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Effect of oculomotor rehabilitation on accommodative responsivity in mild traumatic brain injury

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Abstract—Accommodative dysfunction is a common oculomotor sequelae of mild traumatic brain injury (mTBI). This study evaluated a range of dynamic (objective) and static (subjective) measures of accommodation in 12 nonstrabismic individuals with mTBI and near vision-related symptoms before and after oculomotor training (OMT) and placebo (P) training (6 wk, two sessions per week, 3 h of training each). Following OMT, the dynamics of accommodation improved markedly. Clinically, there was a significant increase in the maximum accommodative amplitude both monocularly and binocularly. In addition, the near vision symptoms reduced along with improved visual attention. None of the measures were found to change significantly following P training. These results provide evidence for a significant positive effect of the accommodatively based OMT on accommodative responsivity. Such improvement is suggestive of oculomotor learning, demonstrating considerable residual brain-visual system plasticity in the adult compromised brain.

Key words: accommodation, accommodative dysfunction, accommodative training, acquired brain injury, mild traumatic brain injury, neuroplasticity, oculomotor learning, oculomotor rehabilitation, traumatic brain injury, vision rehabilitation.

INTRODUCTION

Accommodation is the process whereby the crystalline lens changes its dioptric power to focus precisely and maintain the object of interest at the high-resolution fovea [1]. It is a complex neurological control process involving optical, sensory, motor, perceptual, cognitive, pharmacological, and biomechanical aspects. The accommodative system has four components [2–4]: blur-driven, or "reflex" accommodation; vergence accommodation; proximal accommodation; and tonic accommodation. These four components, along with modulation from the pupil, interact nonlinearly to produce the overall dynamic and static accommodative response profile, with disparity and blur being the two primary drives under normal binocular-viewing conditions in visually normal individuals [1,4–6].

Based on neurophysiological and anatomical experiments, the neural network of accommodation is quite extensive. Its pathway involves the following primary structures: retinal cones, optic nerve, lateral geniculate

Abbreviations: AA = amplitude of accommodation, AE = accommodative excess, AI = accommodative insufficiency, AS/R = accommodative stimulus/response, CISS = Convergence Insufficiency Symptom Survey, cpm = cycles per minute, D = diopter, DoD = Department of Defense, FEF = frontal eye field, MRI = magnetic resonance imaging, mTBI = mild traumatic brain injury, NPA = near point of accommodation, NRA = negative relative accommodation, OD = right eye, OMT = oculomotor training, OS = left eye, P = placebo, pons = pontis, PRA = positive relative accommodation, SEM = standard error of mean, SD = standard deviation, SS = steady-state, SUNY = State University of New York, TBI = traumatic brain injury, VSAT = Visual Search and Attention Test.

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nucleus, occipital lobe, posterior parietal cortex, frontal eye field (FEF), and the FEF sending projections via the internal capsule to the main oculomotor nucleus, as well as the parasympathetic accessory oculomotor nucleus (i.e., Edinger-Westphal nucleus) [1,7–9]. In addition, the rostral superior colliculus projects to the Edinger-Westphal nucleus via the primary, shorter route through the pretectum and also through a secondary, longer route through the nucleus reticularis tegmenti pontis (pons), cerebellar cortex, and cerebellar nuclei. In addition, the cerebellum has been demonstrated to act as a gain "calibrator" to optimize and maintain response accuracy, as well as to facilitate predictive tracking. Since the accommodative neural pathway is quite extensive, any injury to the multitude of brain and contiguous structures may adversely affect the accommodative system. Commonly associated with the rotational acceleration of the head, injuries involving the highly susceptible midbrain area, which houses accommodation-related neurons, could result in an accommodative dysfunction [10].

It is well established that due to the coup-contrecoup nature, and overall complexity and pervasiveness of a brain insult, traumatic brain injury (TBI) frequently results in a myriad of visual disturbances, including accommodative abnormalities [11–14]. However, there is a relative paucity of research that has investigated and confirmed the effect of TBI on accommodative function, especially in a comprehensive and objective manner. There were also study limitations in past studies [10–11,14–17].

Past studies have reported on three main categories of accommodative abnormality in the adult population with TBI. They are (1) accommodative insufficiency (AI), the most common finding; (2) accommodative excess (AE) or pseudomyopia; and (3) dynamic accommodative infacility. Accommodative function is usually defined and determined by the clinically assessed maximum amplitude of accommodation (AA). When this measure is significantly lower than the age-matched normal value [18], it is referred to as AI. Based on this criterion, 10 to 33 percent of the population with mild TBI (mTBI) was diagnosed with AI [10,15–17]. This has been confirmed in other studies [10,19–20].

In contrast to AI, AE has also been reported in patients with mTBI, but generally with less frequency [11]. In a sample of 161 patients with mTBI, 19 percent exhibited accommodatively based pseudomyopia [19]. In a recent retrospective study of 160 patients with mTBI, approximately 4 percent were clinically diagnosed with AE [10]. There have also been several case studies reporting the rare but significant and related development of persistent bilateral accommodative spasm in individuals with TBI [21–23]. Since these studies showed accommodative spasm bilaterally, it was suggestive of a central defect. Magnetic resonance imaging (MRI) findings of one patient showed lesions involving subcortical white matter consisting of left temporal lobe areas, periventricular region, cerebellar vermis, and dorsal pons, all of which are areas involved in accommodation. However, no lesions were detected in the midbrain [22].

The least studied accommodative deficit in TBI has been dynamic accommodative infacility. This is diagnosed when a patient exhibits a slowed accommodative response (i.e., reduced peak velocity) to a change in dioptric lens power or target distance, which can occur alone or in conjunction with either AI or AE [11]. The aforementioned retrospective study also found that approximately 4 percent of the 160 patients with mTBI were diagnosed with accommodative infacility [10]. This has also been reported in a recent case series in three patients with mTBI [24].

While many clinically based studies have evaluated accommodative function following TBI, as described previously, only one laboratory prospective study employed an objective assessment [14]. A range of dynamic and static parameters of accommodation were evaluated in 12 individuals with mTBI (mean age: 31 yr; 6 mo to 13 yr following TBI) and near vision symptoms (e.g., intermittent blur). All parameters were compared with 10 visually normal, age-matched individuals (mean age: 27 yr). Accommodative dynamics to a 2 diopter (D) step (2 D ↔ 4 D) accommodative stimulus measured using the WAM 5500 autorefractor (Grand Seiko; Hiroshima, Japan) revealed significantly decreased peak velocity for both increasing and decreasing steps of accommodation in the group with mTBI when compared with the normal group. This reduced peak velocity (~35% less) was associated with a significantly prolonged response time and a correlated increase in time constant for both increasing and decreasing steps of accommodation in the group with mTBI when compared with the normal group. No difference was observed in the accommodative response magnitude and steady-state (SS) response variability between the two groups. The global clinical analog of the laboratory-tested accommodative dynamics was assessed using accommodative flipper facility. Reduced accommodative facility was not found, despite the laboratory-based measures that revealed slowed dynamics in the group with mTBI. This discrepancy could be due to the power of the lens flipper

used. Powers of ±2.00 D are the clinic norm for testing accommodative facility [25]; in contrast, Green et al. used lower-powered ±1.00 D flipper lenses, because their subjects had a relatively wide age range (18–40 yr) [14]. With repeated testing, the group with mTBI exhibited a significantly reduced flipper rate, suggestive of accommodative fatigue. In addition, several static aspects of accommodation were assessed in their study, which were significantly reduced in the group with mTBI as compared with the normal group. AA was reduced by ~1.5 D under both monocular (6.5 D) and binocular (7.1 D) viewing conditions in comparison with Duane's mean age-matched value (8–9 D) [18]. Of the subjects, 50 percent exhibited reduced values for relative accommodation (positive relative accommodation [PRA] and negative relative accommodation [NRA]) and 50 percent had an abnormal accommodative convergence to accommodation ratio. Hence, subjects with mTBI in general exhibited slowed dynamics and overall reduced accommodative ability over a range of parameters.

There is a total lack of data on accommodatively based oculomotor training (OMT) in mTBI. While many clinical studies and case reports evaluated accommodative dysfunction diagnostically, therapeutic efficacy was not assessed comprehensively, although the findings were positive [24–25]. Based on the previously mentioned studies, it is clear that individuals with mTBI experience a wide spectrum of accommodative deficiencies that impinge and adversely affect their near work abilities and produce disturbing symptoms that reduce their overall quality of life. Thus, abundant evidence in the clinical vision literature supports the notion that targeted, specific, and repetitive programmed vision therapy procedures (i.e., motor learning) can remediate patients with accommodative and binocular vision disorders as a consequence of mTBI [25]. While evidence from clinical studies exists on the efficacy of accommodative training in the population with TBI [24–25], there is a total lack of data on laboratory-based objective recordings of accommodation in these individuals following OMT. Moreover, no study evaluated the effect of comprehensive oculomotor rehabilitation (involving vergence, version, and accommodation) on objective (dynamic/laboratory) and subjective (clinical/static/symptom-rating scale/subjective attention) measures of oculomotor and related parameters and their possible interactions.

Thus, the purpose of the current investigation was to evaluate the effect of accommodative training on key clinical and laboratory parameters in individuals with mTBI reporting near work symptoms before and after OMT performed in the clinic, purposely without a home-based component to assure consistency and control of the training. The training involved all three main oculomotor subsystems: vergence, accommodation, and version. All measures were compared after placebo (P) training. For the purpose of the present article, only the oculomotor subsystem of accommodation is considered.

METHODS

Subjects

Twelve adult subjects (8 females, 4 males) between the ages of 23 and 33 yr (mean ± standard deviation [SD]: 29 ± 3 yr) with documented mTBI, having an injury onset of >1 yr (1–10 yr postinjury) to avoid possible contamination from the natural recovery process [26], participated in the study. See **Table 1** for demographics. They all manifested several near work-related symptoms and at least one clinical sign reflecting accommodative dysfunction (e.g., reduced near point of accommodation [NPA] or reduced facility). All had stable general health and absence of any significant cognitive dysfunction. Sample size was calculated using a power analysis program (G*Power, Heinrich-Heine-Universität Düsseldorf; Düsseldorf, Germany) at an alpha level of 0.05 with a power set at 0.80 using two key parameters of accommodation (i.e., NPA and accommodative facility). Subjects were identified by their university-based healthcare provider and were recruited from the Raymond J. Greenwald Vision Rehabilitation Center at the State University of New York (SUNY) College of Optometry, University Optometric Center of New York. Each subject received a comprehensive vision examination at the Raymond J. Greenwald Vision Rehabilitation Center prior to participating in the experiment. The vision examination included detailed refractive, binocular/oculomotor, and ocular health assessment.

Study Design

A crossover, interventional experimental design of a single-blind nature (for the subject) was used. In this design, each subject acted as his or her own control, thus negating undesirable intersubject variability. Each subject received OMT (treatment A) and P training (treatment B). During phase 1, every odd-numbered subject first received treatment A and every even-numbered subject first received treatment B, and vice-versa during phase 2. This was an interventional study of 15 wk duration. It consisted of

Table 1.
Demographics of population with mild traumatic brain injury (mTBI).

Patient	Age (yr)	Age at mTBI (yr)	Etiology of mTBI	Visual Symptoms/Complaints
JM01	25	23	Head hit against metal rod	Slow reading, skipping lines.
TB02	27	22	Head hit with baseball bat	Intermittent diplopia, poor concentration, intermittent blur at near.
BR03	30	27	Assault	Eye strain, difficulty reading, poor focusing ability.
CR04	31	25	MVA	Eye strain, headache.
EK05	25	22	MVA	Difficulty performing computer work, eye strain.
KO06	24	22	Fall	Difficulty performing ophthalmoscopy, eye strain.
DB07	29	27	MVA	Intermittent blur, intermittent diplopia, difficulty reading, skipping lines, visual motion sensitivity.
AN08	28	27	Fall	Headache, near vision blur, intermittent diplopia.
DJ09	33	31	MVA	Blurry vision, intermittent diplopia, difficulty reading, peripheral visual motion sensitivity.
SR10	29	25	MVA	Headache, intermittent diplopia at near, trouble focusing at near, dry eye, hyperacusis, photosensitivity, eye strain.
AK11	33	31	Assault	Difficulty shifting focus, blur at near, loss of place while reading, visual fatigue, headache, nausea, loss of balance.
NM12	31	25	Fall	Intermittent diplopia, imbalance, difficulty reading.

MVA = motor vehicle accident.

12 wk of the two treatment phases, 6 wk each phase, separated by 1 wk, for a total of 9 h of OMT and 9 h of P training, 3 h for each oculomotor system (accommodation, vergence, and version). In addition, there was a 3 wk measurement period: 1 wk before phase 1 treatment, 1 wk after phase 1 treatment, and 1 wk after phase 2 treatment. During these testing and training periods, subjects did not perform any other oculomotor-based vision rehabilitation to avoid contamination of test results [27].

The study consisted of the following phases:

1. Week 1: Initial baseline measures. All evaluative procedures (described later) were recorded over two separate test sessions (each session lasting up to 1.5 h, including rest periods to prevent fatigue), each separated by at least 2 d.
2. Weeks 2–7: Phase 1 treatment. Six weeks of either OMT or P training. Subjects received two training sessions per week. Each session was 60 min in duration, involving 45 min of actual training with the remainder of the time consisting of short interspersed rest periods for the subject. Total training time was 9 h.
3. Week 8: Repeat baseline measures. Same as week 1.
4. Weeks 9–14: Phase 2 treatment. Six weeks of either OMT or P training (same as phase 1).
5. Week 15: Repeat baseline measures. Same as week 1.

Evaluative Procedures

The evaluative procedures included the clinically based subjective, laboratory-based objective, and subjective visual attention testing and a near vision symptom-related scale questionnaire. All clinical parameters were measured using standardized clinical techniques [28]. All laboratory-based objective measures were performed using commercially available instrumentation with well-established test protocols for version, accommodation, and vergence [14,29–30]. All measures were noninvasive and recorded with the subject's habitual distance refractive correction in place. The order of testing was randomized over the 2 d of measurements. For the purpose of this article, accommodative measures alone are described.

Clinical Measures

Several study-related, near vision-specific, selected binocular vision-related tests and related parameters were assessed under standard clinical room illumination (80 Lux). Testing sequence was randomized. It included NPA, NRA, PRA, and accommodative facility (using ±2.00 D flipper lenses). In addition, the WAM 5500 autorefractor was used to assess the accommodative stimulus/response (AS/R) function [1,14] to a high-contrast reduced Snellen chart stimuli monocularly in the right eye (OD); the left eye (OS) was fully occluded with a black eye patch. Subjects were instructed to focus on the 20/30 line. For

each stimulus/viewing condition, five measurements were obtained, and the average spherical equivalent (sphere + 1/2 cylinder value) was determined. The slope of the linear regression fit using stimuli and responses at each dioptric level provided the closed-loop accommodative gain value [31].

Laboratory Measures

First-order accommodative dynamics to 2 D increasing and decreasing step responses were obtained using the commercially available WAM 5500 objective, infrared, open-field autorefractor with a reported resolution of 0.01 D and approximately 5 Hz sampling rate [14]. This sampling rate is sufficient for acquiring valid accommodative dynamic responses based on the Nyquist criterion [32]. Subjects monocularly viewed a line of high-contrast 20/30 Snellen letters having a luminance of 36 cd/m^2 positioned at 2 D that were on a white background and a high-contrast 20/60 word with a luminance of 36 cd/m^2 at 4 D on a transparent background. The WAM 5500 autorefractor was aligned with the OD, as well as with both accommodative stimuli. Subjects received two or more practice trials before the actual testing. When instructed, the subject changed focus between the stimuli for 15 to 20 responses. Mean response amplitude (magnitude of response change), peak velocity (a point during the dynamic trajectory at which maximum change in response amplitude occurs over a specific time interval), time constant (the time for the exponential response to attain 63% of the final amplitude), SS response level (final SS response amplitude), and SS response variability (SD of the SS response level within the measured window of time) were calculated for both increasing and decreasing steps obtained from the OD [14].

Subjective Visual Attention Test

A subjective correlate of visual attention was assessed using the Visual Search and Attention Test (VSAT). It involves a search (for a letter or a symbol) and cancellation (cross-out) task that was developed by Trenerry et al. [33]. It assesses global sustained visual attention while scanning to search for selected letters or symbols. Test-retest reliability for the VSAT was 0.95. Calculated sensitivity and specificity were 0.88 and 0.86, respectively. The test was performed binocularly at the subject's habitual near work distance with correction. Following two practice trials, the actual test trial was performed. Percentile scores were calculated from the age-matched normative table for the two test sheets. This test is frequently used in the clinical optometric [34], medical [35], and neuropsychological domains [36].

Symptom Scale

Individual symptoms related to near work were rated by the subjects using the Convergence Insufficiency Symptom Survey (CISS), whose sensitivity (0.978) and specificity (0.87) have been already demonstrated [37]. The test-retest reliability was found to be 0.88. It is comprised of a 15-item questionnaire probing near reading-related symptoms, such as intermittent blur, diplopia, headache, skipping lines, and loss of concentration. The severity of symptoms is scaled from 0 to 4, i.e., from least symptomatic to most symptomatic. The total score was compared before and after each of the two training phases. A reduction in overall score of 10 or more was considered to reflect a significant reduction of symptoms. A score of 0 indicates being absolutely symptom-free, and a score of 60 represents maximal symptomatology. A score of 16 or lower is considered to represent being relatively asymptomatic.

Treatment Protocol

Treatment A: Oculomotor Training

The OMT was performed along the midline at 0.4 m, two sessions per week, for a total of 6 wk. Training was performed with constant verbal and visual feedback, motivation, repetition, and active participation of the subject to maximize attention. For the purpose of the present article, however, only the accommodative training and related results are discussed. See **Table 2** for the accommodative training protocol.

For step AA training, various magnitudes of positive and negative spherical lenses were used. The basic principle behind the training was to maintain the target vergence demand constant at 0.4 m (2.5 MA) and increase the accommodative demand [38]. The accommodative targets were texts of various sizes ranging from 20/60 to 20/20 presented on a computer screen at 0.4 m. As the treatment

Table 2.
Training protocol for accommodation.

Stimulus Parameter	Training Period Duration (min)	Total Training Duration (min)
Step Amplitude Right Eye ± Lenses	5	15
Step Amplitude Left Eye ± Lenses	5	
Step Facility (binocularly) ± Lenses	5	

progressed and the subject demonstrated improvement, the level of task difficulty was increased by reducing target size and increasing lens power. While the subjects monocularly fixated the target, lenses were introduced manually at 0.5 D increments in front of the eye. After introducing each lens, subjects were instructed to focus the text as rapidly as possible. The focused text was maintained for 15 to 20 s to train sustaining ability. Hence, the goal of the training was not only to achieve rapid focus but also to maintain the accommodative response with accuracy and comfort. Such response maintenance would reflect the accommodative adaptation mechanism [39]. Accommodation training with minus lenses to increase the accommodative response was terminated at the point at which subjects could no longer focus with their maximum effort. This was repeated with positive lenses to reduce the accommodative response. The order of positive and negative lens training, as well as the eye trained at each session, was randomized.

For step accommodative facility training, combinations of plus and minus lens flippers (±0.50, ±0.75, ±1.00, ±1.50, and ±2.00 D) were used while maintaining vergence constant at 0.4 m (2.5 MA). The accommodative targets were similar to those used in the amplitude training described previously. Based on the subject's ability to focus, the magnitude of the lens flipper power was chosen—the poorer the ability, the lower the initial lens power. Subjects bifixated targets on a computer screen and were instructed to fuse and focus as rapidly as possible and to achieve the maximum number of lens flipper cycles possible.

Treatment B: Placebo Training

Similar to OMT, P training was performed along the midline at 0.4 m, two sessions per week, for a total of 6 wk [27]. For the purpose of the present article, only the accommodative training and related results are discussed.

The P training did not involve any blur stimulation, because this is the primary drive for the accommodative system [1]. Plano powered/colored accommodative flipper step training was the P analog of the oculomotor accommodative flipper step training. This P training involved repetitive and systematic alternation of the flippers every 15 to 20 s monocularly and binocularly, without any spherical lens power changes (i.e., plano/colored lenses), while the subjects either read a text paragraph or watched a cartoon movie at 0.4 m on a computer screen, similar to that performed for OMT.

Data Acquisition and Analyses for Objective Recordings

The recorded files were saved as .csv files by the WAM 5500 autorefractor software. They were then transferred into Excel (Microsoft Corporation; Redmond, Washington) for detailed analyses. Three artifact-free (e.g., blink-free) increasing and three artifact-free decreasing accommodative responses were selected for analysis from the OD traces for each subject. There were approximately 7 to 10 increasing and 7 to 10 decreasing responses in total for each subject. Blinks were identified by 200 to 300 ms large deflections in the recordings and were discarded in the analysis. The middle three blink-free responses were used for analysis. An exponential decay function was fit to the dynamic trajectory, and the response amplitudes and time constants were obtained using GraphPad Prism software (GraphPad Software Inc; La Jolla, California). The goodness of fit was assessed from the r^2 values of each individual response fit. The mean r^2 value for both increasing and decreasing steps was greater than 0.8 for each subject. The peak velocities were derived from first-order differentiation of the exponential equation. The mean amplitude, time constant, peak velocity, mean SS response level, and SS response variability of the responses at baseline, post OMT, and post P training were compared statistically using GraphPad Prism software. For each subject, the mean for each parameter was calculated, then the overall group mean was computed [14].

STATISTICAL ANALYSES

Combined Group

The key objective of the study was to evaluate the effect of OMT in individuals with mTBI and oculomotor-based near vision symptoms. The main analyses included a comparison of baseline measures before and after OMT using paired two-tailed *t*-tests. Data from all 12 subjects were analyzed and presented as the combined group results. For subjects who received OMT first, baseline measures from week 1 (baseline) and baseline measures from week 8 (post OMT) were used for the analyses. For those subjects who received P training first, baseline measures from week 1 (baseline) and baseline measures from week 15 (post OMT) were used for analyses. For subgroup analyses, a repeated-measures, one-way analysis of variance and Tukey post hoc analyses were performed for comparisons between baseline, OMT, and P training. Correlations between relevant objective and subjective parameters were performed using linear regression. Furthermore, the effect

size was calculated using the G*Power software for the key parameters, which included binocular AA, binocular accommodative facility, and peak velocity for increasing step accommodation. Values greater than 0.5 were considered as having large effects of treatment.

Subgroup

See **Appendix** (available online only) for detailed subgroup analyses.

RESULTS

Combined Group Analysis

Laboratory-Based Objective Measures

The dynamic trajectories of the monocular step accommodative responses were fit using an exponential, one-phase decay function [14]. The dynamic parameters derived from the fit were compared before (baseline) and after completion of OMT (post OMT). There was a significant increase (~30%) in peak velocity for both increasing ($t(11) = 3.61$, $p = 0.01$, effect size = 0.6) and decreasing ($t(11) = 3.65$, $p = 0.01$) steps of accommodation following OMT (**Figure 1**). Concomitantly, there was a significant (and predicted) decrease (~40%) in the related time constant for both increasing ($t(11) = 4.17$, $p = 0.01$) and decreasing ($t(11) = 4.7$, $p = 0.01$) steps of accommodation (**Figure 2**). **Figure 3** presents unedited accommodative 2 D, objective step response traces in a typical subject with mTBI before and after OMT. Slowed dynamic trajectories were evident before training (see arrows) at baseline, which became significantly more rapid following OMT. This positive training effect is evident in **Figure 4**, which presents samples of the exponential fit of increasing and decreasing step accommodative response before and after OMT in the same subject. Faster motor responses were evident. See **Table 3** for the group mean (±1 standard error of mean [SEM]) values at baseline and post OMT. All four of the initially abnormal parameters improved significantly following OMT, although they did not normalize.

The other dynamic parameters did not change following OMT. This is attributed to the parameters already being normal at baseline; hence, no positive effect was anticipated. There was no significant difference in the response amplitudes for either increasing ($t(11) = 0.43$, $p = 0.67$) or decreasing ($t(11) = 0.75$, $p = 0.46$) steps of accommodation. Both the SS response dioptric level and the SS response variability did not differ significantly for either increasing ($t(11) = 0.55$, $p = 0.59$, and $t(11) = 1.31$, $p = 0.21$, respectively) or decreasing ($t(11) = 0.61$, $p = 0.54$, and $t(11) = 0.34$, $p = 0.74$, respectively) steps of accommodation after training.

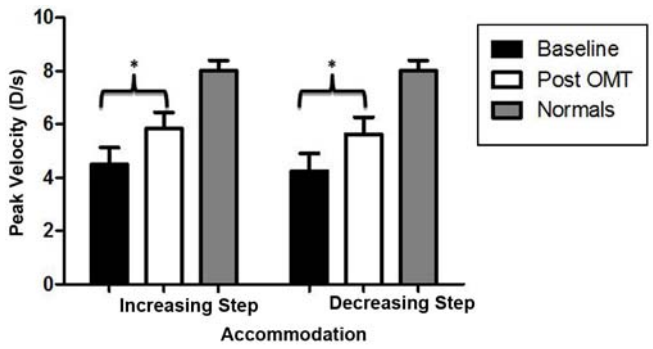

Figure 1.
Group mean peak velocity of accommodation before (baseline) and after oculomotor training (post OMT) in mild traumatic brain injury in comparison with normal. Error bars indicate +1 standard error of mean. *Significantly increased from baseline. D = diopter.

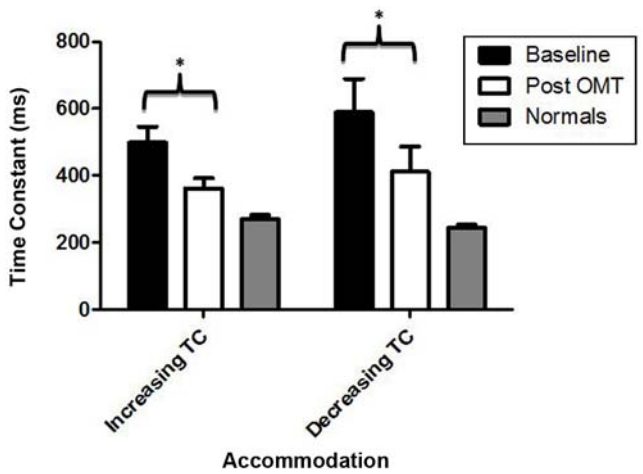

Figure 2.
Group mean time constant (TC) for accommodation before (baseline) and after oculomotor training (post OMT) in mild traumatic brain injury in comparison with normal. Error bars indicate +1 standard error of mean. *Significantly decreased from baseline.

Clinically Based Subjective Measures

All clinic parameters related to accommodation were compared before (baseline) and after OMT (post OMT). See **Table 4** for mean (±1 SEM) values at baseline and post

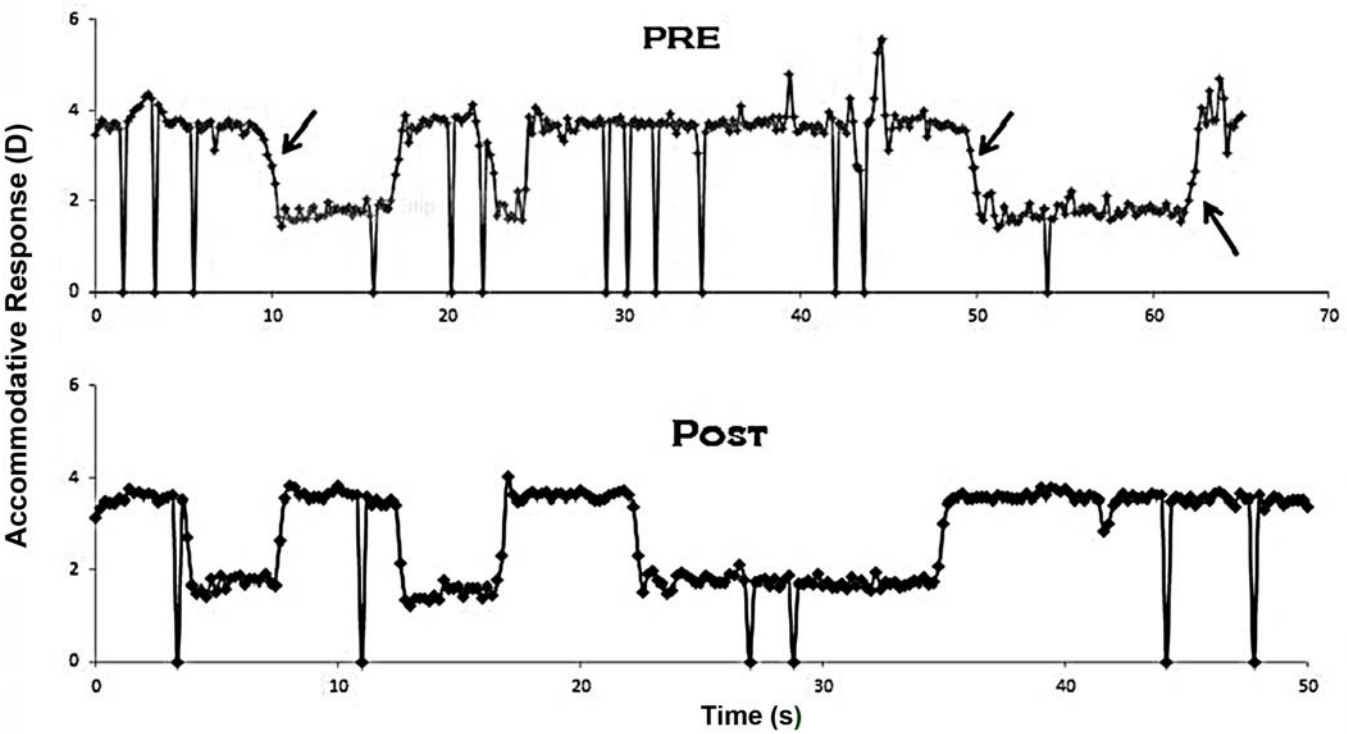

Figure 3.
Monocular accommodative responses as function of time. Unedited two-dimensional step accommodative traces in typical subject with mild traumatic brain injury before (pre) and after (post) oculomotor training. Large deflections represent blinks. Arrows denote slowed dynamic trajectory. D = diopter.

OMT. All six of the parameters that were abnormal at baseline improved significantly with OMT. There was a large and significant (~220%) increase in lens flipper accommodative facility both monocularly (OD: $t(11) = 6.24$, $p \leq 0.001$, and OS: $t(11) = 5.84$, $p = 0.01$) and binocularly ($t(11) = 4.87$, $p = 0.01$, effect size = 1.1) following OMT (**Figure 5**), and it normalized. Similarly, AA increased (~30%) significantly both monocularly (OD: $t(11) = 3.68$, $p = 0.01$, and OS: $t(11) = 4.07$, $p = 0.01$) and binocularly ($t(11) = 4.41$, $p = 0.01$, effect size = 1.1) with OMT (**Figure 6**), and it nearly normalized. The accommodative gain did not change significantly ($F(2,94) = 0.26$, $p = 0.76$) with OMT. Similarly, there was no significant difference in either the PRA ($t(11) = 1.35$, $p = 0.20$) or NRA ($t(11) = 1.38$, $p = 0.19$) values following OMT. However, the accommodative gain, NRA, and PRA values were already normal at baseline; hence, no positive training effect was anticipated.

Other Subjective Tests

The CISS total score significantly reduced ($t(11) = 3.69$, $p < 0.01$) from a mean value of 37 ± 4 to 28 ± 3 following OMT. This indicated a reduction in near vision-related symptoms following OMT. In addition, the increases in AA following training were also significantly correlated with reduction in symptoms, as evident from the decreased CISS score (**Figure 7**).

With respect to visual attention at baseline, and based on the age-matched norms, 4 of the 12 subjects were abnormal by scoring below the 2nd percentile [33]. In addition, one subject had borderline abnormality, and the remaining seven subjects scored in the normal range. Following OMT, however, the percentile scores for 10 of the 12 subjects (80%) increased. The group mean VSAT percentiles increased significantly ($t(11) = 4.43$, $p < 0.01$) from the 32nd (±9) to the 50th (±10) percentile following OMT. This indicated increased visual attentional aspects concurrent with OMT. However, the mean baseline value was already normal in the present study population. Lastly, the improved subjective attention based on the increased VSAT percentile correlated significantly with the increased AA following OMT (**Figure 8**).

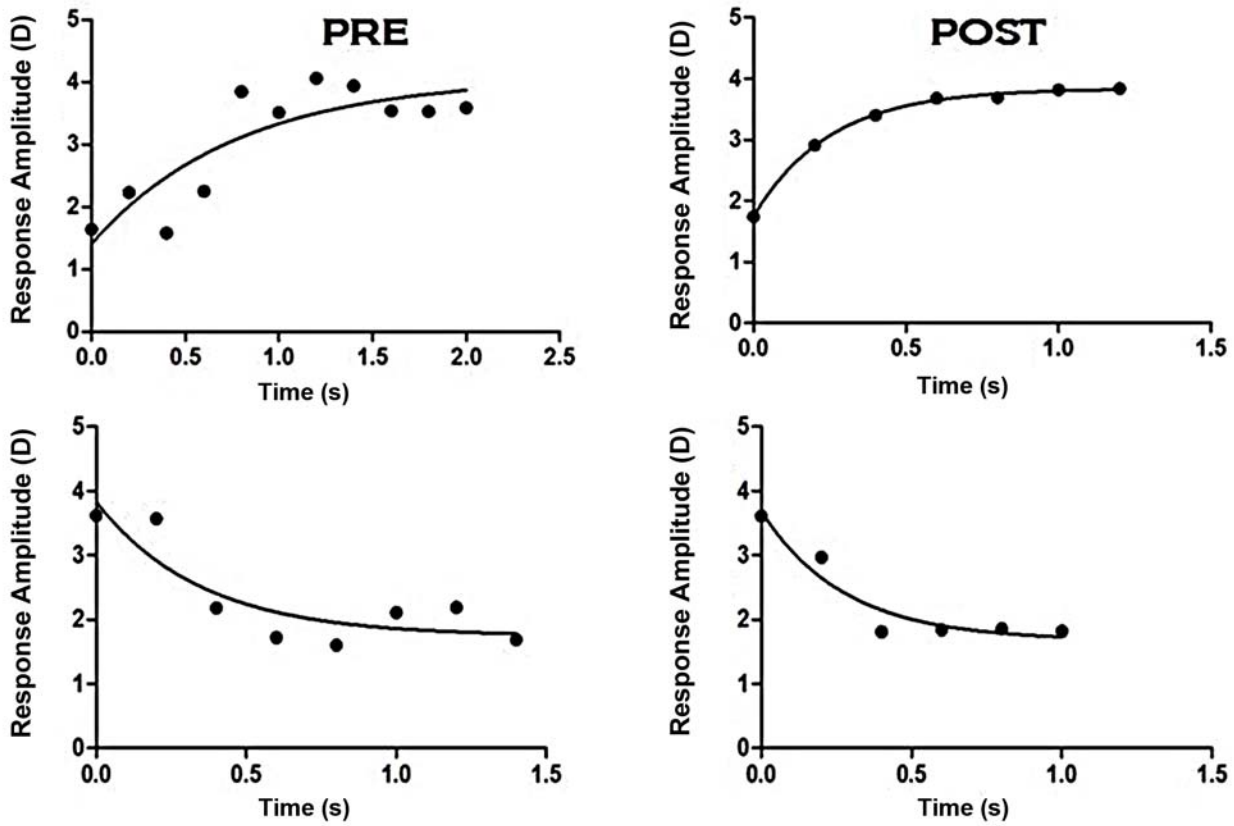

Figure 4.
Accommodative dynamic trajectory as function of time. Exponential fit of two-dimensional step accommodative dynamic trajectory before (left column) and after (right column) oculomotor training for increasing (top row) and decreasing (bottom row) step accommodation in typical subject with mild traumatic brain injury. D = diopter.

Subgroup Analysis

There was no statistically significant effect ($p > 0.05$) of P training on any accommodative parameters tested both clinically and laboratory-wise. See **Appendix** (available online only) for details.

DISCUSSION

The present study evaluated a wide range of dynamic and static measures of accommodation before and after accommodatively based OMT in individuals with mTBI who reported near work-related symptoms of an oculomotor nature following head trauma. With only 3 h of direct accommodative training per se distributed over 6 wk, marked improvements were found in several key dynamic and static behaviors of accommodation that were abnormal at baseline. Of the 10 laboratory parameters assessed, 4 were found to be abnormal at baseline, and all 4 improved significantly with OMT. Similarly, of the nine clinical parameters assessed, six were found to be abnormal at baseline, and all six improved significantly with OMT. Thus, the improvement rate was 100 percent. Such a high percentage of individuals with mTBI showing significant improvement in accommodation is remarkable given their ages and compromised brains. The results were also compared with an equal dosage of P training. None (0%) of the accommodative parameters were found to have a significant effect from the P training.

Training Effect on Accommodative Dynamics

At baseline, the dynamic trajectory for both increasing and decreasing steps of accommodation exhibited slowed responsivity. This was evident from the reduced peak velocities along with the correlated increased time

Table 3.
Mean ± 1 standard error of mean values of laboratory-based objective parameters for monocular steps of accommodation before (baseline) and after oculomotor training (post OMT).

Dynamic Parameter	Baseline	Post OMT	*p*-Value
Peak Velocity (D/s)			
Increasing Step	4.5 ± 0.6	5.8 ± 0.6	<0.01*
Decreasing Step	4.2 ± 0.7	5.6 ± 0.6	<0.01*
Time Constant (ms)			
Increasing Step	499 ± 47	362 ± 31	<0.01*
Decreasing Step	589 ± 99	412 ± 75	<0.01*
Steady-State Response Level (D)			
Increasing Step	3.42 ± 0.10†	3.46 ± 0.10	0.59
Decreasing Step	1.74 ± 0.08†	1.79 ± 0.07	0.54
Steady-State Variability (D)			
Increasing Step	0.14 ± 0.02†	0.11 ± 0.01	0.21
Decreasing Step	0.11 ± 0.01†	0.10 ± 0.01	0.74
Response Amplitude (D)			
Increasing Step	1.94 ± 0.13†	1.91 ± 0.08	0.67
Decreasing Step	1.88 ± 0.10†	1.83 ± 0.08	0.46

*Statistically significant.
†Normal at baseline.
D = diopter.

Table 4.
Mean ± 1 standard error of mean clinically based subjective parameters of accommodation before (baseline) and after oculomotor training (post OMT).

Clinical Parameter	Baseline	Post OMT	*p*-Value
Amplitude of Accommodation (D)			
OD	6.2 ± 0.6	7.9 ± 0.5	<0.01*
OS	5.9 ± 0.6	7.9 ± 0.5	<0.01*
OU	6.9 ± 0.6	8.8 ± 0.5	<0.01*
Accommodative Facility (cpm)			
OD	5 ± 1.0	11 ± 2.0	<0.01*
OS	5 ± 1.0	11 ± 2.0	<0.01*
OU	5 ± 1.5	11 ± 2.0	<0.01*
Positive Relative Accommodation (D)	2.5 ± 0.4†	3.1 ± 0.3	0.20
Negative Relative Accommodation (D)	2.1 ± 0.2†	2.3 ± 0.1	0.19
Accommodative Gain	0.86 ± 0.13†	0.88 ± 0.10	0.76

*Statistically significant.
†Normal at baseline.
cpm = cycles per minute, D = diopter, OD = right eye, OS = left eye, OU = both eyes.

constant values. The group mean peak velocity (~4.4 D/s) at baseline was ~40 percent less than that found in normal individuals (8 D/s) for the same stimulus amplitude (i.e., 2 D) [14,40–41] for both increasing and decreasing steps of accommodation. Following OMT, there was a significant increase in peak velocity by ~30 percent from the baseline value for both increasing and decreasing steps of accommodation, although peak velocity did not normalize (**Figure 1**). Subjects now attained their SS response level more rapidly. Concomitantly, the time constant exhibited a correlated significant decrease (**Figure 2**). These two dynamic parameter changes were correlated for both increasing and decreasing steps of accommodation, as one might expect due to their inverse nature [1].

The lens flipper facility rate is the clinical analog for the overall laboratory-based response, thus incorporating and effectively combining all dynamic parameters (i.e., peak velocity, time constant, and latency) into a single, global, validated metric [38,42]. Based on the mean normative values [43] for monocular (11 cycles per minute [cpm]) and

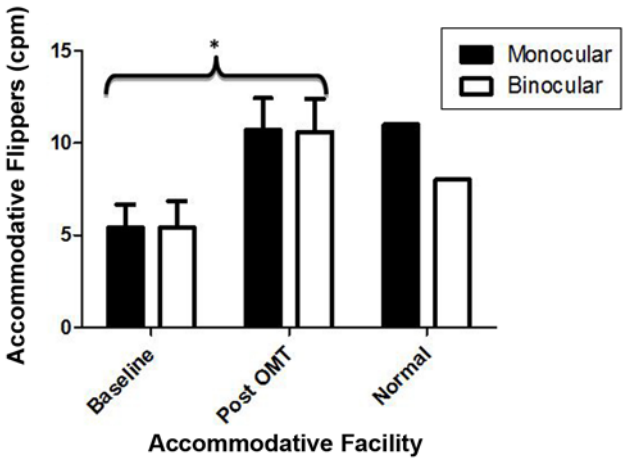

Figure 5.
Group mean accommodative facility before (baseline) and after oculomotor training (post OMT) in mild traumatic brain injury in comparison with expected clinic norm for monocular and binocular accommodative facility. Error bars indicate +1 standard error of mean. *Significantly increased from baseline. cpm = cycles per minute.

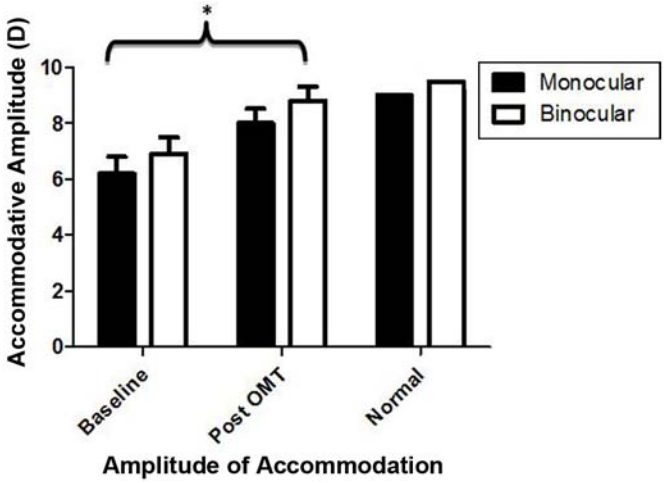

Figure 6.
Group mean amplitude of accommodation before (baseline) and after oculomotor training (post OMT) training in mild traumatic brain injury in comparison with Duane's age-matched normal values for monocular and binocular accommodation [18]. Error bars indicate +1 standard error of mean. *Significantly increased from baseline. D = diopter.

binocular (8 cpm) accommodative facility values at baseline, the rates were found to be ~40 percent less in individuals with mTBI. Following OMT, subjects could perform the

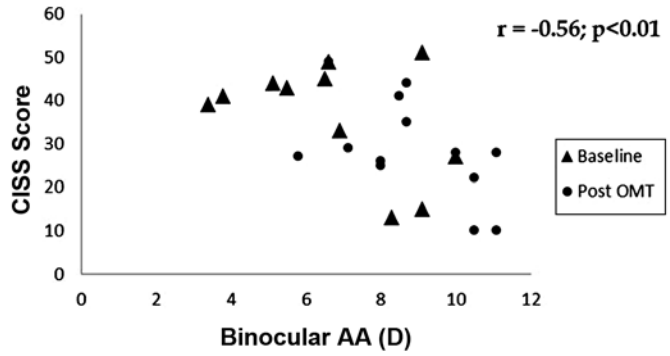

Figure 7.
Correlation of Convergence Insufficiency Symptom Survey (CISS) score and binocular amplitude of accommodation (AA) showing significant decrease in CISS score with significant increase in AA. D = diopter, OMT = oculomotor training.

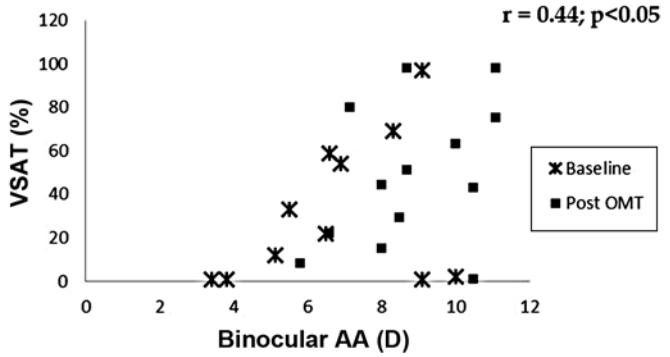

Figure 8.
Correlation of Visual Search and Attention Test (VSAT) percentile and binocular amplitude of accommodation (AA) showing significant increase in VSAT percentile with significant increase in AA. D = diopter, OMT = oculomotor training.

task (±2.00 D lens flipper) more rapidly, with a large and significant twofold increase in the facility rates both monocularly and binocularly. The accommodative facility rates normalized following training (**Figure 5**).

Both before and after OMT, the accommodative response amplitudes for increasing and decreasing steps of accommodation were accurate (i.e., within the estimated depth of focus) but significantly slower before OMT. This finding of accuracy suggested the presence of normal visual feedback with respect to blur detection and processing [31]. This was confirmed from the normal accommodative (closed-loop) gain values found in these individuals

as measured from the AS/R function [44]. The mean SS response level and SS variability values were within normal limits at baseline, and they did not change with OMT for either increasing or decreasing steps of accommodation. Since the response amplitudes remained unaltered with training, the observed changes in dynamic responsivity can be attributed to an increase in the pulse and not the step neural signal [45–46] (discussed later).

Training Effect on Static Measures of Accommodation

The NPA (i.e., AA) is the main static diagnostic parameter used in the clinic for assessment of accommodative dysfunctions. It denotes the maximum accommodation that can be exerted by the ciliary muscle on the crystalline lens. It is one of the most frequently found abnormal accommodative parameters in mTBI [10,13–14,25,47]. While a reduced monocular AA is attributed solely to an accommodative disorder, a reduced binocular AA may be due to a combination of both accommodative (i.e., blur-driven accommodation) and vergence (i.e., disparity-driven accommodation) dysfunction [38]. Based on Duane's age-matched data for AA [18], individuals with mTBI in the present study exhibited reduced amplitudes at baseline both monocularly and binocularly, on average by 33 and 28 percent, respectively. Following OMT, the AA increased significantly by ~28 percent from baseline value under both monocular and binocular conditions. While subjects attained 89 percent of the expected norm monocularly, it completely normalized binocularly (93%) (**Figure 6**). Thus, the improvements demonstrate a large increase in the magnitude of the patient with mTBI's maximum accommodative ability. Neurophysiologically, one may speculate that this improvement in maximum amplitude reflects an increase in neuronal firing (through recruitment) and/or better synchronization of the accommodatively based midbrain and related neurons [48–49]. A recent pilot study has shown increased activity in the brain stem area following improved convergence amplitude subsequent to vergence training assessed using the functional MRI technique [49]. We speculate a similar neurophysiological underpinning for the improved AA, because accommodation and vergence share strong cross-coupling. In addition, an increase in AA was also significantly correlated with reduction in symptoms, as evident from the decreased CISS score (**Figure 7**), as well as improved subjective attention from the increased VSAT percentile scores (**Figure 8**).

The training did not have an effect on the relative AAs (NRA and PRA). Under the noncongruent test condition [50], where vergence was maintained constant at 0.4 m and the accommodative demand was systematically altered using minus and plus lenses, the relative AAs were found to be normal at baseline; hence, no changes with training were expected.

In Relation to Previous Literature

The present study results provide the first objectively based data demonstrating the positive effect of OMT on accommodative responsivity in individuals with mTBI. Reduction of accommodative responsivity (e.g., decreased peak velocity) found at baseline in the present study was consistent with the findings of Green et al., who reported similarly slowed dynamic behavior for both increasing and decreasing steps of accommodation in individuals with mTBI [14]. The normal response amplitudes and SS response variability found in the present study were also consistent with their findings. In contrast, the reduced lens flipper facility rates (monocular and binocular) found in the present study at baseline were not reported in the previous prospective study in the population with mTBI [14]. They did not find a significant difference between the normal and mTBI groups. However, Green et al. used ±1.00 D flipper lens to test accommodative facility [14], while the present study used a much higher dioptric demand level of ±2.00 D flipper lens, which is the clinical norm to diagnose accommodative dysfunctions [38]. It is therefore important for clinicians to use ±2.00 D flipper lens to assess accommodative infacility, which can be left undiagnosed when tested with such low-powered lenses, or perhaps use age-based lens flipper norms [38]. To support the present study findings, Ciuffreda et al. found accommodative infacility in the population with mTBI retrospectively (~4%) using the ±2.00 D lens flipper [10].

Several of the static accommodative findings assessed at baseline were consistent with some earlier clinical reports [10,15–17,19]. As discussed in the "Introduction" section, the most common finding was AI. Although infrequently reported, a few studies have reported AE (or spasm) [21–23]. The present study did not find such accommodative behavior in the individuals evaluated, likely due to its extreme rarity.

While the maximum AA was markedly reduced at baseline, gain of the accommodative system was normal within the tested range (2–5 D), both before and after training, as deduced by the slope of the AS/R function, which directly reflects the system's closed-loop gain [31,44]. This finding confirms Green et al. [14], who

reported similar normal gain values in subjects with mTBI (0.8) and normal subjects (0.87). Training expanded the upper level of the linear and nonlinear zones of accommodation of the AS/R function [1,10], as evident from the increased AA. While similar gain values were obtained within the measured linear range (2–5 D), the OMT extended the zone of the focusable region beyond 5 D. Increase in the AA by ~2 D subsequent to the OMT confirmed the retrospective clinical findings of Ciuffreda et al. [25] and the clinical cases by Scheiman and Gallaway that also found improvement in AA following OMT [24].

From the present findings as well as from previous studies that assessed dynamic and static parameters of accommodation, it is apparent that the dynamic laboratory-based peak velocity and the clinically based dynamic lens flipper facility, along with the static clinically based AA, are the *key* parameters in the population with mTBI to diagnose accommodative dysfunctions [10,14–17,47]. While such a finding is also possible in other non-mTBI-based accommodative dysfunctions (i.e., AI), detailed case history will specify the etiology of the anomaly. Although treating the population with mTBI for accommodative and/or binocular vision disorders using conventional OMT procedures might be challenging given the complexity of more general factors [51], such as fatigue, chronic headache, memory deficits, and physical ailments, as well as other non-oculomotor-based vision problems, such as visual field defects and photosensitivity, a considerable degree of oculomotor-based treatment effect has been reported in this population, as described previously. Improvement in the critical parameters of accommodation, such as AA, along with significant reduction in the near vision-related symptoms, is suggestive of considerable and pervasive treatment effect in individuals with mTBI. The findings of the present investigation, along with the aforementioned studies, support the notion that targeted, specific, repetitive, programmed therapy procedures can remediate via oculomotor learning (discussed later) a range of accommodative and binocular vision disorders occurring as a consequence of the mTBI. Symptoms were ameliorated along with concurrent normalization of clinical signs, as well as subjective visual attention, in the present study.

Neurophysiological Implications

The neural control mechanism of accommodation has been postulated to be similar to the saccadic [52] and vergence [53] systems. The final neural signal for accommodation is proposed to consist of a small pulse/phasic signal and a step/tonic signal [45–46]. While the pulse controls the velocity of the accommodative response, the step controls the final accommodative SS response level. While height of the pulse signal determines the peak velocity, height of the step signal determines the final SS dioptric level. Evidence from nonhuman primate studies suggests that although the midbrain (e.g., supra oculomotor area) houses a majority of near response neurons, several other areas, such as FEF, cerebellar nucleus, and pons, to name a few, consist of neurons that also fire during accommodation [48,54]. Cells in these areas contain both phasic and tonic cells that fire in relation to velocity and position, respectively.

Based on the results of the present investigation at baseline and earlier studies [14], the primary neural deficit in the patient with mTBI is believed to be the pulse component. This can account for the reduced peak velocity and related increased time constant at baseline. Reduction in pulse height is speculated to be derived from a combination of decreased firing rate of the phasic (burst) cells and a reduced number of phasic cells, possibly resulting from shearing of axons following TBI. Since the appropriate accommodative response level was eventually attained, this suggests that the step component had the appropriate mean height. Following OMT, one may speculate that the increase in peak velocity was because of an increase in pulse height (presumably because of the increased firing rate) as a result of oculomotor learning and neuroplasticity (discussed later), thus resulting in faster motor responsivity to attain the final SS position. Unlike vergence [49], there is no study in the literature that monitored cortical activity related to accommodative training in humans with mTBI. Although vergence training alone [49] can indirectly influence and possibly train accommodation indirectly via the vergence-accommodation cross-link [55–56], a discrete neuroimaging study involving accommodation only before and after OMT is critical in humans.

Neuroplasticity and Oculomotor Learning Effects

Basic learning is comprised of repeated stimulation of a particular task, which initially comprises a trial-and-error mechanism and eventually becomes an associated learning process. This automaticity is achieved through increase in synaptic number and strength, and it is referred to as Hebbian learning [57–59]. The process of learning a new task not only involves functional and behavioral changes due to repeated practice, but it also

includes a spectrum of underlying mechanisms, such as biochemical and cellular changes, as well as structural changes including increased synapse number, firing rate, increased axonal/dendritic arborization, etc. [58]. While neuroplasticity in response to an external stimulus is common in a normal brain, these mechanisms have also been identified in the relearning process following an insult to the brain [58]. It is central to the recovery process independent of the time duration elapsed after the injury. Regaining functional loss following TBI could be either through a natural recovery process, where neurotransmission is restored in the adjacent spared location, or through retraining. Retraining involves functional recovery through relearning a particular task that was compromised following an injury, and thus forms the basis for any type of neurorehabilitation. This is achieved through restoring activity in spared brain areas within the affected region that were inactive due to disuse, and now through recruiting new regions remote from the injury site that have similar functional abilities but did not contribute predominantly before the injury.

With regard to the present study, following TBI, a global type of injury resulting in a diffuse axonal injury could compromise white matter integrity [60], thus resulting in slowed responsivity (e.g., slowed accommodation). The presumed decreased number of synapses, reduced firing rate, reduced synchrony, and/or lack of correlation within and across the specific brain regions may cause loss of automaticity, and hence an overall reduction in the system's maximum amplitude (e.g., NPA), as found at baseline [27]. Accommodatively based vision rehabilitation acts to regain accommodative function through repeated stimulation with different magnitudes of blur over a period of time (e.g., several weeks). A combination of repeated stimulation with these various amounts and types of blur (negative and positive), increasing task level difficulty (e.g., progressively reducing target size), active participation of the subjects with high attention, presence of visual and verbal feedback, sensitized visual feedback related to the blur (i.e., perceptual learning) [61], and high motivation of the subjects to perform the task over the training period resulted in a significant OMT effect and relearning process.

Study Limitations

The study had some potential limitations. First, accommodative ramp (i.e., slow constant velocity) responses were not evaluated. This should be performed to assess both of these key control aspects of accommodation, per models of the vergence system [62]. Second, due to technical constraints, latency for accommodation was not assessed in the present study. This information would have provided insight regarding possible sensory information processing delays, especially given the fact that blunt trauma affects brain areas diffusely. Last, evaluation of accommodative dynamics under binocular viewing conditions would provide additional insight into the influence of vergence and its training on the overall accommodative dynamic behavior.

Future Directions

The present study evaluated the global aspects of OMT on several critical parameters of accommodation, along with vergence and version. There is a paucity of data on the neurological correlates of OMT that results in functional changes. Hence, functional and structural brain imaging studies are critical to assess for correlation with the behavioral changes, and then to use this information to plan for future targeted treatment accordingly. Persistence of the treatment effect is still an ongoing evaluation. All subjects are being reevaluated at 3 and 6 mo after the completion of training, and this will be the topic of a future publication. Based on the results from these follow-up studies, future therapies will be planned to improve and retain their oculomotor function and reduce symptoms even further. While it might be challenging to restore complete normalcy in these individuals, the current level of improvement attained was appreciated by the subjects. Future studies should be conducted to assess whether additional OMT would result in greater levels of normalcy or whether the possibility is limited by the underlying neural damage to the brain. Long-term training distributed over 6 to 12 mo intervals may be necessary to maintain the initial improvements (booster therapies). Last, investigations should be extended in a larger sample size and more diverse group (e.g., moderate TBI) to generalize the treatment effects, and longer follow-up (1–5 yr) may be necessary.

CONCLUSIONS

Oculomotor rehabilitation was effective in individuals with mTBI who reported near work-related symptoms of an oculomotor basis. An overall improvement in nearly all of the critical, abnormal parameters of accommodation was observed both objectively and subjectively following OMT. Improved oculomotor behavior was

attributed to effective oculomotor learning effects in these individuals.

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Study concept and design: P. Thiagarajan, K. J. Ciuffreda.
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Analysis and interpretation of data: P. Thiagarajan, K. J. Ciuffreda.
Drafting of manuscript: P. Thiagarajan, K. J. Ciuffreda.
Critical revision of manuscript for important intellectual content: P. Thiagarajan, K. J. Ciuffreda.
Statistical analysis: P. Thiagarajan.
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Study supervision: K. J. Ciuffreda.
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Participant Follow-Up: We do not plan to inform participants of the publication of this study. However, they have been encouraged to check PubMed (http://www.ncbi.nlm.nih.gov/pubmed) for study publications.

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