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Accommodation in mild traumatic brain injury

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Abstract—Accommodative dysfunction in individuals with mild traumatic brain injury (mTBI) can have a negative impact on quality of life, functional abilities, and rehabilitative progress. In this study, we used a range of dynamic and static objective laboratory and clinical measurements of accommodation to assess 12 adult patients (ages 18–40 years) with mTBI. The results were compared with either 10 control subjects with no visual impairment or normative literature values where available. Regarding the dynamic parameters, responses in those with mTBI were slowed and exhibited fatigue effects. With respect to static parameters, reduced accommodative amplitude and abnormal accommodative interactions were found in those with mTBI. These results provide further evidence for the substantial impact of mTBI on accommodative function. These findings suggest that a range of accommodative tests should be included in the comprehensive vision examination of individuals with mTBI.

Key words: accommodation, accommodative dysfunction, brain injury, head injury, rehabilitation, TBI, traumatic brain injury, vision, vision rehabilitation, visual dysfunction.

INTRODUCTION

Accommodation refers to the change in shape and curvature of the crystalline lens of the eye that occurs when an individual attempts to obtain and maintain a focused, high-resolution retinal image of an object of regard [1], including changing focus from far-to-near and near-to-far. There are four components of accommodation [1–2]. Blur-driven, or reflex, accommodation likely provides a large contribution to the overall accommodative response. Blur-driven accommodation involves the typically automatic focusing ability when one changes fixation from one object to another in depth in response to the correlated blurred retinal image. Vergence accommodation refers to that accommodation driven by the neurological crosslink from fusional (i.e., disparity) vergence to accommodation per the convergence accommodation-to-convergence ratio. Vergence accommodation also provides a large contribution to the overall accommodative response. Proximal accommodation is that component of accommodation due to knowledge of the apparent/perceived nearness of an object in one's surround. Lastly, tonic accommodation refers to the default accommodative response in the absence of blur, disparity, and proximal stimuli. Tonic accommodation is commonly thought to result from baseline neural input from dual innervation of the ciliary muscle, namely the parasympathetic

Abbreviations: AC/A = accommodative convergence-to-accommodation, ANOVA = analysis of variance, AS/R = accommodative stimulus/response, CL = confidence limit, D = diopter, mTBI = mild traumatic brain injury, NRA = negative relative accommodation, PD = prism diopter, PRA = positive relative accommodation, SD = standard deviation, SEM = standard error of the mean, SUNY = The State University of New York, TBI = traumatic brain injury.

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and sympathetic systems [3–4]. These latter two components provide only a small contribution to the overall accommodative response under normal viewing conditions [5]. The four components interact nonlinearly to produce the overall dynamic and static accommodative response [5].

Neural Pathways of Accommodation

Based on human and, to a lesser extent, nonhuman primate studies, **Figure 1** presents a brief summary of the neural pathway of the blur-driven aspect of the accommodative system. Since the accommodative neural pathway is extensive, any injury to the multitude of brain and contiguous neural structures may adversely affect the accommodative system.

Previous Literature on Accommodation in Mild Traumatic Brain Injury

The previous literature has revealed three types of accommodative dysfunctions in traumatic brain injury (TBI): accommodative insufficiency, pseudomyopia/spasm of accommodation, and dynamic accommodative infacility.

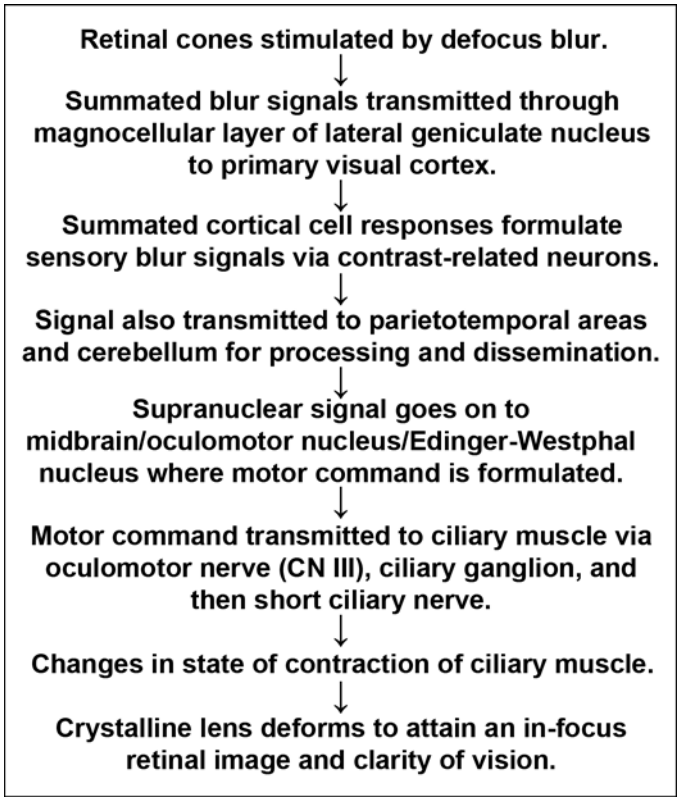

Figure 1.
Sensory and motor pathway for monocular blur-driven accommodation.
CN = cranial nerve.

Many of the earlier studies employed accommodative amplitude as the primary or sole index of accommodative dysfunction. Patients manifesting decreased accommodative amplitude are clinically diagnosed with accommodative insufficiency [6–7]. Three prospective studies [8–10] and one retrospective study [11] reported that approximately 10 to 40 percent of mild TBI (mTBI) patients exhibited accommodative insufficiency. Another study found that 16 percent of a sample of 161 nonpresbyopic head injury patients manifested accommodative insufficiency, which the authors termed "poor accommodation" [12]. This accommodative insufficiency was based on the following diagnostic criteria: the patient was under 35 years of age and complained of blur at near that was reduced with the addition of plus lenses; furthermore, the insufficiency was confirmed with the measurement of a reduced accommodative amplitude and/or positive relative accommodation (PRA) [12]. With regard to whiplash injuries, which can be conceptualized as an "indirect," and perhaps very mild, form of TBI [13], several studies found that approximately 18 to 33 percent of whiplash patients exhibited reduced accommodative amplitude [14–15], while another study showed statistically significant differences (i.e., reduction) in accommodative amplitude between 19 whiplash patients and 43 control subjects using the minus-lens test method [16]. Lastly, a case study reported on a 20-year-old male patient with TBI who exhibited a persistent inability to accommodate in one eye 3 years after the injury [17]. Additionally, the patient manifested a markedly reduced accommodative convergence-to-accommodation (AC/A) ratio (1.33:1) that returned to normal (3:1) without treatment 18 months after the injury [17].

Although accommodative insufficiency has been the most common accommodative abnormality studied in TBI [11], several authors have reported overaccommodation, also termed accommodative excess, pseudomyopia, or even frank "accommodative spasm" [6]. In a sample of 161 nonpresbyopic head injury patients, 19 percent exhibited pseudomyopia [12]. This pseudomyopia was diagnosed if the patient reported blur at distance that could be corrected with minus lenses when the patient had no previous history of such a prescription and, furthermore, if a cycloplegic refraction elicited either emmetropia, low hyperopia, or significantly less myopia

[12]. In a recent retrospective study of 160 mTBI patients, Ciuffreda et al. found that approximately 4 percent were clinically diagnosed with accommodative excess [11], with 41 percent having some type of clinically documented accommodative dysfunction. Several case studies have also reported the rare but significant development of persistent accommodative spasm in individuals with TBI [18–20]. These spasms often persisted 7 to 10 years despite long-term use of cycloplegic eye drops, such as atropine, to combat the accommodative spasm.

The least-studied accommodative effect in TBI has been dynamic accommodative infacility, which is diagnosed when a patient exhibits a slowed accommodative response to a change in either dioptric lens power or target distance that can occur either alone or in conjunction with either accommodative insufficiency or excess [6]. Ciuffreda et al. also found that approximately 4 percent of 160 mTBI patients were diagnosed with accommodative infacility [11]. This accommodative infacility has also been reported in a recent case series of mTBI patients [21].

Accommodative vision rehabilitation (i.e., vision therapy) has been successfully performed in adult patients with brain injury. In an extension of Ciuffreda et al.'s study [11], 33 of the 160 mild TBI patients received optometric vision rehabilitation [22–23], with 30 of them (90%) improving markedly in at least one sign and one symptom [24]. Another study dealing with optometric vision rehabilitation tracked the improvement of eight patients with mTBI [21]. Five of the patients exhibited accommodative dysfunctions, with all five manifesting reduced accommodative amplitude and two exhibiting slowed accommodative facility [21]. Both patients with accommodative infacility improved significantly, and four of the five with reduced accommodative amplitude resolved as well. In addition, the use of moderately powered plus single-vision spectacle lenses (e.g., +1.00 diopter [D]) at near has been found to reduce the accommodative demand and, in turn, lessen near symptoms [25]. Such spectacle lenses may be prescribed in isolation or, more typically, in conjunction with accommodative vision rehabilitation.

The purpose of the current study was to investigate a wide range of static and dynamic aspects of accommodation in visually symptomatic patients with mTBI. Only with such a wide and relatively comprehensive range of accommodative parameters can one fully understand the system and its interactions, as well as relate these measures to the patient's symptoms, with an aim of more focused and targeted therapeutic intervention.

Static parameters included push-up and minus-lens accommodative amplitude, relative accommodative ranges (PRA/negative relative accommodation [NRA]), accommodative stimulus/response (AS/R) function, AC/A ratio, near heterophoria, and tonic accommodation (see **Appendix** for ophthalmic glossary, available online only). None of the previous studies assessed all of these accommodative functions in the same patient population, and in addition, some of these parameters have never been studied in this population. Furthermore, a novel approach of this study was the incorporation of a series of dynamic measures of accommodative function.

METHODS

Subjects

The patient population was composed of 12 individuals with near vision symptoms and a well-documented history of mTBI. All received a comprehensive vision examination including refractive status, binocular assessment, and ocular health appraisal at the Raymond J. Greenwald Rehabilitation Center at The State University of New York (SUNY)/State College of Optometry. Included in the vision assessment were monocular and binocular visual acuity (distance and near), refractive status (distance and near), binocular sensorimotor state, oculomotor function (near), color-vision testing, and ocular health (including dilated fundus examination, ophthalmoscopy, biomicroscopy, applanation tonometry, and automated visual fields). Subjects ranged from 18 to 40 years of age, with a mean ± standard deviation (SD) age of 31 ± 7. Three were males, and nine were females. Ten of the twelve subjects had blunt head injury; thus, the group was relatively homogeneous. All had 20/25 or better corrected visual acuity at distance and near. See **Table 1** for patient demographics and vision characteristics.

The visually normal control group was composed of 10 individuals from the student and staff populations of SUNY/State College of Optometry. All had 20/20 or better corrected visual acuity at distance and near. None had a history or diagnosis of either TBI or accommodative or vergence dysfunction. Ages ranged from 22 to 35 years, with a mean ± SD age of 27 ± 4.5. The mean age of this group was not significantly different from the mTBI group (t-test, $p < 0.05$). Three were males, and seven were females.

Table 1.
Demographic data for 12 subjects with mild traumatic brain injury (TBI).

Subject	Age (yr)	Age at First TBI (yr)	No. of TBIs	Etiology of TBI	Current Medication	Refractive Correction (D)/ (Visual Acuity)	Symptom/ Complaint	Current/Prior Vision Therapy (VT)
TBI-A1	26	21	1	MVA.	Lamictal, TheraTears 1% gel.	OD: +2.00 –0.75 × 10; OS: +1.50 –0.50 × 155 (20/20).	OD blur, eyestrain/ fatigue, photosensitivity, reading-related difficulty (comprehension & losing place), dry eye, headaches, & poor balance.	None.
TBI-A2	40	27	3	Alcohol/pills overdose (1994); MVA (2004); fall (2004).	Benadryl, Proventil, Singulair, Allegra, Claritin, Celebrex, simvastatin, two unknown urology & constipation drugs because of baclofen pump.	OD: –1.50 –1.00 × 90; OS: –1.75 –1.00 × 95 (20/25).	Occasional diplopia (near & far), eyestrain, blur, dry eye, photosensitivity, dizziness, decreased concentration, memory lapses/ impairment, & poor balance.	None.
TBI-A3	34	34	1	MVA.	Levothyroxine sodium 88 mg, verapamil HCl 240 mg, metoprolol succinate 200 mg, spironolactone 50 mg, Glumetza 500 mg, isometheptene-APAP-dichloral, Nasonex 50 mg, Albuterol, Allegra, Ambien, Neurontin, Ritalin.	OD: –3.25; OS: –3.50 (20/25).	Headaches, slight blur, occasional diplopia (near and far), trouble focusing (near), dry eye, lost olfaction, hyperacusis, photosensitivity, frequent nausea, & eyestrain.	Currently in VT with 3 sessions completed at time of testing.
TBI-A4	36	34	1	MVA.	Aricept, Effexor, Concerta, Xanax, Solodyn.	OD: –3.25 –0.75 × 160; OS: –3.75 –0.75 × 170 (20/20).	Occasional diplopia, loses place when reading, sharp occipital headaches, dull general headaches, nausea, trouble focusing (near), & "eyes separate" when reading.	Currently in VT with 15 sessions completed at time of testing.
TBI-A5	28	19	1	Fence post dropped on head from excavator.	Claritin, Lipoflavinoid supplement.	OD: –1.75 –1.00 × 180; OS: –2.75 (20/20).	Occasional monocular diplopia OD (infrequent), floaters OD, uncomfortable feeling OD, tinnitis, dizziness, headaches, vestibular migraine, eyestrain with computers, & photosensitivity.	None.
TBI-A6	25	11	1	MVA (hit by car).	No current.	OD: –4.50; OS: –3.75 (20/20).	Occasional blur, especially after periods of near work, & headaches.	None.

Table 1. (cont)
Demographic data for 12 subjects with mild traumatic brain injury (TBI).

Subject	Age (yr)	Age at First TBI (yr)	No. of TBIs	Etiology of TBI	Current Medication	Refractive Correction (D)/ (Visual Acuity)	Symptom/ Complaint	Current/Prior Vision Therapy (VT)
TBI-A7	27	24	1	Assault.	No current.	OD: +4.75; OS: +4.75 (20/20).	Occasional diplopia, occasional blur, eyestrain/fatigue, & difficulty with long periods of reading.	None.
TBI-A8	40	36	1	Assault.	Hydrocodone plus acetaminophen, Lidoderm patch 5%, Meclizine HCl, Lunesta, Wellbutrin, Aleve, Hepapressin injection 2×/wk, immune plus response, allergy shots weekly, herbal supplements.	OD: –3.00 –0.50 × 160; OS: –3.75 –0.50 × 160 (20/20).	Decreased reading time, dizziness, headaches, photosensitivity, eyestrain, blurry vision, & lightheadedness with external motion.	Currently in VT, with 36 sessions completed at time of testing.
TBI-A9	28	27	1	Insulin overdose.	Effexor, Namenda, Aricept.	OD: –3.50; OS: –4.50 (20/20).	Visual-spatial deficits, difficulty reading, trouble tracking words on a page, & impaired fine motor skills.	Previously completed 5 sessions of VT 5 months before testing.
TBI-A10	37	29	1	Encephalopathy.	DDAVP, Plaquenil, Multivitamins.	OD: –7.75 –2.00 × 30; OS: –8.50 –1.25 × 165 (20/25).	Headaches, dizziness, occasional diplopia, dry eye, photosensitivity, & eye strain.	Previously completed 16 sessions of VT approximately 3 years before testing.
TBI-A11	37	36	1	MVA.	No current.	OD: –4.00; OS: –4.50 (20/20).	Eyestrain, hazy vision OS, tearing OS, headaches, photosensitivity, reading-related difficulty (comprehension & losing place), increased sensitivity to visual motion, & depth perception problems.	Currently in VT, with 5 sessions completed at time of testing.
TBI-A12	18	11	1	MVA.	No current.	OD: –0.75; OS: –0.75 (20/20).	Headaches, reading-related difficulty (comprehension & losing place), photosensitivity, occasional diplopia, periodic motion sickness, & eyestrain with computers.	None.

MVA = motor vehicle accident, OD = right eye (Latin *oculus dexter*), OS = left eye (Latin *oculus sinister*).

Instrumentation

Dynamic

We obtained accommodative step responses [1] using the commercially available WAM 5500 objective, infrared, open-field autorefractor (**Figure 2**) (Grand Seiko; Hiroshima, Japan). In the dynamic mode, we collected continuous measurements of the refractive state five times per second (5 Hz). No other standard clinical device has this dynamic capability, either to grossly assess the overall dynamic trajectory visually on the monitor screen as the subject is responding or to assess the individual response parameters (e.g., peak velocity) quantitatively following the test session using standard analysis programs. The WAM 5500 provides a reliable dynamic measure of accommodation and overall refractive state. The lens flipper test [22] provides a clinically based global assessment of the overall dynamic responses subjectively, but not objectively, as does the WAM 5500. The spherical dioptric range is –22D to +22D, with a reported resolution of 0.01D. Up to 10D of cylindrical refractive error can be measured with a reported resolution of 0.01D, with an axis resolution of 1°. Accommodative response traces, data tables, graphical displays, and statistical analyses were completed using Microsoft Excel (Microsoft Corporation; Redmond, Washington) and GraphPad Prism (GraphPad Software, Inc; La Jolla, California). Clinical accommodative facility [22] was assessed using +1.00/–1.00D rather than the conventional +2.00/–2.00D lens flipper because of the relatively older ages of the subjects [26].

Figure 2.
The WAM 5500 open-field autorefractor system is used to measure static and dynamic aspects of accommodation. It is composed of an open-field viewing area for subjects, joystick for eye and target alignment, accommodative stimulus mounted on near-point rod, response-viewing window on lower left, and computer to store responses for further analysis.

Static

We collected data for tonic accommodation [1] and AS/R curves [1] using the WAM 5500. In the manual mode, the examiner obtained single measurements of sphere, cylinder, and axis. AS/R plots, data tables, graphical displays, and statistical analyses were completed as previously described. Horizontal and vertical heterophoria and the stimulus AC/A ratio were determined in the phoropter using the von Graefe method and a 6 × 6 matrix of 20/20 letters on the clinical, near, reduced Snellen chart [27]. Minus-lens accommodative amplitude, PRA, and NRA were all determined in the phoropter using the line of 20/30 letters on a reduced Snellen chart [27]. Push-up accommodative amplitude was measured in free space using the line of 20/30 letters on a reduced Snellen chart as the target [27].

Procedures

The sequence of test procedures is outlined in detail in the following sections and summarized in **Figure 3**. Not all test procedures were performed on subjects in both groups. When well-established values taken from large sample sizes from the literature were available (e.g., accommodative amplitude), these were used as the normative data for comparison with the mTBI group. The following test procedures from the sequence shown in **Figure 3** were performed on all subjects in both groups: 2, 3, 4, and 5. The remaining tests were only performed on subjects in the mTBI group. The distance refractive error of each subject was fully corrected during all tests with either contact lenses or spectacles.

Dynamic

There is a good correlation between the clinical flipper rate and objectively recorded changes in crystalline lens dynamics [1]. The initial dynamic test was the lens flipper, which we used to assess baseline accommodative facility in each subject in each group. Before testing, the subjects were allowed adequate time to familiarize themselves with the accommodative flipper lenses and procedure, as well as to practice several lens alternations.

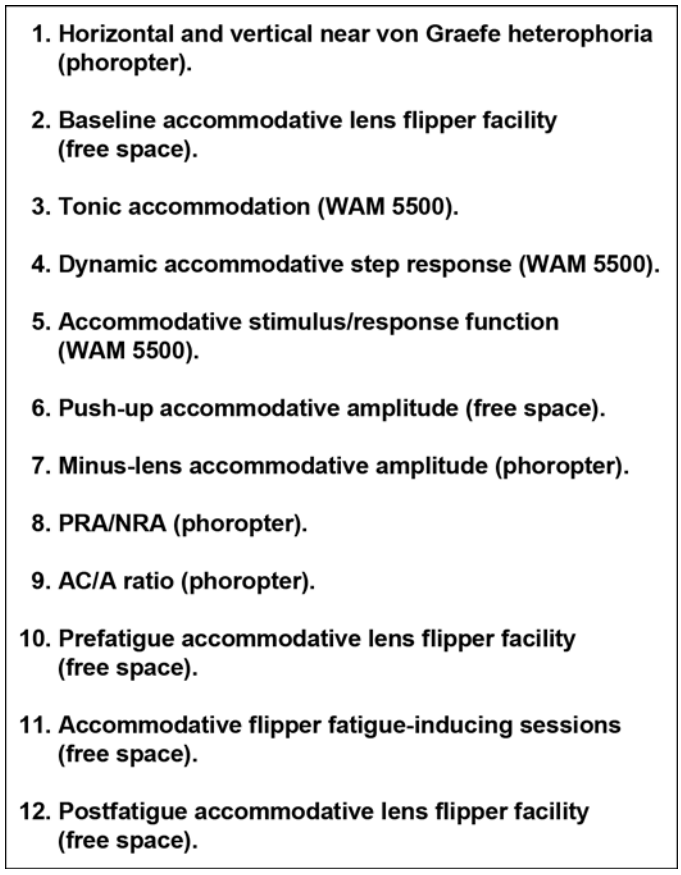

Figure 3.
Sequence of research protocol procedures. AC/A = accommodative convergence-to-accommodation, PRA/NRA = positive relative accommodation/negative relative accommodation.

Then, we assessed binocular and monocular accommodative flipper facility using a 1-minute test for each condition with +1.00/–1.00D lenses [28]. A line of 20/30 letters on a high-contrast Snellen near chart having a luminance of 31 cd/m^2 was positioned 40 cm (2.5D) from the patient along the midline to provide effective stimulus levels of 1.5D and 3.5D as the lenses were alternated. The subject was instructed to repeatedly alternate the lenses as rapidly as possible as the target letters came into focus. We also emphasized that the subjects should attempt to achieve as many lens alternations as possible during the 1-minute test period. This test was performed once monocularly for each eye and then binocularly.

We then, with the autorefractor in the dynamic mode, obtained measurements of monocular accommodative step responses over a period of approximately 120 seconds. Subjects viewed a line of high-contrast 20/30 Snellen letters having a luminance of 36 cd/m^2 positioned at 50 cm (2D) on a white background and a high-contrast 20/60 word with a luminance of 36 cd/m^2 at 25 cm (4D) on a transparent background. The autorefractor was aligned with the right eye, as well as with both accommodative stimuli. When instructed, the subject changed focus between the stimuli. There were approximately 10 to 20 changes in focus during the test period depending on the quality of the responses and presence of unwanted blink artifacts. These stimulus levels did not intrude into the subjects' nonlinear region of accommodative responsivity to any considerable degree [1].

Static

We assessed the vertical and horizontal near heterophorias in the phoropter using the von Graefe technique. The subject maintained focus on a 6 × 6 matrix of 20/20 letters on the clinical, near, reduced Snellen chart at 40 cm (2.5D). The stimulus had a luminance of 31 cd/m^2. Care was taken to displace the prisms slowly at a constant velocity of approximately 2 prism diopters (PDs)/s to provide slow and continuous ramp disparity stimulation [29]. Four measurements were taken, two from each direction to minimize directional biases effects, and the average value was determined.

We assessed tonic accommodation objectively using the autorefractor in the manual mode. The test room was almost totally darkened, and the subject was instructed to relax and imagine looking into the distance. After 3 minutes, five measurements were obtained, and the average spherical equivalent was determined.

In the manual mode, we then used the autorefractor to assess the AS/R function [1]. Accommodative steady-state responses to high-contrast reduced Snellen chart stimuli having a luminance of 36 cd/m^2 positioned at 2D, 2.5D, 3D, 4D, and 5D were measured monocularly in the right eye and then binocularly, in a random sequence with respect to both eye and stimulus level. Subjects were instructed to focus on the 20/30 line. For each stimulus/viewing condition, five measurements were obtained, and the average spherical equivalent was determined.

Accommodative amplitude was the next parameter assessed. Push-up accommodative amplitude was determined by averaging two measurements for each of the right and left monocular trials, as well as the binocular trials. A reduced Snellen chart was displaced toward the subject at a constant speed of approximately 0.5D/s to provide ramp blur stimulation [30]. The subject was

instructed to sustain focus on the 20/30 line having a luminance of 31 cd/m^2 and to indicate when the letters exhibited the first slight sustained blur and could no longer be kept in focus with effort. The distance from the Snellen chart to the spectacle plane (i.e., spectacle accommodation) was measured [31]. Minus lens accommodative amplitude was determined monocularly in the phoropter for both the right and left eyes. The subject was instructed to view, and maintain in focus, the 20/30 line of a reduced Snellen chart having a luminance of 31 cd/m^2 at a distance of 40 cm (2.5D). In 0.25D increments, minus lenses were added every 2 to 3 seconds, until the patient reported the first slight sustained blur that could no longer be cleared with effort, also referenced to the spectacle plane. The mean monocular and binocular push-up accommodative amplitudes for the mTBI subjects were compared with age-matched Duane's literature values [7]. Precise age-matched measurements were obtained from Duane's mean values in order to directly compare each mTBI subject with exact age-appropriate normative values.

Both the PRA and NRA were determined in the phoropter. These tests were performed while subjects were binocularly viewing and maintaining in focus the 20/30 line of a high-contrast reduced Snellen chart at 40 cm (2.5D). This target had a luminance of 31 cd/m^2. Depending on the test, either minus or plus lenses were slowly introduced every 2 to 3 seconds in 0.25D steps, until the first slight sustained blur was obtained that could no longer be cleared with effort. Suppression checks were added by placing a pen between the patient and the Snellen chart and ensuring that the pen appeared diplopic while the patient viewed the Snellen chart.

Lastly, the stimulus AC/A ratio was assessed in the phoropter by measuring the near horizontal heterophoria at four accommodative stimulus levels. The patient was instructed to maintain focus on a 6 × 6 matrix of high-contrast 20/20 Snellen letters on the clinical near chart at 40 cm (2.5D). The chart had a luminance of 31 cd/m^2. Spherical lenses were added to provide additional stimulus values of 1.5D, 3.5D, and 4.5D in order of increasing dioptric stimulus level. The average of two measurements was determined for each stimulus level. The stimulus AC/A ratios were established by plotting the horizontal heterophoria at each stimulus level and determining the slope of the best-fit linear regression.

Lens Flipper Fatigue Test

At the end of all the dynamic and static testing, we remeasured binocular accommodative lens flipper facility in the mTBI group only to assess for visual fatigue effects. First, we obtained the prefatigue lens flipper value, which was then immediately followed by a continuous 3-minute period of lens flipper alternation in an attempt to induce fatigue in the subject. For the prefatigue test, we instructed subjects to alternate the flipper lenses every 10 seconds upon command of the examiner. During this 10-second period, the subject attempted to attain and maintain target clarity. Immediately after this test, subjects were exposed to a 3-minute fatigue inducing session. Then, subjects repeated the same 1-minute binocular accommodative flip per facility procedure as described previously (postfatigue lens flipper value) to assess for any fatigue effects (i.e., decrement in the post- vs prefatigue lens flipper value).

RESULTS

Dynamic

Individual Data

Figure 4 presents the dynamic accommodative step responses from a typical control subject (N-3), as well as a spectrum of responses (i.e., very mild to severe) from selected subjects with mTBI. Subject N-3 exhibited consistent responses with relatively small steady-state variability. Subject TBI-A8 exhibited a profile similar to that of the control subject with respect to overall response variability and response-to-response consistency. For example, at the 4D level, mean steady-state response variability was similar (i.e., 0.13D vs 0.11D), and successive responses were highly consistent both dynamically and statically. In contrast, in subjects TBI-A9 and TBI-A10, the mean steady-state response variability was markedly increased, being 0.25D and 0.22D, respectively. Furthermore, response consistency was poor.

Figure 5 presents, with an expanded time scale, the dynamic accommodative step responses from a typical control subject (N-2) and a subject with mTBI (TBI-A9) manifesting one of the most highly abnormal profiles found in this group. Subject N-2 exhibited little variability with respect to the two mean steady-state levels or for the intervening dynamic response trajectories. In contrast,

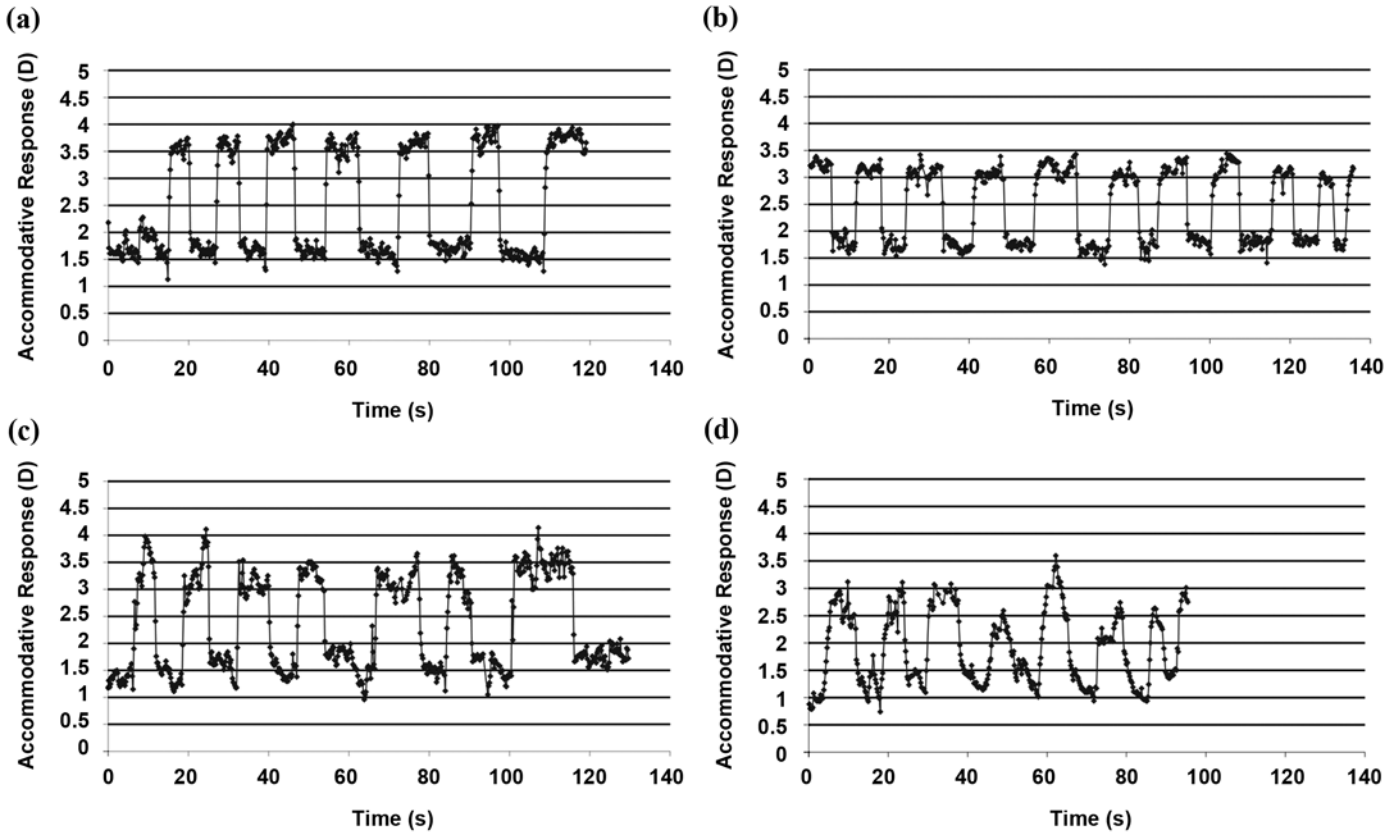

Figure 4.
Dynamic accommodative responses to near stimuli (2D and 4D) as a function of time in **(a)** a control subject (subject N-3) and in three mTBI subjects manifesting **(b)** approximately normal (subject TBI-A8) and **(c)–(d)** significantly abnormal responses (subjects TBI-A9 and -A10, respectively). Monocular viewing with the right eye. mTBI = mild TBI, TBI = traumatic brain injury.

subject TBI-A9 manifested both highly variable mean steady-state levels and dynamic response trajectories.

Figure 6 presents the individual dynamic accommodative step responses, along with the fitted exponential curves, in a typical control subject (N-5) and in a subject with mTBI (TBI-A10) manifesting considerable response dysfunction. In comparison to the control subject, the subject with mTBI exhibited markedly slowed dynamic responses, being approximately three times slower for increasing accommodation and about twice as slow for decreasing accommodation with respect to both the response time constant and related peak velocity.

Group Data

The mean time constants (± 1 standard error of the mean [SEM]) were 0.271 s ± 0.011 s and 0.245 s ± 0.009 s in the normal group for increasing and decreasing accommodation, respectively, whereas they were 0.430 s ± 0.039 s and 0.337 s ± 0.017 s in the mTBI group, respectively. A one-way analysis of variance (ANOVA) revealed a significant effect for the factor of time constant ($F(3,40) = 11.88$, $p < 0.001$). The Bonferroni multiple comparison post hoc test revealed several differences. The mTBI population exhibited significantly increased time constants for both increasing ($p < 0.05$) and decreasing ($p < 0.05$) accommodation when compared with the control group. Additionally, within the mTBI group, the mean time constant for increasing accommodation was significantly ($p < 0.05$) increased when compared with that for decreasing accommodation.

The mean peak velocities (±1 SEM) were 8.0 D/s ± 0.4 D/s and 8.0 D/s ± 0.4 D/s in the control group for increasing and decreasing accommodation, respectively, whereas they were 5.1 D/s ± 0.6 D/s and 6.1 D/s ± 0.5 D/s, respectively, in the mTBI group. A one-way ANOVA revealed a significant effect for the factor of peak velocity

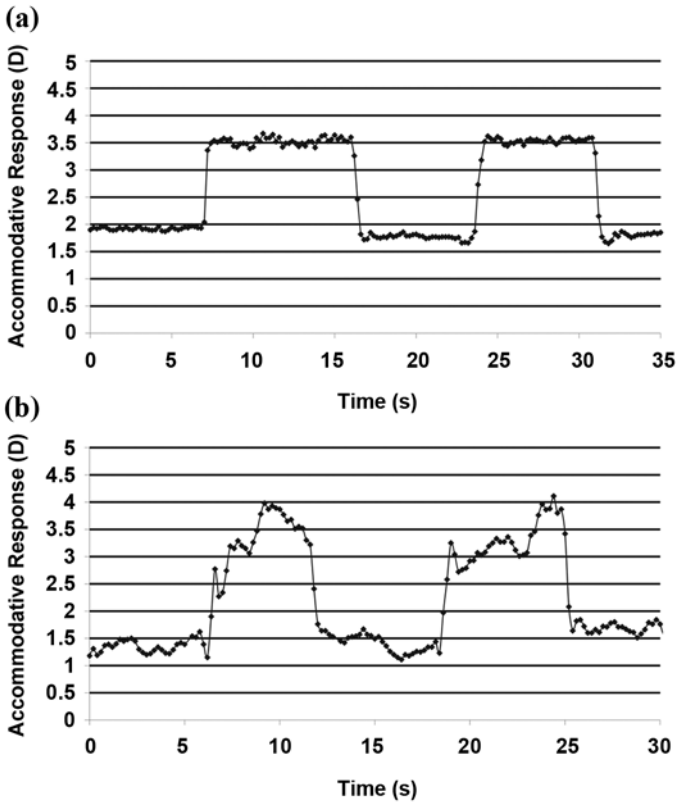

Figure 5.
Dynamic accommodative responses to near stimuli (2D and 4D) as a function of time in **(a)** control subject and **(b)** subject with mild traumatic brain injury manifesting significant response abnormalities. Monocular viewing with the right eye. Expanded time scale.

($F(3,40) = 8.575$, $p < 0.001$). The Bonferroni multiple comparison post hoc test revealed that the mTBI population exhibited significantly slowed peak velocities for both increasing ($p < 0.05$) and decreasing ($p < 0.05$) accommodation when compared with the control group.

Accommodative response variability for the control group showed mean (±1 SEM) response variability of 0.132D ± 0.013D and 0.151D ± 0.010D at the 2D and 4D stimulus levels, respectively, whereas the mTBI group manifested mean response variability of 0.123D ± 0.011D and 0.167D ± 0.016D at these same levels, respectively. A one-way ANOVA comparing the factor of response variability revealed no significant difference ($F(3,40) = 2.453$, $p = 0.07$). However, 17 percent (2/12) of the mTBI subjects exhibited variability equal to or exceeding the control group mean 95 percent upper confidence limit (CL) at the 2D stimulus level. Furthermore, 50 percent (6/12) of the mTBI subjects manifested variability equal to or exceeding the control group mean 95 percent upper CL at the 4D stimulus level.

Accommodative step response magnitudes for the control group exhibited mean (±1 SEM) values of 1.59D ± 0.06D and 3.42D ± 0.08D at the 2D and4D stimulus levels, respectively, whereas the mTBI group had mean values of 1.56D ± 0.08D and 3.18D ± 0.12D at these same levels, respectively. A one-way ANOVA revealed a significant effect for the factor of response magnitude ($F(3,40) = 116.5$, $p < 0.001$). That is, in both groups, the magnitude was higher at the 4D level than the 2D level. The Bonferroni multiple comparison post hoc test revealed no significant differences between the control and mTBI groups at either the 2D or the 4D level for the relevant comparisons ($p > 0.05$).

Accommodative response mean (±1 SEM) gain values were 1.04 ± 0.04 and 0.91 ± 0.03 in the control group for increasing and decreasing accommodation, respectively, whereas they were 0.88 ± 0.05 and 0.87 ± 0.04 in the mTBI group, respectively. A one-way ANOVA revealed a significant effect for the factor of mean gain ($F(3,40) = 3.018$, $p = 0.04$). However, the Bonferroni multiple comparison post hoc test indicated no significant differences between the control and mTBI group mean gain values for either increasing or decreasing accommodation for the relevant comparisons ($p > 0.05$).

Monocular and binocular mean (±1 SEM) accommodative flipper facility rates were 16.1 cpm ± 1.2 cpm, 16.0 cpm ± 1.2 cpm, and 15.6 cpm ± 1.2 cpm in the control group for the right eye, left eye, and binocularly, respectively, whereas they were 15.2 cpm ± 1.9 cpm, 14.6 cpm ± 1.8 cpm, and 15.3 cpm ± 1.4 cpm in the mTBI group, respectively. A one-way ANOVA revealed no significant effect for the factor of accommodative flipper facility rate ($F(5,70) = 0.152$, $p = 0.98$).

Mean (±1 SEM) pre- and postfatigue accommodative flipper facility rates for the mTBI group were 16.3 cpm ± 1.1 cpm and 13.8 cpm ± 1.0 cpm pre- and postfatigue, respectively. A paired *t*-test confirmed a significant effect of the 3-minute fatigue session on decreasing the accommodative flipper facility rate ($t(11) = 3.686$, $p = 0.004$). Ten (approximately 83%) of the mTBI subjects manifested a decrease in flipper rate following the 3-minute session, while one patient remained the same and one increased slightly.

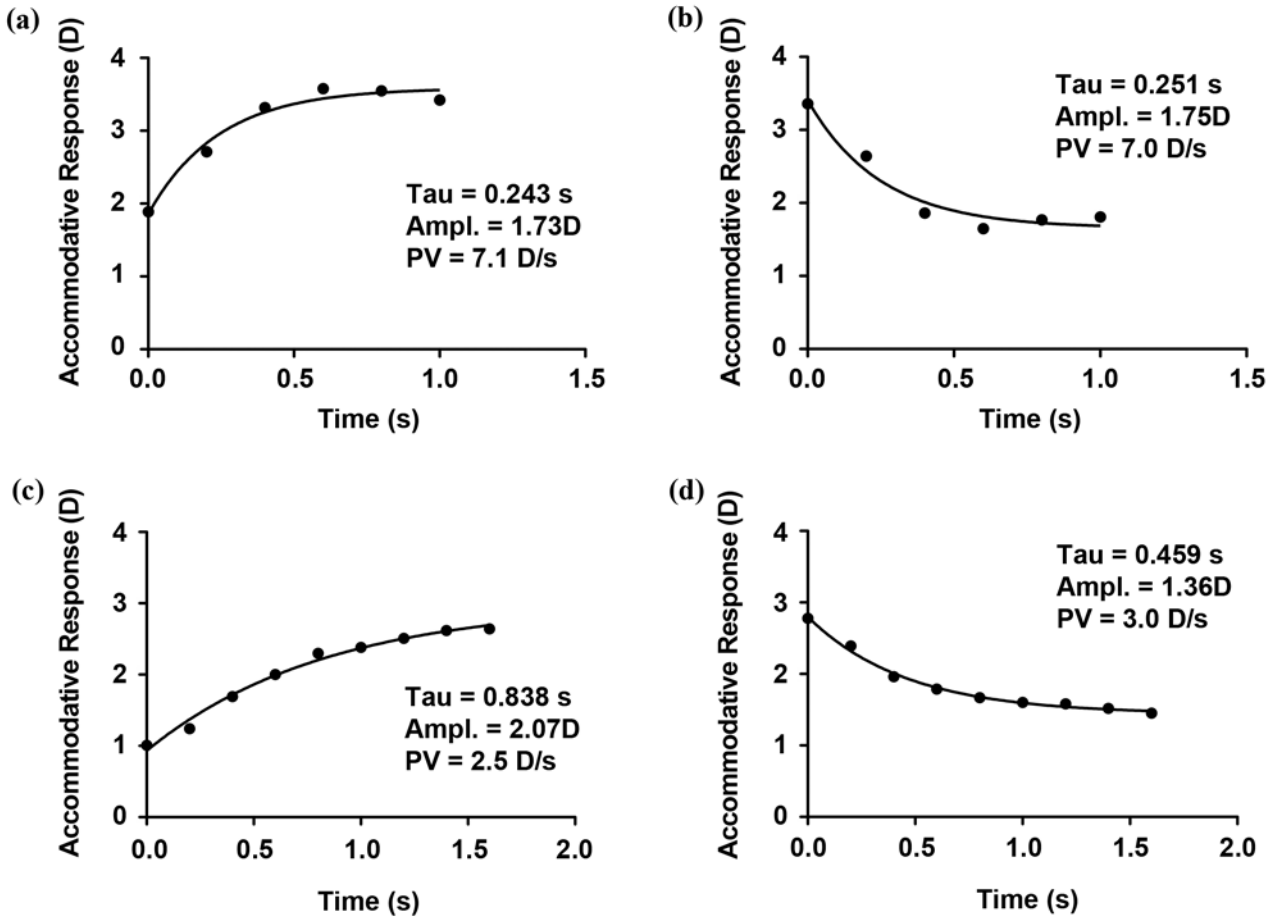

Figure 6.
Exponential fit to raw data (accommodative response as function of time) for typical control subject (subject N-5) for **(a)** increasing and **(b)** decreasing accommodation and mTBI subject (subject TBI-A10) manifesting more severe dynamic abnormalities for both **(c)** increasing and **(d)** decreasing accommodation. Ampl. = response amplitude, PV = peak velocity, Tau = time constant.

Static

The mean accommodative amplitude values were 6.63D, 6.38D, and 7.15D in the mTBI group for the right eye, left eye, and binocularly, respectively. The mean normal age-matched Duane's values were 8.23D and 8.68D for monocular and binocular testing, respectively. A repeated-measures ANOVA revealed a significant effect for the factor of accommodative amplitude ($F(4,11,44) = 9.156$, $p < 0.001$). The Bonferroni multiple comparison post hoc test indicated significant differences between the mTBI patients and Duane's normative monocular accommodative amplitude values for both the right ($p < 0.05$) and left ($p < 0.05$) eyes. Additionally, 67 percent (8/12) of the mTBI subjects manifested an interocular difference in push-up and/or minus-lens monocular accommodative amplitudes of 1.00D or more (**Table 2**), even though the mTBI group mean monocular accommodative amplitude values did not indicate significant overall interocular differences. The Bonferroni multiple comparison post hoc test also indicated significant ($p < 0.05$) differences between the mTBI and Duane's binocular accommodative amplitude values. Furthermore, 67 percent (8/12) of mTBI subjects exhibited greater than a 10 percent reduction in accommodative amplitude, with a range of 14 to 49 percent lower than Duane's age-matched mean values (**Table 2**). Only one subject exhibited an accommodative amplitude approximately 18 percent greater than Duane's mean, while the remaining three subjects were within 5 percent of Duane's mean value (**Table 2**).

Table 2.
Accommodative amplitude characteristics and deviation from Duane's mean normative values in 12 subjects with mild traumatic brain injury (TBI).

Subject	Age (yr)	PU Amplitude (D)			ML Amplitude (D)		Deviation from Duane's Mean Norms	
		OD	OS	OU	OD	OS	Absolute (D)	Percentage (%)
TBI-A1	26	**6.50**	**8.00**	6.50	**3.50**	**7.50**	–3.70	–36.3
TBI-A2	40	4.25	3.87	3.75	3.25	3.25	–2.45	–39.5
TBI-A3	34	**9.00**	**7.12**	8.37	4.00	3.50	0.37	4.6
TBI-A4	36	5.00	5.00	5.50	1.25	1.25	–1.90	–25.7
TBI-A5	28	**4.00**	**5.25**	5.00	3.75	4.00	–4.70	–48.5
TBI-A6	25	**8.25**	**7.12**	10.00	6.00	6.25	–0.40	–3.8
TBI-A7	27	**7.12**	**6.00**	8.37	**6.50**	**5.00**	–1.63	–16.3
TBI-A8	40	3.62	3.75	3.87	**3.00**	**4.75**	–2.33	–37.6
TBI-A9	28	**5.75**	**7.37**	6.87	**3.25**	**4.25**	–2.83	–29.2
TBI-A10	37	5.87	5.37	7.12	3.00	3.50	0.00	0.0
TBI-A11	37	**6.00**	**3.50**	6.25	**5.25**	**3.75**	–0.85	–13.6
TBI-A12	18	14.25	14.25	14.25	9.00	8.75	2.15	17.8
Mean ± SD	31.33 ± 6.95	6.63 ± 2.90	6.38 ± 2.90	7.15 ± 2.90	4.31 ± 2.06	4.65 ± 2.03	–1.52 ± 1.89	–19.0 ± 20.5
SEM	2.01	0.87	0.87	0.87	0.59	0.59	0.57	6.2

Note: Bold values indicate a difference of 1.00D or more between the two eyes.
ML = minus lens, OD = right eye (Latin *oculus dexter*), OS = left eye (Latin *oculus sinister*), OU = both eyes (Latin *oculus uterque*), PU = push-up, SD = standard deviation, SEM = standard error of the mean.

Table 3 presents the stimulus AC/A ratio, PRA, NRA, and near horizontal and vertical heterophoria for each mTBI subject. The control population mean AC/A ratio is 4 ± 2 PD/D [32]. Approximately 17 percent (2/12) manifested AC/A ratios at or above 6 PD/D, which is considered abnormally high [32]. Furthermore, 25 percent (3/12) of the mTBI subjects exhibited AC/A ratios at or below 2 PD/D, which is considered abnormally low [32]. Additionally, one subject was unable to perform the task because of highly excessive tearing that frequently resulted when the patient became overly fatigued. Therefore, 50 percent of the individuals with mTBI exhibited abnormality in the stimulus AC/A ratio. Regarding relative accommodation values, 50 percent (6/12) of the mTBI subjects exhibited either reduced values for both PRA and NRA [32] or an NRA value exceeding the PRA value by 1.00D or more. With respect to the near heterophoria, 64 percent (7/12) of the mTBI subjects manifested values outside of the normal range (0–6 exophoria) [32]. Five exhibited esophoria, while two exhibited exophoria of greater than 6 PDs. Five patients had vertical hyperphoria of small to moderate amounts (0–2 PD).

Monocular and binocular AS/R mean (± 1 SEM) slope values were 0.872 ± 0.030 and 0.828 ± 0.037 in the control group for monocular and binocular viewing, respectively, whereas they were 0.778 ± 0.043 and 0.809 ± 0.037 in the mTBI group, respectively. A one-way ANOVA revealed no effect for the factor of mean slope ($F(3,38) = 1.029$, $p = 0.39$).

Monocular and binocular accommodative responses were measured at the five tested accommodative stimulus levels for both the control and mTBI groups. No statistically significant differences were found between the control and mTBI groups' accommodative responses at any of the five stimulus levels (t-test, $p > 0.05$). Additionally, F-tests were performed on the same data to assess for possible differences in variance between the control and mTBI groups at each stimulus level. The mTBI group exhibited a significantly increased variance when compared with the control group only at the monocular stimulus levels of 2D ($F(11,8) = 5.873$, $p = 0.02$) and 3D ($F(11,8) = 5.273$, $p = 0.03$). The variance was 0.32D versus 0.13D at 2D and 0.42D versus 0.18D at 3D for mTBI versus control group, respectively. Furthermore, using a

Table 3.
Measurements of AC/A ratio, PRA/NRA, and heterophoria in 12 subjects with mild traumatic brain injury (TBI).

Subject	AC/A Ratio (PD/D)	PRA (D)	NRA (D)	Horizontal Near Phoria (PD)			Vertical Near Phoria (PD)
TBI-A1	4.20	–3.75	3.00	**5 Eso**			0
TBI-A2	2.75	**–1.25**	**1.25**	**8.5 Exo**			0
TBI-A3	5.50	**–0.75**	**0.50**	**3.25 Eso**			0
TBI-A4	6.00	**–1.00**	**1.00**	**11 Eso**			0
TBI-A5*	6.65	–2.50	1.50	4 Exo			Hyper
TBI-A6	2.70	**–0.75**	**2.75**	3.5 Exo			0
TBI-A7	4.30	**–2.00**	**3.75**	**5.5 Eso**			Hyper
TBI-A8†	NA	**–1.25**	**2.50**	**14 Eso**			0
TBI-A9	–0.53	–2.00	2.75	2.75 Exo			Hyper
TBI-A10	0	–2.50	2.75	6 Exo			Hyper
TBI-A11	3.00	–1.75	2.50	0			0
TBI-A12	2.00	–7.25	2.50	**7.25 Exo**			Hyper
				Eso (n = 5)	Exo (n = 6)	Ortho (n = 1)	
Mean ± SD	3.32 ± 2.31	–2.23 ± 1.80	2.23 ± 0.95	7.75 ± 4.54	5.33 ± 2.28	0 ± 0	0.54 ± 0.78
SEM	0.70	0.52	0.27	2.03	0.93	0	0.23

Note: PRA/NRA bold values are either low, have an NRA of 1.00D, or have an NRA more than the PRA. Phoria bold values indicate phorias outside Morgan's norms (0–6 exo for horizontal near heterophoria).
*Patient manifested dramatic increase in eso with 3.5D and 4.5D stimuli (AC/A).
†Patient was not able to perform task because of excessive tearing (AC/A).
AC/A = accommodative convergence-to-accommodation, eso = esophoria, exo = exophoria, Hyper = hyperphoria, NA = not applicable, NRA = negative relative accommodation, Ortho = orthophoria, PD = prism diopter, PRA = positive relative accommodation, SD = standard deviation, SEM = standard error of the mean.

nonparametric analysis, we found that the mTBI group exhibited greater variance than the control group at all five accommodative stimulus levels for both the monocular (sign test, $p = 0.03$) and binocular (sign test, $p = 0.03$) test conditions.

Tonic accommodation mean values (±1 SEM) were 0.16D ± 0.21D and 0.60D ± 0.43D in the control and mTBI groups, respectively. An unpaired t-test revealed no significant difference ($t(20) = 0.852$, $p = 0.40$). However, 33 percent (4/12) of the mTBI subjects exhibited a tonic accommodation value outside the control group mean 95 percent CL.

DISCUSSION

The results of the present study revealed significant differences for a range of dynamic accommodative functions between the mTBI group and the control group/normative literature values. First, and never investigated before in this population, were laboratory-based parameters of accommodation, such as time constant, peak velocity, and clinically based response fatigue. All subjects with mTBI manifested decreased peak velocity and related increased time constant. Furthermore, a significant fatigue effect was observed in the mTBI group with respect to binocular accommodative flipper facility rate, which is contrary to previous findings in visually normal subjects [28,33]. Earlier studies suggested an increased frequency of accommodative infacility in the mTBI patient population [6,11]. Our study agrees with these earlier patient findings.

The present study also highlighted various static accommodative parameters that may be adversely affected by mTBI. Nearly all the patients with mTBI exhibited abnormalities in monocular and/or binocular accommodative amplitude, a basic clinical measure; thus, this measure may represent a potential simple marker for accommodative TBI effects. The presence of accommodative amplitude abnormalities is consistent with, and expands upon, numerous earlier studies [8–12,14–17,21]. Additionally, a higher percentage of abnormalities were

observed in the mTBI group with regard to the stimulus AC/A ratio, PRA/NRA, and near horizontal phoria. Again, the current findings agree with, and expand upon, previous studies relating to these parameters in this population [12,17]. Lastly, steady-state response variability was increased in the mTBI population under certain test conditions.

Relation to Human Neurological Studies

With the variety of possible TBI etiologies and the more global nature of the insult, accommodative dysfunction may be especially prevalent in the mTBI population. The high percentage of accommodative abnormalities revealed in the present study, as well as two recent clinical studies [11,34], supports this hypothesis. Accommodation may be affected by disturbances in the accommodation-related cortical, cerebellar, and/or brain stem areas and the related axonal pathways (**Figure 1**). Therefore, accommodative effects of TBI could potentially result from a direct blow to a key cortical or cerebellar area, secondary intracranial edema, hematoma, hemorrhage causing increased pressure or decreased blood flow to critical structures, or shearing forces causing diffuse axonal injury along the vital pathways.

Various human lesion case studies have provided additional evidence regarding the possibility of accommodative deficits resulting from injury to the just-mentioned brain structures [35–38]. These case studies reveal the potential for deficient accommodative dynamics and reduced accommodative amplitude resulting from various injury sites within the brain. Further human studies using careful clinical and objective measures of accommodation, as well as brain imaging, would be helpful in elucidating the affected neural pathways. For example, step, ramp, and steady-state stimuli, as used in the present study, could be assessed concurrent with functional magnetic resonance imaging in humans with mTBI.

Impact on Quality of Life

Symptoms of accommodative deficit, such as blur, intermittent diplopia, and near work asthenopia, could negatively affect reading ability (a primary problem in mTBI [11,34,39–40]), ambulation, driving, and visual detection/discrimination tasks [25,41]. This negative effect may be exacerbated by the frequently reported dizziness, nausea, and general visual fatigue in these individuals [25]. The presence of any of these symptoms may limit subjects' ability to enjoy, or even participate in, routine avocational activities. Furthermore, this effect could interfere with performance of vocational tasks, such as reading, which may result in loss of income and related employment benefits. Such a domino effect may lead to inadequate progress in other rehabilitative services (e.g., cognitive therapy) involving a range of general and specific visual demands [42–43]. Fortunately, these accommodative dysfunctions can be successfully remediated (~90% of patients [24]) with relatively simple optometric vision therapy paradigms [22–23] involving the principles of perceptual and motor learning [44] and/or the prescription of low-powered plus lenses for near work [25].

Study Limitations

There were three potential study limitations. The first was the relatively small sample size. However, the consistency of the abnormal findings, especially with respect to the dynamic parameters, suggests that the present sample size was sufficient and representative of that found in individuals with mTBI and related near vision symptoms. Furthermore, with this sample size, the power was sufficient to control for family wise error. The second limitation is the relative heterogeneity of the mTBI test population. The population encompassed several different specific etiologies of mTBI, although the majority could be categorized as "blunt injury." We found remarkably consistent abnormalities across the group (e.g., peak velocity and accommodative amplitude). Thus, this consistency would suggest that the present findings are representative of this population. Third, the accommodative latency, or reaction time, could not be assessed as one of the dynamic parameters because of a basic design limitation of the WAM 5500 autorefractor that was used to obtain the objective dynamic accommodative parameters.

Future Directions

There are several directions for future studies. First, an expanded visual fatigue paradigm that relates to common TBI complaints should be developed. This paradigm could include accommodative flipper facility using lenses of increased powers and/or comprehension tasks dealing with prolonged reading incorporating various amounts of accommodative demand over time. Next, both neurophysiological and bioengineering models of the accommodative system that accurately portray the response abnormalities of the TBI population would provide insight into the anomalous functional mechanism at multiple levels. Additionally, computed tomography, standard

magnetic resonance imaging, functional magnetic resonance imaging, and diffusion tensor imaging in patients with specific accommodative deficits could lead to a better understanding of the precise brain areas involved, as well as investigate the effect of successful vision rehabilitation on the affected neural sites. Furthermore, research into vision rehabilitation for this population could lead to an increased number of patients regaining independence, rejoining the workforce, and renewing their passion for their previous hobbies or recreational activities, in addition to promoting gains in other rehabilitation programs (e.g., occupational therapy) [42–43].

CONCLUSIONS

A range of dynamic and static accommodative abnormalities was found in a population of adult patients with mTBI. These dysfunctions are likely to have adverse consequences on a variety of activities of daily living, as well as impede other types of rehabilitative therapies. Fortunately, they can be remediated by vision rehabilitation and/or a near plus lens spectacle correction.

Five parameters would be predicted to produce the highest yield in terms of detecting an accommodative dysfunction/problem in an mTBI population: accommodative amplitude, accommodative lens flipper facility fatigue, stimulus AC/A ratio, horizontal near heterophoria, and PRA/NRA. Our results suggest that these tests be incorporated into the basic clinical armamentarium in those clinical practices and hospitals (e.g., a Department of Veterans Affairs polytrauma center) in which mTBI patients are likely to be examined. Furthermore, these five tests could also be used in a visual screening modality by hospital technical and related therapy staff (e.g., a low-vision technician or an occupational therapist) for subsequent referral, if needed, to the appropriate clinic for more comprehensive and specialized testing and possibly vision rehabilitation. With such targeted, high-yield, and cost-effective testing, patient care would be improved and rendered to a greater number of patients with mTBI and related visual symptoms.

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