Available online at www.sciencedirect.com
SCIENCE DIRECT
Brain Research Protocols 14 (2004) 1–12
BRAIN RESEARCH PROTOCOLS
www.elsevier.com/locate/brainresprot

Protocols

Reading-related oculomotor testing and training protocols for acquired brain injury in humans

Ying Han[a], Kenneth J. Ciuffreda[a,*], Neera Kapoor[b]

[a]*Department of Vision Sciences, Raymond J. Greenwald Rehabilitation Center, SUNY/State College of Optometry, 33 West 42nd Street, New York, N.Y. 10036, USA*
[b]*Department of Clinical Science, Raymond J. Greenwald Rehabilitation Center, SUNY/State College of Optometry, 33 West 42nd Street, New York, N.Y. 10036, USA*

Accepted 23 June 2004
Available online 4 August 2004

Abstract

Many individuals with acquired brain injury (ABI) report reading problems of oculomotor origin. These may include frequent loss of place, skipping of lines and difficulty shifting to the next line of print. We describe two protocols for the testing and training of reading-related eye movements in adult individuals with ABI (traumatic brain injury [TBI] and stroke with hemianopia), who experience oculomotor-based symptoms when reading. These protocols use objective eye movement recording techniques and computer-based stimulus presentation and analysis. One protocol tests and the other trains basic horizontal and vertical versional eye movements (fixation, saccades and pursuit), as well as reading eye movements using simulated single and multiple line dynamic arrays. In addition, a reading rating-scale questionnaire is administered before and after completion of training to assess subjective reading improvement. In all paradigms, the target consists of a 0.5° luminous square, which is displayed on a computer monitor positioned 40 cm from the subject along the midline. All testing and training are conducted under binocular viewing conditions with optical correction in place. There are two modes of training: normal internal oculomotor visual feedback either alone (4 weeks) or in conjunction with external oculomotor auditory feedback (4 weeks) administered in a counterbalanced manner within each diagnostic group. Training is performed 1 h, twice weekly for the 8 weeks. Oculomotor testing is conducted before, midway and after training. Following training, reading-related eye movements and reading ability improved as assessed both subjectively and objectively. These protocols provide a systematic approach to the quantitative and comprehensive testing and training of reading-related eye movement skills and behaviors in the ABI population manifesting oculomotor-based reading dysfunctions. Furthermore, the training protocol results in the rapid remediation of the eye movement deficits, which appear to transfer to activities of daily living.

Theme: Motor systems and sensorimotor integration
Topic: Oculomotor system

Keywords: Oculomotor rehabilitation; Reading; Traumatic brain injury (TBI); Cerebral vascular accident (CVA, stroke); Acquired brain injury (ABI); Oculomotor adaptation; Visual attention; Visual feedback; Auditory feedback

1. Type of research

These protocols consist of laboratory-based procedures to assess, test, train and rehabilitate reading-related oculomotor skills and behaviors in individuals with acquired brain injury (ABI) who manifest oculomotor dysfunctions with correlated symptoms during reading [9]. For example, individuals with stroke and hemianopia frequently complain of loss of place, skipping lines and difficulty shifting to the next line of print during reading [8]. Similar but less sophisticated protocols, and of a less comprehensive nature, have been used successfully by us and others for many years in the diagnostic assessment of individuals with reading

* Corresponding author. Tel.: +1 212 780 5132; fax: +1 212 780 5124.
E-mail address: kciuffreda@sunyopt.edu (K.J. Ciuffreda).

1385-299X/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.brainresprot.2004.06.002

dysfunctions of an oculomotor origin [2–5,7,11–13,20,21,29,31]. However, training-related paradigms remain a rarity [33,34].

ABI refers to those conditions that produce sudden cranial insult resulting in immediate neurological deficit [30]. Thus, it is not of a congenital, degenerative, developmental or genetic origin. There are two major categories or groups of acquired brain injury: traumatic brain injury (TBI) in which there is an external insult to the brain such as a blow to the head, and cerebral vascular accident (CVA), or stroke, in which there is internal insult to the brain such as hemorrhage from a ruptured cerebral blood vessel [8,35]. Due to the pervasive nature of the insult which affects large regions of the brain, the consequences are broad and can affect the sensory, motor, perceptual, cognitive, language, psychological and/or behavioral domains. One area of interest in which many patients with ABI are affected (~65%) is the oculomotor system [8]. The oculomotor neural network is extensive, thus leading to multiple eye movement subsystem deficits from a single cranial insult. Furthermore, many of the same areas of the brain contribute to multiple oculomotor functions. For example, the frontal, parietal and cerebellar regions each participate in both saccadic and pursuit neural oculomotor control [2,24]. The resultant oculomotor dysfunctions, either in isolation or more typically in conjunction with deficits in the other non-oculomotor systems mentioned earlier, can have adverse educational, social, vocational, avocational and economic impact on the individual. Furthermore, presence of oculomotor deficits can hinder the overall rehabilitative effort [16,25], and thus represent a negative prognostic indicator.

Despite the widespread oculomotor consequences in patients with acquired brain injury, there is a paucity of studies involved in reading-related oculomotor rehabilitation using objective documentation of remediation effects [9,33,34]. Furthermore, no comprehensive oculomotor testing and training protocols have been established. Therefore, we propose a comprehensive testing and training protocol targeting oculomotor reading-related skills using two modes of training in the acquired brain-injury population.

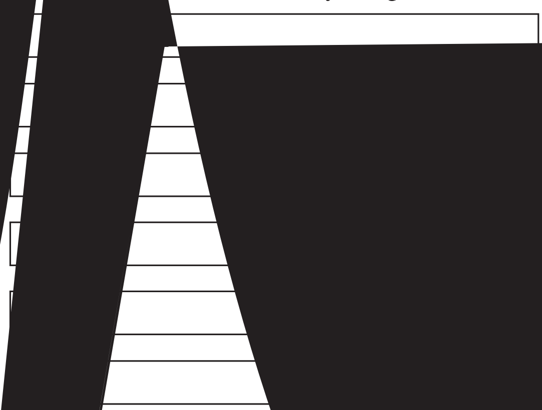
2. Time required

(a) Optometric clinic examination of each subject per testing session: 0.5 h.
(b) Preparation of the computer programs and apparatus for stimulus presentation and training of each subject per session: 1.0 h.
(c) Preparation of the computer programs and apparatus for stimulus presentation and testing of each subject, and administration of the subjective reading rating-scale questionnaire, per session: 1.5 h.
(d) Complete data analysis, statistical analysis and graphical display of oculomotor findings for each subject per test session, as well as the group and subgroup findings: 12 h.

3. Materials

(a) Phoropter for clinical assessment of refractive state of the eye (non-cycloplegic) and binocular sensory-motor status [1].
(b) Direct and indirect ophthalmoscopes, and slit-lamp with Goldmann applanation tonometric component, to assess internal and external ocular health and anatomical structural integrity; Ishihara color vision test; Humphrey Visual Field Analyser [1].
(c) Head–chin rest to maintain head stability and a fixed distance between the eyes and stimulus monitor during the testing and training sessions.
(d) Spectacle or contact lenses, if needed, to correct refractive error to see the target clearly during the testing and training sessions.
(e) Reading rating-scale questionnaire (Appendix A) [9].
(f) OBER2 specialized computer-based, binocular, two-dimensional, infrared eye movement recording system for stimulus development (Nystrom language), presentation on a 12.5-in. monitor and data acquisition (IOTA Eye Trace Systems, Sundsvall, Sweden) [23].
(g) Custom-designed electronic two-dimensional auditory oculomotor feedback control unit (IOTA Eye Trace Systems, Sundsvall, Sweden).
(h) Conventional computer system [Gateway, Poway, CA; Intel(R) Pentium IV] for data transport from OBER2 eye movement system/files into ASCII files, and then into Excel 2000 (Microsoft, Seattle, WA) and Origin 6.1 (Origin Lab, Northhampton, MA) computer programs for data analysis and graphical display, and into Statistica 6.0 (StatSoft, Tulsa, OK) for statistical analysis.
(i) Visagraph II specialized computer-based horizontal, infrared eye movement recording system for reading assessment using standardized graded text, and providing computer-automated objective analysis with graphical display of both the non-processed and processed (i.e., electronically filtered) reading eye movements (Taylor Associates, Huntington, NY) [13].

[redacted]



(2) [redacted] laboratory training [redacted] 2. The subject receives [redacted] for weeks 2, 3, 4 and [redacted] (referred to as T1, see [redacted] is 60 min in duration. This [redacted] training, with the remainder [redacted] short interspersed rest periods for [redacted] for changing the stimulus input to [redacted] week 6, the subject is re-evaluated [redacted] and in the clinic.

[redacted] The subject is again seen twice weekly during weeks [redacted] 8, 9 and 10 for the second phase of training in the laboratory (referred to as T2, see Fig. 1).

[redacted] In week 11, the subject is re-evaluated both in the laboratory and in the clinic.

[redacted] The subject is re-evaluated 3 months post-training in the laboratory and in the clinic.

[redacted] The study employs a cross-over experimental design in [redacted] each subject receives two training modes: (1) oculo- [redacted] rehabilitation with visual feedback only and (2) [redacted] rehabilitation with combined visual and audi- [redacted] feedback (see Fig. 2). Subjects are assigned to one of the two training modes in a counterbalanced manner separately for each of the two diagnostic groups. That is, if a subject were initially assigned to the visual feedback mode (V) for the first phase of training (T1), that subject will cross over to receive the combined visual and auditory feedback mode (V+A) for the second phase of training (T2), and vice versa for the next subject, in that diagnostic group (i.e., either TBI or CVA). Thus, all training, evaluations and analyses are performed separately for the TBI and CVA diagnostic groups to compare training effects, and then combined for the overall group effect.

4.2. Testing protocol (Table 1)

(i) The reading rating-scale questionnaire developed and validated by us (see Appendix A) addresses the following areas: (1) the length of time that the subject can read comfortably, (2) the subject's ability to understand what has [redacted]. This testing [redacted] upon entry

[redacted] assessment includes [redacted] near with full refractive [redacted] point of convergence, phoria at [redacted] vergence ranges at distance and [redacted] saccadic and pursuit testing, and the [redacted] eye movement (DEM) saccadic test [1].

(iv) Simulated "reading": two simulated reading patterns are used: a multi-line (ML), full-screen, simulated reading test paradigm and a single-line (SL), simulated reading test paradigm.

(1) The full-screen, simulated reading test paradigm incorporates a randomly spaced (1–3° step displacements), horizontally moving test target in place of words equivalent to a 100-"word" paragraph. The test

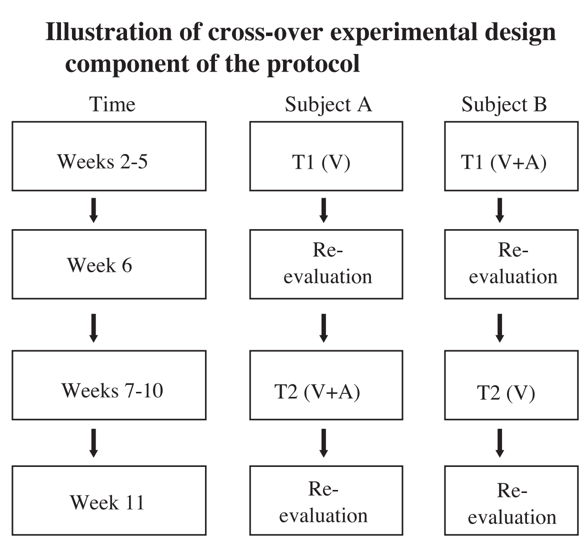


Fig. 2. Illustration of cross-over experimental design component of the protocol.

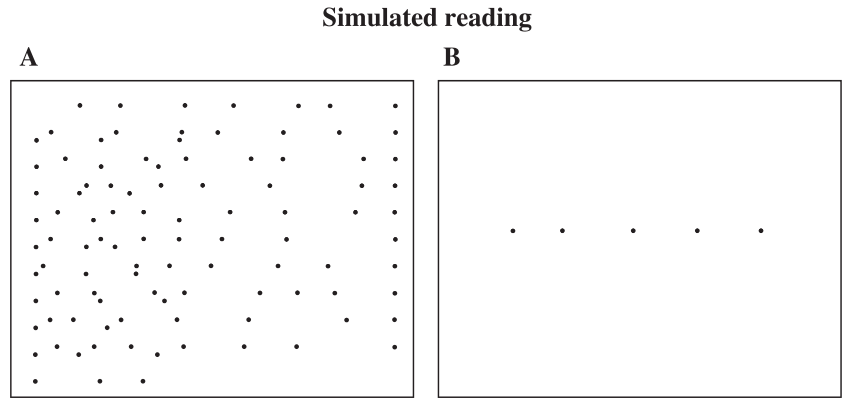


Fig. 3. Simulated reading dynamic arrays. (A) Multiple line and (B) single line.

target moves step-wise and sequentially (i.e., from left to right) to positions on the screen as depicted in Fig. 3A starting in the upper left hand corner and shifting across to the right for each "line" presented sequentially downward for a total of 120 s. Each of the 12 rows has 10 dot positions.

(2) In Fig. 3B, the single-line, simulated reading test paradigm is depicted. The test target moves step-wise and sequentially left-to-right to the five positions on the screen, steps back to the left-most position, and then repeats the cycle five times for a total of 60 s.

In both cases, the subject is instructed to follow the moving target accurately with a single saccade, as they would do during normal reading. This paradigm allows sequential, rhythmical reading eye movement patterns to be trained and reinforced without involving the cognitive, perceptual and linguistic load that occurs during actual reading [14,26]. Hence, both paradigms represent pure

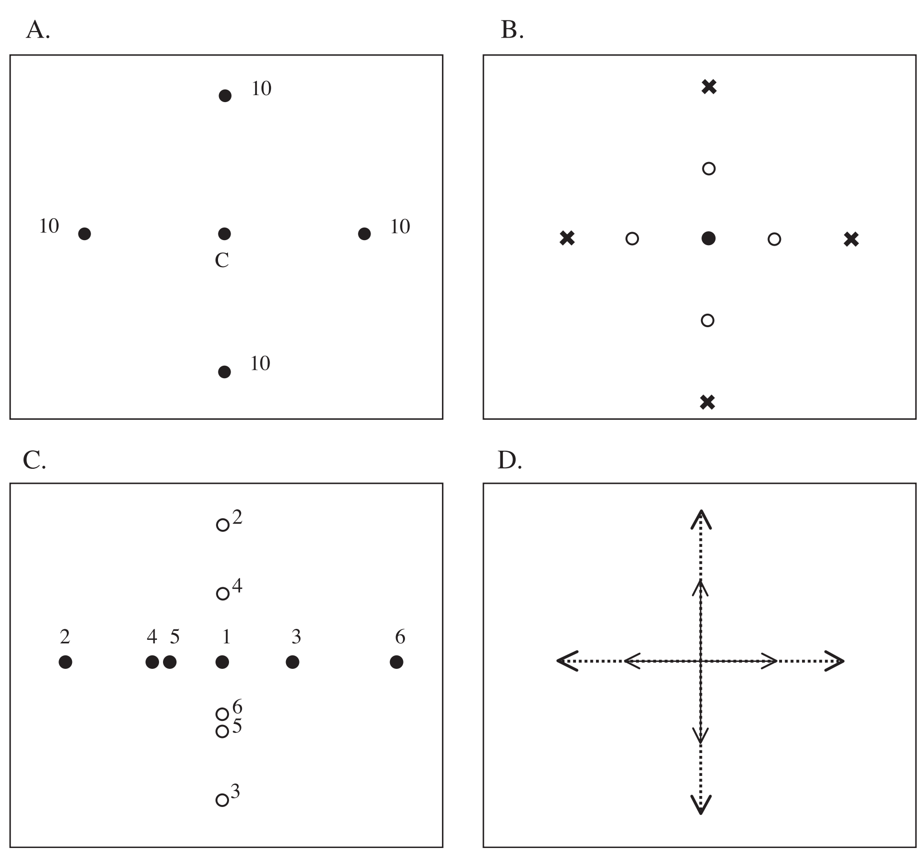


Fig. 4. Two-dimensional versional stimulus arrays. (A) Fixation and (B) predictable saccades. Open circles=±5° and filled circles and x's=±10°. (C) Non-predictable saccades. Open circles=vertical stimuli and filled circles=horizontal stimuli. (D) Pursuit. Inner arrows=±5° and outer arrows=±10°.

Table 1
Oculomotor testing protocol sequence

Stimulus	Test duration (min)
1. Central fixation	0.5
2. Horizontal predictable saccades (±10° amplitude, 0.33 c/s step intervals)	0.5
3. Vertical predictable saccades (±10° amplitude, 0.33 c/s step intervals)	0.5
4. Horizontal random saccades (0.5–10° amplitudes, 0.3–3.8 s step intervals)	0.5
5. Vertical random saccades (0.5–10° amplitudes, 0.3–3.8 s step intervals)	0.5
6. Horizontal pursuit (±10° amplitude, 4.1°/s velocity)	1.0
7. Vertical pursuit (±10° amplitude, 5.4°/s velocity)	1.0
8. Multiple-line simulated reading (full page, 34° centered field, 1.3° amplitudes, 1.0 c/s step intervals)	2.0
9. Single-line simulated reading (12° centered field, 3° step displacements, 0.33 c/s step intervals)	1.0
10. Multiple-line silent reading (Visagraph, level 3, 2 selections)	unlimited (approximately 7.5)
11. Multiple-line silent reading (Visagraph, level 10, 2 selections)	unlimited (approximately 7.5)
Total testing time	≅22.5 min

oculomotor training tasks, which are related directly to the motor-based aspects of the reading process.

Specific analysis for simulated reading included mean saccade frequency ratio (i.e., ratio of the total number of saccades executed as compared with the total number of stimulus step changes) and related standard error of the mean (SEM) for each stimulus pattern. In addition, representative binocular, two-dimensional plots of simulated reading under both test conditions are graphically displayed to assess qualitatively the overall global characteristics and patterns of the simulated reading profile.

(v) Reading eye movement measurements.

Reading eye movements (horizontal position of both eyes) are recorded objectively using the commercially available Visagraph II system [13]. It consists of the following: (1) an infrared, limbal reflection eye movement monitoring and recording system (resolution=0.25°, bandwidth=dc to 50 Hz and linear range=±20°), (2) hard copy of the test text at 10 graded reading levels (grades 2 through high school) based on Taylor's normative data [32], with ten 100 word validated and standardized paragraphs at each grade level, (3) computer software to analyze the eye movements and display the grade-related oculomotor-based performance profiles for each of the basic reading eye movement parameters automatically (reading rate, grade level, overall reading efficiency, comprehension, span of recognition, duration of fixation, and number of progressive and regressive fixations), and (4) hard copy of both the unprocessed and processed (i.e., electronically filtered) binocular reading eye movements along with the tabulated grade-normative oculomotor performance levels.

Reading ability is assessed in two ways: first, to determine the grade-level-based global reading performance and, second, to determine below grade-level-based global reading performance [28]. (1) Subjects read two separate paragraphs at high school grade-level, resulting in the Visagraph reading oculomotor assessment as described in the above paragraph; the first is a practice paragraph. This provides a multi-faceted, objective assessment of oculomotor-based performance at the subject's normal reading level, which includes oculomotor, linguistic, perceptual and cognitive components combined in a standard test format.

Table 2
Oculomotor training protocol sequence

Stimulus	Test duration (min)
1. Central fixation (0°, midline)	1.5
2. Horizontal predictable saccades (±5° amplitude, 0.33 c/s step intervals)	2.0
3. Horizontal pursuit (±10° amplitude, 4.1°/s velocity)	1.5
4. Multiple-line simulated reading (full page, 34° centered field)	2.0
Subtotal	7.0
5. Leftward fixation (10° left of midline)	1.5
6. Horizontal predictable saccades (±10° amplitude, 0.33 c/s step intervals)	2.0
7. Horizontal pursuit (±10° amplitude, 4.1°/s velocity)	1.5
8. Single-line simulated reading (13° centered field)	1.0
Subtotal	6.0
9. Rightward fixation (10° right of midline)	1.5
10. Vertical predictable saccades (±5° amplitude, 0.33 c/s step intervals)	2.0
11. Vertical pursuit (±5° amplitude, 4.1°/s velocity)	1.5
12. Multiple-line simulated reading (full page, 34° centered field)	2.0
Subtotal	7.0
13. Upward fixation (10° above midline)	1.5
14. Vertical predictable saccades (±10° amplitude, 0.33 c/s step intervals)	2.0
15. Vertical pursuit (±10° amplitude, 4.1°/s velocity)	1.5
16. Single-line simulated reading (13° centered field)	1.0
Subtotal	6.0
17. Downward fixation (10° below midline)	1.5
18. Horizontal non-predictable saccades (0.5–10° amplitudes, 0.3–3.8 s step intervals)	2.0
19. Multiple-line simulated reading (full page, 34° centered field)	2.0
Subtotal	5.5
20. Central fixation (0°, midline)	1.5
21. Vertical, non-predictable saccades (0.5–10° amplitudes, 0.3–3.8 s step intervals)	2.0
22. Single-line simulated reading (13° field, centered on midline)	1.0
Subtotal	4.5
Total training time	=36.0

Table 3
Total oculomotor training time (16 sessions) for each eye movement type

Type	Time (min)
Fixation, central	48
Fixation, peripheral	96
Horizontal saccades	96
Vertical saccades	96
Horizontal pursuit	48
Vertical pursuit	48
Simulated reading (SL)	48
Simulated reading (ML)	96
Total training time	=576 min (9.6 h)

(2) Then, subjects read two additional individual paragraphs at reading level three followed with a similar assessment of reading; the first is a practice paragraph. The reading eye movement results at the two different grade levels are compared to assess the effect of text level difficulty on reading ability.

(vi) Basic binocular horizontal and vertical versional eye movements are assessed objectively using the OBER2 recording system [23]. Auditory oculomotor feedback hardware related to horizontal and vertical eye position changes has been customized and integrated into the standard OBER2 eye movement system, wherein a voltage from the eye movement system related to eye position is converted to a correlated tone. The auditory tone generator has a position-to-tone resolution of 0.25° both horizontally and vertically, and it has a frequency range from 2000 to 5000 Hz. The standard OBER2 system consists of a goggle-mounted, infrared limbal reflection eye movement system having a resolution of 0.25°, bandwidth=dc to 120 Hz and a linear range of ±20° horizontally and vertically. The computer-controlled test stimuli are presented binocularly and tests the following basic eye tracking behaviors [2]: fixation, saccades, pursuit and simulated reading (Fig. 4). The target consists of a single 0.5° bright square of light viewed on an otherwise dark high-resolution 12.5-in. display monitor at a 40-cm test distance.

(a) Fixation: the target is presented in the five positions specified (0, ±10°) in Table 1, each viewed for a 30-s test duration. Any fixational abnormalities (i.e., increased drift, large and/or frequent saccadic intrusions, and nystagmus [6]), which may adversely affect reading are documented and quantified.
(b) Saccades: *Non-predictable*: within a range of either ±5° or ±10° relative to the midline, the test target is rapidly shifted (i.e., with an instantaneous step displacement) with both temporal (i.e., timed sequence) and spatial (i.e., positional change) randomization for a 30-s test duration separately for horizontal and vertical saccades. Any saccadic anomalies that may adversely affect reading (e.g., marked hypometria) are documented. *Predictable*: using the same stimulus range as above, the target now changes position at a constant frequency of 0.33 cycles/s.
(c) Pursuit: with an amplitude of either ±5° or ±10° relative to the midline, the test target is moved smoothly at a constant velocity of either 4.1°/s or 5.4°/s for the 60-s test duration. This tests horizontal and vertical smooth pursuit tracking ability. Any pursuit anomalies that may adversely affect reading are documented, such as gain (i.e., the ratio of eye velocity to target velocity) [2].

4.3. Training protocol (Tables 2 and 3)

Each subject is seen twice weekly for a total of 4 weeks for each of the two training mode phases. Subjects who

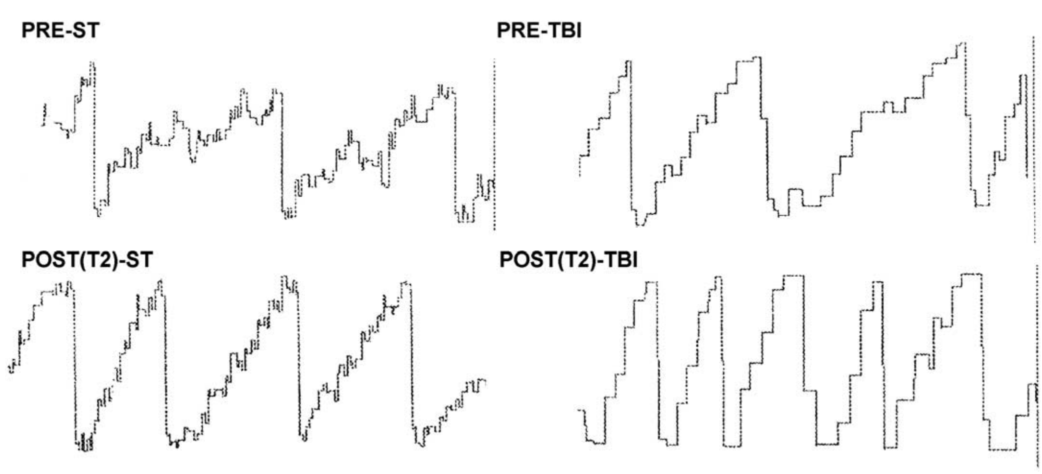


Fig. 5. Horizontal reading eye movements in a stroke subject (left) before (PRE-ST) and after [POST(T2)-ST] training, and in a traumatic brain injury subject (right) before (PRE-TBI) and after [POST(T2)-TBI] training. Reading rate improved by 25% in each subject primarily due to a reduced number of progressive and regressive saccadic eye movements. Up is left, and down is right; the time period shown is equal for each subject comparison.

started with visual feedback (V) in the T1 training phase cross-over to the combined visual and auditory feedback (V+A) for the T2 training phase starting week 7, and vice versa (see Fig. 2), separately considered for each of the two diagnostic groups (TBI and CVA). Fixation, pursuit, saccades and simulated reading are trained using the oculomotor tasks described earlier in the evaluative procedures (see Tables 2 and 3).

4.3.1. Apparatus

The objective eye movement recording system is identical to that described under the testing procedures for the two training modes (V and V+A), with the only difference being the feedback training mode. Further, the tasks in the two training modes are similar to that described earlier for the evaluation of basic eye tracking movements (i.e., fixation, saccades, pursuit and simulated reading), except for the duration of stimulus presentation in most cases (see Tables 1 and 2).

4.3.2. Procedures

The sole difference in the training between the two modes is that the V mode incorporates only normal internal visual oculomotor feedback, while the V+A mode incorporates both this visual and external auditory oculomotor feedback concurrently. The auditory oculomotor feedback for V+A is incorporated by adding an auditory tonal change related to the subject's eye position [13,17]. At the initial combined feedback mode training session, the subject receives a verbal description of the tonal expectations for optimal tracking, as described below. In addition, they listen to an audiotape depicting the optimal oculomotor-related sounds as performed by a highly experienced, visually normal subject.

In the combined visual and auditory feedback mode (V+A), a tone related to eye position is present at all times during visual tracking of the target:

(i) For *simulated reading*, subjects are instructed to generate a single and discrete tonal change for each discrete step displacement of the target, per the verbal description and audio example. The more regular the tonal changes, the more rhythmical the eye movements.

(ii) For *fixation*, subjects are instructed to maintain the tone constant, per the verbal description and audio example. The steadier the tone, the steadier the fixational eye movements.

(iii) For *saccades*, subjects are instructed to generate a single, discrete, and rapid tonal change for each step displacement of the target, per the verbal description and audio example. Such a tonal change would be created by a single accurate saccade, as desired. Any undesirable subsequent corrective saccades would be heard as additional discrete and rapid tonal changes, but with smaller tonal variation as these will typically be of smaller amplitude.

(iv) For *pursuit*, subjects are instructed to create a smooth and continuous change in tone, per the verbal description and audio example. Such a tonal change would be created by saccade-free pursuit. The presence of saccades within (i.e., superimposed upon) the basic oculomotor smooth pursuit movement creates undesirable discrete tonal variations interspersed within the desired continuous tonal change.

Eye movements are trained for a total of 36 min per training session. Rest periods are interspersed to prevent

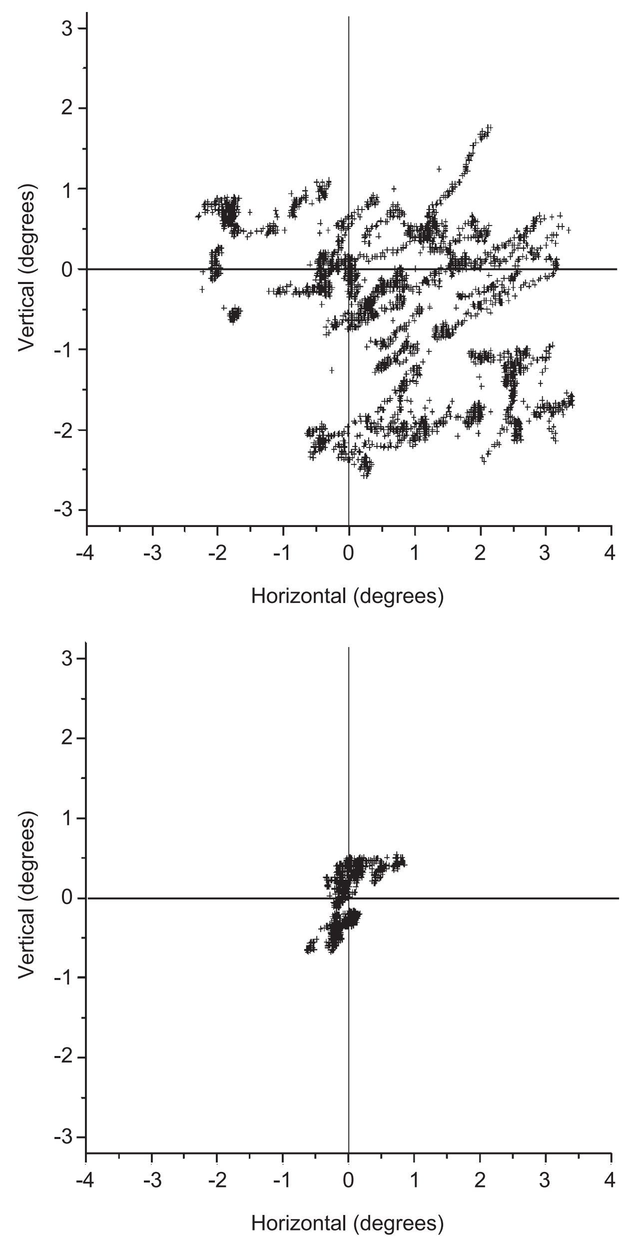


Fig. 6. Two-dimensional (horizontal and vertical) fixational eye movements in a stroke subject with hemianopia and visual neglect before (PRE) (top) and after [POST(T2)] (bottom) training. Before training, fixational error was large and biased into the "seeing" hemi-field. After training, fixational error markedly decreased, and the fixation pattern became more symmetric.

fatigue of the subject, thereby making the total training session time 60 min in duration.

5. Results

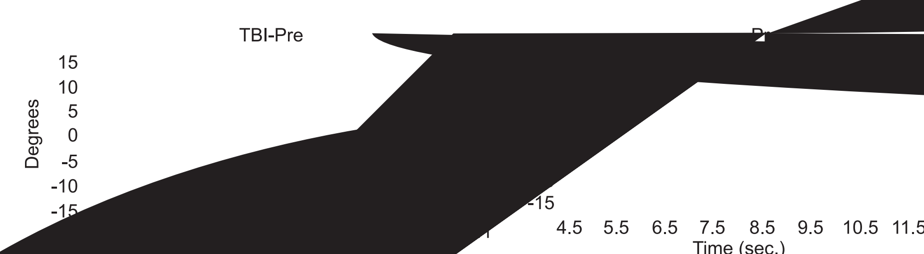
Over the past 25 years, we have applied and developed numerous versions of the horizontal saccadic and pursuit testing, as well as fixation, protocols in a large population of individuals (n=500) having a range of oculomotor dysfunctions, as mentioned earlier [2–5,7,11–13,21,29,31]. Thus, the present testing protocol evolved and expanded based on considerable direct laboratory testing in patients manifesting a broad area of clinical oculomotor dysfunctions. For the latest refined version, we have applied and fully completed these testing and training protocols in 14 individuals with acquired brain injury, including 9 with traumatic brain injury and 5 with combined stroke and hemianopia, over the past 2 years. The detailed results and statistical analyses are presented elsewhere [9,10], and only a summary with selected examples (Figs. 5–7) will be given in the present paper. These two protocols were also applied to five other subjects with acquired brain injury who, for a variety of reasons (e.g., difficulty obtaining reliable transportation services), did not complete the study. In addition, use of these protocols is ongoing in five other subjects.

With regard to the results of the subjective reading rating-scale questionnaire for the combined group, the responses to each of the five questions revealed significant improvement (p<0.01, non-independent t-test). All targeted aspects improved: length of time of reading comfort, understanding of the material, attentional focus during reading and reading strategy. The greatest improvement was found in question one dealing with length of time of comfortable reading. This increased from approximately 5–10 to 15–30 min for the combined group; the most remarkable change occurred in a stroke subject in which reading comfort time increased from 1 to 30 min.

When the subjective group findings were subdivided into the categories of stroke and traumatic brain injury, the majority of significant effects were found in the latter group. All five questions reflected significant subjective improvement (p<0.01, non-independent t-test), with question one related to reading comfort exhibiting the largest gain. In the stroke group, the results were significant for questions one and three (p<0.05, non-independent t-test), with questions 2, 4 and 5 revealing positive trends (p<0.10, non-independent t-test). The greatest change was found for question one dealing with reading comfort. The marked subjective improvement in overall reading ability was also reflected in the objective basic versional eye movement findings [9,10].

The simulated reading saccade ratio results for the multiple (ML) and single (SL) line training revealed similar positive findings. For the combined group, there were significant improvements in both the T1 and T2 training phases for both the ML and SL conditions when compared with the pre-training levels (p<0.05, repeated measures ANOVA). More consistent relative improvement was found in the traumatic brain injury group.

The Visagraph reading results were mixed for the combined group. The level three findings revealed little positive change with training, except for comprehension which exhibited an improvement trend (p<0.10, repeated measures ANOVA). However, there was somewhat greater evidence of a positive training effect for the adult [redacted] reading, as there were improvement [redacted]



repeated measures ANOVA) with respect to fixations/100 words, regressions/100 words and comprehension level.

When the Visagraph results were divided into the two diagnostic groups, however, the positive training effects were more evident. Most of the positive group results were attributed to the stroke group at level 10 reading. There were either significant effects (p<0.05, repeated measures ANOVA) or positive trends (p<0.10, repeated measures ANOVA) with respect to fixations/100 words, regressions/100 words and comprehension level. For the traumatic brain injury group, however, there was little evidence of a positive training effect except for the fixations/100 words (p<0.10, repeated measures ANOVA). Examples of reading eye movements in one traumatic brain injury subject and one stroke subject before and after training are present in Fig. 5. The improved reading pattern is evident in the traces.

With regard to training-related effects on the basic versional eye movement aspects (i.e., fixation, saccades and pursuit), all exhibited significant improvement (p<0.05, repeated measures ANOVA). An example of midline fixation and predictable saccadic tracking in two stroke subjects before and after training are presented in Figs. 6 and 7, respectively. The details of our quantitative and statistical analyses are the topic of a separate report [10].

There was no training order effect for either the entire group or either diagnostic group (p>0.05, repeated measures ANOVA).

The 3-month follow-up data revealed retention of the post-training improvement (t-test, p>0.05) except for the three fixation parameters (i.e., horizontal, vertical and radial errors), which regressed close to the initial post-training values (t-test, p<0.05). This suggests more extensive and intensive fixation training be performed, as well as a shorter follow-up period. If regression is found, training is to be re-instituted until significant improvement is once again established. Moreover, in the future, we will incorporate both 3- and 9-month follow-up test periods to ascertain the short- and long-term training efficacy.

6. Discussion

Both the basic versional and simulated reading testing and training protocols were readily developed, and modified in the pilot stage, prior to actual use with the brain-injured population, incorporating the Nystrom language software program with the OBER2 computerized eye movement system [23]. Furthermore, our own custom-designed software programs, as well as the commercially available Excel and Origin software programs, provide for flexible and powerful oculomotor testing and training protocols for use with patients having acquired brain injury. These protocols may also be useful in other non-ABI diagnostic groups such as amblyopia, strabismus, nystagmus, reading disability and macular degeneration, in which oculomotor dysfunctions also prevail [2].

The current testing and training protocols have been easily and readily applied to a range of adults (ages 26–73 years) with acquired brain injury. We believe they should be applied to children in the future, but with a more interesting test target such as a “smiling face”, flickering and rotating star, randomly changing numbers, etc. to foster a high level of attention and visual engagement. These protocols are safe, painless and well-tolerated. However, when subjects report some degree of visual or general body and/or mental fatigue, or some degree of inattention, short (1–5 min) rest periods are provided. Thus, all sessions are, in effect, either divided by natural rest demands, or by small groupings as specified in the training protocol. Hence, while the total actual stimulus testing (22.5 min) and training (36 min) times are well under 1 h, with the necessary rest periods as well as the need for some repetition of the basic instructions, the total testing and training times each approach 1 h. Before beginning each testing and training session, the individuals are provided with instructions, as needed, about the aims and general/specific procedures to minimize the total duration of each session, as well as to assist this population in which short-term memory and cognitive problems are common [15]. No major discomfort or fear was evident when the individuals wore the infrared testing and training eye movement goggles. In fact, when the auditory feedback mode was added in the training phase, subjects were amused at the novelty of “hearing” their eyes move, and, furthermore, appreciated the instantaneous, direct and easily interpretable information it provided to them regarding both their immediate and overall oculomotor performance.

The results from the level 3 reading materials revealed little abnormal for either the entire group or each diagnostic group. We believe this to be due to a saturation, or “ceiling” effect, as the material was already too easy for them at the pre-training test session. In the future, we will either delete this level three test or may elect to use a level only two grades below the subject’s typical reading level [28].

This is the first formal oculomotor rehabilitation testing and training protocol for reading remediation in the ABI population that incorporated both visual and auditory-based feedback modes. Thus far, our own sense, as well as that of the subjects who have completed both protocols, is that they has been able to use both the separate and the combined visual and auditory information about eye position and related oculomotor performance quite readily, with relatively rapid improvements evident. We believe that auditory feedback should be incorporated in conjunction with the normal visual feedback in future rehabilitation paradigms for oculomotor dysfunctions in both reading-related and more general eye movement problems to maximize potential effectiveness.

The absence of a training order effect suggests lack of differential effectiveness of the two modes. However, most subjects strongly preferred the combined mode, as they could hear and thus monitor their own oculomotor performance continuously in a more direct and overt manner. This may also be due to the relatively small sample sizes and inherent oculomotor response variability in this population.

Many of the ABI population have binocular vergence (i.e., tracking targets in-depth) dysfunction in addition to their versional (i.e., tracking targets laterally) dysfunction [8]. Thus, we propose that specific vergence testing and training protocols be developed and incorporated into the basic versional tracking and specific reading-related protocols, as needed based on the specific clinical signs and symptoms manifested by the individual. In Appendix B, we provide a framework for such a vergence protocol based on our knowledge derived from bioengineering control system models [18], as well as our clinical and laboratory work in this area over the past two decades.

6.1. Alternative protocols

Two alternative training protocols exist, both of which are based on normal external visual feedback alone. Zihl [33,34] has provided a specific reading-related training program for stroke patients with hemianopia. It involves a simple but important horizontal oculomotor adaptive maneuver. The individual is, in effect, trained to adjust the neural gain of their saccadic eye movement system gradually. Thus, they do not foveate the middle of the word as is conventionally done, but rather are conditioned to foveate either the beginning or end of the new word depending on the side of their hemianopia. In this way, the entire word falls upon the "seeing" or normal hemiretina. Success with stroke patients having hemianopia has been good, but Zihl's protocol does not apply to the traumatic brain injured population, where hemianopia and other discrete and/or large visual defects are rarely present [19]. The second program (guided reading) is less specific and employs use of an electronic moving aperture effectively overlayed upon computer text (Taylor Associates, Huntington, NY). One word at a time is exposed in a left-to-right reading sequence with intervening right-to-left movements to shift to the beginning of the next line of print [32]. The speed of the aperture can be progressively increased as reading speed and performance improves. This protocol has been used clinically for patients having oculomotor-based reading dysfunction for a range of diagnostic groups [32]. Anecdotely, this training paradigm has also been found to be helpful in the brain-injured population in our clinic, but no formal studies have been conducted.

7. Quick procedure

7.1. Test protocol

(i) Administer reading rating-scale questionnaire to establish subjective (i.e., perceived) level of reading disability.
(ii) Perform clinical ocular health assessment to assure lack of any other ocular health problems that may confound interpretation of results, as well as for baseline purposes.
(iii) Perform clinical binocular vision evaluation to document presence of any binocular vision anomalies that may need to be considered for the testing (and training) protocol, as well as for baseline purposes.
(iv) Testing of reading-related saccadic eye movements objectively using simulated reading paradigm in the laboratory.
(v) Testing of actual reading eye movements objectively using the level 3 and 10 paragraphs in the laboratory.
(vi) Testing of basic binocular horizontal and vertical versional eye movements objectively, and storing results in the computer for subsequent analysis and display.

7.2. Training protocol

(i) Using either the visual feedback mode alone, or the combined visual and auditory feedback mode, in a cross-over experiment design to train simulated reading eye movements.
(ii) As in (i) regarding feedback mode to train versional fixational eye movements.
(iii) As in (i) regarding feedback mode to train versional saccadic eye movements.
(iv) As in (i) regarding feedback mode to train versional pursuit eye movements.

Acknowledgments

This research was supported by a grant from the Langeloth Foundation. We thank Drs. J. Ygge and R. Bolzani for providing us with custom software programs for some of the data analysis and graphical display. We thank Drs. Feldman and Ficarra for statistical assistance.

Appendix A. Reading rating-scale questionnaire

Please circle the appropriate answer to the following questions:

1. How long can you read comfortably?

(A) Before training:

(1) 0–5 min	(2) 5–10 min	(3) 10–15 min	(4) 15–30 min	(5) 30+ min

(B) After training:

(1) 0–5 min	(2) 5–10 min	(3) 10–15 min	(4) 15–30 min	(5) 30+ min

2. How would you rate your ability to understand what you read?

(A) Before training:

(1) poor	(2) fair	(3) good	(4) very good	(5) excellent

(B) After training:

(1) poor	(2) fair	(3) good	(4) very good	(5) excellent

3. How would you rate your ability to attend while you read in a quiet solitary environment?

(A) Before training:

(1) poor	(2) fair	(3) good	(4) very good	(5) excellent

(B) After training:

(1) poor	(2) fair	(3) good	(4) very good	(5) excellent

4. How would you rate your ability to attend while you read in a noisy environment with other people in the room?

(A) Before training:

(1) poor	(2) fair	(3) good	(4) very good	(5) excellent

(B) After training:

(1) poor	(2) fair	(3) good	(4) very good	(5) excellent

5. How would you describe your reading strategy?

(A) Before training?

(1) impulsive and inaccurate	(2) impulsive but accurate	(3) deliberate but inaccurate	(4) deliberate and accurate

(B) After training?

(1) impulsive and inaccurate	(2) impulsive but accurate	(3) deliberate but inaccurate	(4) deliberate and accurate

Appendix B. Vergence testing and training protocol

Vergence: The overall horizontal, symmetric (i.e., midline) vergence responses are tested and trained using step and ramp stimuli to activate both the slow and fast vergence neural controller components [18]. Due to the physical nature of the stimuli, they contain combined disparity, blur and proximal vergence drive components [27] to simulate naturalistic viewing conditions.

(1) *Step stimuli*: Three targets are present consisting of fine etched lines subtending an overall size of 10 mm on clear plexiglas, with each plexiglas plate (20 mm^2) containing built-in miniature bulbs to provide independent trans-illumination to the targets [22]. These targets are placed on an optical bench along the subject's midline at distances of: (1) 100 cm (1 m angle, 1 diopter), (2) 33 cm (3 m angles, 3 diopters) and (3) 20 cm (5 m angles, 5 diopters). The middle target (an asterisk, *) is illuminated initially. Then, at a random time (between 2 and 4 s) under computer control, either the far (a cross, +) or near (an ×) target will be illuminated, thus providing both spatial and temporal stimulus randomization. The subject is instructed to follow and binocularly fuse the illuminated target. For testing, the cycle is repeated to obtain 10 artifact-free (i.e., no intrusive blinks) convergence and 10 divergence responses. For training, the stimuli are presented for a total of 3 min.

(2) *Ramp stimuli*: The 'X' plexiglas target described above is now the sole target. It is placed along the subject's midline upon a computer-controlled, precision electromechanical track. The target is illuminated continuously. It moves at a constant velocity of 4 cm/s starting at the far position (100 cm) and slowly moving inward to the near position (20 cm), and then slowly moving back to the initial far position (100 cm). The subject is instructed to follow and

binocularly fuse the target throughout the entire excursion. The test range is the same as that used for the disparity vergence step stimuli described earlier. For testing, this cycle is repeated for a total of 160 s. For training, the stimulus is presented for 5 min.

Specific data analyses for overall horizontal vergence includes [2]:

(1) the "main sequence" peak velocity/amplitude relationship for step tracking,
(2) mean amplitude gain for step tracking,
(3) mean velocity gain for ramp tracking and
(4) mean latency for step tracking.

In addition, representative binocular horizontal plots of vergence are graphically displayed and presented to assess qualitatively the overall global characteristics and patterns of tracking (e.g., for the presence of saccades that may obscure or interact non-linearly with the dynamic vergence movement), using existing computer software in our laboratory.

References

[1] W.J. Benjamin (Ed.), Borish's Clinical Refraction, W.B. Saunders, Philadelphia, PA, 1998.

[2] K.J. Ciuffreda, B. Tannen, Eye Movement Basics for the Clinician, Mosby Yearbook, St. Louis, MO, 1995.

[3] K.J. Ciuffreda, A.T. Bahill, R.V. Kenyon, L. Stark, Eye movements during reading: case reports, Am. J. Optom. Physiol. Opt. 53 (1976) 389–395.

[4] K.J. Ciuffreda, R.V. Kenyon, L. Stark, Saccadic intrusions contributing to reading disability: a case report, Am. J. Optom. Physiol. Opt. 60 (1983) 242–249.

[5] K.J. Ciuffreda, R.V. Kenyon, L. Stark, Eye movements during reading: further case reports, Am. J. Optom. Physiol. Opt. 62 (1985) 844–852.

[6] K.J. Ciuffreda, D.L. Levi, A. Selenow, Amblyopia: Basic and Clinical Aspects, Butterworth, Boston, 1991.

[7] K.J. Ciuffreda, I.B. Suchoff, M. Marrone, B. Ahmann, Oculomotor rehabilitation in traumatic brain-injured patients, J. Behav. Optom. 7 (1996) 31–38.

[8] K.J. Ciuffreda, Y. Han, N. Kapoor, I.B. Suchoff, Oculomotor consequences of acquired brain injury, in: I.B. Suchoff, K.J. Ciuffreda, N. Kapoor (Eds.), Visual and Vestibular Consequences of Acquired Brain Injury, OEP Foundation Press, Santa Ana, CA, 2001, pp. 77–88.

[9] K.J. Ciuffreda, Y. Han, N. Kapoor, Oculomotor rehabilitation for reading in acquired brain injury, Neurol. Rehabil. submitted for publication.

[10] K.J. Ciuffreda, Y. Han, N. Kapoor, Oculomotor rehabilitation for versional eye movements in acquired brain injury, in preparation.

[11] J. Cooper, K.J. Ciuffreda, P.E. Carniglia, K.M. Zinn, B. Tannen, Orthoptic treatment and eye movement recordings in Guillain-Barre syndrome: a case report, Neuro-Ophthalmology 15 (1995) 249–256.

[12] J. Cooper, G. Pollak, K.J. Ciuffreda, P.K. Kruger, J. Feldman, Accommodative and vergence findings in ocular myasthenia: a case analysis, J. Neuro-Ophthalmol. 20 (2000) 5–10.

[13] B. Fayos, K.J. Ciuffreda, Oculomotor auditory biofeedback training to improve reading efficiency, J. Behav. Optom. 9 (1998) 143–152.

[14] J. Fletcher, Eye-movement rhythmicity and reading, J. Learn. Disabil. 26 (1993) 683–688.

[15] R. Gianutsos, I.B. Suchoff, Neuropsychological consequences of mild brain injury and optometric implications, in: I.B. Suchoff, K.J. Ciuffreda, N. Kapoor (Eds.), Visual and Vestibular Consequences of Acquired Brain Injury, OEP Foundation Press, Santa Ana, CA, 2001, pp. 48–55.

[16] Z. Groswasser, M. Cohen, E. Blankstein, Polytrauma associated with traumatic brain injury: incidence, nature and impact on rehabilitation outcome, Brain Inj. 4 (1990) 161–166.

[17] S. Gur, S. Ron, Training in oculomotor tracking: occupational health aspects, Isr. J. Med. Sci. 28 (1992) 622–628.

[18] G.K. Hung, J.L. Semmlow, K.J. Ciuffreda, A dual-mode dynamic model of the vergence eye movement system, IEEE Trans. Biomed. Eng., BME 33 (1986) 1021–1028.

[19] N. Kapoor, K.J. Ciuffreda, Vision problems, in Neuropsychiatry of Traumatic Brain Injury, Silver, J., Yudofsky, S.C., McAllister, T.W. (Eds), Amer. Psychiatric Press, Inc., Washington, D.C., in press.

[20] N. Kapoor, K.J. Ciuffreda, B. Tannen, Complex regional pain syndrome (type I): associated visual sensorimotor findings, Clin. J. Pain 18 (2002) 93–98.

[21] M. Katz, K.J. Ciuffreda, C.J. Viglucci, Reading performance and eye movements through Varilux 2 and ST-25 lenses, Am. J. Optom. Physiol. Opt. 61 (1984) 196–200.

[22] R.V. Kenyon, K.J. Ciuffreda, L. Stark, Dynamic vergence eye movements in strabismus and amblyopia: symmetric vergence, Investig. Ophthalmol. Vis. Sci. 19 (1980) 60–74.

[23] G.S. Koenig, N.C. Price, M.L. Baird, H.R. Laukkanen, R.L. Yolton, Use of the OBER2 Model B-1200 system for analysis of eye movements during reading, J. Am. Optom. Assoc. 68 (1997) 155–162.

[24] R.J. Leigh, D.S. Zee, The Neurology of Eye Movements, Oxford Univ. Press, New York, NY, 1999.

[25] M.J. Reding, E. Potes, Rehabilitation outcome following initial unilateral hemispheric stroke: life table analysis approach, Stroke 19 (1988) 1354–1358.

[26] G.M. Robinson, Rhythmic organization in speech processing, J. Exp. Psychol. Hum. Percept. Perform. 3 (1977) 83–87.

[27] C.M. Schor, K.J. Ciuffreda, Vergence Eye Movements: Basic and Clinical Aspects, Butterworth, Boston, 1983.

[28] H.A. Solan, Deficient eye movement patterns in achieving high school students: three case histories, Am. J. Optom. Physiol. Opt. 62 (1985) 812–818.

[29] L. Stark, A.T. Bahill, K.J. Ciuffreda, R.V. Kenyon, S. Phillips, Neuro-optometry: an evolving specialty clinic, Am. J. Optom. Physiol. Opt. 54 (1977) 85–96.

[30] I.B. Suchoff, K.J. Ciuffreda, N. Kapoor (Eds.), Visual and Vestibular Consequences of Acquired Brain Injury, OEP Foundation Press, Santa Ana, CA, 200l.

[31] B. Tannen, K.J. Ciuffreda, D.L. Werner, A case of Wallenberg's syndrome: ocular motor abnormalities, J. Am. Optom. Assoc. 60 (1989) 748–752.

[32] E.A. Taylor, The Fundamental Reading Skill, Charles C. Thomas, Springfield, IL, 1966.

[33] J. Zihl, Eye movement patterns in hemianopic dyslexia, Brain 118 (1995) 891–912.

[34] J. Zihl, Rehabilitation of Visual Disorders After Brain Injury, Psychology Press, East Sussex, UK, 2000.

[35] M.G. Zost, Diagnosis and management of visual dysfunction in cerebral injury, in: D.M. Maino (Ed.), Diagnosis and Management of Special Populations, OEP Foundation Press, Santa Ana, CA, 2001, pp. 75–134.