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Accommodative and Vergence Dysfunctions in mTBI: Treatment Effects and Systems Correlations

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ABSTRACT

Background: Traumatic brain injury (TBI) is a global, diffuse type of injury, which results in a constellation of visual dysfunctions. The extensive neural network of the oculomotor system makes it highly vulnerable following a TBI, hence the high prevalence of signs and symptoms related to accommodative and vergence dysfunctions.

Methods: The present study evaluated the therapeutic effects on clinical (subjective) and laboratory (objective) measures, as well as their correlated improvements, following an equal dosage of six weeks of vergence and accommodation training in mild TBI (n=12).

Results: With only three hours of training for each system, significant improvements in both static and dynamic parameters of both systems were found. Maximum amplitude of both systems increased markedly, along with faster dynamics demonstrating speedy responsivity, following training. Several key parameters between the two systems showed significant correlation ($p<0.01$), such as amplitudes ($r = -0.87$) and facilities ($r = 0.88$) of accommodation and vergence.

Conclusions: The present findings demonstrate efficacy of oculomotor rehabilitation in TBI, with the improvements being suggestive of intact neuroplasticity in the compromised adult brain following mTBI.

Keywords: accommodation, mild traumatic brain injury, oculomotor rehabilitation, reading, vergence, vision therapy

Introduction

Based on the severity and site of the injury, a traumatic brain injury (TBI) results in a spectrum of general dysfunctions involving physical, behavioral, cognitive, and emotional aspects.[1] In such a global injury (e.g., coup-contrecoup), occurrence of an isolated dysfunction is rare. Furthermore, such multiple injuries may interact to produce a myriad of symptoms adversely affecting the overall quality of life (QOL) of an individual, as well as their activities of daily living (ADLs). A comprehensive evaluation of these functions is critical to the proper diagnosis and treatment of TBI.[2,3]

Of the multiple systems that could potentially be adversely affected, the extensive neural network of the visual system makes it particularly vulnerable to the impact of a TBI, even in the milder form (mTBI). Since there are 40 brain areas related to vision involving seven of the 12 cranial nerves,[4] the presence of a visual deficit following a TBI is very likely. Visual dysfunctions resulting from a TBI can be broadly classified into oculomotor and non-oculomotor-based as proposed by us.[5] The present paper focuses on the oculomotor-based visual dysfunctions and their remediation in mild TBI (mTBI), specifically involving the vergence and accommodative subsystems and their interactions,[6] based on recent laboratory studies.[7-12]

While an obvious ocular injury (e.g., traumatic cataract, retinal detachment) is readily diagnosed and managed clinically, more subtle binocular vision dysfunctions (e.g., an oculomotor disorder such as mild convergence insufficiency) are frequently not. Oculomotor dysfunctions are common among the general, non-TBI population, with a frequency of occurrence of 20 to 30% in the young adult clinic population having related visual symptoms.[13-16] However, these binocular vision/oculomotor dysfunctions occur at a considerably greater frequency in mTBI.[17,18] For example, approximately 90% of individuals (n=160) with mTBI examined in an optometric clinic setting and having vision-related symptoms were diagnosed with one or more oculomotor dysfunctions following their acute care phase and natural recovery period.[17] Identifying these abnormalities and rehabilitating them are essential to improving one's reading ability, which is a common problem in these patients,[17-21] as well as their QOL and ADLs.

While there is abundant evidence from clinical studies on vergence and accommodative rehabilitation in the TBI population,[22-24] there is a paucity of laboratory-based objective recordings demonstrating the effects of vision rehabilitation. Furthermore, no study investigated the correlation of improvements in each system following an equal "dosage" of treatment. Hence, the purpose of the present investigation was to evaluate the effect of oculomotor-based vision rehabilitation on a range of static and dynamic measures of vergence and accommodation, and furthermore to correlate the rehabilitative effect on the tested selected measures both within and between the two systems.

Methods

Twelve individuals between the ages of 23 and 33 years (mean age: 29±3 years) with medically-documented mTBI participated in the study. To exclude any effects of the natural recovery process (6-9 months) on the test results, only individuals whose head trauma occurred at least one year prior to testing were included. Subjects were recruited from the Raymond J. Greenwald Vision Rehabilitation Center (RJGVRC) at the State University of New York (SUNY), State College of Optometry, University Optometric Center. All received a comprehensive optometric vision examination prior to participating in the investigation, which included refractive, oculomotor, and ocular health assessment. The study was approved by the SUNY Institutional Review Board (IRB) and the US Army Department of Defense (DoD). Written informed consent was obtained prior to participation. All exhibited at least one clinical symptom (e.g., skipping lines while reading, rereading) and one clinical sign (e.g., reduced reading rate with objective Visagraph testing) of a non-strabismic, oculomotor nature related to impaired reading. No subject had a history of vision therapy prior to this study. The subjects had stable general health, intact cognitive function, and no other neurological conditions.

Test Parameters

The test parameters included clinically-based subjective and laboratory-based objective measures of accommodation and vergence. All clinical parameters were measured using conventional, standardized clinical techniques.[25] All laboratory-based objective measures were performed using commercially-available instrumentation with well-established test and data analyses protocols.[7-12] All testing was non-invasive and was recorded with the subject's habitual distance lenses in place, and furthermore, it did not require dilated pupils. The order of testing was randomized over the 2 days of measurements to prevent any sequential order effect that would bias the measurements.

I. Clinical measures: Study-related, near vision-specific, selected binocular vision-related parameters were tested under standard clinical room illumination (80 Lux). Testing sequence was randomized.
It included:

a) Near point of convergence (NPC) break and recovery were assessed.
b) Accommodative amplitude (AA), or near point of accommodation (NPA), was assessed under both monocular and binocular viewing conditions using the push-up technique in free-space.
c) Horizontal near phoria was measured in the phoropter using the von Graefe prism dissociation method.
d) Horizontal near fusional positive (PFV) and negative (NFV) vergence ranges were determined in the phoropter. Both positive relative accommodation (PRA) and negative relative accommodation (NRA) were determined in the phoropter.
e) Accommodative lens facility was assessed outside the phoropter using +/- 2D flipper lenses. Prior to testing, subjects were allowed adequate time to familiarize themselves with the accommodative flipper lenses and practice the test procedure.
f) Vergence prism facility was assessed outside the phoropter using 12^{Δ}BO/3^{Δ}BI flippers. Prior to testing, subjects were allowed adequate time to familiarize themselves with the vergence flipper lenses and practice the test procedure.
g) Stereoacuity at 40cm was recorded in free space using the non-random-dot Titmus stereo test with polaroid lenses.

II. Laboratory-based Objective Measures[7-12]

a) First-order accommodative dynamics to 2D increasing and decreasing step responses were obtained using the commercially-available WAM 5500 objective, infrared, open-field autorefractor (Grand Seiko, Hiroshima, Japan) with a reported resolution of 0.01D and approximately a 5Hz sampling rate. Subjects monocularly viewed a line of high contrast 20/30 Snellen letters having a luminance of 36 cd/m^2 positioned at 2D that were on a white background and a high contrast 20/60 word with a luminance of 36 cd/m^2 at 4D on a transparent background. The autorefractor was aligned with the right eye, as well as with both accommodative stimuli. The fellow left eye was fully occluded with a black eye patch. When instructed, the subject changed focus as rapidly as possible between the two stimuli. There were approximately 15-20 changes in focus between the accommodative stimuli during the test period depending on the quality of the responses and the presence of unwanted blink artifacts. Three artifact-free (e.g., blink free) increasing and 3 decreasing accommodative responses were selected for analysis from the right eye traces for each subject. There were approximately 7-10 increasing and 7-10 decreasing responses in total for each subject. The middle three blink-free responses were used for analysis. An exponential decay function was fit to the dynamic trajectory using Graphpad Prism® software. The peak velocities were derived from first-order differentiation of the exponential equation.
b) Vergence dynamics to symmetric step vergence stimuli were recorded using the Plusoptix Power Refractor II (PRII; Plusoptix, Nuremberg, Germany) based on the principle of infrared videography and

Table 1: Training protocol for vergence and accommodation used during each session

Stimulus	Stimulus Parameter	Training Period Duration (minutes)	Total Training Duration (minutes)
Vergence	Step amplitude (BO/BI)	7	15
	Step facility (BO/BI)	5	
	Ramp	3	
Accommodation	Step amplitude right eye +/- lenses	5	15
	Step amplitude left eye +/- lenses	5	
	Step facility	5	

dynamic retinoscopy, with a sampling rate of 12.5Hz (resolution of <0.9°) for binocular recording. Targets comprised the contiguous red and green fixation LEDs (angular size: 0.28 degrees) located on the measuring head of the PRII at 1m and a white LED (angular size: 0.86 degrees) placed at 0.3m, both aligned along the midline for testing of symmetric convergence and divergence. Subjects were instructed to bifixate the red and green distant LEDs, which were illuminated at all times. They were then instructed to alter their bifixation to the near LED target as rapidly as possible as soon as it was illuminated. There was no verbal warning when the near LED would be illuminated; timing of the target change was random to minimize prediction. When the near target was extinguished, subjects were instructed to change their bifixation back to the far target as quickly as possible. Subjects altered bifixation between the far and near targets approximately 10-15 times to obtain the convergence and divergence responses. Three artifact-free (free of blinks and/or saccades) convergence and 3 divergence responses were selected for analysis from the right eye position traces for each subject from a sample of 7-8 responses in each direction. The middle three blink-free responses were used in the final analysis. An exponential decay function was fit to the traces using Graphpad Prism® software. The peak velocities were derived from first-order differentiation of the exponential equation.

Testing and Training Phases[12]

The study consisted of the following phases:

1. **Baseline measures:** All test measures were recorded over two separate test sessions (each session lasting for up to 1.5 hours, including rest periods to prevent fatigue), separated by at least two days.
2. **Oculomotor training (OMT)**: Subjects received six weeks of OMT (i.e., oculomotor-based vision therapy), two training sessions per week. Each session was 40 minutes in duration, involving 30 minutes of actual training (15 minutes for each system), with the remainder of the time consisting of short and interspersed rest periods for the subject. Total training time of six hours, three hours for each system.
3. **Repeat baseline measures**: On the week following training completion, all test measures were repeated over two separate test sessions.

OMT

At each training session, horizontal vergence was trained for 15 minutes, and accommodation was trained for 15 minutes. While both step (12 minutes) and ramp (3 minutes) components were trained for vergence,[26] step alone was trained for accommodation.[27] During step training, both the amplitude and facility were trained for each subsystem. See Table 1 for details.

Vergence

For vergence, various magnitudes of base-out and base-in (BO/BI) prisms were used. The basic principle behind the training was to maintain the accommodative demand constant at 0.4m (2.5D), with progressive increase in vergence demand (i.e., non-congruent stimulation), with fusion maintained.[16,28] The fusional targets comprised pictures, symbols, numbers, letters, tumbling E, and colors displayed on a computer screen at 0.4m per a program developed in our laboratory.[12] As treatment progressed and the subject demonstrated improvement, the level of task difficulty was increased by using progressively smaller target sizes (subtending 2 to 10 degrees). After introducing each BO prism, subjects were instructed to fuse the target as rapidly as possible. This trained the fast vergence mechanism.[29] The fused percept was maintained for 15-20 seconds. This sustained viewing trained the slow vergence mechanism that maintained the vergence response.[30] Hence, the goal of the training was not only to achieve rapid fusion, but also to maintain the vergence response with accuracy and visual comfort. Such response maintenance would reflect the vergence adaptation mechanism.[31] Base-out training was terminated when the subject could no longer fuse (and/or focus) with their maximum effort. The above was repeated for BI prisms. The order of BO/BI training at each session was randomized.

For step vergence facility training, combinations of progressively increasing BO/BI prism flippers (3^{Δ}BO/1^{Δ}BI,

Table 2(a): Mean static accommodation and vergence measures before (baseline) and after OMT (post-OMT) and their respective percentage of improvement. Italicized = significant improvement (p<0.05).

Static parameter	Baseline	Post-OMT	Percentage of improvement (%)
AA OD	*6.2*	*8*	*29*
AA OS	*5.9*	*7.9*	*34*
Binocular AA	*6.9*	*8.8*	*28*
PRA	2.5	3.1	24
NRA	*2.1*	*2.3*	*10*
NPC break	*15.6*	*9.2*	*41*
NPC recovery	*17.9*	*11.9*	*34*
PFV break	*22*	*27*	*23*
NFV break	*16.5*	*19*	*15*
Stereo	*26.2*	*22.9*	*13*

Table 2(b): Mean dynamic accommodation and vergence measures before (baseline) and after (post-OMT) and their respective percentage of improvement. Italicized = significant improvement (p<0.05). Note all dynamic measures showed significant improvement following OMT.

Dynamic parameter	Baseline	Post-OMT	Percentage of improvement (%)
OD accommodative facility	*5*	*11*	*120*
OS accommodative facility	*5*	*11*	*120*
OU accommodative facility	*5*	*11*	*120*
Inc.acc pk.vel	*4.5*	*5.8*	*29*
Dec.acc pk.vel	*4.2*	*5.6*	*33*
Vergence facility	*5.5*	*10.2*	*85*
Convergence pk.vel	*13*	*18*	*38*
Divergence pk.vel	*11.6*	*13.5*	*16*

6^{Δ}BO/2^{Δ}BI, 9^{Δ}BO/3^{Δ}BI, and 12^{Δ}BO/3^{Δ}BI) were used, while maintaining the accommodative demand constant at 0.4m (2.5D; i.e., non-congruent stimulus conditions). The fusional targets were similar to those used for the above training. Subjects bifixated targets displayed on a computer screen and were instructed to fuse and focus, as rapidly as possible, to achieve the maximum number of cycles possible. As treatment progressed and the subject demonstrated improvement, the level of task difficulty was increased by increasing the prism flipper power strength and by reducing target size.

For ramp vergence training, subjects binocularly tracked a 20/30 letter on an XY plotter over a range of 0.5m to 0.2m at the rate of 0.1 to 1Hz. Task difficulty was increased by tracking at closer distances with the combination of increased speed.

Accommodation

For accommodation, various magnitudes of positive and negative lenses were used. The basic principle behind the training was to maintain the vergence demand constant at 0.4m (2.5MA), with progressive increases in accommodative demand (i.e., non-congruent stimulus conditions).[16,28] The accommodative targets comprised texts of various sizes ranging from 20/60 to 20/20 displayed on a computer screen at 0.4m. As treatment progressed and the subject demonstrated improvement, task difficulty was increased by reducing target size and increasing lens power. After introducing each lens, subjects were instructed to focus the text as rapidly as possible. Focus was maintained for 15-20 seconds to train sustaining ability. Hence, the goal of the training was not only to achieve rapid focus per the transient fast accommodation mechanism,[27,29] but also to maintain the accommodative response with accuracy and comfort. Such response maintenance would reflect the accommodative adaptation mechanism.[32] Positive accommodation training was terminated when subjects could no longer focus with their maximum effort. The above was repeated for negative accommodation. The order of positive/negative training, as well as the eye initially trained at each session, was randomized.

For accommodative facility training, combinations of +/- lens flippers (+/-0.5, +/-0.75, +/-1.00, +/-1.50, and +/-2.00D) were used, while maintaining the vergence demand constant at 0.4m (2.5MA).[16] The accommodative targets were similar to those used for the training described earlier. The initial lens flipper power was chosen based on the subject's ability to focus. Subjects bi-fixated targets displayed on a computer screen and were instructed to fuse and focus as rapidly as possible, as well as to achieve the maximum number of cycles possible. As the treatment progressed and the subject demonstrated improvement, the degree of difficulty was increased by reducing target size and increasing the power of the lens flipper.

Table 3(a): Correlation of pre-post treatment effects between static parameters within and between accommodative and vergence systems. Italicized = significant correlation (p<0.05).

Correlated static parameters	Pearson r value	P value
WITHIN SYSTEM		
AA OD & AA OS	*0.95*	*<0.001*
AA OD & Binocular AA	*0.81*	*<0.001*
PRA & NRA	0.33	0.11
Binocular AA & PRA	*0.51*	*0.01*
NPC break & NPC recovery	*0.98*	*<0.001*
PFV break & NFV break	0.31	0.13
NPC break & PFV break	-0.24	0.25
NPC break & Stereo	*0.54*	*<0.01*
BETWEEN SYSTEMS		
Binocular AA & NPC break	*-0.87*	*<0.001*
PRA & PFV break	*0.44*	*0.03*
NRA & NFV break	0.12	0.56

Table 3(b): Correlation of pre-post treatment effects between dynamic parameters within and between accommodative and vergence systems. Italicized = significant correlation (p<0.05). Note all the dynamic parameters measured within systems correlated significantly.

Correlated dynamic parameters	Pearson r value	P value
WITHIN SYSTEM		
OD accommodative facility & OS accommodative facility	*0.97*	*<0.001*
OD accommodative facility & OU accommodative facility	*0.91*	*<0.001*
Inc.acc pk.vel & Dec.acc pk.vel	*0.87*	*<0.001*
Inc.acc pk.vel & OD accommodative facility	*0.56*	*<0.001*
Dec.acc pk.vel & OD accommodative facility	*0.53*	*<0.001*
Convergence pk.vel & Divergence pk.vel	*0.51*	*0.01*
Convergence pk.vel & vergence facility	*0.53*	*<0.001*
Divergence pk.vel & vergence facility	*0.52*	*<0.001*
BETWEEN SYSTEMS		
OU accommodative facility & vergence facility	*0.88*	*<0.001*
Inc.acc pk.vel & Convergence pk.vel	0.18	0.41
Dec.acc pk.vel & Divergence pk.vel	0.10	0.64

Placebo

There was also analogous placebo training of each system using an interventional cross-over experimental design (OMT versus placebo). See Thiagarajan[12] for details on the placebo training.

The t-test for non-independent means was used for all of the statistical analyses. The probability level for significance was 0.05.

Results

Pre-post Training Effects

Static Values

Following training, both monocular and binocular maximum AA increased significantly (p<0.01). However, the relative amplitudes of accommodation (PRA and NRA) did not change significantly (p>0.05). For vergence, the maximum vergence amplitude and its recovery (NPC break and recovery), along with its relative amplitudes (PFV break and NFV break), increased significantly following the training (p<0.05 in all cases). In addition, stereoacuity exhibited a small but significant improvement (p=0.03). For accommodation and vergence, the parameter showing the largest percentage increase was AA in the left eye (34%) and NPC break (41%), respectively. See Table 2(a) for mean values before and after the OMT and their percentage improvement.

Dynamic values

There was a significant increase in the accommodative peak velocity for both increasing and decreasing monocular steps of accommodation (p<0.01). Concomitantly, there was a significant improvement in the accommodative flipper facility rate both monocularly and binocularly (p<0.01). Similarly, both convergence and divergence peak velocity increased significantly along with marked improvement in vergence flipper facility (p<0.01). For accommodation and vergence, the parameter showing the largest percentage increase was accommodative facility (OD, OS, and OU; 120% for each) and vergence facility (85%), respectively. See Table 2(b) for mean values before and after the OMT and their percentage improvement.

Correlation of Training Effects

Within System

Within the accommodative system, the increase in AA correlated significantly between the two eyes. These monocular improvements in AA also correlated with the binocularly-increased AA values. Furthermore, there was a significant correlation between binocular AA (maximum amplitude) and PRA (relative amplitude). However, there was no significant correlation between the two relative amplitudes of accommodation (PRA and NRA). All dynamic measures of accommodation correlated significantly: monocular accommodative flipper facility between the two eyes, monocular and binocular accommodative flipper facility, increasing and decreasing steps of accommodative peak velocity, and peak velocity and accommodative flipper facility. See Table 3(a) and 3(b) for r and p values.

Within the vergence system, there was a significant correlation between NPC break and NPC recovery, as well as between NPC break and stereoacuity. However, there was no correlation between NPC break and PFV break, or between PFV break and NFV break values. In contrast, all dynamic measures of vergence correlated significantly: convergence and divergence peak velocity, convergence peak velocity and vergence flipper facility, and divergence peak velocity and vergence flipper facility. See Table 3(a) and 3(b) for r and p values.

Between Systems

Both the maximum amplitudes of accommodation (binocular AA) and vergence (NPC break) correlated significantly. Similarly, both positive relative measures of accommodation (PRA) and vergence (PFV break) were highly correlated. However, the negative relative measures for accommodation (NRA) and vergence (NFV break) did not correlate (Table 3(a)).

Dynamically, there was only a significant correlation between binocular accommodative flipper facility and vergence facility. Convergence peak velocity did not correlate with the increasing step accommodative peak velocity, and similarly divergence peak velocity did not correlate with the decreasing step accommodative peak velocity (Table 3(b)).

Placebo

There was no effect on any of the vergence and accommodative parameters following the placebo training. See Thiagarajan for detailed results.[12]

Discussion

The key objective of the present study was to test the hypothesis that "oculomotor rehabilitation is effective in individuals with mTBI having oculomotor-based signs and symptoms following mild traumatic brain injury." Accordingly, the OMT resulted in significant improvement in nearly all aspects of the oculomotor behaviors that were initially abnormal. With only six hours total of laboratory-based training (three hours for each oculomotor subsystem) over six weeks, which is minimal, marked improvements were found in several key dynamic and static behaviors of accommodation and vergence; in contrast, there was no effect of the placebo training on any of the parameters tested. The positive effects of the OMT suggested intact neuroplasticity in the compromised brain following head injury in these adult individuals. Furthermore, the affected oculomotor subsystems per se responded positively to the vision neuro-rehabilitation. Eight out of the eight (100%) dynamic parameters demonstrated significant improvements following OMT, whereas eight of the 10 (80%) static parameters also improved significantly. The remaining two static parameters improved in the predicted direction, although not significantly. With the OMT, the following global changes occurred: 1) accommodation and vergence manifested significantly faster responsivity (increased peak velocity and increased flipper facility), and 2) the maximum response amplitudes of both accommodation and vergence significantly increased (i.e., AA and NPC). These four key parameters may prove to be oculomotor "biomarkers" for the oculomotor diagnosis, and treatment, in mTBI.[33,34]

Static Findings

Several static clinical parameters were found to change markedly following OMT. The maximum amplitude of convergence (NPC) increased significantly (~30-40%); this was evident from the NPC break and recovery values. Several clinical case studies, and a few population studies, that evaluated the effect of OMT in individuals with mTBI support this finding.[22-24,35,36] In addition, under the non-congruent training condition, where accommodation was maintained constant and the vergence demand was systematically altered, relative vergence amplitude increased in both the convergent and divergent directions. This was evident from both the PFV and NFV break values. In addition, this improvement in overall convergence ability enhanced near stereoacuity, presumably by increased vergence response accuracy and hence reduced steady-state fixation disparity vergence error. Thus, the retinal images were falling more closely on corresponding retinal points. Similar to vergence, the maximum accommodative response (i.e., amplitude of accommodation) increased significantly (25-35%) under both monocular and binocular test conditions. This increase in maximum amplitude was true under the naturalistic-viewing congruent conditions (i.e., the vergence and accommodative demands changed equally). However, this was not the case in the non-congruent condition, where vergence was maintained constant and the accommodative demand was systematically altered step-wise, that is, the NRA and PRA tests. However, these relative accommodative values *were* already normal at baseline, and hence the OMT would not be expected to have any further effect.

Dynamic Findings

At baseline, the dynamic trajectory for both convergence and divergence was markedly slow, with it exhibiting reduced peak velocity. The values were abnormally low/slow and below the normal "main sequence" peak velocity versus response amplitude distribution.[37] These results were consistent with recent laboratory baseline findings in this population.[7,38] Following the OMT, however, there was a significant increase in peak velocity by ~40% for convergence and ~20% for divergence. This increase in peak velocity correlated between the convergence and divergence systems (Table 3(b)). The present results are also consistent, in part, with the findings of Alvarez et al in their pilot study.[38] They found similar increases in peak velocity following convergence training, but not for divergence as this was normal at baseline, in the 2 mTBI subjects tested with convergence insufficiency (CI) following 18 hours of similar vision therapy techniques. Furthermore, in the present study, vergence peak velocity was found to correlate with vergence flipper facility rate, as might be expected (Table 3(b)), since peak velocity is a primary parameter embedded in the more global dynamic flipper parameter. At baseline, vergence facility rate was ~50% less than the clinic norm. With OMT, however, subjects could now fuse with the BO and BI prisms rapidly, with a significant two-fold increase in facility rate. However, this value was still below the clinic norm (15±3 cpm).

There were similar findings for the accommodative system. The group mean peak velocity was ~40% less than found in normal individuals for both increasing (2 to 4D) and decreasing (4 to 2D) steps of accommodation at baseline.[8] This result of reduced response velocity in individuals with mTBI is consistent with earlier findings in this population.[8] Following the OMT, however, there was a significant increase in peak velocity by ~30% from the baseline value for both increasing and decreasing steps of accommodation, although it did not normalize. That is, subjects now attained their new, steady-state, response level considerably more rapidly. In addition to the laboratory-based dynamic changes observed, the related critical clinical parameters also exhibited marked and significant improvement following OMT. The above objective findings correlated well with the clinical findings, for example with accommodative flipper (+/- lenses) facility rates, as has been the case in the past in non-TBI, young-adult patients with accommodative insufficiency.[39] At baseline, the accommodative facility rate was ~50% less than the clinic norm, both monocularly and binocularly. Following OMT, however, facility rates increased two-fold and normalized, when compared to the baseline values, under all test conditions.

Correlation of Improvements Within and Between Systems

Correlation of static and dynamic parameters within a system revealed several interesting results (Tables 3(a) and 3(b)).

Within the accommodative system, and following OMT, an increase in the AA in one eye correlated with the AA increase in the fellow eye, as well as with the binocular AA increase, as might be expected due to correlation of accommodation between the two eyes.[40] Furthermore, the binocular AA correlated with PRA, as expected, since both involved training to increase the overall accommodative response level, albeit under different test conditions. These results suggest centrally-based blur processing improvement following OMT. While this was true for increasing accommodation, it was not true for reducing accommodation, as demonstrated by absence of a significant correlation between the monocular AA and the NRA value. This might be due to the different directional aspects of the accommodative training related to system directional and/or response range non-linearity.[41] Similarly, there was an overall and significant improvement in accommodative dynamics, with correlation between increasing and decreasing steps of accommodative peak velocity. This demonstrates faster responsivity reflecting a more time-optimal, neurological control strategy[42] following the OMT. Similarly, the clinical analogue of the laboratory-based accommodative dynamics showed improvement. Accommodative flipper facility correlated between each eye, as well as under monocular and binocular testing conditions. Furthermore, the monocular accommodative facility increase correlated with both increasing and decreasing steps for the laboratory-based accommodative findings. This suggests improved dynamics for both the subjective clinical and the objective laboratory test conditions, per earlier studies in the non-TBI population.[39] Neurophysiologically, this increase in dynamics has been attributed to increase in the firing rate of velocity-related accommodative neurons, as well as improved neural firing synchrony, as found for vergence in humans.[38,43]

Similar improvements were also found within the vergence system. The improved NPC break value correlated with the NPC recovery value, as expected, since both involved increase in convergence function. This suggests that with improved maximum vergence amplitude, there was faster recovery from the transient diplopia typically elicited during such testing. However, unlike accommodation, this increase in maximum vergence amplitude (NPC break) did not correlate with increase in positive relative vergence amplitude (PFV break). This lack of correlation could be attributed to the increased individual variability found for this parameter in several of the subjects. While the improvements were similar in the binocular AA (28%) and the PRA (24%), they were not similar for the NPC break (41%) and the PFV break (23%). This discrepancy could also be a factor contributing to the lack of correlation mentioned above. However, the NPC break correlated with near stereoacuity, thus suggesting improved vergence accuracy and sustain as described earlier. Furthermore, similar to accommodation, the relative amplitudes (PFV and NFV breaks) showed lack of correlation, perhaps owing to the system's directional response non-linearity in the convergent versus divergent directions.[37] While there were mixed findings for some of the static vergence parameters as described above, the laboratory-based vergence dynamics and the related clinically-based vergence flipper facility were highly correlated, as was the case for accommodation. Overall vergence dynamics showed marked improvement. They also exhibited significant correlation between the convergence and divergence peak velocities, as well as between the vergence flipper facility and peak velocity for both convergence and divergence. This faster responsivity was expected, since the global vergence facility parameter is the clinical analogue of the laboratory-based dynamic measure, as described earlier for accommodation.[39] A similar result from a recent pilot study revealed increased cortical activity per fMRI brain imaging with improved vergence dynamics following vergence-only OMT.[38] This has been attributed to increased "neuronal recruitment" and improved "neuronal synchronization" following the OMT.[38,43] Thus, the underlying neural substrates reflecting the oculomotor improvements following vision rehabilitation (i.e., vision therapy) are beginning to be uncovered directly with ongoing advances in brain imaging.

The accommodative and vergence systems are tightly coupled. They interact synkinetically via the cross-links (accommodative-convergence [AC] and convergence-accommodation [CA]).[29] Per models of these two oculomotor systems,[29] any change in disparity vergence will influence accommodation to some extent directly through CA, since CA receives its primary input from disparity vergence. Similarly, any change in blur-driven accommodation will invoke a change in vergence to some extent directly via the AC link, as its primary input is from blur-driven accommodation.[29] Accordingly, accommodative measures under binocular-testing conditions, and related vergence parameters, would be expected to correlate. Both systems' maximum amplitudes (NPC break and binocular AA) correlated significantly, thus showing an overall, coordinated improvement in oculomotor behavior in near visual space, with an increased three-dimensional range for maintaining accurate focus and fusion. Regarding the relative amplitudes, PRA and PFV break alone were correlated, while NRA versus NFV break were not. Again, this could be attributed to individual variability for the negative relative amplitudes, as well as directional response non-linearity of these two systems.[16]

Dynamically, both accommodative and vergence flipper facilities correlated, as expected, due to the aforementioned inter-related interactions between the two systems. However, the laboratory-based finding of peak velocity did not correlate between the accommodation and vergence systems. This is not surprising, however, as the accommodative peak velocity was derived under monocular test conditions, and hence might not correlate with the binocularly-derived vergence peak velocity. Accommodative peak velocity under binocular viewing conditions should be tested, and any correlation assessed in future investigations.

Clinical Implications

The results of our current set of oculomotor-based laboratory investigations,[7-12] and specifically those dealing with vergence and accommodation, provide important guidance and have relevant implications for the contemporary optometric rehabilitative practice. First, the results revealed considerable residual brain/visual system plasticity, more specifically for the oculomotor system per se. No one can deny or doubt efficacy of the OMT, as the laboratory findings were obtained objectively, and the placebo component showed no effect.[10-12] Furthermore, the objective laboratory findings correlated with many of the key clinical parameters, as well as with the subjectively reported reduction in related symptoms.[10-12] Second, the degree of improvement in nearly all parameters was remarkable, since each system received only 3 hours total of OMT. While many of the parameters improved significantly, most did not normalize; there are two possible interpretations. Either there was not sufficient residual brain plasticity to improve further and normalize, or more time should have been devoted to the therapeutic intervention. Typically, those with mTBI receive 20-30 hours of OMT, or more, to attain significant improvements in clinical signs and reduction in symptoms. Thus, a study needs to be performed using different "doses" of OMT, for example, 10, 20, and 30 hours, to assess when the continuation of significant improvement is no longer evident. If the results show that even 30 (or more) hours still results in many parameters not "normalizing," then it suggests somewhat limited residual neural/visual system plasticity in the adult with mTBI.

Conclusions

The findings of this investigation have answered the key question posed in the Introduction: OMT in those with mTBI results in significant improvements, with intersystem correlation, thus suggestive of considerable residual neural/visual system plasticity, even in an adult, damaged brain. This is perhaps more remarkable when one considers that the total OMT was only 3 hours for each system. These findings provide impetus for the optometrist to provide similar types of OMT, in those with oculomotor dysfunctions in mTBI, with a predicted high level of success.

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