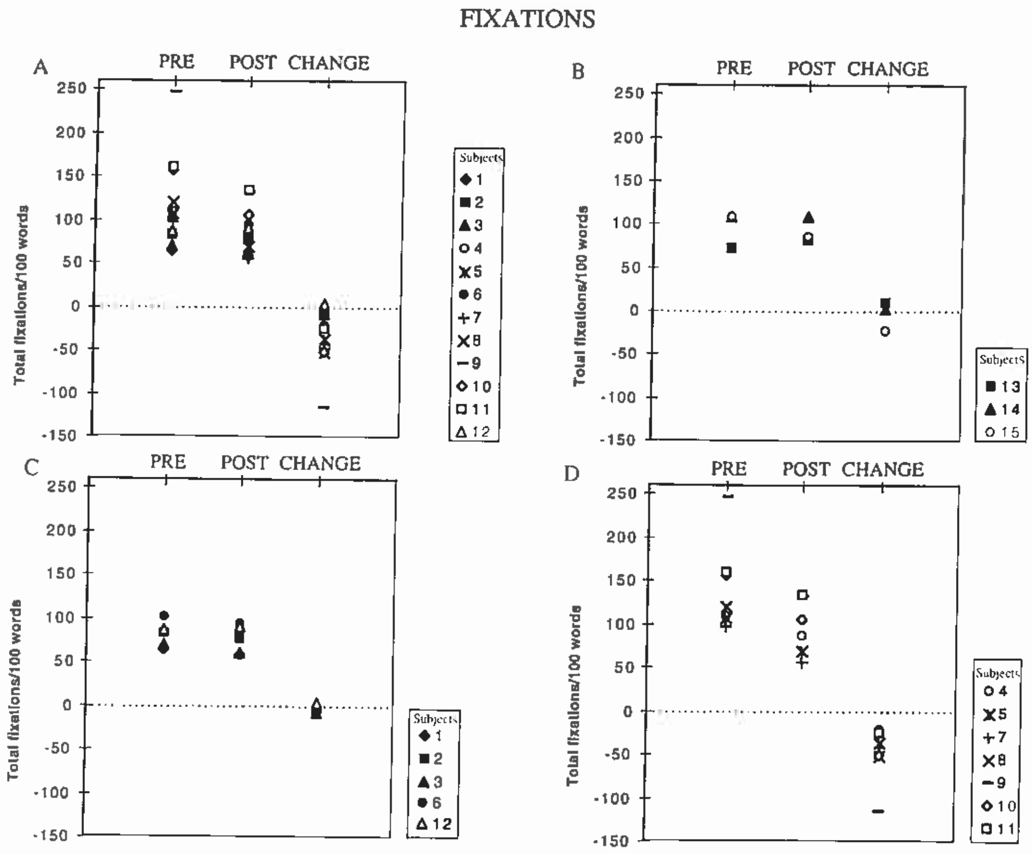

Figure 6. Total number of fixations from the Ober2:Visagraph eye movement recording system prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2:Visagraph grade level 12 or higher (C), or below grade level 12 (D).

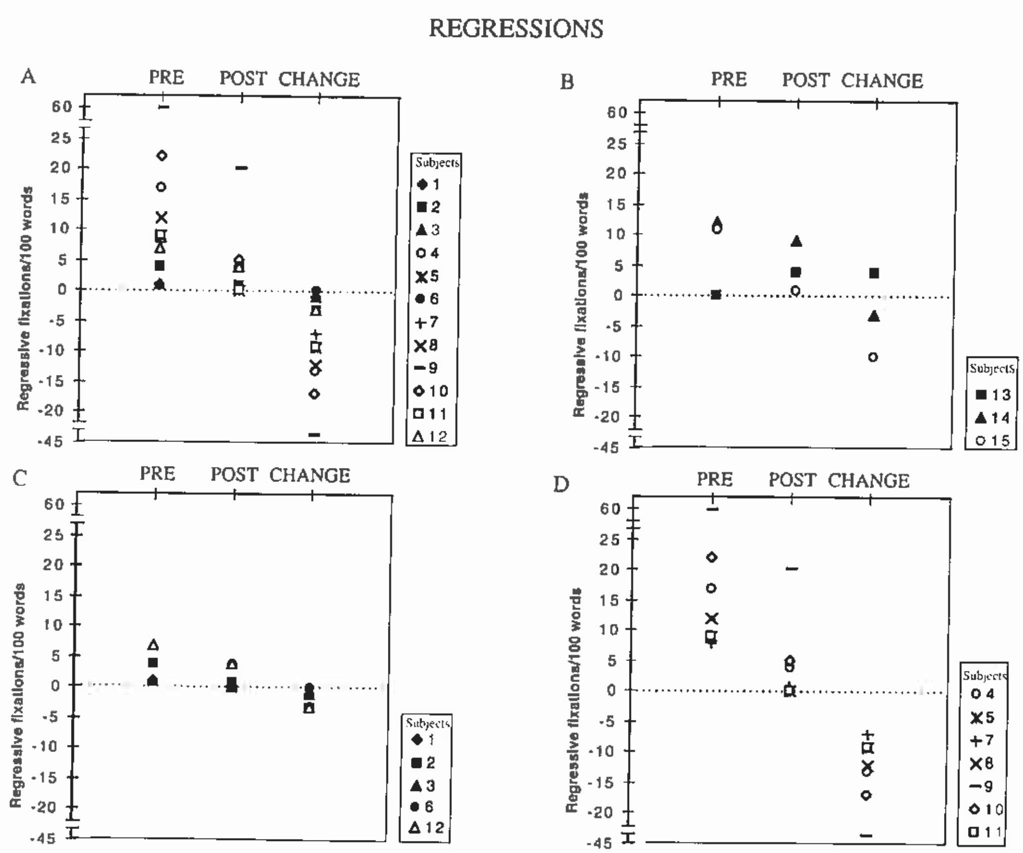

Figure 7. Total number of regressions from Ober2:Visagraph eye movement recording system prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2:Visagraph grade level 12 or higher (C), or below grade level 12 (D).

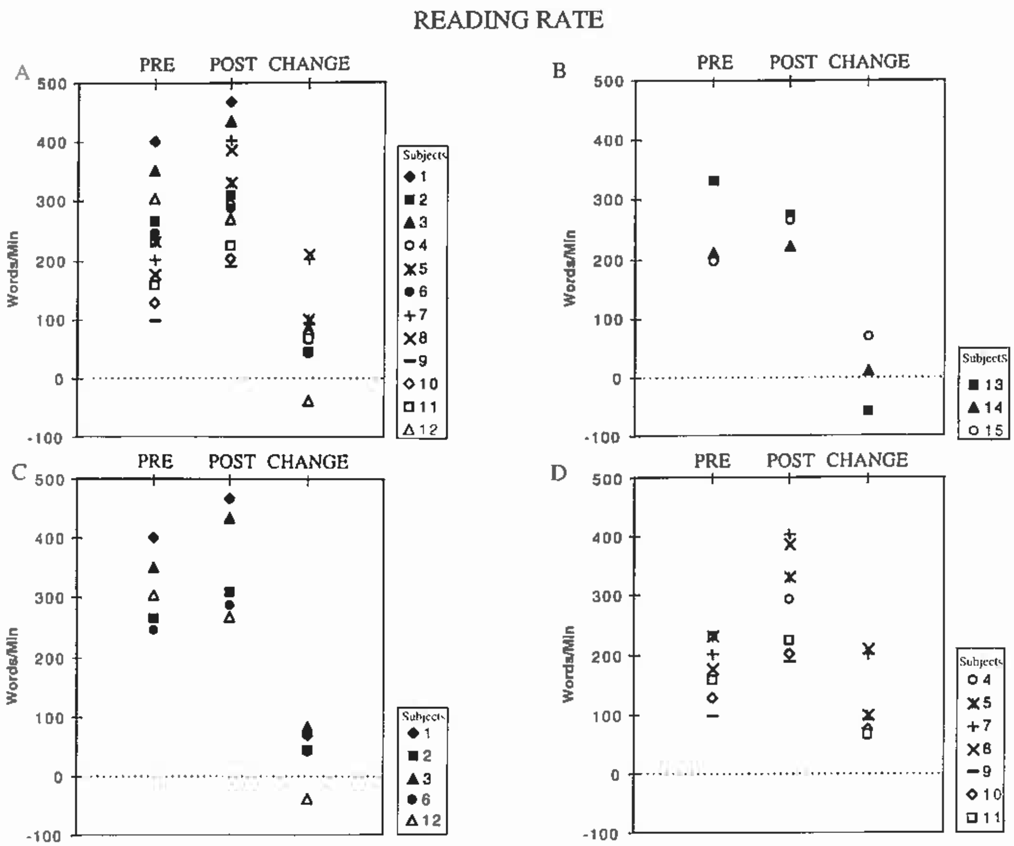

Figure 8. Reading rate from Ober2:Visagraph eye movement recording system prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2:Visagraph grade level 12 or higher (C), or below grade level 12 (D).

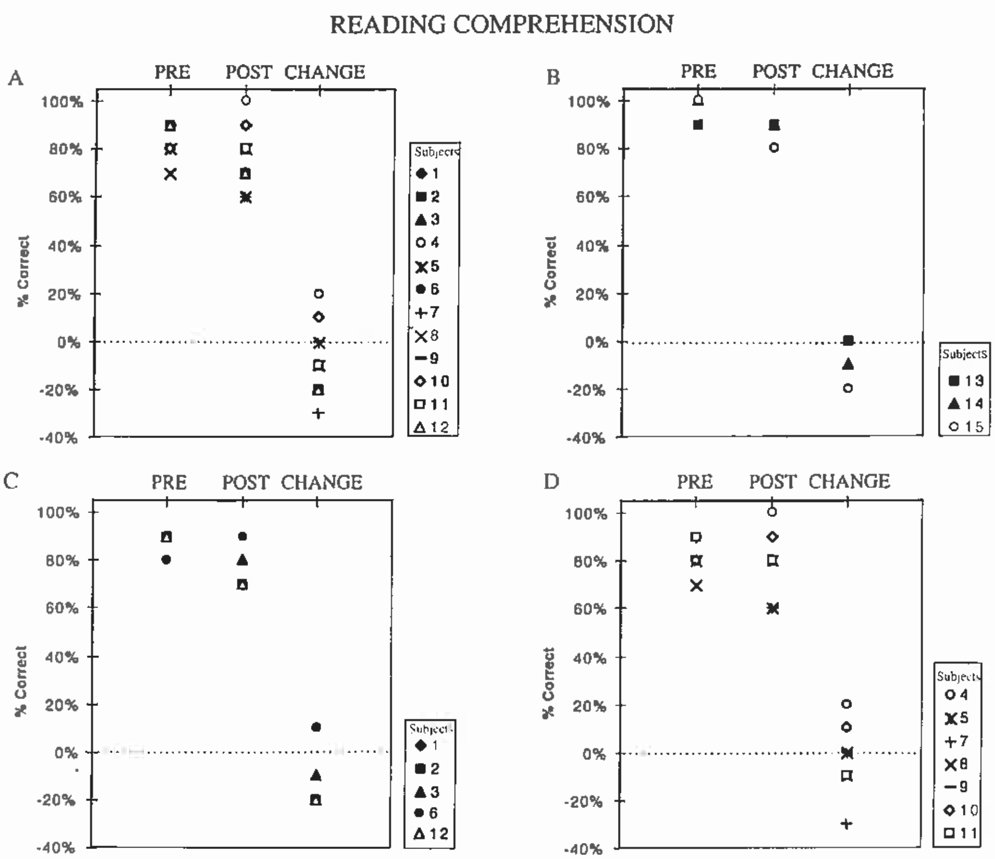

Figure 9. Percent reading comprehension from Ober2:Visagraph eye movement recording system prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2:Visagraph grade level 12 or higher (C), or below grade level 12 (D).

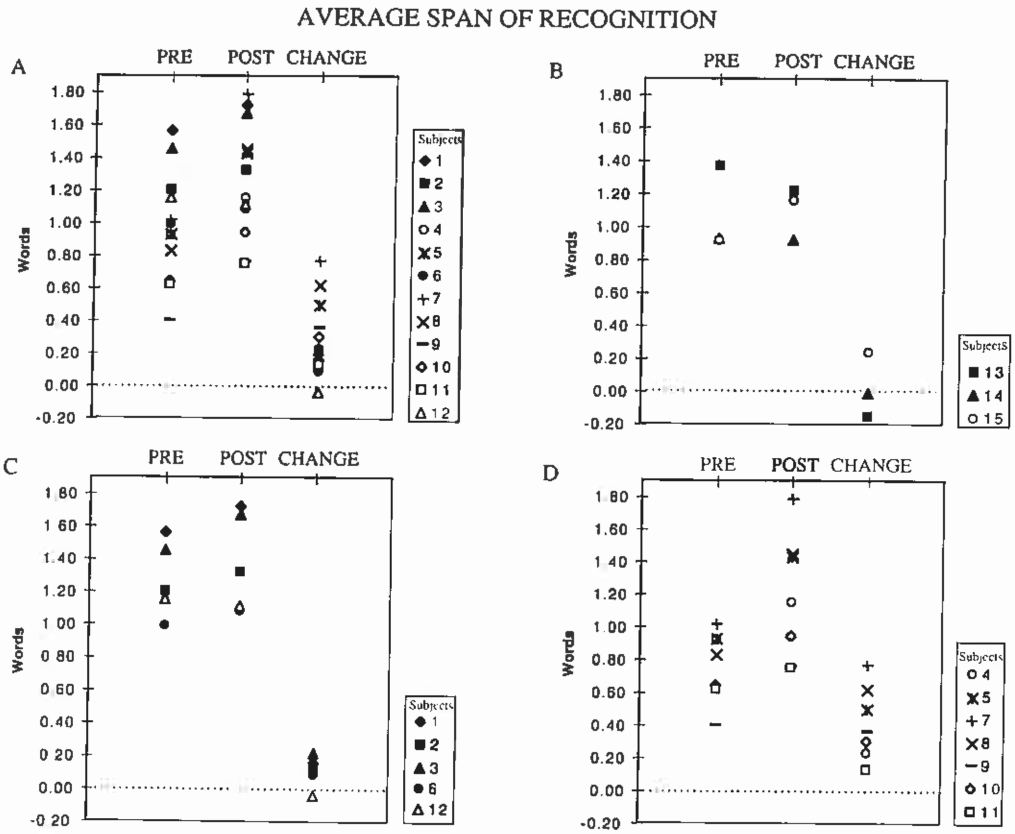

Figure 10. Average span of recognition from Ober2:Visagraph eye movement recording system prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2:Visagraph grade level 12 or higher (C), or below grade level 12 (D).

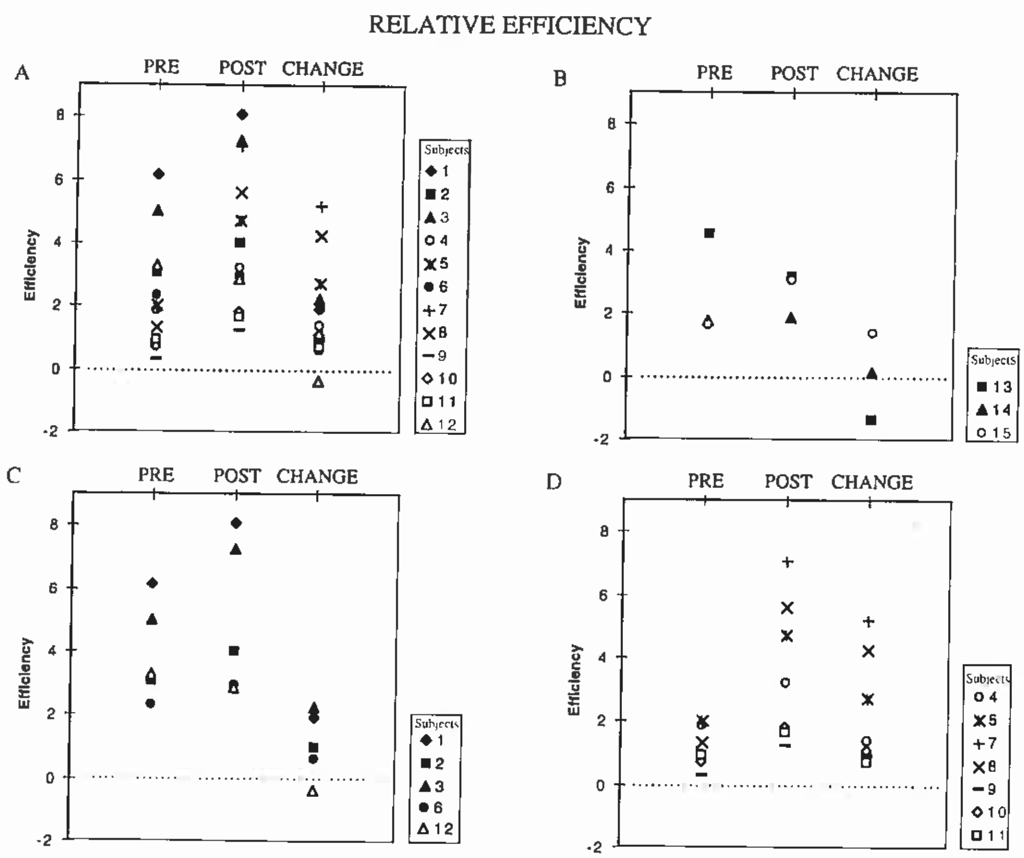

Figure 11. Relative efficiency from Ober2:Visagraph eye movement recording system prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2:Visagraph grade level 12 or higher (C), or below grade level 12 (D).

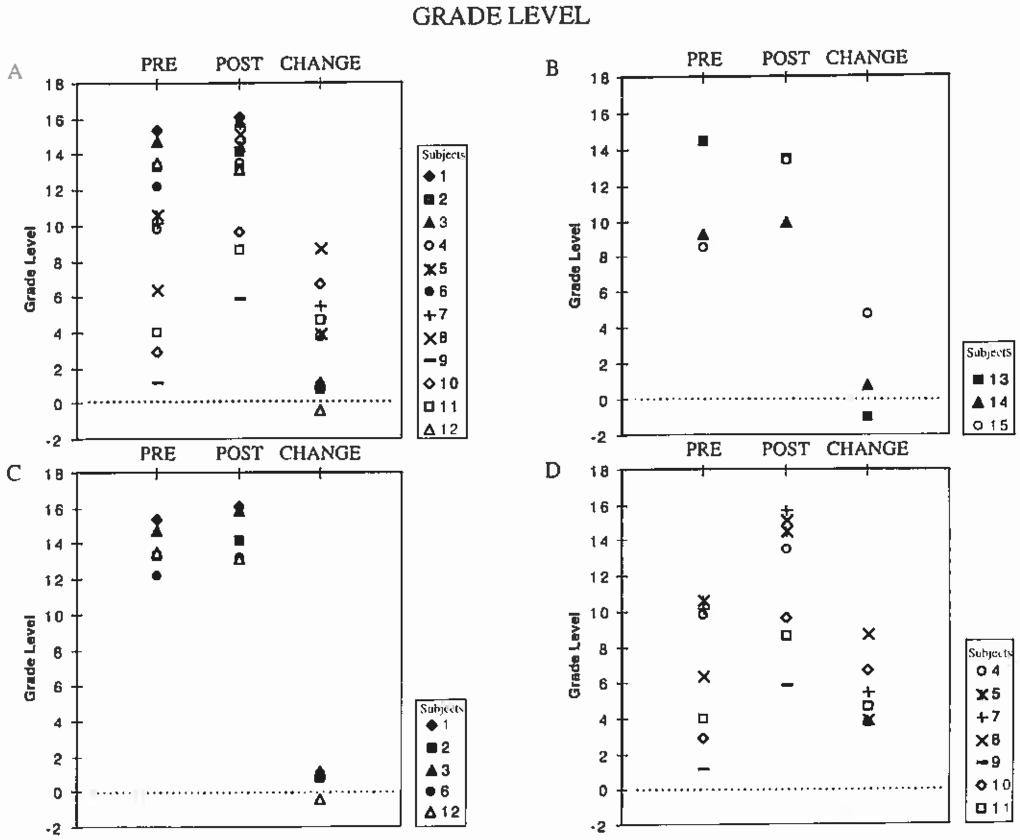

Figure 12. Grade level from Ober2:Visagraph eye movement recording system prior to training (PRE) and after training (POST). The change in pre- and post-training raw scores are also shown (CHANGE). Experimental subjects (A), control subjects (B), experimental subjects subgrouped by Ober2:Visagraph grade level 12 or higher (C), or below grade level 12 (D).

auditory feedback was added. In contrast, in the present study, there was no negative effect of auditory biofeedback on reading eye movements in normals. Although most subjects reported that the tone was initially distracting, this sensation usually subsided by the second session. Interestingly, marked improvement was still found in those few subjects who reported that the auditory feedback was very distracting and that they were unable to adapt to the tonal intrusion even by the fourth session.

Eleven out of the 12 subjects who received auditory feedback during reading exhibited varying degrees of improvement in reading efficiency, as determined by basic eye movement recordings and/or Ober2:Visagraph testing. Furthermore, six out of the 12 subjects exhibited improved reading efficiency based on the objective eye movement recordings taken during the first and fourth sessions alone. Improvement in reading efficiency was found mainly in subjects who were in the low normal reading efficiency subgroup. This is probably due to a saturation or ceiling effect in the high normal subgroup, which consisted of more skilled readers with apparently relatively little room for improvement, at least for the relatively short amount of training provided. Auditory feedback may therefore be therapeutic for a subset of low normal readers. This might include students with normal intelligence and reading interpretive skills, but who remain slow and inefficient readers based solely on their overall immature reading eye movement pattern. Indeed, Solan[6,7] has demonstrated reading improvement in these types of individuals following eye movement training alone. However, auditory feedback would probably not be useful in patients with exclusively language processing deficits as found in many dyslexics.

In addition, oculomotor auditory biofeedback may be beneficial in other individuals with reading problems having at least in part an oculomotor basis. This might include patients with visuospatial dyslexia, nystagmus, saccadic intrusions, or general low vision.[17] One future direction of this investigation is to assess the effectiveness of oculomotor auditory biofeedback in improving reading efficiency in congenital nystagmats.

It is interesting to note that two of the three control subjects demonstrated a modest and consistent improvement in reading efficiency based on the direct oculomotor recordings taken at the predetermined points during the first and fourth training sessions (Figure 3). Here the subjects were instructed to try to be aware of their eye movements and to attempt to move their eyes in a regular, rhythmical manner, with an accurate single return-sweep saccade. Although these individuals did not receive any auditory biofeedback, they were instructed in a specific manner that drew considerable attention to their eye movements. While this may at first glance appear to contradict Carmichael and Dearborn,[5] we think these researchers in fact are correct with respect to normal, non-trained readers during casual reading activities. Changes in the instruction set, however, such that individuals pay closer attention to their oculomotor movements during reading and intensely practice the motor skill,[18] appear to have a positive impact in some cases. This is consistent with patient reports of being cognizant of rereading lines of print, which is then documented by objective oculomotor recordings.[19-21] Furthermore, it is consistent with reports based on objective findings that head trauma patients can improve their saccadic abilities by practicing simple saccadic tracking paradigms in the presence of normal visual feedback alone.[22,23] Clearly, this is a fertile area for future experimental work in normals, as well as those patients manifesting a variety of reading and related oculomotor disorders.

During the course of this study, it was found that reading eye movement data obtained from the Ober2:Visagraph appeared to be quite variable between runs across many of the subjects. This variability could be due to the short length of the paragraphs used for assessment, familiarity with the topical content of the reading material, and perhaps volitional changes in reading strategy. Furthermore, small changes or variability in reading eye movement patterns may translate into large changes in the designated grade level per the standard Taylor table;[2] for example, at the higher grade levels, one or two fewer or greater number of regressions can result in a one or two grade level difference. This is an inherent problem in any reading-related oculomotor analysis. These are somewhat troublesome findings, since the Ober2:Visagraph is routinely used by many to evaluate reading ability in clinic patients. The Ober2:Visagraph may be useful in determining basic performance profiles, such as a slow, average, or fast reader, but it may not be a valid indicator of relatively small changes in reading efficiency, such as one and perhaps even two grade levels, with its current instructions and reading selections. In light of these findings, the best approach may be to familiarize the patient with the task by performing a trial run, and then conducting multiple runs which are averaged. Such an experiment is currently being conducted in our laboratory. Finally, as with other clinical tests, the Ober2:Visagraph findings should be regarded as only one piece of information used in the overall diagnosis and treatment of patients with reading dysfunctions.

In conclusion, auditory biofeedback did not have any deleterious effect on reading efficiency in normal subjects. Additionally, it clearly had a large and positive effect in a subset of low normal level readers. Further studies in such readers, as well as in those with frank oculomotor anomalies, will help to establish the usefulness of auditory biofeedback at improving reading efficiency in patients representing a broad spectrum of diagnostic groups.

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Corresponding author:
Kenneth J. Ciuffreda, O.D., Ph.D.
SUNY/State College of Optometry
Department of Vision Sciences
100 East 24th Street
New York, N.Y. 10010
kciuffreda@sunyopt.edu

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