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ABSTRACT

THE EFFECT OF VERGENCE VISION TRAINING ON BINOCULARLY NORMAL SUBJECTS

**by
Henry Talasan**

Vergence is the disjunctive (inward or outward) movement of the eyes that is stimulated by retinal disparity (difference of where an image is projected to the retina and the fovea). A recent randomized clinical trial showed the efficacy of vision therapy for children with the binocular dysfunction known as convergence insufficiency is 73%. However, it is unknown whether binocularly normal persons will have any significant change to their vergence ocular motor system if they participate in vision training sessions. A total of ten ($n = 10$) binocularly normal persons participated in this study (18 to 28 years of age). A haploscope with an integrated infrared video-based eye tracking system manufactured by ISCAN presented vergence stimuli to the subject to record eye movement data before and after 12 hours of vision therapy with a custom LabVIEW program. Vision therapy entailed a random walk of 2° and 4° steps at near and far space along with ramps ranging from 1° to 20° of total vergence angular rotation. All processing and statistical analyses were conducted in MATLAB. All subjects experienced a significant decrease in time to peak velocity ($p < 0.05$). However, each subject's peak velocity values were subject dependent and either increased, decreased, or maintained at the same level after training. The peak velocity of responses to 2° steps began to approach a more critically damped linear control system after vision training supporting an improvement in the accuracy of responses. Data support

that even in binocularly normal control subjects; vision therapy improves vergence eye movements quantified as significant improvements in the time to fuse the new target and significantly more accurate responses compared to each subject's baseline measurements..

**THE EFFECT OF VERGENCE VISION TRAINING ON BINOCULARLY
NORMAL SUBJECTS**

**by
Henry Talasan**

**A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering**

Department of Biomedical Engineering

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TABLE OF CONTENTS

| Chapter | Page |
|--|------|
| 1 INTRODUCTION | 1 |
| 1.1 The Visual System.. | 1 |
| 1.2 The Vergence System | 6 |
| 1.2.1 Factors in Vergence Dynamics | 7 |
| 1.2.2 Models of the Vergence System | 9 |
| 1.3 Heterophoria | 10 |
| 1.4 Binocular Dysfunctions | 11 |
| 1.5 Objective | 12 |
| 2 METHODOLOGY | 13 |
| 2.1 Subjects/Screening | 13 |
| 2.2 Experimental Set-up | 15 |
| 2.2.1 Instrumentation | 15 |
| 2.2.2 VisualEyes Software, Stimuli Presentation, and Data Collection | 16 |
| 2.3 Experimental Procedure | 17 |
| 2.3.1 Assessment Procedure | 17 |
| 2.3.2 Training Procedure | 20 |
| 2.4 Data Analysis | 21 |
| 2.4.1 Data Processing | 21 |
| 2.4.2 Velocity Data Hypothesis Testing | 22 |
| 2.4.3 Analysis of Damped Responses | 22 |
| 2.4.4 Phase Data and Response Amplitude | 24 |
| 3 RESULTS | 25 |

| | |
|---|----|
| 3.1 Peak Velocity Results | 25 |
| 3.2 Damping Changes | 29 |
| 3.3 Phase Data and Response Amplitude | 32 |
| 4 DISCUSSION and CONCLUSIONS | 35 |
| 4.1 Discussion | 35 |
| 4.2 Conclusions and Future Work | 37 |
| APPENDIX A DATA | 39 |
| REFERENCES | 58 |

LIST OF TABLES

| Table | Page |
|---|-------------|
| 2.1 Summary of Subjects | 15 |
| 2.2 Conversions of the Phoria Level to Initial Position in Experiment | 19 |
| 3.1 Summary of Peak Velocity Data | 30 |
| 3.2 Summary of Time to Peak Velocity Data | 31 |
| 3.3 Post-hoc Analysis of Peak Velocities | 32 |
| 3.4 Summary of Damping Changes | 34 |
| 3.5 Summary of Response Amplitude to Target (R:T) Ratio | 40 |

LIST OF FIGURES

| Figure | Page |
|---|-------------|
| 1.1 Diagram of the eye | 1 |
| 1.2 Diagram of the retina | 2 |
| 1.3 The visual pathway | 3 |
| 1.4 Visual processing pathways | 4 |
| 1.5 Left human eyeball with EOM | 6 |
| 1.6 Dual Mode Model | 10 |
| 2.1 Haploscope experimental set-up | 16 |
| 2.2 Stimuli used in experiment | 17 |
| 2.3 Assessment stimuli movements | 20 |
| 2.4 Assessment procedure protocol | 21 |
| 2.5 Vergence training exercises | 22 |
| 2.6 Damped responses characteristics | 24 |
| 2.7 Extrapolation of the initial response amplitude | 26 |
| 3.1 Typical vergence eye movement data | 29 |
| 3.2 Comparison of damped systems | 35 |
| 3.3 Examples of response changes in damping | 36 |
| 3.4 Frequency graph of damping changes | 37 |
| 3.5 Phase plots of damped systems | 38 |
| 3.6 Phase data | 39 |

LIST OF SYMBOLS

| | |
|------------|-------------------------|
| $^{\circ}$ | Degrees of eye rotation |
| Δ | Diopters |
| α | Significance Level |

CHAPTER 1

INTRODUCTION

1.1 The Visual System

The visual system allows humans to perceive the world around them from colors to the shapes of objects. However, the visual system is very complex and precise coordination of both the motor and sensory systems of the visual system in order to construct a single image.

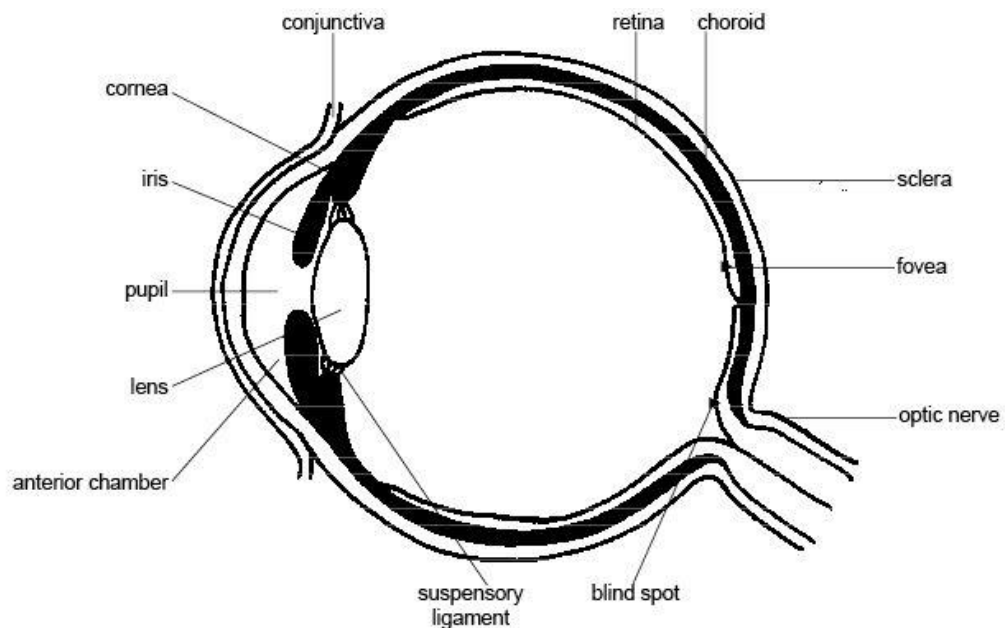


Figure 1.1 Diagram of the eye
Source: [60]

The eye is an intricate organ that is composed of three layers, the sclera (outer layer), the choroid (middle layer) and the retina (inner layer) shown in Figure 1.1. The lens that is connected to the ciliary body adjusts the lens' shape to focus the light onto the macula, a region in the back of the eye. In the center of the macular is the fovea, the area responsible for sharp and central vision.

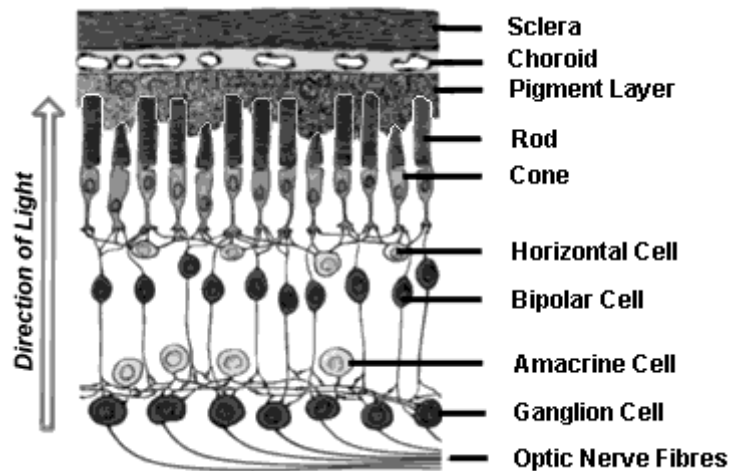


Figure 1.2 Diagram of the retina and the types of cells it contains.
Source: [61]

The retina functions to process light that comes into the eye into an image. The retinal image is essentially a flat representation of the environment. However, when retinal images of both the left and right eyes are combined, the concept of space can be derived. [1] The retina consists of five main cell types: photoreceptors, bipolar cells, amacrine cells, horizontal cells and ganglion cells (Figure 1.2). The two types of photoreceptors are called cones and rods. Rods mediate vision in dim light and are located outside the macula whereas cones are for color vision and are located within the macula. When an image has been processed, the visual information is transmitted to the cerebral cortex via the optic nerve. [2]

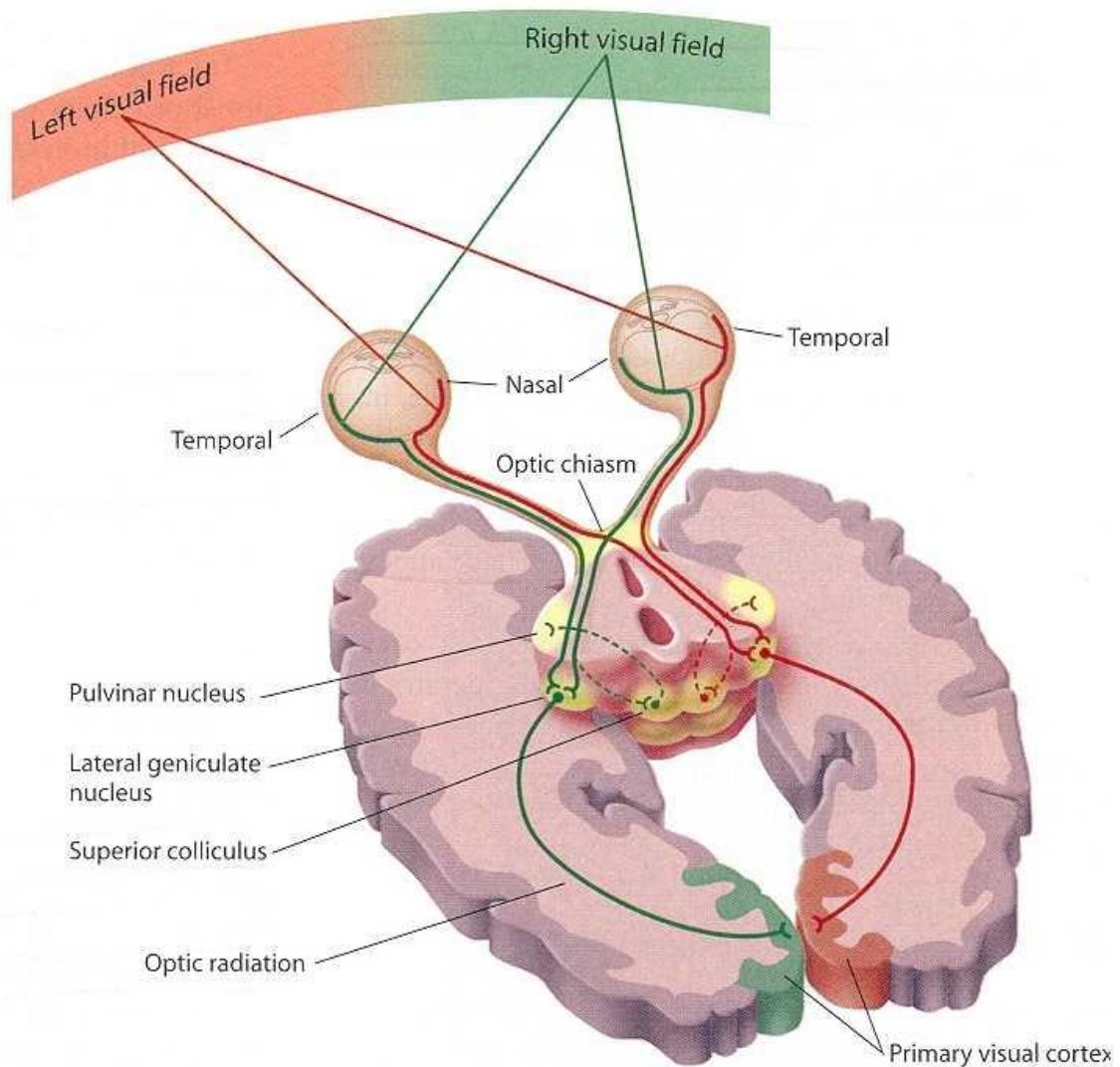


Figure 1.3 The visual pathway.
Source: [62]

Figure 1.3 depicts the visual pathway that the visual information takes towards the primary visual cortex in the cerebellum. The optic nerves from the left and right eye cross at the optic chiasm in the hypothalamus of the brain. In this area, the visual information is combined and divided with respect to the visual fields. The optic chiasm allows the visual information to be combined and divided according to which visual field it is from. The nasal retinal region of the

right eye and temporal retinal region of the left eye make up the right visual field, while the temporal retinal region of the right and the nasal retinal region of the left are responsible for the left visual field. The left side of the primary visual cortex receives information about the right visual field while the right side of the primary visual cortex obtains information from the left. [2]

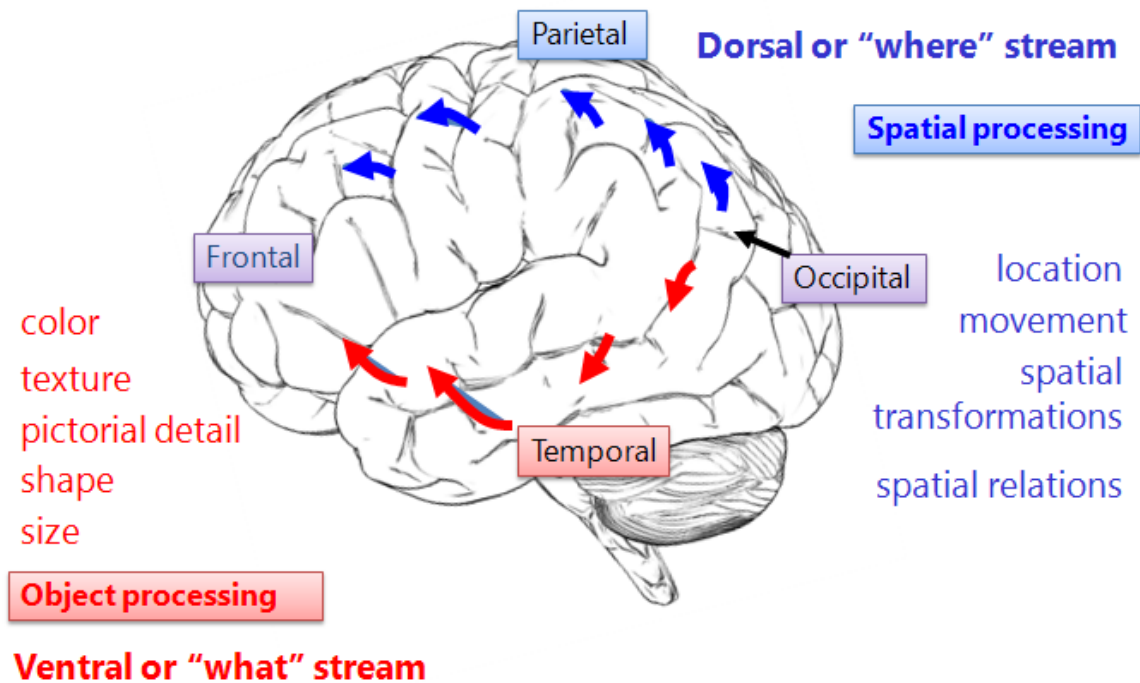


Figure 1.4 Visual processing in the cerebellum featuring the Ventral and Dorsal pathways
Source: [63]

The primary visual cortex transmits the information to two primary pathways, the dorsal stream and the ventral stream shown in Figure 1.4. The dorsal stream, or the "where stream", travels from the occipital lobe to the parietal lobe. It is involved in spatial processing. Visual information within the ventral stream, or the "what stream", begins at the occipital lobe and then progresses towards the temporal lobe. This pathway is involved in interpreting object processing information such as the color, size, or shape of the object. [2]

In addition to the processing in the cerebellum, more information is processed in the pretectum that lies between the thalamus and the midbrain, the superior colliculus in the midbrain, and the suprachiasmatic nucleus within the hypothalamus. These regions are responsible for the pupillary light reflex, the circadian rhythm, and the coordination of head and eye movements, respectively.

[2]

The eye is innervated by six extraocular muscles (EOM): the superior, inferior, medial, and lateral recti muscles and the superior and inferior obliques (see Figure 1.5). These muscles allow rotation of the eye about the x, y, and z axes. The superior and inferior oblique muscles are responsible for intorsion and extorsion movements of the eyes, respectively. The medial rectus acts as a principal adductor, the lateral rectus as a principal abductor, the inferior rectus as the principal elevator and superior rectus as the principal depressor. [3] Adductor and abductor rotate the eyes toward and away from the nose, respectively whereas the elevator and depressor rotate the eyes upward and downward, respectively. There are several units that can measure magnitude of eye rotation: diopters (Δ), degrees ($^\circ$), and meter-angles.

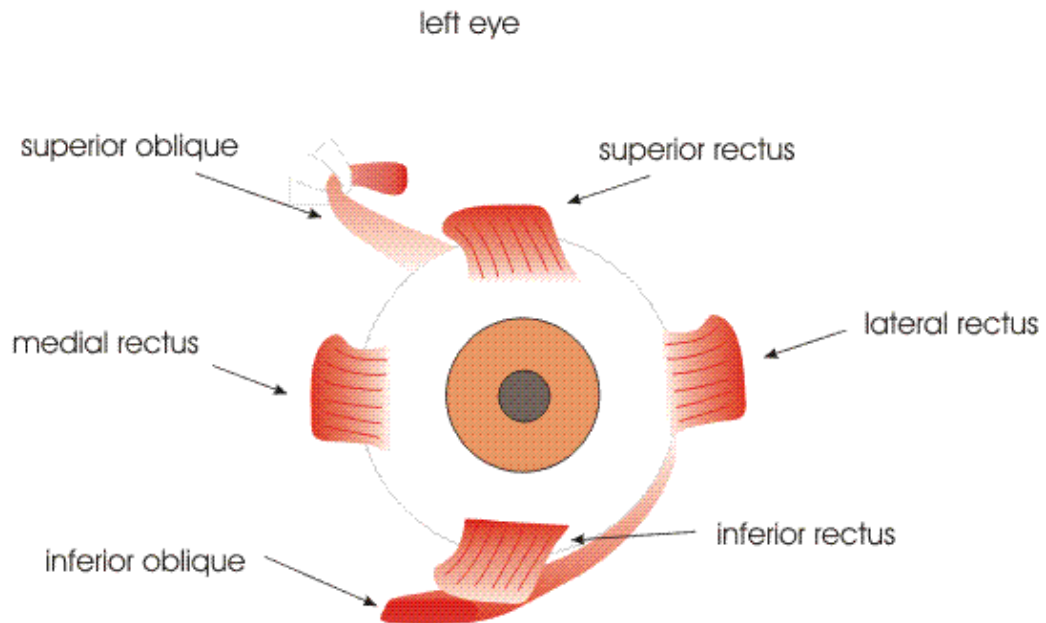


Figure 1.5 Schematic drawing of the left human eyeball with the extraocular muscles
Source: [64]

Humans use many different kinds of eye movements including the following types: saccades, smooth pursuit, and vergence movements. Saccades are rapid side to side eye movements used to redirect gaze, smooth pursuit movements track moving targets, and vergence movements as the primary study in this thesis will be explained more in-depth in the next section.

1.2 The Vergence System

Vergence is a disjunctive eye movement responsible for spatial depth. There are two types of eye movements within the vergence systems, convergence (the inward rotation of the eyes) and divergence (outward rotation of the eyes) that

track targets from far to near and near to far, respectively.

There are three primary stimuli to the vergence system that enable clear, single binocular vision of close or distant objects. These are disparity, retinal blur, and proximity. The tonic vergence level is reached when there is an absence of vergence cues. Disparity is the difference of where a new target is relative to the old target. If the disparity is large enough, one of the targets is perceived as diplopic (double image) because the images fall outside Panum's Fusional area. Retinal blur controls accommodative-vergence which in turn controls the lens. By controlling the lens, the target becomes focused and clear. Proximal cues are gathered from experience and estimates the distance of an object. Lastly, dark vergence or tonic vergence is the resting position of the eyes in the absence of all three visual cues.

1.2.1 Factors in Vergence Dynamics

The horizontal vergence system maintains the images on the retina with precision, but some error persists. The remaining disparity is known as fixation disparity. Fixation disparity is the vergence error between the fixation point and the target plane where the fixation point may be in front of (crossed) or behind (uncrossed) the target plane. [4-7] Previous studies have shown that there is a strong relationship between fixation disparity and vergence dynamics. [8-11] Patel's neural network model also predicts the asymmetry of convergence and divergence peak velocities by using fixation disparities. [12-14]

Factors such as prediction [15-17], adaptation [16,18], age [19], fatigue

[20], and phoria adaptation [13, 21-24] influence the vergence dynamics. One study by Alvarez et al. (2006) has reported that divergence peak velocity is influenced by the initial vergence position; if the eyes are more converged, then the divergence velocity is faster. On the other hand, convergence did not show significant dependence on initial vergence position. [25] A recent study demonstrates that with a more controlled environment, convergence does demonstrate dependence on vergence initial position; if the eyes are less converged, then the convergence velocity is faster. [26]

Rambold et al. (2006) showed that vergence showed an age-related increase in latency and decrease in peak velocity. [19] However, Yang and colleagues (2009) reported no aging effect on the peak velocity of vergence. [27] Fatigue has also been shown to decrease vergence peak velocity where the reduction in peak velocity was related to the number of repetition of vergence stimuli. [20]

Several studies have reported inconsistencies in the temporal relationship between convergence and divergence movements. One study stated that divergence and convergence have similar latency. [28] Some have reported that convergence latency is less than divergence latency while others have reported that convergence has a longer latency than divergence. [17, 29-31] Alvarez et al. (2005) reported that the stimulus range, the initial vergence position, strongly influenced the divergence and convergence latency. Convergence latency was shorter compared to divergence latency for stimuli located at far space and vice versa for the stimulus located at near space. Furthermore, vergence latency has

been shown to vary between individuals accounting for some of the controversy reported in the literature. [32]

Different types of stimuli also affects vergence dynamics. The oscilloscope line stimulus such as the one depicted in Figure 2.2A was found to keep accommodation constant while a Difference-of-Gaussian (DOG) like in Figure 2.2B shown negligible accommodative stimulation. [65] Also, it has been reported that the peak velocity of vergence was not significantly different for the various types of accommodative stimuli. [21, 33]

1.2.2 Models of the Vergence System

A rich history exists in the literature that describes the model-representation of the neural control of the disparity-vergence system. [12, 28, 34-39] These models can be classified into two categories: 1) negative feedback control or 2) pre-programmed control operating synergistically with a negative feedback control. The models with only negative feedback control are continuously modified such that the error between the input and output is adjusted until the error is negligible. Negative feedback control models can be further separated into a single negative feedback control [28, 35, 36], or multiple channels where each channel is operated using separate negative feedback controls. [12, 37]

One model that incorporates pre-programmed control is the Dual Mode Model. It includes a pre-programmed (transient) component and a feedback (sustained) component where the transient component influences the peak velocity of the response and the sustained component attains the accuracy of the

final position. [34, 38] When a person looks from far to near two very different control systems are activated. For example, a baseball batter tracks a ball with the smooth tracking vergence system utilizing feedback control. With feedback control, the visual system views the external world and decides how much to rotate the eyes in order to keep the object of interest on the fovea. This control paradigm results in high accuracy at the expense of requiring more time to make the movement. Hence, feedback controlled movements are slow. However, a student who fixates on the blackboard and then fixates on a nearby book uses a step vergence response to quickly transition from far to near which is initially controlled via a pre-programmed component. With pre-programmed control, the brain takes a snapshot of the external world, and devises a command to move the eyes to the new target but does not acquire more external visual information until the pre-programmed response is complete. These movements are fast but not as accurate as feedback controlled movements. The Dual Mode Model is shown in Figure 1.6.

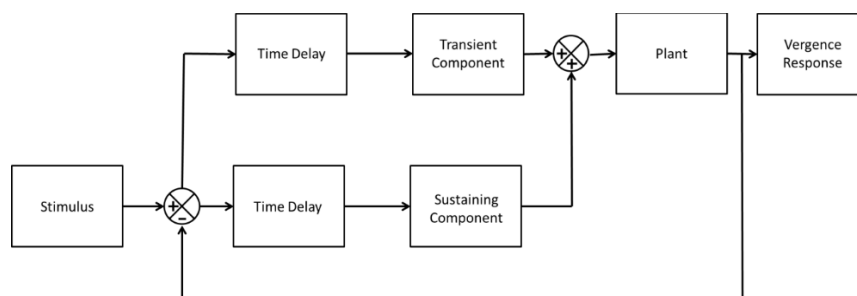


Figure 1.6 Dual Mode Model

1.3 Heterophoria

Heterophoria (more commonly referred to simply as phoria) is the tendency for

one or both eyes to wander away from the position where both eyes are looking together in the same direction. [66] There are two methods to measure phoria, associated and dissociated. Associated heterophoria is when both eyes perceive a visual stimulus and can be measured as the prism needed to correct a fixation disparity while the person perceives a binocular stimulus. [40] Dissociated heterophoria is measured when the binocular stimulus is absent. [41-43] A common clinical technique uses the Maddox rod test where one eye is occluded. The occluded eye will then deviate to its “resting position” by rotating inward, rotating outward, or remain in its current position. These three positions are termed esophoria, exophoria, and orthophoria, respectively.

If a person fixates on a stimulus for a prolonged amount of time, a change in the phoria may occur. This phenomenon is known as phoria adaptation. Phoria adaptation may be induced by sustained fixation to targets [42], a stereoscope [44], prisms [45], or lenses. In other words, if a person fixates on a near target for a long time, his phoria level may shift inward or experience an esophoric shift in phoria. The same can be said for when a person maintains fixation on a far target as well.

1.4 Binocular Dysfunctions

Binocular dysfunctions such as convergence insufficiency, convergence excess, divergence insufficiency, and divergence excess affect a person’s vergence system. Binocular dysfunctions may cause symptoms such as headaches, blurred vision, vision fatigue, or double vision when working at near or far

distances. [46] Therefore, these dysfunctions negatively impact activities of daily living.

Convergence insufficiency (CI) is a dysfunction of particular interest. A common diagnosis for CI is when the person's exophoria is greater at near than at distance and the patient has one or both of the following: a remote near point of convergence or decreased fusional vergence. Current treatments of this dysfunction include the following: surgery or home-based therapy solutions such as home-based pencil push-ups or office-based vision therapy. However, studies have reported that patients treated with office-based vision therapy improve better than patients who only do home-based therapy. [47] Office-based treatment procedures include: the brock string, binocular accommodative facility, vectograms, computer orthoptics, etc. [46]

1.5 Objective

This study will quantify differences in the ocular motor system of binocularly normal persons before and after training by using a haploscope with an integrated eye movement system to record eye movements. Normal binocular vision was defined as having a normal near point of convergence (NPC) of less than 10 cm, assessed by measuring the distance a high acuity target was perceived as diplopic along the subject's midline [54], and a normal stereopsis (\leq 50 seconds of arc), assessed by the Randot Stereopsis Test (Bernell Corp., South Bend, IN, USA). It is hypothesized that the difference between vergence

movements before and after the training sessions may be minimal and we may not see any significant changes since these subjects are asymptomatic.

CHAPTER 2

METHODOLOGY

An experimental procedure was devised to serve as an assessment protocol for binocularly normal subjects' vergence system around their phoria level. Subjects underwent this assessment protocol before and after a specified training regimen. A haploscope with eye movement recording instrumentation was utilized for both the assessment protocol and training regimen. Data were processed and analyzed using MATLAB. This section describes the set-up of the experiment and the experimental protocols used within this study.

2.1 Subjects/Screening

Ten binocularly normal subjects between the ages of 18 and 28 years participated in this study. Subjects consisted of six males and four females. Subjects signed informed consent approved by the NJIT Institution Review Board which is in accordance to the Declaration of Helsinki. Table 2.1 summarizes the subjects and their visual parameters.

To be eligible for the study, the subjects had to have normal binocular vision defined as a near point of convergence less than 10 cm, 20/20 corrected (if needed) acuity, stereopsis less than 70 sec of arc, a phoria level between (4 esophoria to 6 exophoria), and no history of neurological or eye disease or dysfunction. These parameters are measured using following clinical tests: the Maddox rod test, stereopsis tests, and the near point of convergence test. The

Maddox rod test records subject's phoria level (i.e., the resting position of the eyes) in Δ . In order to calculate the phoria into units of degrees from units of Δ , the following equation is used:

$$\theta = \tan^{-1} \frac{\Delta}{100} \quad \text{Equation 2.1}$$

Where, θ is eye rotational angle in degrees. The stereopsis tested whether the subject has normal depth perception. The near point of convergence is the distance along midline that a person perceives a high acuity target as double measured with a ruler in cm.

Table 2.1 Summary of Subjects

| # | I.D. | Age/Gender | Phoria (Δ) | Stereopsis (sec) | | NPC (cm) |
|----|------|------------|---------------------|------------------|--------|----------|
| | | | | Fine | Coarse | |
| 1 | CER | 21/F | 6 EXO | 30 | 250 | 9 |
| 2 | CXY | 21/M | ORTHO | 20 | 250 | 3 |
| 3 | HXT | 23/M | 2 EXO | 20 | 250 | 6 |
| 4 | JAK | 20/F | 4 EXO | 40 | 250 | 3 |
| 5 | JIM | 21/F | 4 EXO | 30 | 250 | 6 |
| 6 | KDK | 22/F | 2 EXO | 20 | 250 | 7 |
| 7 | PPP | 28/M | 6 EXO | 20 | 250 | 3 |
| 8 | SJL | 26/M | 4 EXO | 20 | 250 | 6 |
| 9 | SRC | 20/M | ORTHO | 25 | 250 | 2 |
| 10 | TAC | 18/M | ORTHO | 30 | 250 | 3 |

2.2 Experimental Set-up

2.2.1 Instrumentation

The experimental set-up can be seen in Figure 2.1. For this study, the ISCAN RK-826PCI binocular tracking system (Burlington, MA) was the instrumentation used to non-invasively record horizontal eye movements using the pupil as a natural anatomical marker. This device can also detect vertical movements of the pupil, the movements of the reflection from the corneal surface, and the pupil diameter. This system utilizes an infrared emitter and camera to capture the eye movement data. The infrared emitter bathes the subject's eyes in infrared light at a wavelength of 950 nm with a power of 1.2 mW/cm^2 , which is considerably lower than the ANSI Z136 specification safety limit of 10 mW/cm^2 . Two specialized cameras, one for each eye, quantify the absence of infrared light from the pupil and determine the location of the centroid of the pupil with ISCAN's software. The manufacturer reports an average accuracy of 0.3° over a $\pm 20^\circ$ horizontal and vertical range.

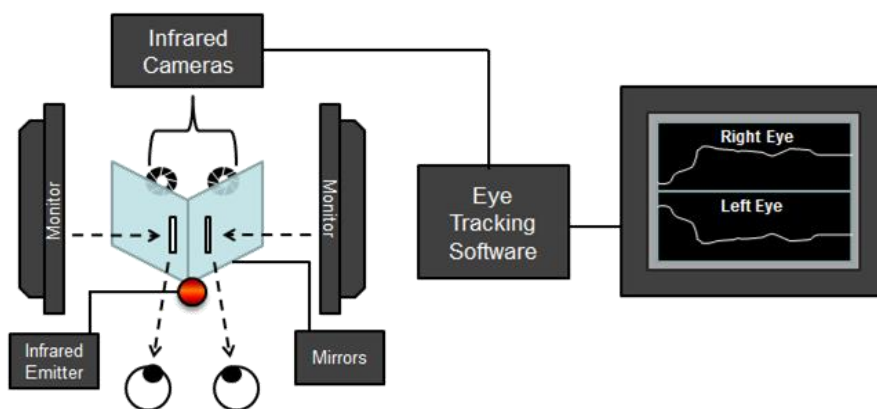


Figure 2.1 Haploscope experimental set-up that simulates disparity vergence while the eye tracking instrumentation records eye movements.

2.2.2 VisualEyes Software, Stimuli Presentation, and Data Collection

A custom LabVIEW™ (National Instruments, Austin, TX) program named VisualEyes controlled the stimuli presentation and data collection from the instrumentation. This software was designed to independently generate visual stimuli to the left and right eye with the use of two monitors and partially reflecting mirrors. [48] As can be seen in Figure 2.1, VisualEyes produces a stimulus in each monitor that is transposed onto the mirrors. The mirrors then reflect the stimulus to each eye, simulating a symmetrical disparity vergence stimulus along the subject's midline. The total distance that the stimulus travels is kept at 40 cm throughout the experimental procedure. This is to keep accommodation constant. A 12-bit digital acquisition (DAQ) card (National Instruments 604 E series, Austin, TX) digitized the eye movement data recorded from each eye from the ISCAN instrumentation with a sample frequency of 500 Hz.

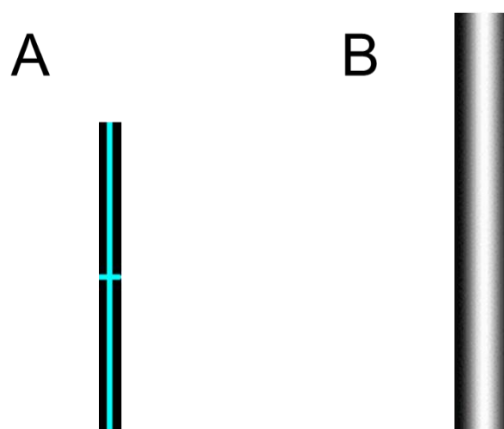


Figure 2.2 Stimuli used in the assessment procedure (A) and the training procedure (B).

2.3 Experimental Procedure

2.3.1 Assessment Procedure

In order to determine whether changes occur to the vergence ocular motor system, an assessment procedure was devised to be given to the subjects before and after their training regimen. The assessment protocol was different than the training protocol to reduce the influence of procedural learning. This assessment procedure revolved around the subject's phoria level to reduce the influence of phoria adaptation. Prior research has shown that phoria adaptation is significantly correlated to the subject's current phoria position. [21, 22, 26, 55] It was assumed that the subject's phoria level was consistent throughout the procedure. As previously stated, the vergence system has limitations on the convergence and divergence ranges. This was one of the main reasons why this study constrained the phoria level of subjects to 4 esophoria to 6 exophoria. Table 2.2 presents the conversion between a subject's phoria level and the initial position of their assessment protocol as per Equation 2.1. As can be seen, subjects with a 6 exophoria and a 4 exophoria had visual stimuli that share the same initial vergence angle. This was done purposefully to widen the range of possible subjects. If a subject had a phoria level in between these values, the adjacent phoria level closer to orthophoria was chosen (e.g., if subject measured phoria level was 3 exophoria, then 2 exophoria was chosen since 2 exophoria was closer to orthophoria).

Table 2.2 Conversion of the phoria level to initial position in experiment

| <u>Phoria Level (Δ)</u> | <u>Monocular Initial Position ($^{\circ}$)</u> | <u>Binocular Position ($^{\circ}$)</u> |
|---|---|---|
| 4 esophoria | 6.52 | 13.04 |
| 2 esophoria | 5.37 | 10.74 |
| orthophoria | 4.22 | 8.44 |
| 2 exophoria | 3.07 | 6.14 |
| 4 exophoria | 1.92 | 3.84 |
| 6 exophoria | 1.92 | 3.84 |

Four types of movements were presented with the stimulus shown in Figure 2.3 and recorded during an assessment: steps, disappearing steps, ramps, and step ramps. Step movements are instantaneous vergence movements from one symmetrical vergence angle to another. Step movements were presented at the following: two initial positions: the subject's phoria level or 2° divergent or convergent from the phoria level. A disappearing step takes an initial vergence step to a target but distinguishes after 0.100 seconds. The 100 msec duration is used because the latency of a vergence response is at least 160 msec hence the response is mostly the preprogrammed portion of the vergence system. Ramps gradually move toward the target position at a constant velocity. Finally, step ramps involve a step that is immediately followed by a ramp. All steps in the assessment were 2° binocular steps (i.e., a 1° rotational movement for each eye) and all ramps had a speed of $1^{\circ}/s$. As presented in the Figure 2.3, this study utilized a total of 12 types of movements. However, only the convergence and divergence steps were analyzed in this study in the interest of

time and brevity.

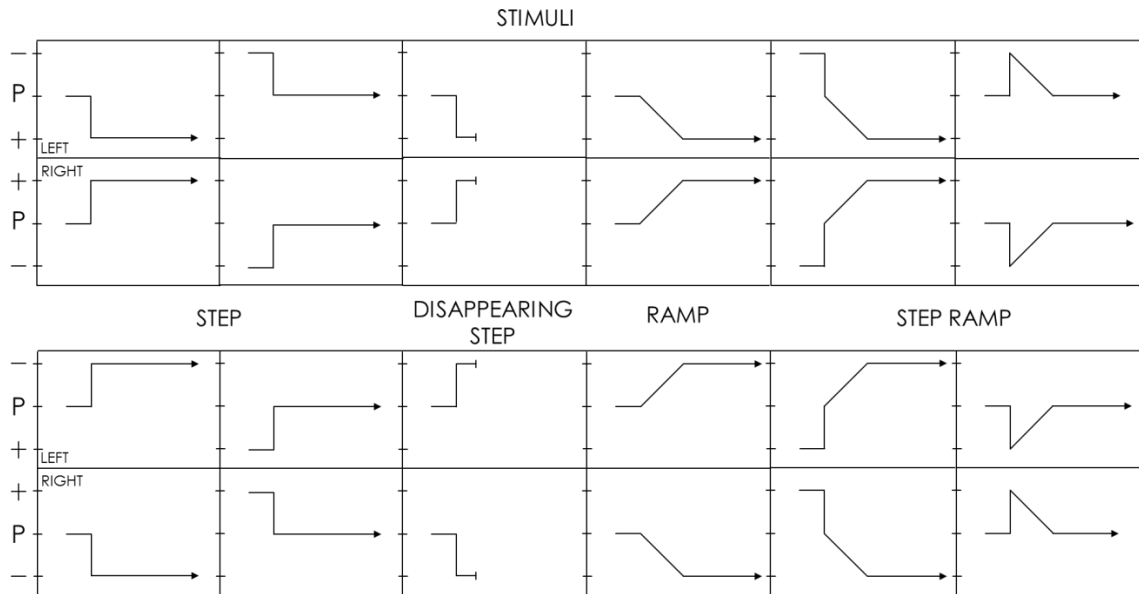


Figure 2.3 Different types of stimuli movements to be presented for the left and right eye (12 in total). Convergence (top) and divergence (bottom) movements are shown. P denotes subject's phoria level. (+) is one degree (monocular) positive of the phoria level. (-) is one degree (monocular) negative of the phoria level.

Figure 2.4 shows the sequence of the assessment. The subject is first dark adapted for 5 minutes to allow for uncoupling of accommodation and vergence to relax both systems [49, 50]. Then, a phoria measurement is taken. Each loop consisted of a 6-point monocular calibration (3 points per eye covering the range of visual stimuli presented) and 20 vergence stimuli (2 trials of each movement) that totals to 6 calibrations and 100 recorded movements. The 6-point calibration was done similarly to the phoria measurement but three calibration points are shown to both the left and right eye. Since subjects had the affinity to drift from their initial position, both the phoria measurement and 6-point calibration were difficult to correctly obtain. Therefore, the phoria measurement

was ultimately not used, and a 2-point calibration method was used to replace the 6-point calibration method. The order of the movements was randomized so the subject could not predict when the next movement would be presented and which stimulus type or direction (converging or divergence) would be presented. A random delay of 0.5 to 2.0 sec before the movement reduced anticipatory cues which are known to alter the temporal and dynamic properties of vergence responses. [56-59] Each subject performed the assessment procedure twice on different days for test-retest repeatability both before and after vergence training.

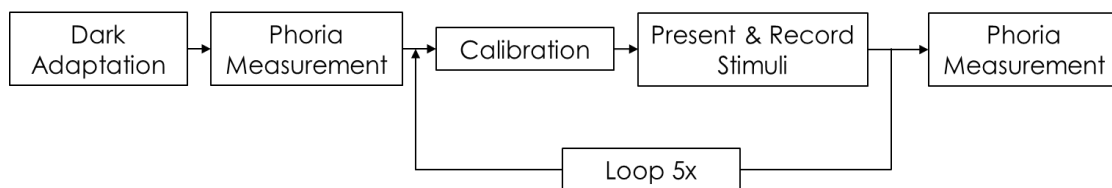


Figure 2.4 Experimental protocol for assessment procedure.

2.3.2 Training Procedure

Each subject then underwent 12 one-hour vergence training sessions in the haploscope. Each session consisted of: 2 five-minute trials of a random walk at far, 2 five-minute trials of a random walk at near, and 4 five-minute trials of ramps that range from 1° to 20° at 1 °/sec, 2 °/sec, 4 °/sec, and 8 °/sec (see Figure 2.5). The random walk trial randomizes 2 degree or 4 degree vergence steps within the “far” or “near” range. The “far” range is defined at 1 – 5 degrees of vergence angular position whereas the “near” range is defined at 16 – 20 degrees of eye rotation. As with the assessment procedure, a random delay precedes each step.

The sequence of the trials for a session was changed depending on whether the training day was odd or even to counterbalance the near and far visual stimulation.

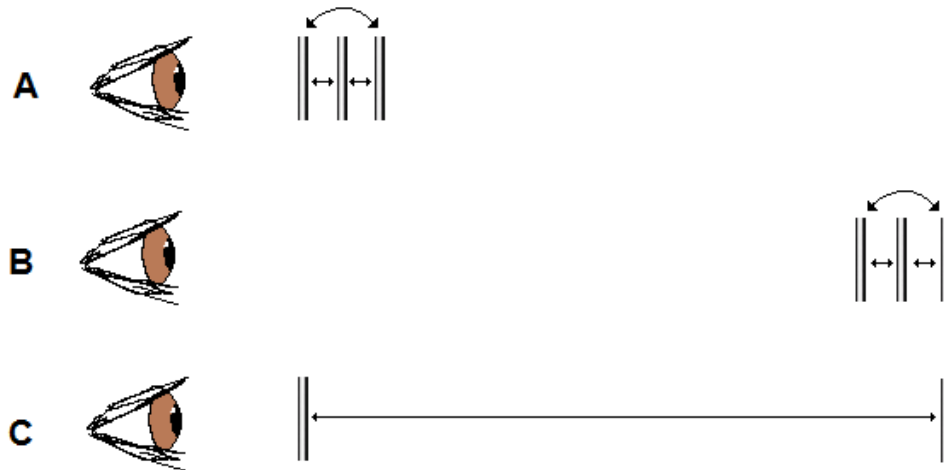


Figure 2.5 Types of vergence training exercises used in the training procedure. Figures (A) and (B) presents random walks at near and far, respectively. Figure (C) presents ramp movements.

2.4 Data Analysis

2.4.1 Data Processing

Data was imported into and analyzed with MATLAB. The complete vergence movement for each movement was done by subtracting the raw left eye data from the raw right eye data. This is done with the assumption that the resolutions when the data were gathered of both eyes were exactly the same. As previously stated, a 2-point calibration was used. Some more assumptions were made in order to do this: that the subjects start at the initial position as they initiate the movement and end at the target 2° away after fixating on it for a second. The first

50 points were used as the initial position and the average of the last 100 points were used as the target position. Other steps in data processing include low-pass filtering the data (a fourth-order Butterworth filter with a cutoff frequency at 50 Hz), blink removal, removal of outliers (i.e., any responses that were more than 2 standard deviations from the mean), and acquisition of the velocity trace of each movement. Blinks are easily identified because the signal saturates at the upper and lower bound when the eye image is lost due to closing the eye.

2.4.2 Velocity Data Hypothesis Testing

Hypothesis testing was performed on the data collected. This test compared the peak velocity and time to peak velocity of each type of stimulus for each subject before and after vergence training. Hypothesis testing for the peak velocity utilized a paired t-Test assuming unequal variances where the null hypothesis is that there is no change in the peak velocity value after vergence training ($\alpha = 0.05$). Hypothesis testing for the time to peak velocity utilized a paired t-Test assuming unequal variances where the null hypothesis is that there is no decrease in the time to peak velocity ($\alpha = 0.05$). A repeated measures ANOVA was performed on the peak velocities of each type of movement across all subjects, before and after training.

2.4.3 Assessment of Damped of Responses

The average position data of each step movement showed characteristics of damped second-order systems. Figure 2.6 presents the qualities of each of the

three types of damping used to categorize the each of the average movements of each subject. To be an underdamped response, the data must exhibit overshoots and a relatively high amplitude velocity (although the velocity is not always the case). To be considered an overdamped response, the data must exhibit distortion of its velocity waveform and a relatively small amplitude velocity. For critically damped responses, none of the above are exhibited.

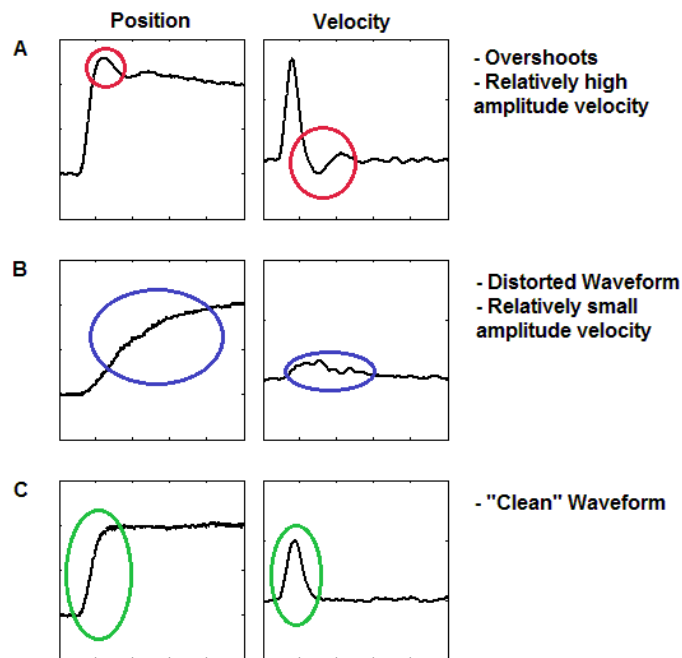


Figure 2.6 Examples of position and velocity traces of different types of damped responses. The characteristics to the right are used to classify responses into one of these categories: (A) underdamped responses, (B) overdamped responses, and (C) critically damped responses.

Only the data from before training were categorized. The data after vergence training were compared to their before training counterparts to see if any changes to the responses occurred. If the pre-training data were considered underdamped, then a reduction in the overshoots would be considered a shift towards being critically damped. If the pre-training data were considered

overdamped, then a less distorted waveform in the velocity trace and an increase in peak velocity would be considered a shift towards being critically damped.

2.4.4 Response Amplitude of Movements

The damping ratio of the responses proved difficult to obtain, therefore in an attempt to quantify the degree of damping of each movement, the phase data of the movements were plotted to measure the initial response amplitudes. The technique to attain the response amplitude was previously published by Alvarez *et al.* [51] By plotting velocity as a function of position, the dynamics of the response with respect to position can be analyzed. The response amplitude is the position in degrees at which the velocity reaches zero. In order to account for the fusion sustaining phase, a second-order polynomial fit was done on the phase data at a specific interval (around 0.25 to 0.5 seconds) where the fusion initiating phase is dominant. The positive root of the fitted curve served as the response amplitude of the fusion initiating phase. The response amplitude to target ratio was calculated for each movement.

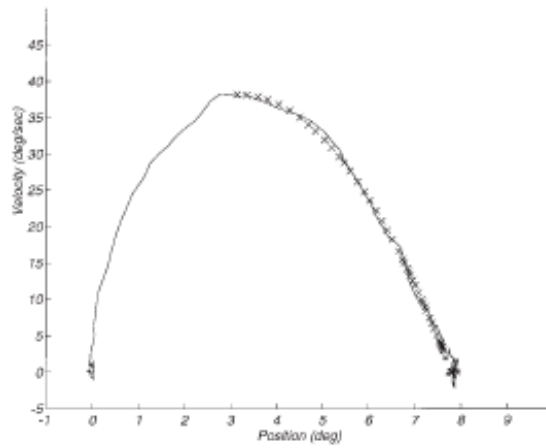


Figure 2.7 The extrapolation of the initial response amplitude by plotting velocity data versus positional data. The solid line is recorded data. X's indicate the fitted second-order polynomial curve.

Source: [51]

CHAPTER 3

RESULTS

3.1 Peak Velocity Results

Typical vergence eye movement data for a step is shown in Figure 3.1. All data starts at the instant when the stimulus initiates movement. As can be seen in the figure, the peak velocity, V_P , and the time to peak, T_P , is measured from the velocity trace. Tables 3.1 and 3.2 summarize these values. These tables also show the results of the paired t-Tests comparing the pre-training and post-training values of V_P and T_P for convergence steps from phoria, divergence steps to phoria, divergence steps from phoria, and divergence steps to phoria for each subject. For peak velocities, 17 out of the 40 total movements show a significant difference ($\alpha = 0.05$) before and after training with 8 out of the 10 subjects showing differences in at least one of the movements. Of those that show significance, 7 had an increase in velocity. The highest average peak velocity with one standard deviation was 19.09 ± 3.09 °/s for subject 7's convergence step towards the phoria level after training while the lowest average peak velocity with one standard deviation was 4.01 ± 0.66 °/s for subject 3's divergence step away from the phoria level before training. For the repeated measures ANOVA on the mean peak velocities of each type of movement across all subjects, before and after training, Mauchly's test indicated that the assumption of sphericity had been violated ($p < 0.001$), so the Greenhouse-Geisser correction was used. There was no significant effect of treatment ($F(1.869,$

16.823)=17.079, $p < 0.001$). The post-hoc analysis for the paired t-Tests is summarized in Table 3.3; note that the adjusted α value is 0.00625. For times to peak, 31 out of 40 total movements show a significant difference ($\alpha = 0.05$) before and after training. All subjects had at least one movement that had a significantly lower time to peak. The slowest average time to peak was 0.535 ± 0.099 seconds for subject 3 before training and the fastest was 0.287 ± 0.008 seconds for subject 10.

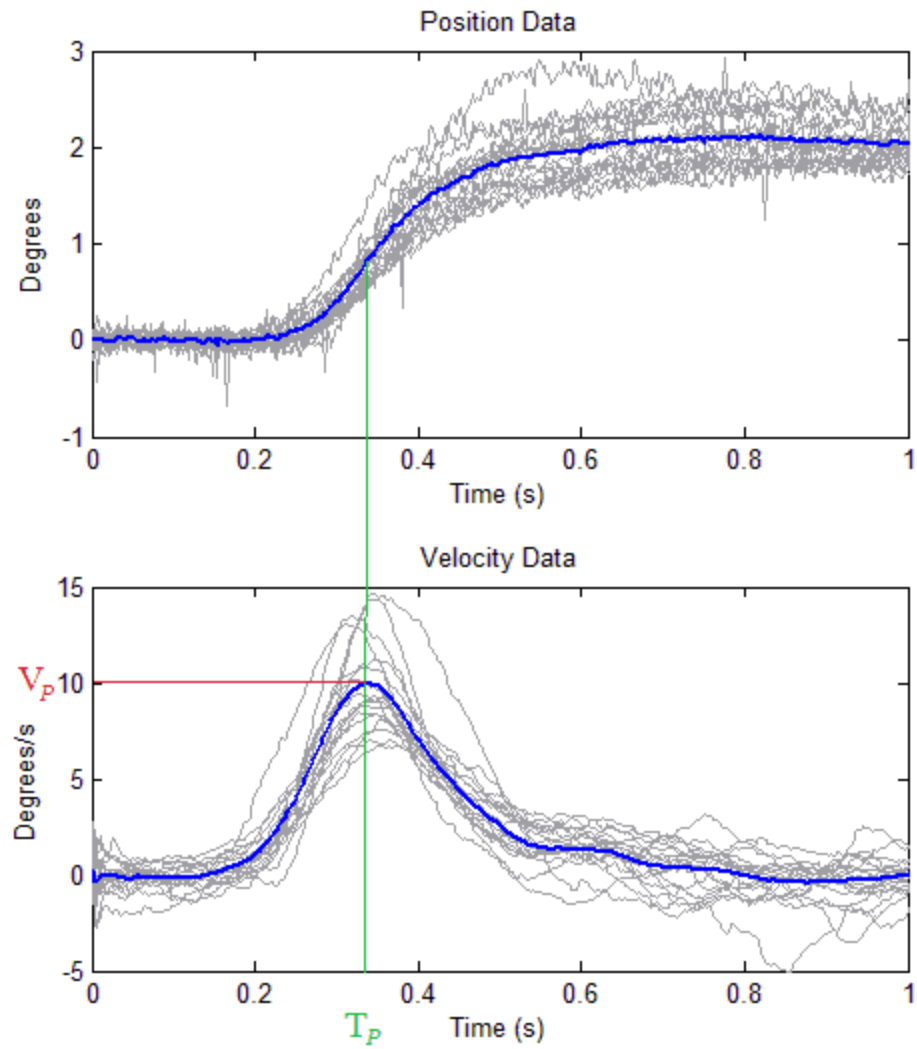


Figure 3.1 Typical vergence eye movement data. Shown are a position trace (top) and a velocity trace (bottom) versus time. Grey lines indicate a single trial. The blue line indicates the mean vergence movement. Time to Peak T_P and Peak Velocity V_P (shown) are derived from the velocity trace.

Table 3.1 Summary of Peak Velocity Data

A = convergence step from phoria
 C = divergence step from phoria

B = divergence step to phoria
 D = convergence step to phoria

| Subject | Movement | V_p (°/s) (before) | N | V_p (°/s) (after) | N | p-value |
|---------|----------|----------------------|-----------|---------------------|-----------|------------------|
| 1 | A | 8.61 ± 1.53 | 18 | 7.69 ± 1.01 | 14 | 0.051 |
| | B | 10.22 ± 1.67 | 33 | 8.97 ± 1.21 | 34 | <0.001 |
| | C | 7.37 ± 0.69 | 12 | 6.30 ± 1.00 | 14 | 0.004 |
| | D | 13.94 ± 1.87 | 30 | 9.96 ± 1.95 | 38 | <0.001 |
| 2 | A | 8.18 ± 1.54 | 16 | 9.30 ± 1.45 | 16 | 0.018 |
| | B | 8.92 ± 1.55 | 27 | 9.31 ± 1.32 | 30 | 0.119 |
| | C | 6.13 ± 1.26 | 17 | 7.46 ± 1.89 | 17 | 0.034 |
| | D | 11.62 ± 1.79 | 26 | 11.48 ± 1.86 | 32 | 0.838 |
| 3 | A | 10.58 ± 1.97 | 16 | 11.45 ± 1.61 | 15 | 0.272 |
| | B | 6.07 ± 0.77 | 24 | 8.53 ± 2.03 | 34 | 0.013 |
| | C | 4.01 ± 0.66 | 15 | 7.20 ± 1.42 | 18 | <0.001 |
| | D | 17.38 ± 2.47 | 32 | 17.09 ± 2.72 | 35 | 0.519 |
| 4 | A | 9.64 ± 0.87 | 18 | 9.02 ± 2.05 | 17 | 0.995 |
| | B | 11.47 ± 1.28 | 33 | 9.10 ± 1.80 | 36 | <0.001 |
| | C | 9.92 ± 0.91 | 12 | 8.74 ± 1.24 | 16 | 0.0662 |
| | D | 14.08 ± 1.60 | 30 | 12.34 ± 1.45 | 34 | 0.955 |
| 5 | A | 8.14 ± 0.84 | 15 | 10.29 ± 2.59 | 19 | 0.005 |
| | B | 9.70 ± 1.45 | 36 | 7.93 ± 1.04 | 35 | <0.001 |
| | C | 7.53 ± 0.77 | 17 | 7.11 ± 1.44 | 18 | 0.294 |
| | D | 10.33 ± 1.25 | 27 | 13.74 ± 3.34 | 37 | 0.001 |
| 6 | A | 11.48 ± 1.56 | 15 | 9.16 ± 1.48 | 15 | <0.001 |
| | B | 8.64 ± 1.20 | 26 | 7.44 ± 0.84 | 25 | <0.001 |
| | C | 7.43 ± 1.43 | 15 | 7.11 ± 1.64 | 14 | 0.572 |
| | D | 13.73 ± 1.69 | 28 | 10.29 ± 0.82 | 24 | <0.001 |
| 7 | A | 18.24 ± 3.45 | 14 | 15.07 ± 3.46 | 15 | 0.020 |
| | B | 7.98 ± 1.16 | 26 | 7.98 ± 0.91 | 25 | 0.984 |
| | C | 6.31 ± 1.24 | 18 | 5.75 ± 1.38 | 19 | 0.199 |
| | D | 18.66 ± 1.42 | 12 | 19.09 ± 3.09 | 14 | 0.648 |
| 8 | A | 8.95 ± 1.86 | 16 | 8.33 ± 1.52 | 18 | 0.376 |
| | B | 5.07 ± 1.66 | 33 | 4.75 ± 0.89 | 27 | 0.982 |
| | C | 4.95 ± 1.29 | 16 | 4.69 ± 1.41 | 12 | 0.666 |
| | D | 9.15 ± 2.09 | 28 | 10.04 ± 2.15 | 29 | 0.147 |
| 9 | A | 9.54 ± 2.35 | 18 | 8.25 ± 2.04 | 16 | 0.155 |
| | B | 7.92 ± 1.07 | 28 | 8.46 ± 0.94 | 26 | 0.186 |
| | C | 5.81 ± 0.66 | 17 | 6.69 ± 0.97 | 17 | 0.009 |
| | D | 10.46 ± 1.47 | 23 | 9.35 ± 1.49 | 36 | 0.005 |
| 10 | A | 12.21 ± 2.40 | 17 | 13.23 ± 2.78 | 16 | 0.481 |
| | B | 7.49 ± 1.45 | 35 | 8.17 ± 1.44 | 28 | 0.184 |
| | C | 5.89 ± 1.49 | 12 | 6.99 ± 1.56 | 13 | 0.080 |
| | D | 14.54 ± 2.43 | 32 | 15.22 ± 2.90 | 27 | 0.288 |

Table 3.2 Summary of Time to Peak Velocity Data

A = convergence step from phoria
 C = divergence step from phoria

B = divergence step to phoria
 D = convergence step to phoria

| Subject | Movement | T _p (s) (before) | N | T _p (s) (after) | N | p-value |
|---------|----------|-----------------------------|----|----------------------------|----|---------|
| 1 | A | 0.380 ± 0.030 | 18 | 0.325 ± 0.029 | 14 | <0.001 |
| | B | 0.373 ± 0.032 | 33 | 0.297 ± 0.024 | 34 | <0.001 |
| | C | 0.369 ± 0.039 | 12 | 0.321 ± 0.019 | 14 | <0.001 |
| | D | 0.410 ± 0.039 | 30 | 0.332 ± 0.027 | 38 | <0.001 |
| 2 | A | 0.393 ± 0.015 | 16 | 0.337 ± 0.024 | 16 | <0.001 |
| | B | 0.388 ± 0.016 | 27 | 0.343 ± 0.019 | 30 | <0.001 |
| | C | 0.402 ± 0.023 | 17 | 0.361 ± 0.023 | 17 | <0.001 |
| | D | 0.396 ± 0.023 | 26 | 0.333 ± 0.021 | 32 | <0.001 |
| 3 | A | 0.318 ± 0.016 | 16 | 0.302 ± 0.012 | 15 | 0.065 |
| | B | 0.462 ± 0.037 | 24 | 0.398 ± 0.031 | 34 | 0.002 |
| | C | 0.535 ± 0.099 | 15 | 0.431 ± 0.048 | 18 | 0.002 |
| | D | 0.320 ± 0.014 | 32 | 0.303 ± 0.014 | 35 | 0.002 |
| 4 | A | 0.295 ± 0.014 | 18 | 0.332 ± 0.051 | 17 | 0.258 |
| | B | 0.315 ± 0.017 | 33 | 0.289 ± 0.034 | 36 | <0.001 |
| | C | 0.321 ± 0.016 | 12 | 0.309 ± 0.025 | 16 | 0.005 |
| | D | 0.291 ± 0.013 | 30 | 0.298 ± 0.017 | 34 | 0.011 |
| 5 | A | 0.399 ± 0.023 | 15 | 0.337 ± 0.016 | 19 | <0.001 |
| | B | 0.425 ± 0.024 | 36 | 0.380 ± 0.026 | 35 | <0.001 |
| | C | 0.419 ± 0.038 | 17 | 0.385 ± 0.033 | 18 | 0.005 |
| | D | 0.421 ± 0.021 | 27 | 0.361 ± 0.016 | 37 | <0.001 |
| 6 | A | 0.342 ± 0.036 | 15 | 0.315 ± 0.026 | 15 | 0.016 |
| | B | 0.387 ± 0.021 | 26 | 0.354 ± 0.025 | 25 | <0.001 |
| | C | 0.377 ± 0.038 | 15 | 0.369 ± 0.030 | 14 | 0.266 |
| | D | 0.325 ± 0.025 | 28 | 0.321 ± 0.018 | 24 | 0.282 |
| 7 | A | 0.297 ± 0.012 | 14 | 0.295 ± 0.012 | 15 | 0.346 |
| | B | 0.354 ± 0.016 | 26 | 0.338 ± 0.015 | 25 | <0.001 |
| | C | 0.363 ± 0.042 | 18 | 0.347 ± 1.246 | 19 | 0.112 |
| | D | 0.326 ± 0.021 | 12 | 0.302 ± 0.009 | 14 | 0.001 |
| 8 | A | 0.385 ± 0.029 | 16 | 0.354 ± 0.032 | 18 | 0.004 |
| | B | 0.440 ± 0.074 | 33 | 0.392 ± 0.026 | 27 | <0.001 |
| | C | 0.389 ± 0.236 | 16 | 0.369 ± 0.052 | 12 | 0.387 |
| | D | 0.408 ± 0.088 | 28 | 0.361 ± 0.027 | 29 | 0.014 |
| 9 | A | 0.373 ± 0.023 | 18 | 0.344 ± 0.022 | 16 | <0.001 |
| | B | 0.462 ± 0.029 | 28 | 0.358 ± 0.025 | 26 | <0.001 |
| | C | 0.439 ± 0.074 | 17 | 0.373 ± 0.036 | 17 | 0.001 |
| | D | 0.377 ± 0.008 | 23 | 0.354 ± 0.032 | 36 | 0.100 |
| 10 | A | 0.331 ± 0.021 | 17 | 0.298 ± 0.014 | 16 | 0.001 |
| | B | 0.344 ± 0.037 | 35 | 0.308 ± 0.031 | 28 | 0.030 |
| | C | 0.315 ± 0.024 | 12 | 0.328 ± 0.050 | 13 | 0.551 |
| | D | 0.323 ± 0.014 | 32 | 0.287 ± 0.008 | 27 | 0.011 |

Table 3.3 Post-hoc Analysis of Peak Velocities

| | | Paired Differences | | | | | t | df | Sig. (2-tailed) |
|---------|---------------------|--------------------|----------------|-----------------|---|----------|--------|----|-----------------|
| | | Mean | Std. Deviation | Std. Error Mean | 95% Confidence Interval of the Difference | | | | |
| | | | | | Lower | Upper | | | |
| Pair 1 | CtP_pre - CfP_pre | 2.83200 | 2.16908 | .68592 | 1.28033 | 4.38367 | 4.129 | 9 | .003 |
| Pair 2 | CtP_pre - DtP_pre | 5.04100 | 3.57317 | 1.12993 | 2.48491 | 7.59709 | 4.461 | 9 | .002 |
| Pair 3 | CtP_pre - DfP_pre | 6.85400 | 3.55484 | 1.12414 | 4.31102 | 9.39698 | 6.097 | 9 | .000 |
| Pair 4 | CtP_pre - CtP_post | .52900 | 2.16811 | .68562 | -1.02198 | 2.07998 | .772 | 9 | .460 |
| Pair 5 | CtP_pre - CfP_post | 3.21000 | 2.19139 | .69298 | 1.64238 | 4.77762 | 4.632 | 9 | .001 |
| Pair 6 | CtP_pre - DtP_post | 5.32500 | 2.84658 | .90017 | 3.28868 | 7.36132 | 5.916 | 9 | .000 |
| Pair 7 | CtP_pre - DfP_post | 6.58500 | 3.09424 | .97848 | 4.37151 | 8.79849 | 6.730 | 9 | .000 |
| Pair 8 | CfP_pre - DtP_pre | 2.20900 | 3.85510 | 1.21909 | -.54877 | 4.96677 | 1.812 | 9 | .103 |
| Pair 9 | CfP_pre - DfP_pre | 4.02200 | 3.59279 | 1.13614 | 1.45187 | 6.59213 | 3.540 | 9 | .006 |
| Pair 10 | CfP_pre - CtP_post | -2.30300 | 2.42962 | .76831 | -4.04104 | -.56496 | -2.997 | 9 | .015 |
| Pair 11 | CfP_pre - CfP_post | .37800 | 1.66520 | .52658 | -.81321 | 1.56921 | .718 | 9 | .491 |
| Pair 12 | CfP_pre - DtP_post | 2.49300 | 3.34185 | 1.05678 | .10239 | 4.88361 | 2.359 | 9 | .043 |
| Pair 13 | CfP_pre - DfP_post | 3.75300 | 3.44666 | 1.08993 | 1.28741 | 6.21859 | 3.443 | 9 | .007 |
| Pair 14 | DtP_pre - DfP_pre | 1.81300 | .79382 | .25103 | 1.24513 | 2.38087 | 7.222 | 9 | .000 |
| Pair 15 | DtP_pre - CtP_post | -4.51200 | 4.13940 | 1.30899 | -7.47315 | -1.55085 | -3.447 | 9 | .007 |
| Pair 16 | DtP_pre - CfP_post | -1.83100 | 3.37536 | 1.06738 | -4.24558 | -.58358 | -1.715 | 9 | .120 |
| Pair 17 | DtP_pre - DfP_post | .28400 | 1.41444 | .44729 | -.72783 | 1.29583 | .635 | 9 | .541 |
| Pair 18 | DfP_pre - DfP_post | 1.54400 | 1.42664 | .45114 | .52345 | 2.56455 | 3.422 | 9 | .008 |
| Pair 19 | DfP_pre - CtP_post | -6.32500 | 4.05213 | 1.28140 | -9.22372 | -3.42628 | -4.936 | 9 | .001 |
| Pair 20 | DfP_pre - CfP_post | -3.64400 | 3.19947 | 1.01176 | -5.93276 | -1.35524 | -3.602 | 9 | .006 |
| Pair 21 | DfP_pre - DtP_post | -1.52900 | 1.68677 | .53340 | -2.73564 | -.32236 | -2.867 | 9 | .019 |
| Pair 22 | DfP_pre - DfP_post | -.26900 | 1.35002 | .42692 | -1.23475 | .69675 | -.630 | 9 | .544 |
| Pair 23 | CtP_post - CfP_post | 2.68100 | 1.42570 | .45085 | 1.66111 | 3.70089 | 5.947 | 9 | .000 |
| Pair 24 | CtP_post - DtP_post | 4.79600 | 3.38680 | 1.07100 | 2.37323 | 7.21877 | 4.478 | 9 | .002 |
| Pair 25 | CtP_post - DfP_post | 6.05600 | 3.48062 | 1.10067 | 3.56611 | 8.54589 | 5.502 | 9 | .000 |
| Pair 26 | CfP_post - DtP_post | 2.11500 | 2.63943 | .83466 | -.22687 | 4.00313 | 2.534 | 9 | .032 |
| Pair 27 | CfP_post - DfP_post | 3.37500 | 2.69465 | .85212 | 1.44736 | 5.30264 | 3.961 | 9 | .003 |
| Pair 28 | DfP_post - DfP_post | 1.26000 | .87286 | .27602 | .63559 | 1.88441 | 4.565 | 9 | .001 |

Legend

- CtP – convergence step to phoria
- CfP – convergence step from phoria
- DtP – divergence step to phoria
- DfP – divergence step from phoria
- '_pre' indicates before training
- '_post' indicates after training

3.2 Damping Changes

This section presents the results of any damping changes to the responses that have occurred after training. Table 3.4 presents the summary of the damping changes. In Table 3.4, the first letter represents the damping category (i.e., underdamped, overdamped, critically damped) that the average movement response demonstrated before training. The second letter represents whether there was a shift towards a critically damped response. If there was a shift, the second letter would be a "C". If no notable shift was seen, the letter would stay the same. For example, if the first letter was U for underdamped and no change was seen, the second letter would be U as well. Figure 3.3 provides examples of how the changes were categorized. The frequency plot of these changes can be seen in Figure 3.4. In total 12 responses started as critically damped and sustained, 25 responses demonstrated a shift toward critically damped, and 3 responses were either underdamped or overdamped responses that demonstrated no notable shift toward a critically damped system.

Table 3.4 Summary of Damping Changes

Movement Type:

A = convergence step from phoria
C = divergence step from phoria

B = divergence step to phoria
D = convergence step to phoria

| Subject | Movement Type | | | |
|---------|---------------|-------|-------|-------|
| | A | B | C | D |
| 1 | C → C | U → C | C → C | U → C |
| 2 | U → C | O → C | O → C | U → C |
| 3 | U → C | O → C | O → C | U → C |
| 4 | O → C | U → C | C → C | C → C |
| 5 | O → C | U → C | C → C | U → U |
| 6 | C → C | U → C | C → C | U → C |
| 7 | U → C | U → C | O → O | U → C |
| 8 | C → C | O → C | O → O | C → C |
| 9 | C → C | U → C | O → C | C → C |
| 10 | C → C | O → C | O → C | U → C |

Legend:

C: Critically Damped

O: Overdamped

U: Underdamped

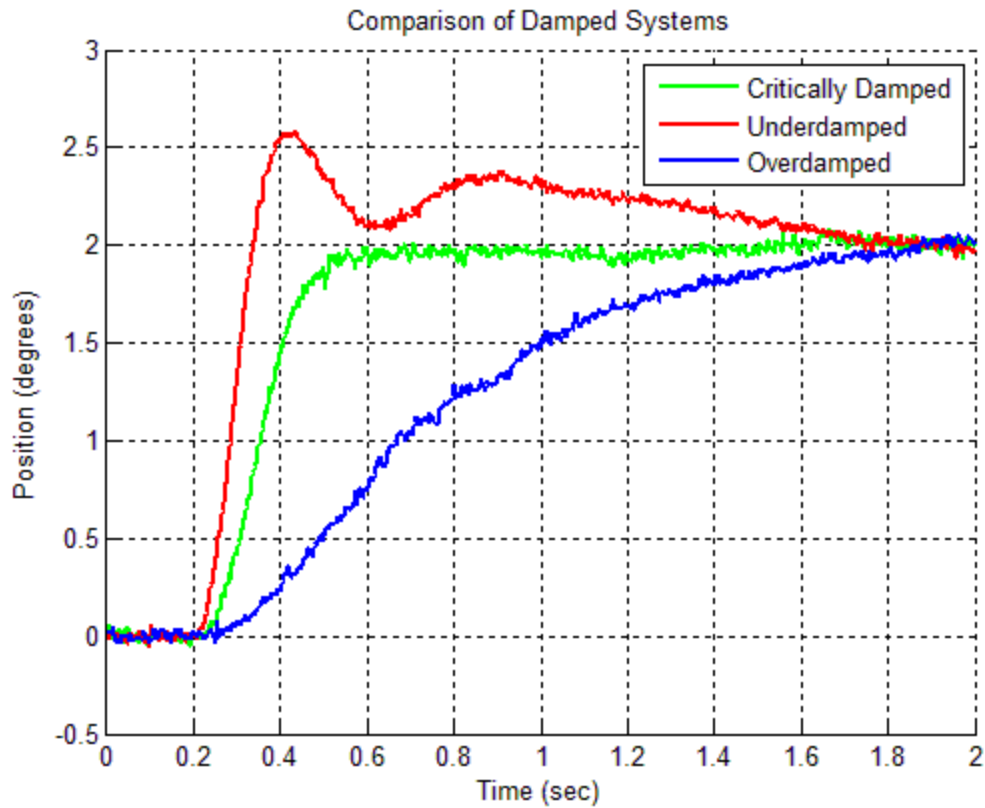


Figure 3.2 Comparison of the example positional traces of responses that are critically damped (green), underdamped (red), and overdamped (blue). The critically damped and underdamped responses are convergence steps, while the overdamped response is a divergence step.

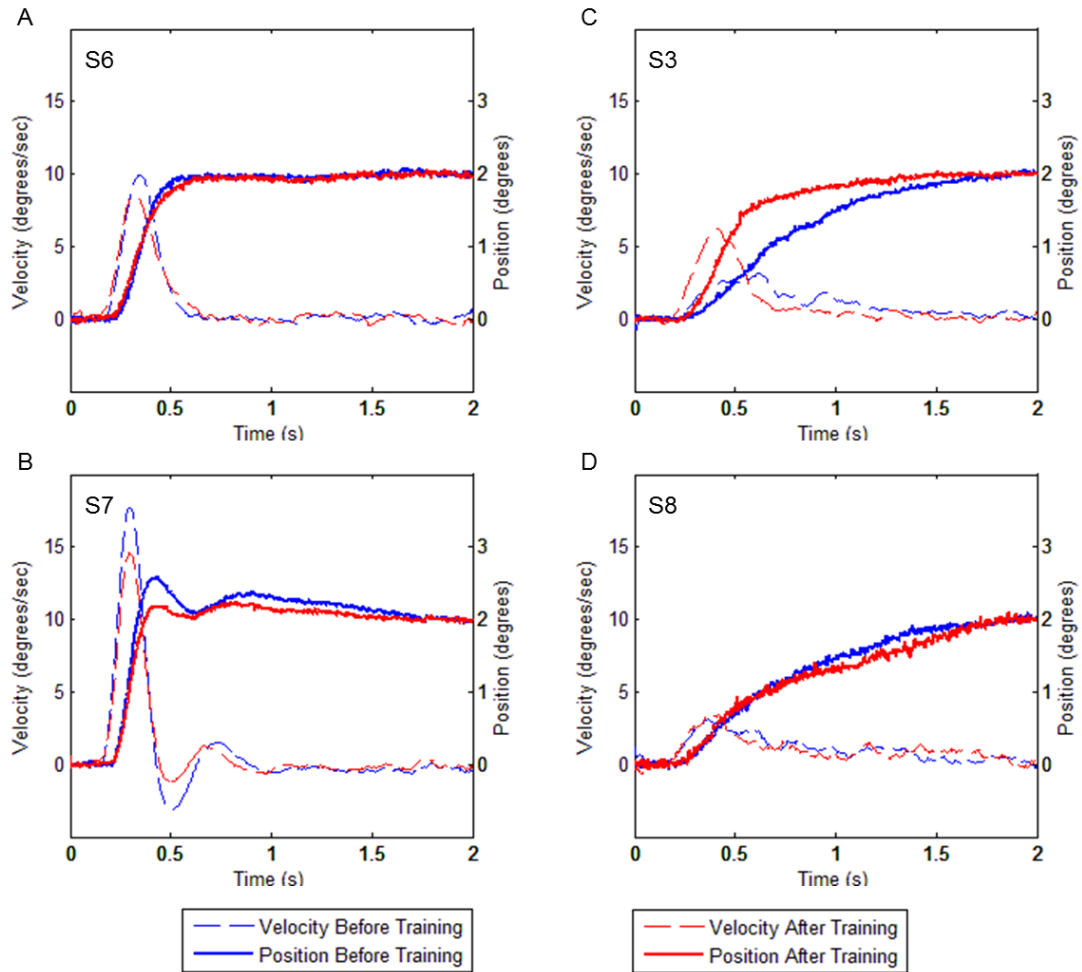


Figure 3.3 Positional and velocity data that shows average responses of one type of movement that (A) stayed critically damped, (B) became more critically damped from an underdamped state, (C) became more critically damped from an overdamped state, and (D) showed little to no change in damping after vergence training. Solid lines represents position data before (blue) and after (red) training. Dashed lines represents velocity data before (blue) and after (red) training. (A) and (B) are convergence steps while (C) and (D) are divergence steps.

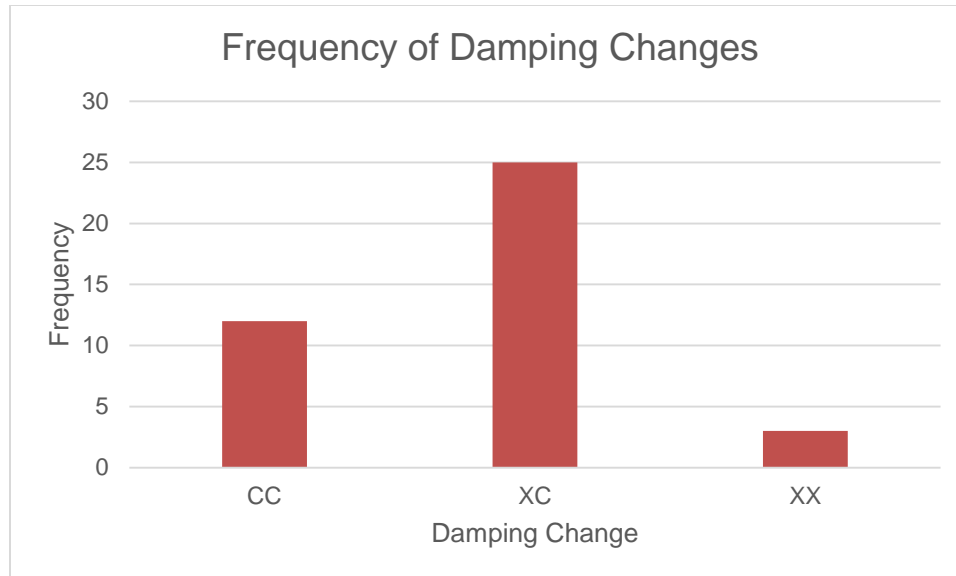


Figure 3.4 Frequency plot of damping changes of the average response of all step stimuli across all subjects. CC denotes critically damped response before and after training. XC denotes a shift toward a critically damped from either an undamped or overdamped response. XX denotes a damped response that showed little to no notable shift to a critically damped response.

3.3 Phase Data and Response Amplitude

The response amplitude to target ratios are provided in Table 3.5. Highlighted are ratios that get closer to 1 meaning that the response amplitude is the target. 24 of the 40 (60 %) total movements analyzed showed a shift towards 1. Figure 3.6 contains the phase plots of the examples in Figure 3.3. 19 of those 24 (79 %) had a shift towards a critically damped state. 6 of the 16 (38 %) that did not show a shift towards a ratio of 1 had a shift towards a critically damped state.

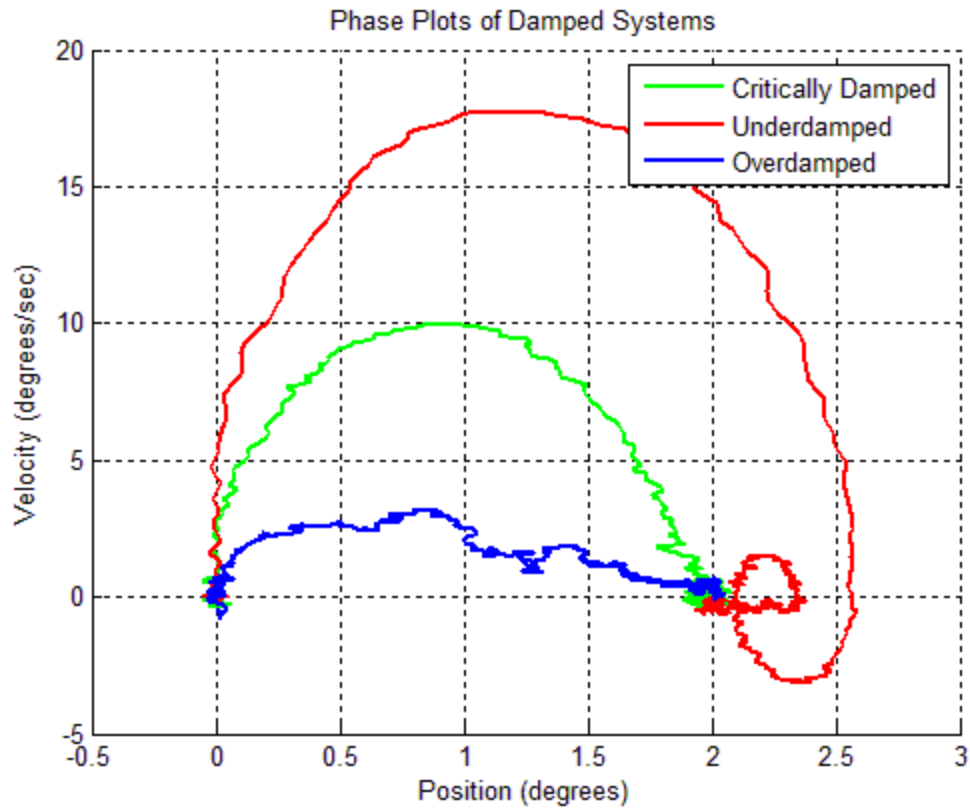


Figure 3.5 Comparison of the example phase plots of responses that are critically damped (green), underdamped (red), and overdamped (blue). The critically damped and underdamped responses are convergence steps, while the overdamped response is a divergence step.

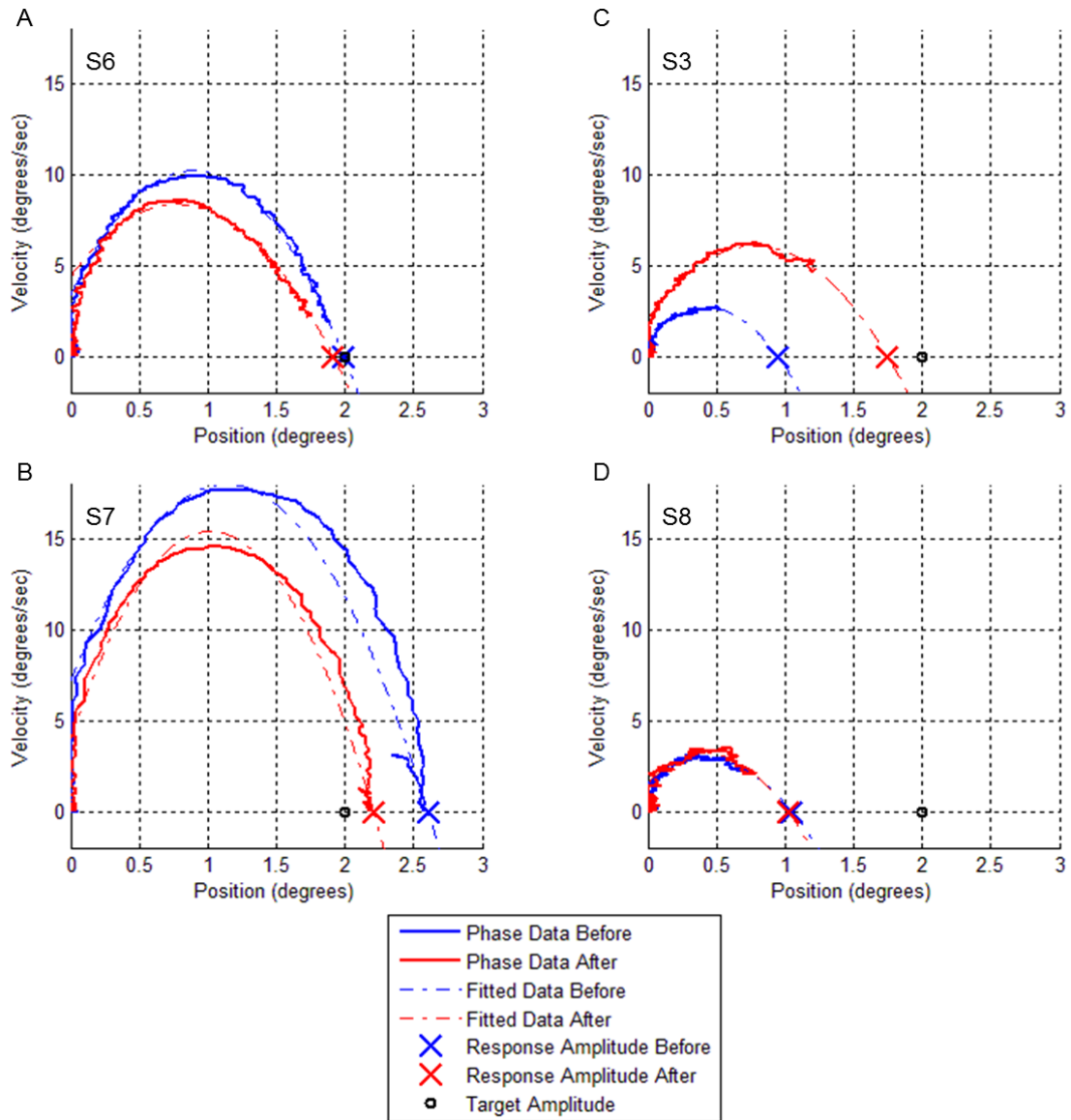


Figure 3.6 Phase data that shows average responses that (A) stayed critically damped, (B) became more critically damped from an underdamped state, (C) became more critically damped from an overdamped state, and (D) showed little to no change in damping after vergence training.

Table 3.5 Summary of Response Amplitude to Target (R:T) Ratio

A = convergence step from phoria

B = divergence step to phoria

C = divergence step from phoria

D = convergence step to phoria

| Subject | Movement | R:T Ratio (before) | R:T Ratio (after) | Shift to C.D.? |
|---------|----------|--------------------|-------------------|----------------|
| 1 | A | 0.91 | 0.90 | N |
| | B | 1.13 | 0.83 | Y |
| | C | 0.79 | 0.77 | N |
| | D | 1.37 | 1.09 | Y |
| 2 | A | 0.86 | 0.86 | Y |
| | B | 1.02 | 0.88 | Y |
| | C | 0.67 | 0.78 | Y |
| | D | 1.11 | 0.99 | Y |
| 3 | A | 0.89 | 0.95 | Y |
| | B | 0.90 | 0.96 | Y |
| | C | 0.47 | 0.87 | Y |
| | D | 1.32 | 1.27 | Y |
| 4 | A | 0.88 | 0.90 | Y |
| | B | 1.01 | 0.84 | Y |
| | C | 0.82 | 0.84 | N |
| | D | 1.10 | 1.08 | N |
| 5 | A | 0.89 | 0.99 | Y |
| | B | 1.13 | 0.90 | Y |
| | C | 0.83 | 0.84 | N |
| | D | 1.16 | 1.27 | N |
| 6 | A | 0.99 | 0.95 | N |
| | B | 1.12 | 1.00 | Y |
| | C | 0.95 | 0.89 | N |
| | D | 1.14 | 1.06 | Y |
| 7 | A | 1.30 | 1.10 | Y |
| | B | 0.88 | 0.85 | Y |
| | C | 0.64 | 0.56 | N |
| | D | 1.49 | 1.40 | Y |
| 8 | A | 1.04 | 1.02 | N |
| | B | 0.78 | 0.66 | Y |
| | C | 0.52 | 0.51 | N |
| | D | 0.97 | 1.08 | N |
| 9 | A | 0.95 | 0.92 | N |
| | B | 1.24 | 1.09 | Y |
| | C | 0.92 | 0.92 | Y |
| | D | 1.09 | 1.08 | N |
| 10 | A | 1.05 | 1.05 | N |
| | B | 0.91 | 0.95 | Y |
| | C | 0.57 | 0.83 | Y |
| | D | 1.26 | 1.21 | Y |

CHAPTER 4

DISCUSSION and CONCLUSIONS

4.1 Discussion

The results suggest reaction times quantified as the time to peak velocity significantly decreases after vision training for binocularly normal subjects. This coincides with the findings of Pare and Munoz who observed that the saccadic reaction times when presented with a visual target in monkeys decreased after training [52]. Interestingly, the results show that peak velocity does not always increase with training. Only 7 of the total 40 movements indicated that peak velocity increased. Therefore if it is assumed that training will improve efficiency in an action, it may be concluded that an increase speed in oculomotor movements does not necessitate an increase in efficiency of the fusion initiating phase.

To look at how efficient the responses became, it was apparent to look at the second-order dynamics of the eye movements. As the results indicate, responses after training tended to become a more critically damped response. Also, those that were initially critically damped showed no notable change towards an overdamped or underdamped response. Therefore, it is arguable to state that the critically damped state is the most efficient response for oculomotor movements. If this is the case, this may explain why there is no increase in velocity across all subjects and why different studies report mixed findings on the subject. [15, 53]

One interesting thing to note is that out of the 16 total movements that step towards the phoria (i.e., convergence step to phoria and divergence step to phoria) level that were not critically damped before training, 13 or 81% of them were considered to be underdamped whereas overdampness occurred more frequently in movements away from the phoria level. This may suggest two things: (1) the second-order dynamics are different at different initial positions and (2) phoria plays a more weighted role in the dynamics. For the latter, one may be able to presume that phoria will tend to pull the vergence movements toward it resulting in the underdamped effect when the movement is toward the phoria level and an overdamped effect when the movement is away from the phoria.

As the phase results show, most of the movements that tended to shift towards critically damped also had their response amplitude to target ratio move closer to 1. However, this was not always the case. This may be due to fixation disparity where the fixation gaze of the subject is different from the target. Studies have shown that fixation disparity may have a large role in vergence dynamics. [8-11] Since the steps used were only 2° steps, an instance of fixation disparity may affect the movement even more so than that of a 4° or 6° movement.

For subjects such as subject 8 who showed no discernable effect to the second order dynamics of his movements after training may have had a lack of motivation to complete the training sessions. This is most likely due to the characteristics of the training procedure which were it was long, repetitive, and boring.

4.2 Conclusions and Future Work

This study suggests that the training method utilizing the haploscope affects the oculomotor system. Also, the findings in this study show disagreed with the initial hypothesis that a significant change in the ocular motor system occurs in binocularly normal controls with the onset of training. These preliminary results indicate that the ocular-motor system may become more efficient through training. This is evidenced by the decrease in latency by all subjects and that a majority of the subjects showed a positive change (i.e., a shift towards a critically damped response) in their vergence second-order dynamics.

This study focused on the fusion initiating component of vergence movements. The fusion sustaining component may prove to be interesting as well along with the other unanalyzed movements such as the disappearing step and the ramp.

Future work includes a better method to quantify the second-order dynamics is necessary. The initial way of categorizing the data into groups contained bias. There were movements that may be considered critically damped, but ultimately was categorized as overdamped. Using another method may eliminate this bias and provide a better way to analyze the second order dynamics of the movements. The ideal case would be to extract the damping ratio of each response. The damping ratio is basically a quantification of how damped the system is. Critically damped responses have a damping ratio of 1, overdamped have damping ratios of less than 1, and underdamped responses

have damping ratios greater than 1. However, the difficulty in getting the damping ratio is the method of modeling the responses as a system with second-order dynamics. There may be other methods that can be utilized such as looking at the velocity traces or the ICA of the responses.

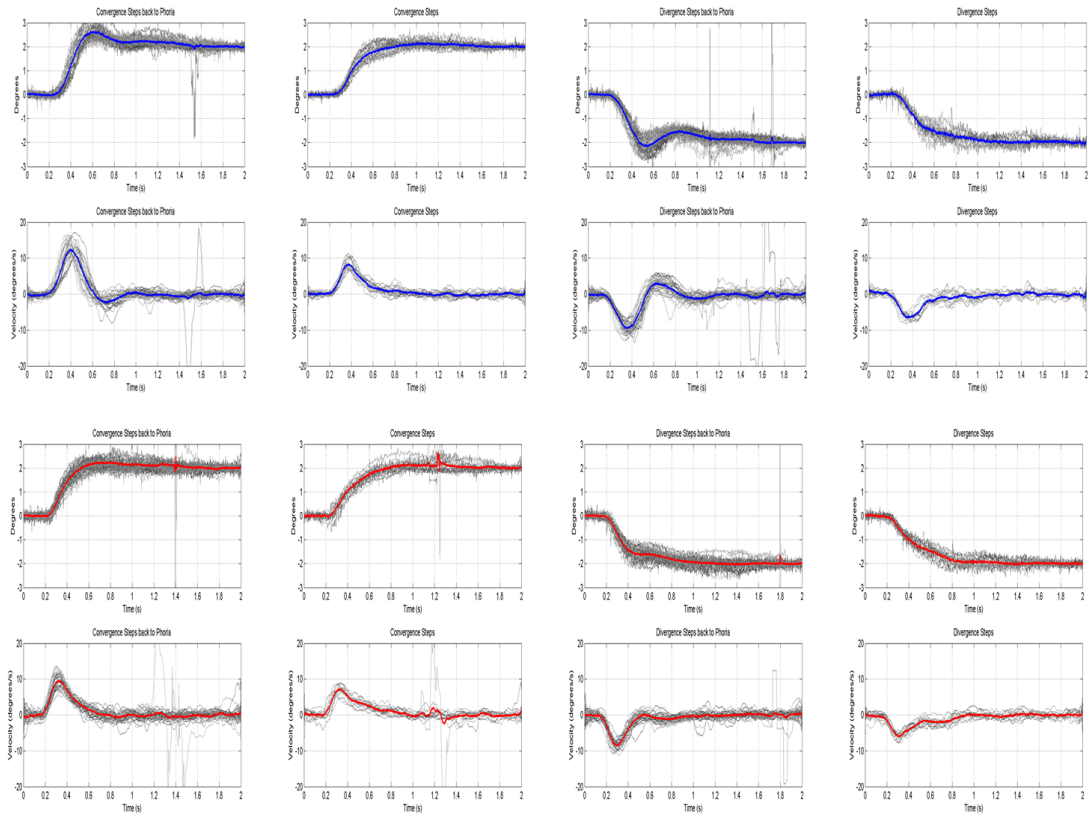
Other future experiments may include (but not limited to) isolating the component of training that affected the ocular motor system the most, using 3D gaming with the training as a foundation as an attempt to improve motivation, and study people with binocular disorders using this training method and see how their second-order dynamics is affected.

APPENDIX A

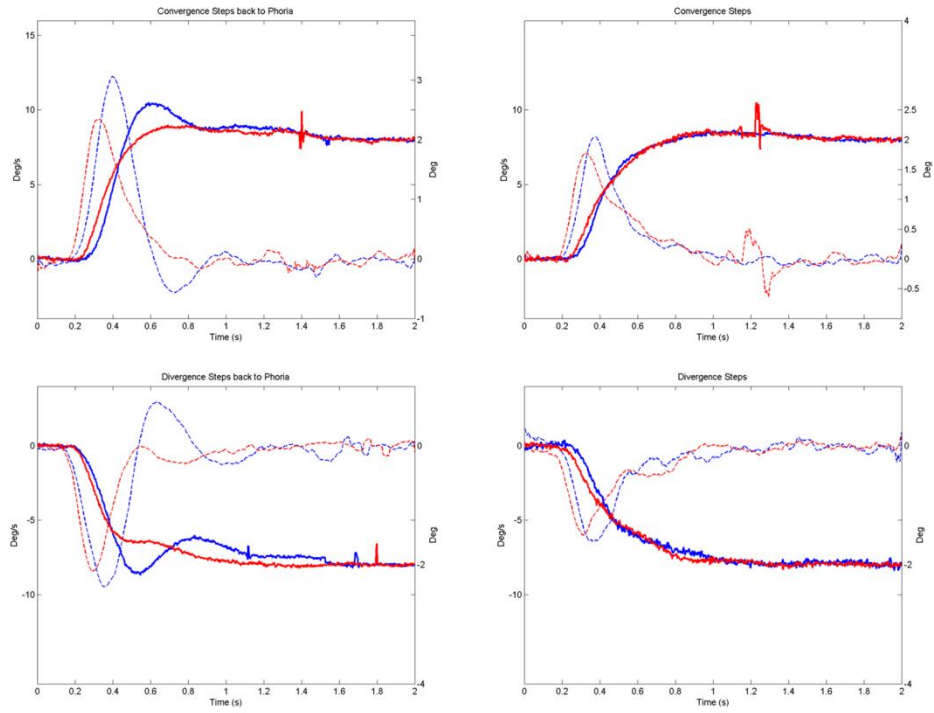
Subject 1 – CER 21/F

| | | |
|---------------------|---------|--------|
| | Before | After |
| Phoria (Δ) | 4 EXO | 4 EXO |
| NPC (cm) | 9 | 2 |
| Blur/break/recovery | 13/9/13 | 9/2/4 |
| | Fine | Coarse |
| Stereopsis (sec) | 30 | 250 |

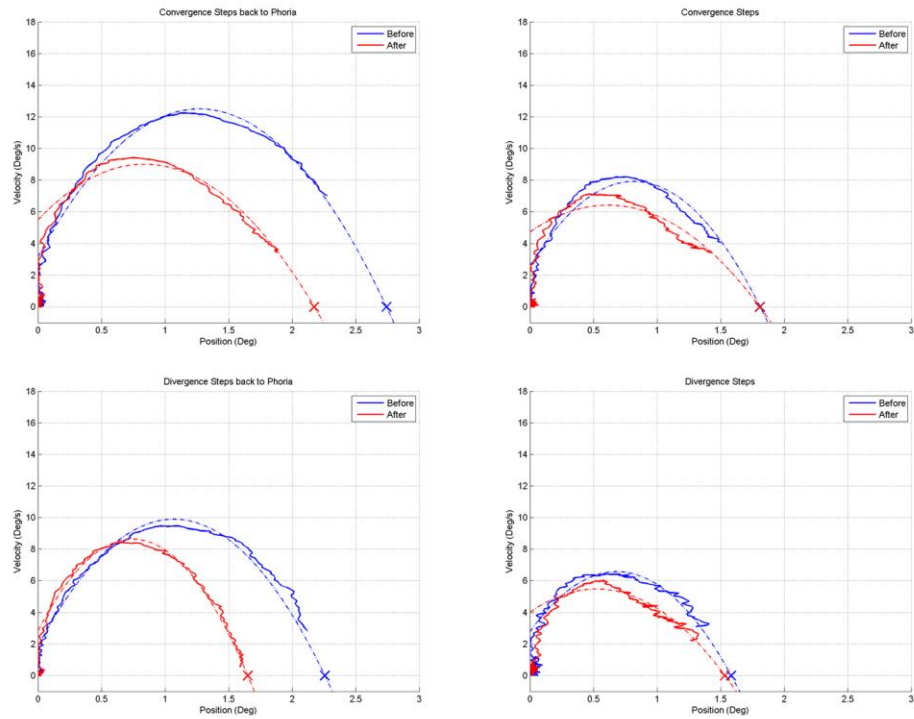
Position and Velocity Traces



Before/After Plots



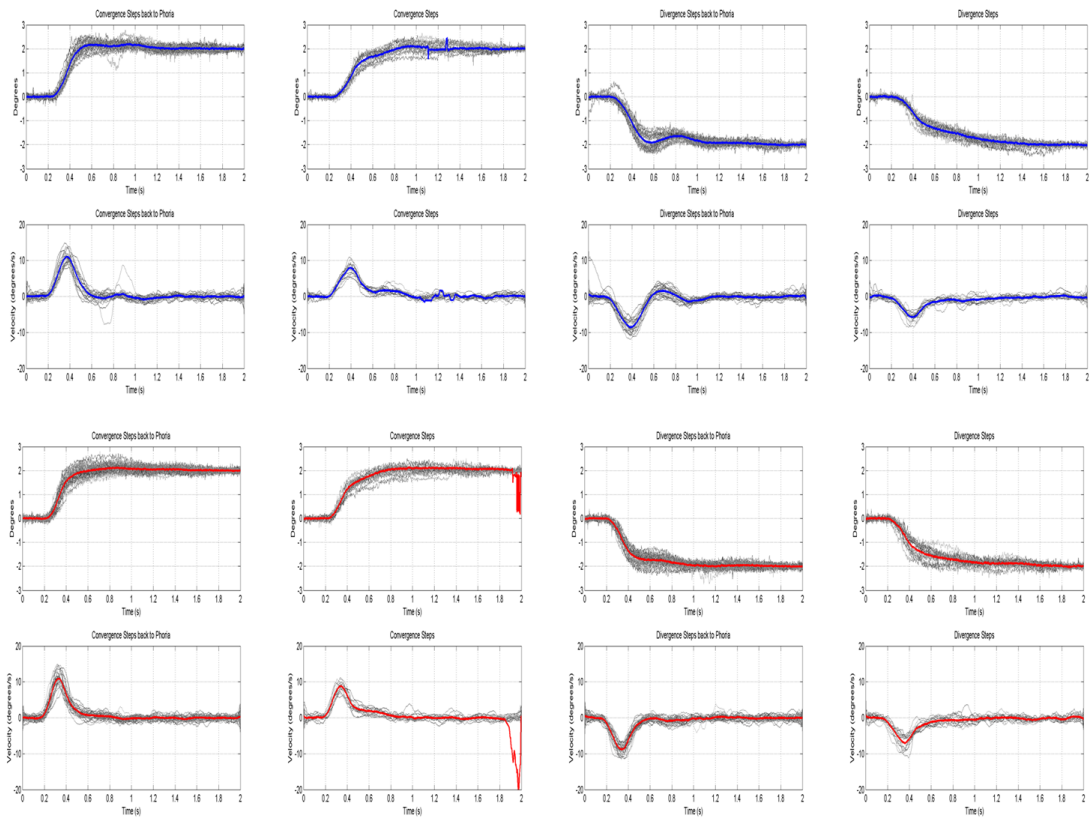
Phase Plots



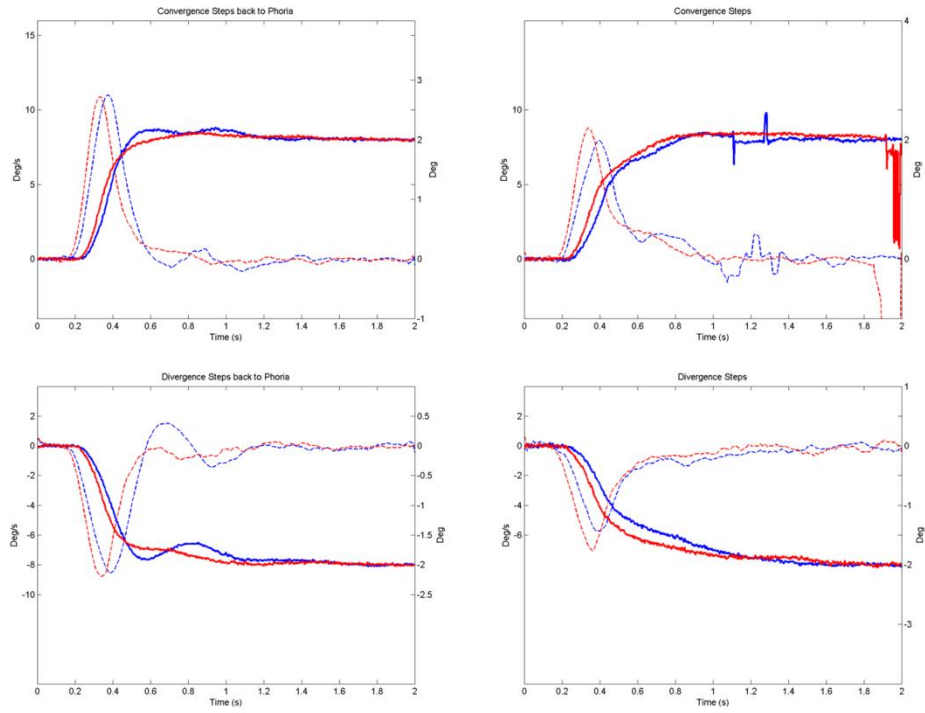
Subject 2 – CXY 21/M

| | Before | After |
|---------------------|--------|--------|
| Phoria (Δ) | ORTHO | ORTHO |
| NPC (cm) | 3 | 4 |
| Blur/Break/Recovery | 9/3/6 | 9/4/8 |
| | Fine | Coarse |
| Stereopsis (sec) | 20 | 250 |

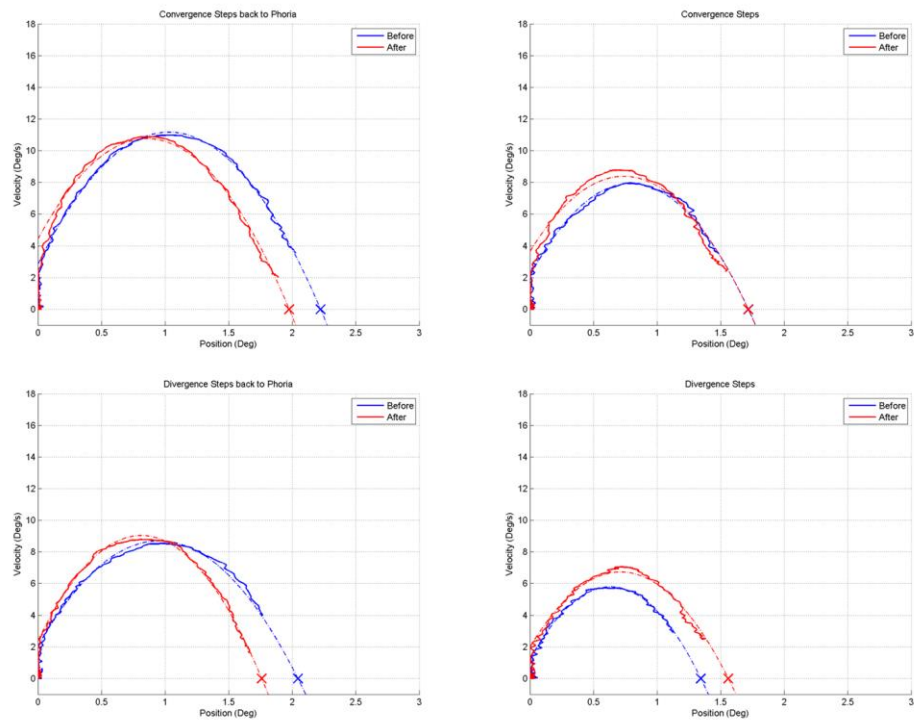
Position and Velocity Traces



Before/After Plots



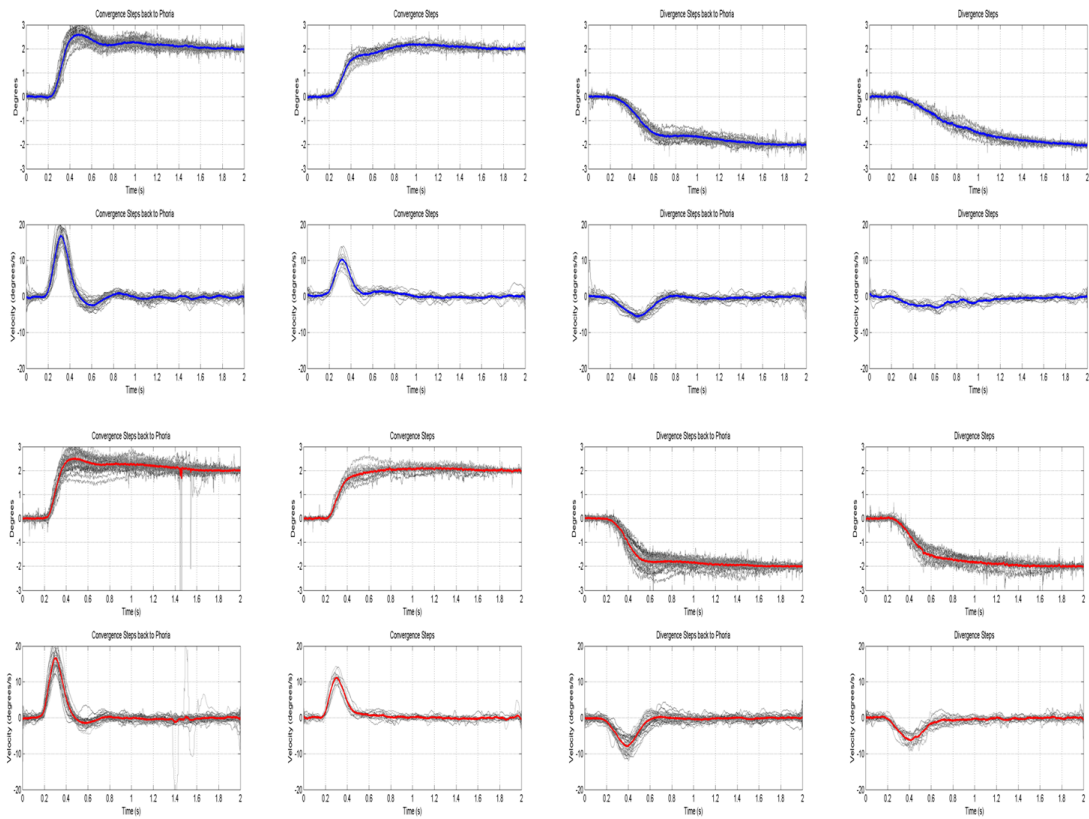
Phase Plots



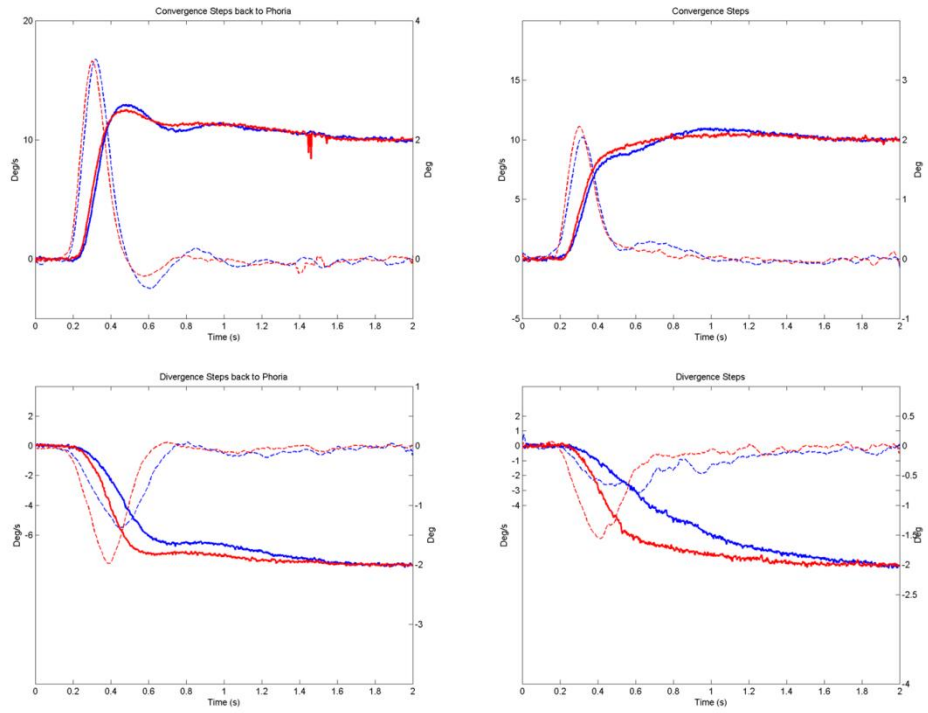
Subject 3 – HXT 23/M

| | | |
|---------------------|---------|--------|
| | Before | After |
| Phoria (Δ) | 2 EXO | ORTHO |
| NPC (cm) | 6 | 5 |
| Blur/Break/Recovery | 10/6/11 | 8/5/6 |
| | Fine | Coarse |
| Stereopsis (sec) | 20 | 250 |

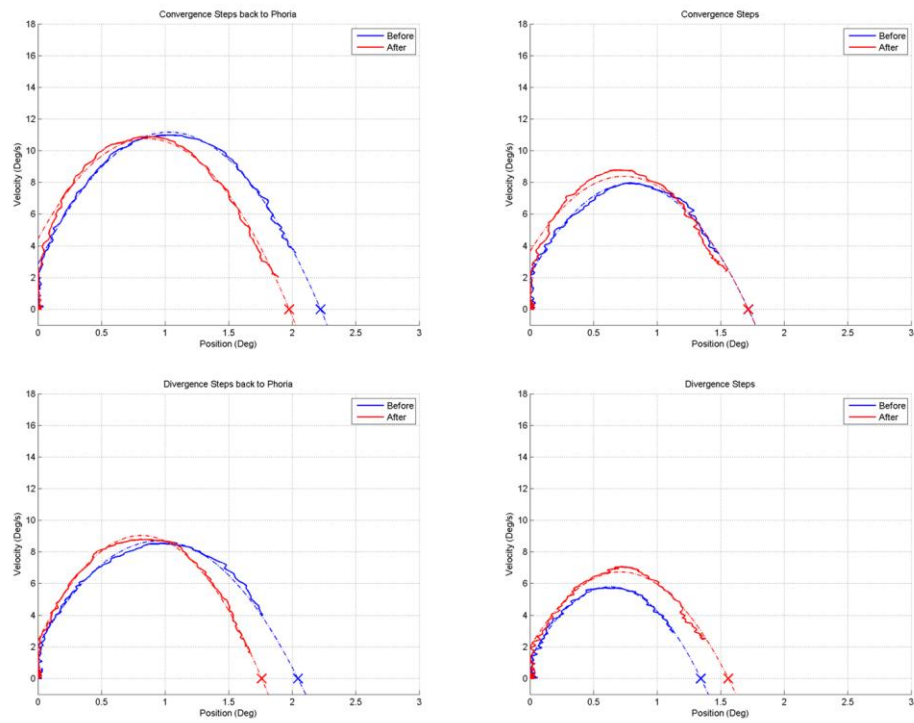
Position and Velocity Traces



Before/After Plots



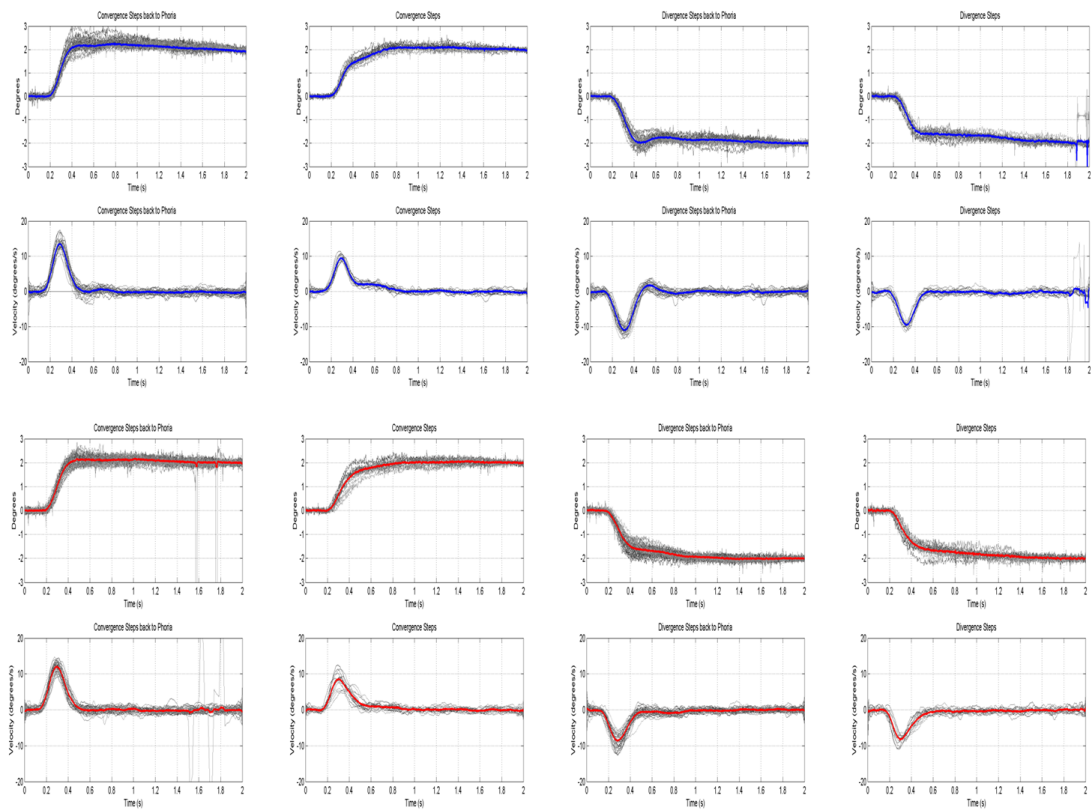
Phase Plots



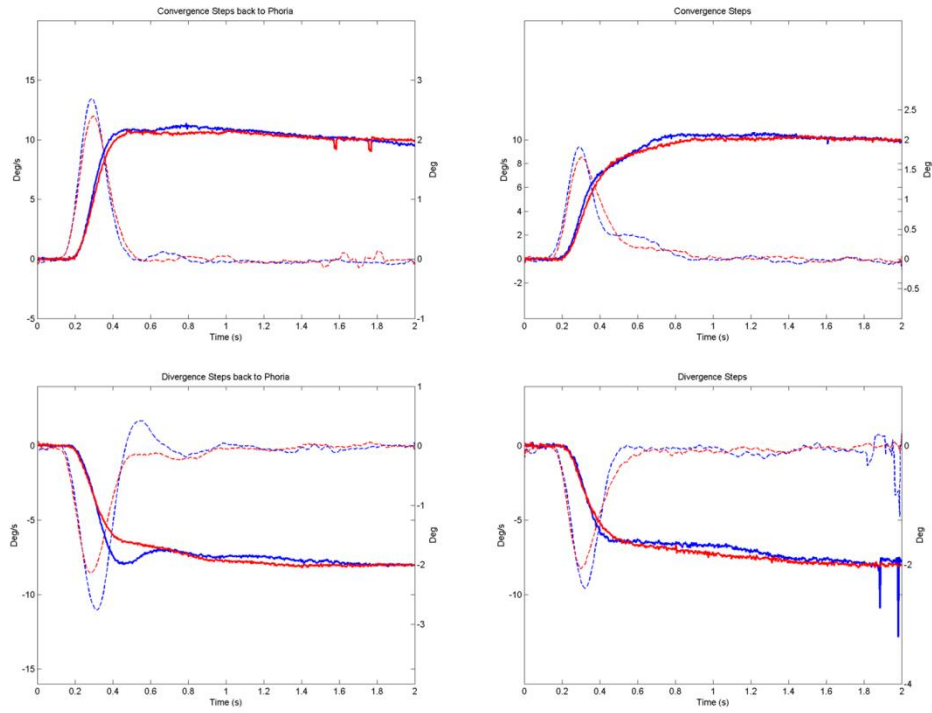
Subject 4 – JAK 20/F

| | Before | After |
|---------------------|--------|---------|
| Phoria (Δ) | 2 EXO | 2 EXO |
| NPC (cm) | 3 | 4 |
| Blur/Break/Recovery | 10/3/5 | 10/4/10 |
| | Fine | Coarse |
| Stereopsis (sec) | 40 | 250 |

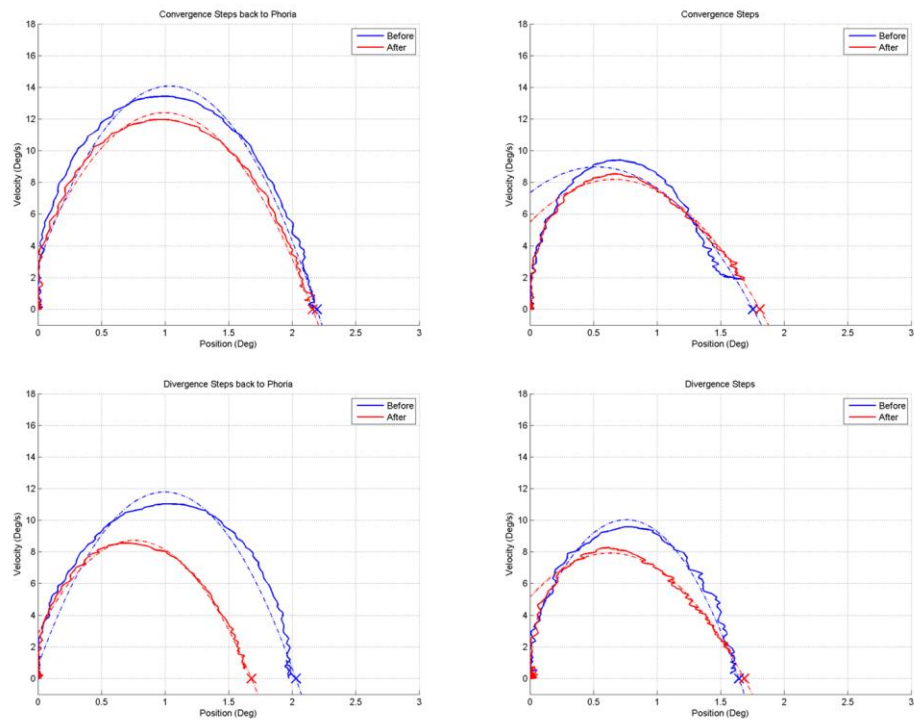
Position and Velocity Traces



Before/After Plots



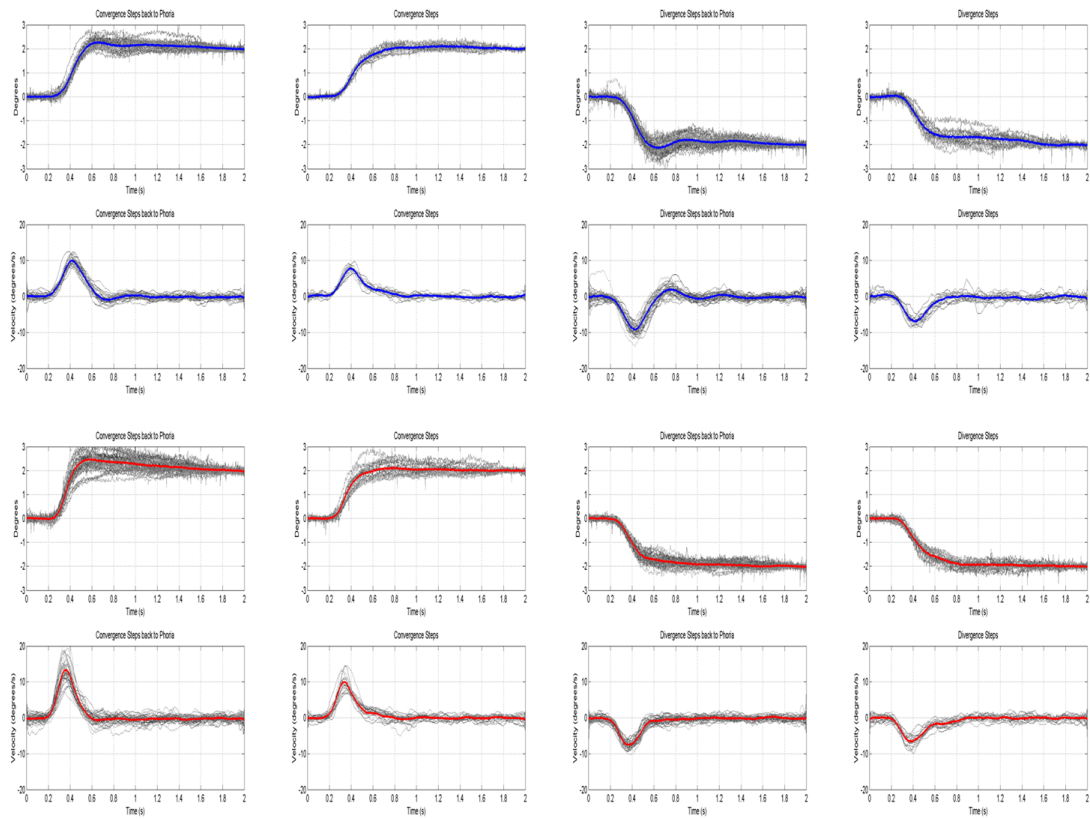
Phase Plots



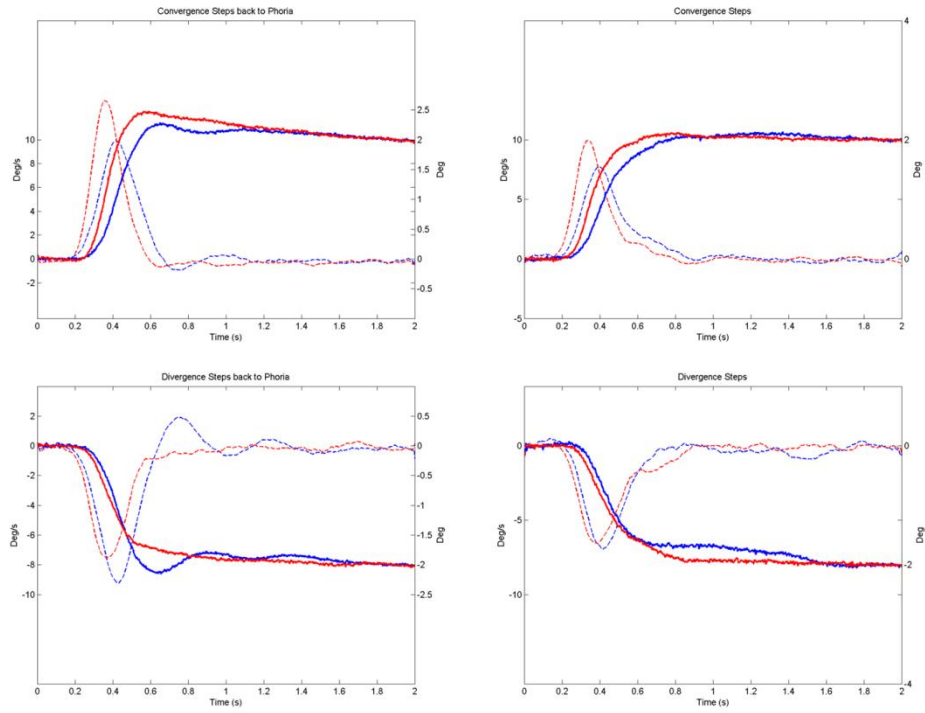
Subject 5 – JIM 21/F

| | Before | After |
|---------------------|---------|--------|
| Phoria (Δ) | 6 EXO | 8 EXO |
| NPC (cm) | 6 | 4 |
| Blur/Break/Recovery | 10/6/12 | 8/4/6 |
| | Fine | Coarse |
| Stereopsis (sec) | 30 | 250 |

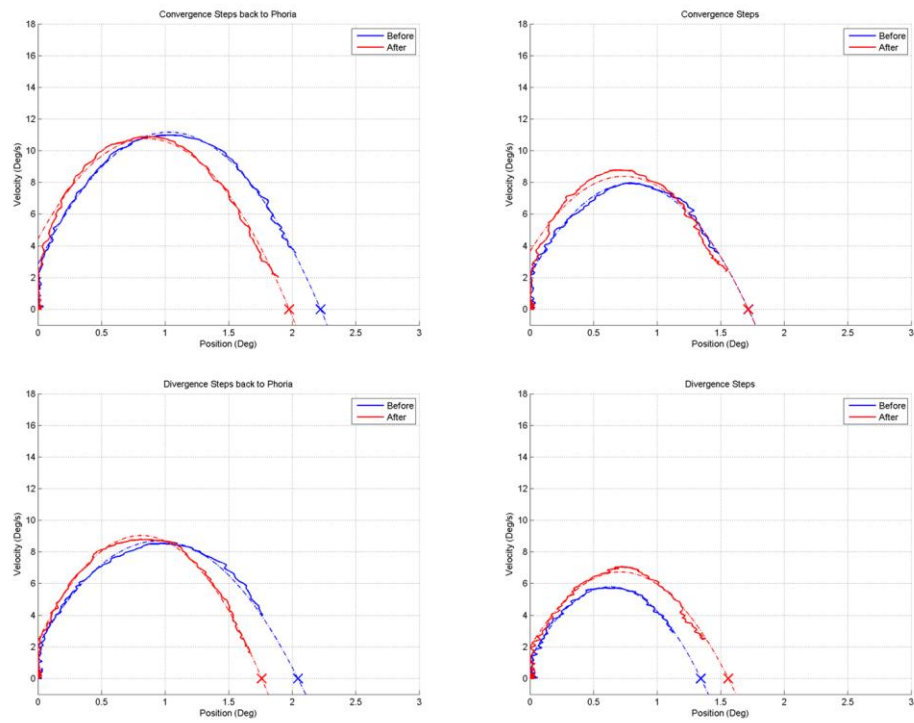
Position and Velocity Traces



Before/After Plots



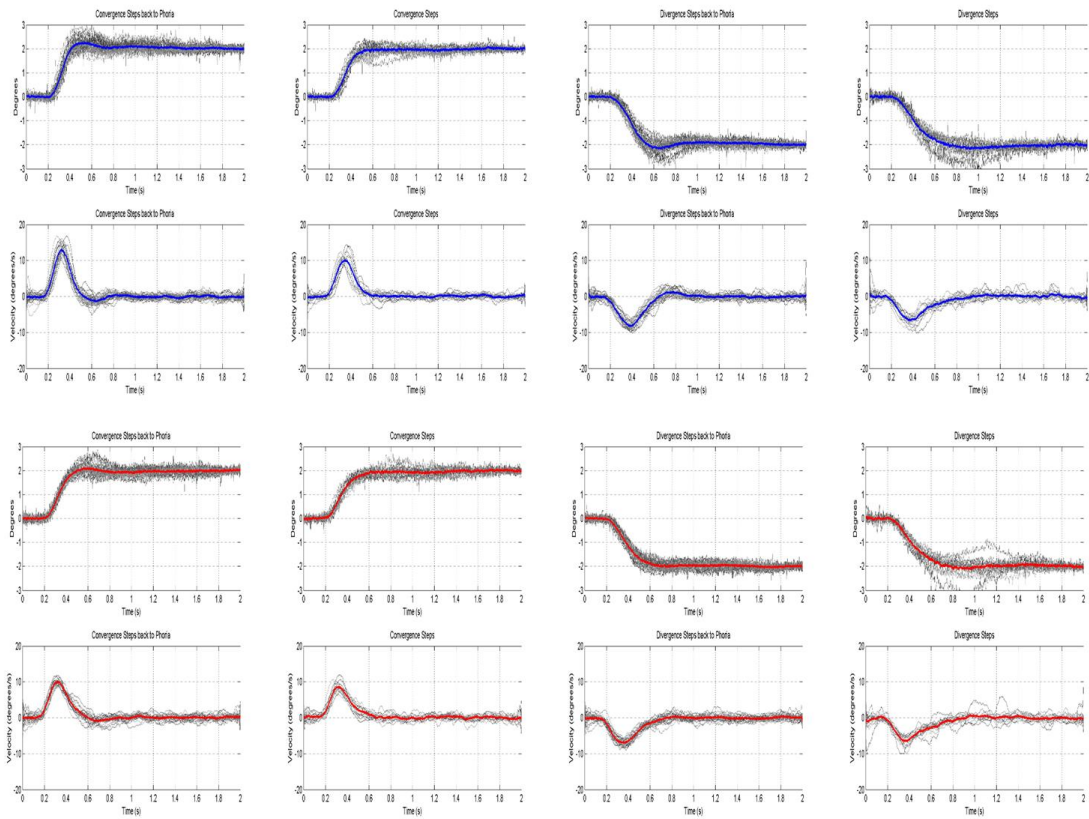
Phase Plots



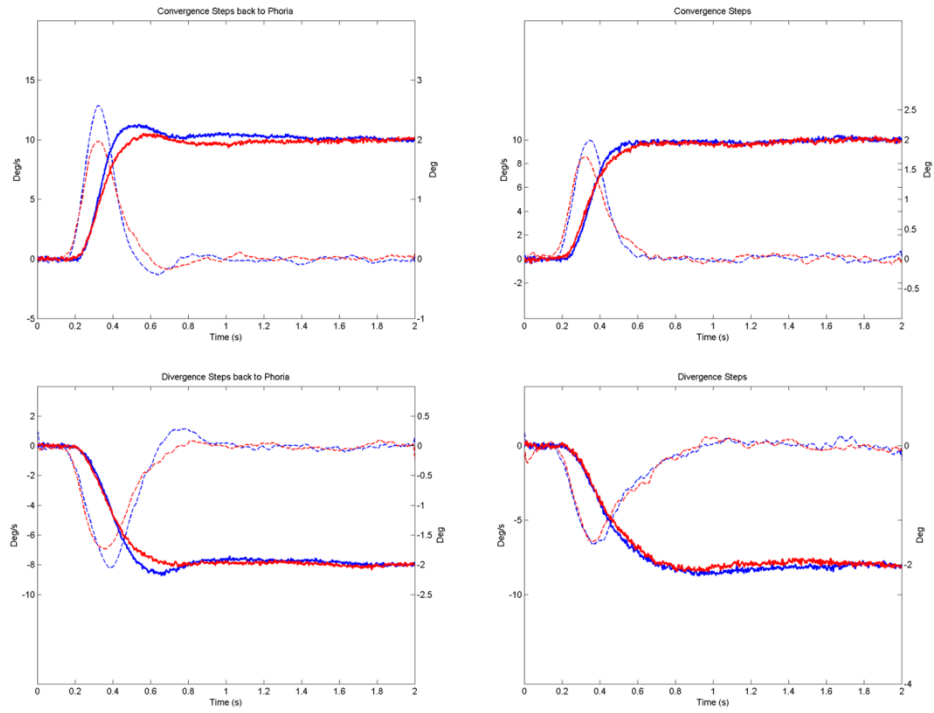
Subject 6 – KDK 22/F

| | Before | After |
|---------------------|--------|--------|
| Phoria (Δ) | 2 EXO | ORTHO |
| NPC (cm) | 3 | 3 |
| Blur/Break/Recovery | 7/3/6 | 7/3/4 |
| | Fine | Coarse |
| Stereopsis (sec) | 20 | 250 |

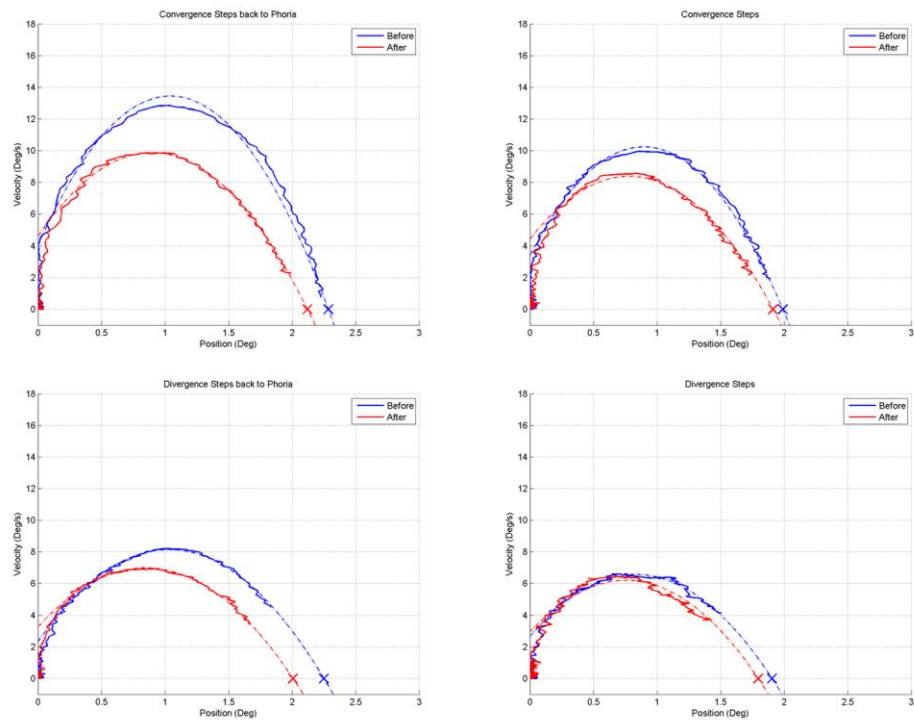
Position and Velocity Traces



Before/After Plots



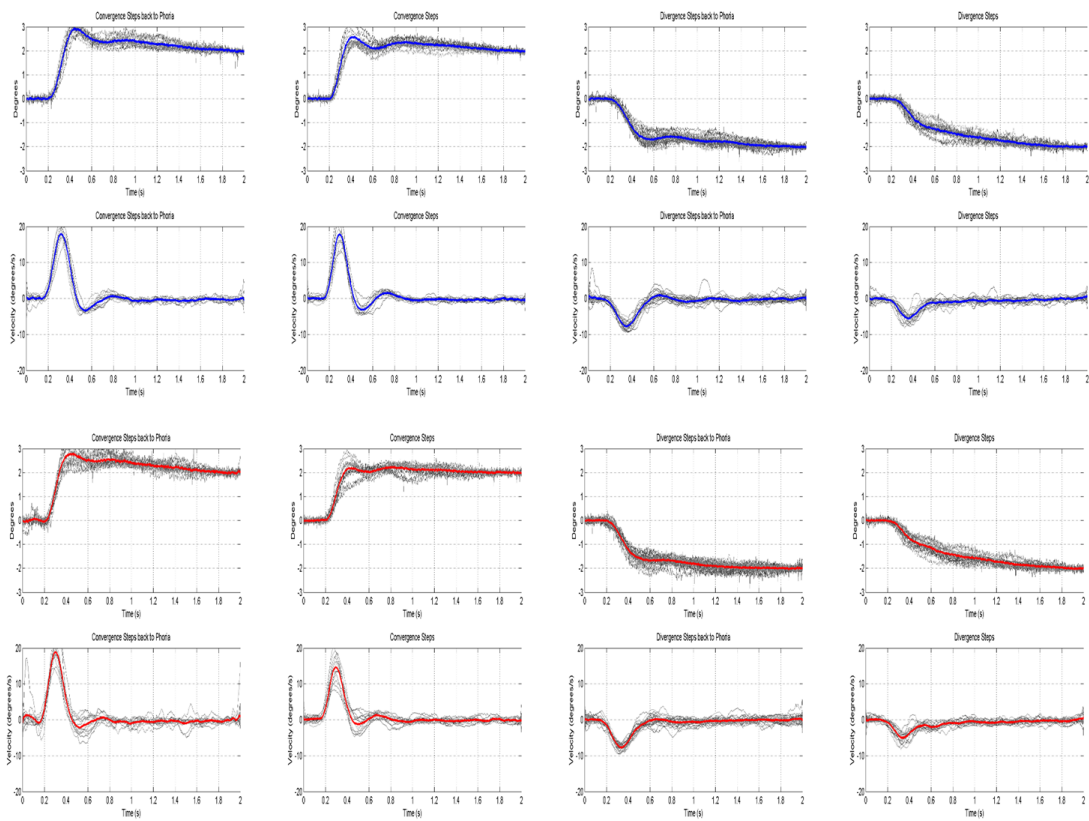
Phase Plots



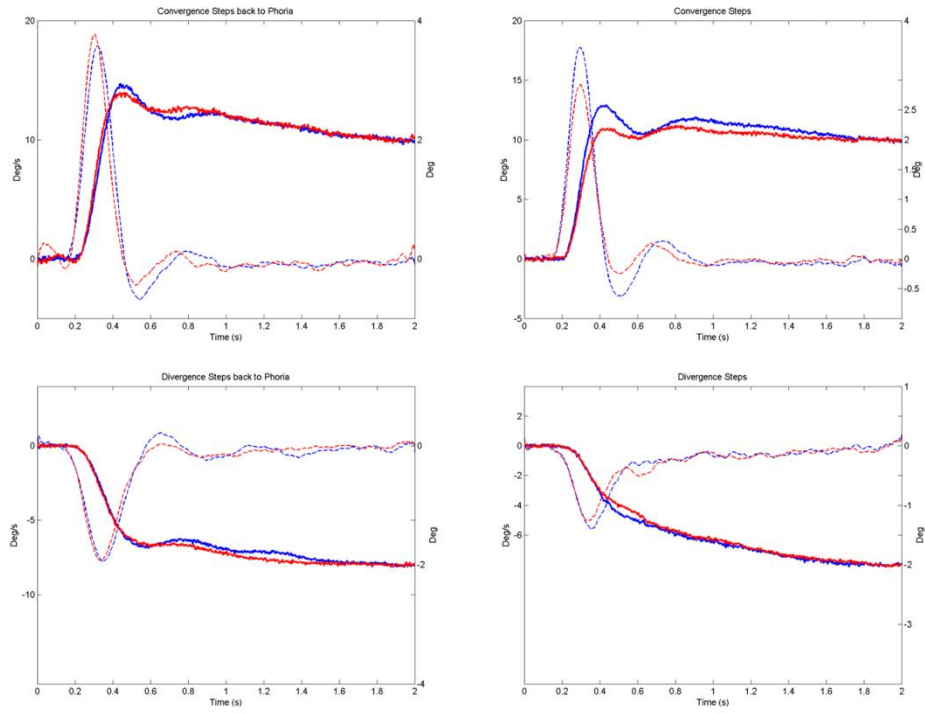
Subject 7 – PPP 28/M

| | Before | After |
|---------------------|---------|---------|
| Phoria (Δ) | 6 EXO | 6 EXO |
| NPC (cm) | 9 | 7 |
| Blur/Break/Recovery | 14/7/14 | 10/4/12 |
| | Fine | Coarse |
| Stereopsis (sec) | 30 | 250 |

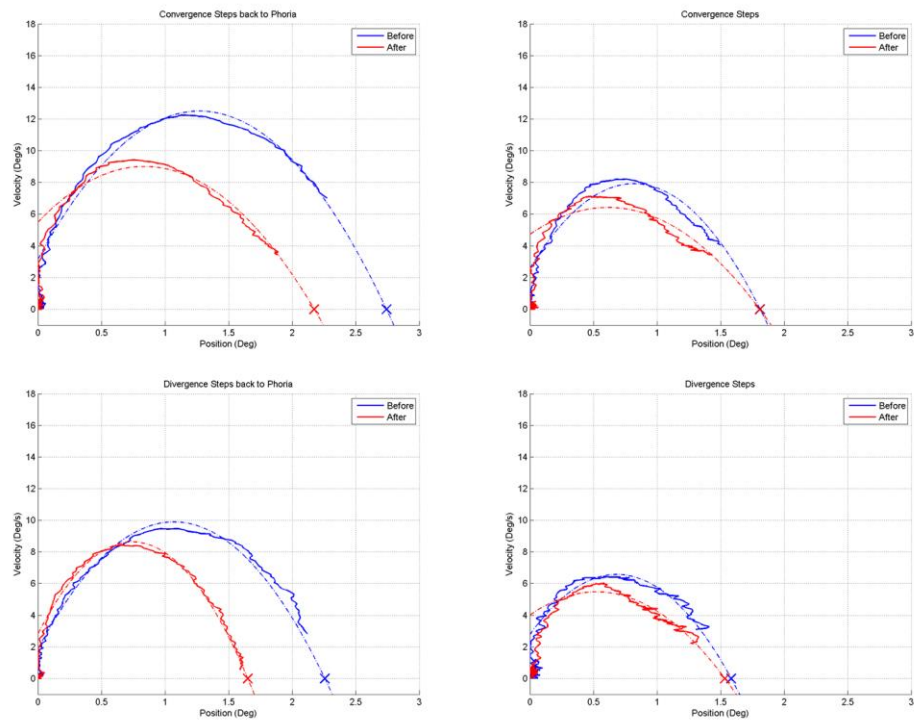
Position and Velocity Traces



Before/After Plots



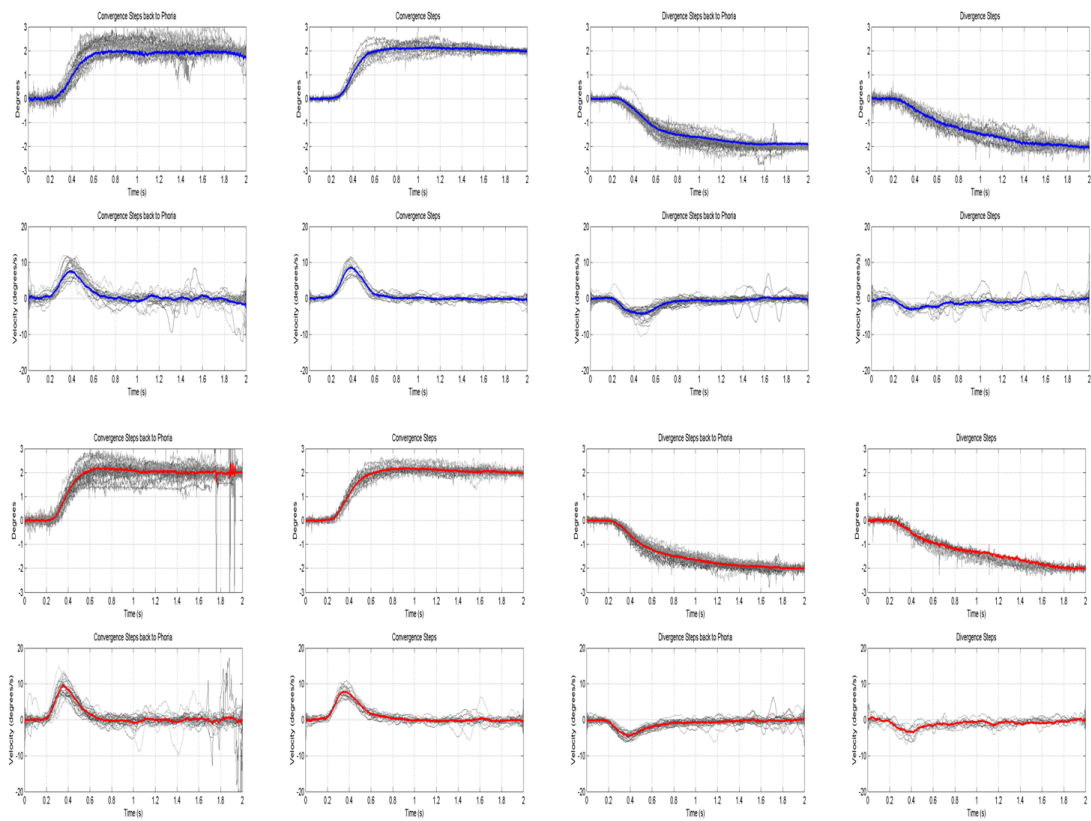
Phase Plots



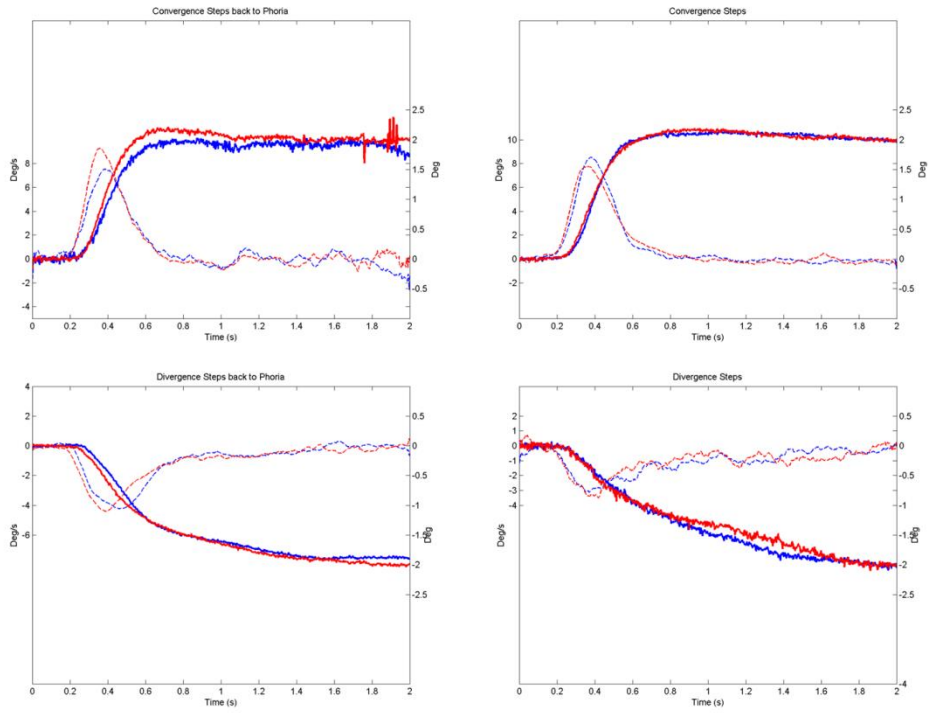
Subject 8 – SJL 26/M

| | | |
|---------------------|---------|---------|
| | Before | After |
| Phoria (Δ) | 4 EXO | 2 EXO |
| NPC (cm) | 6 | 4 |
| Blur/Break/Recovery | 12/6/10 | 10/4/12 |
| | Fine | Coarse |
| Stereopsis (sec) | 20 | 250 |

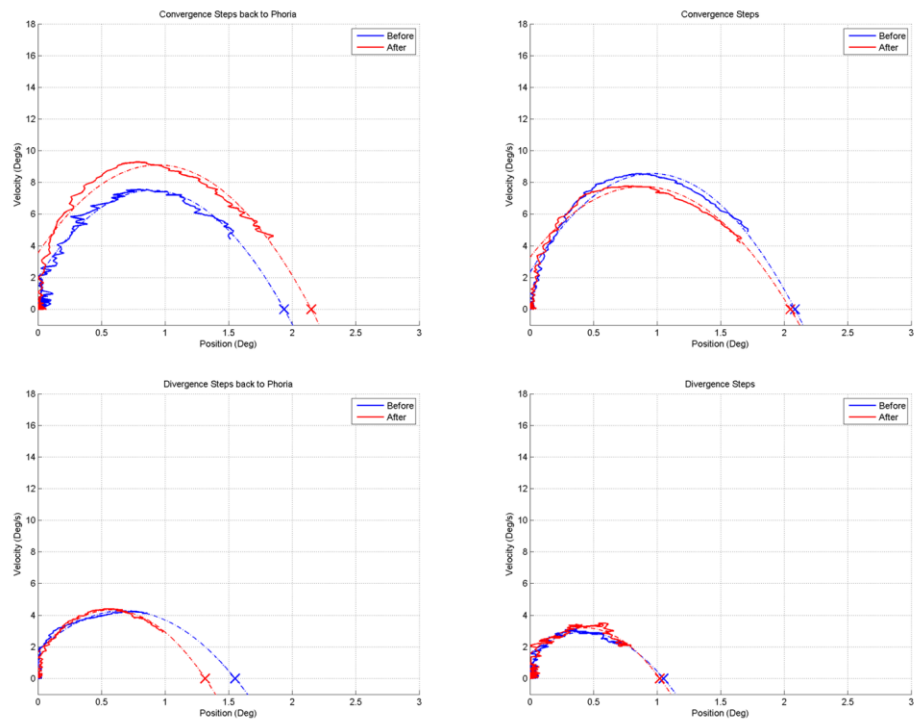
Position and Velocity Traces



Before/After Plots



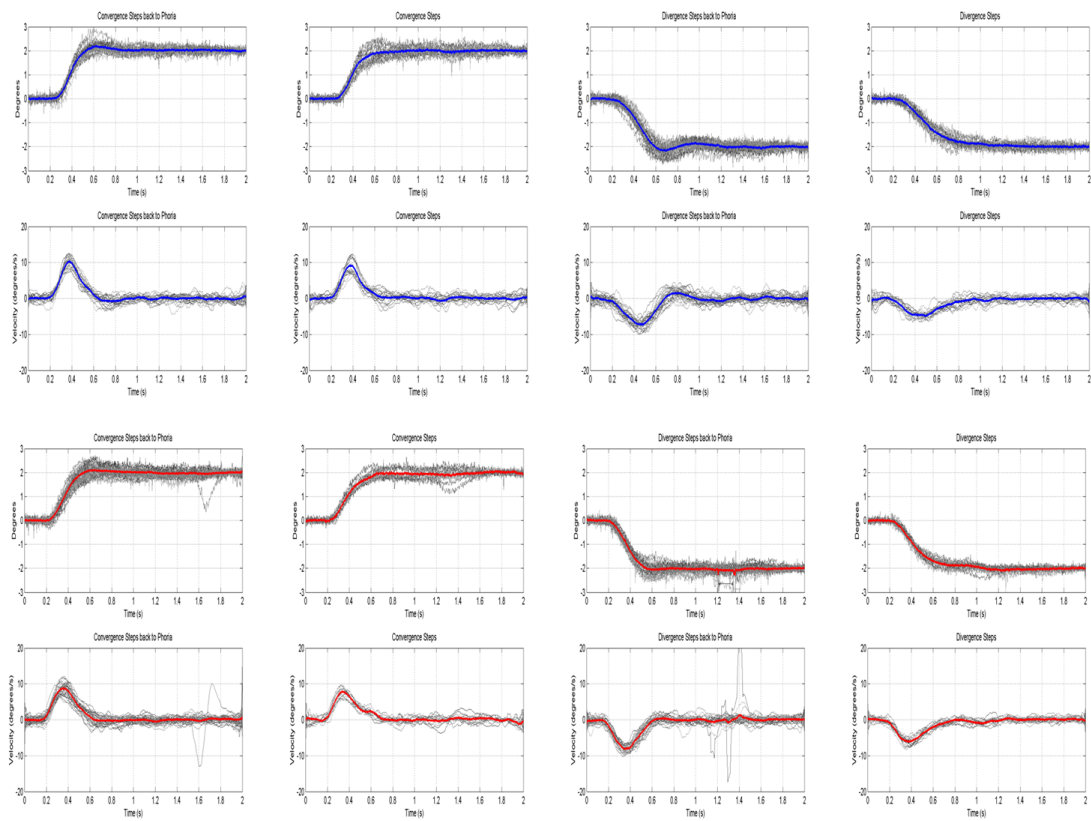
Phase Plots



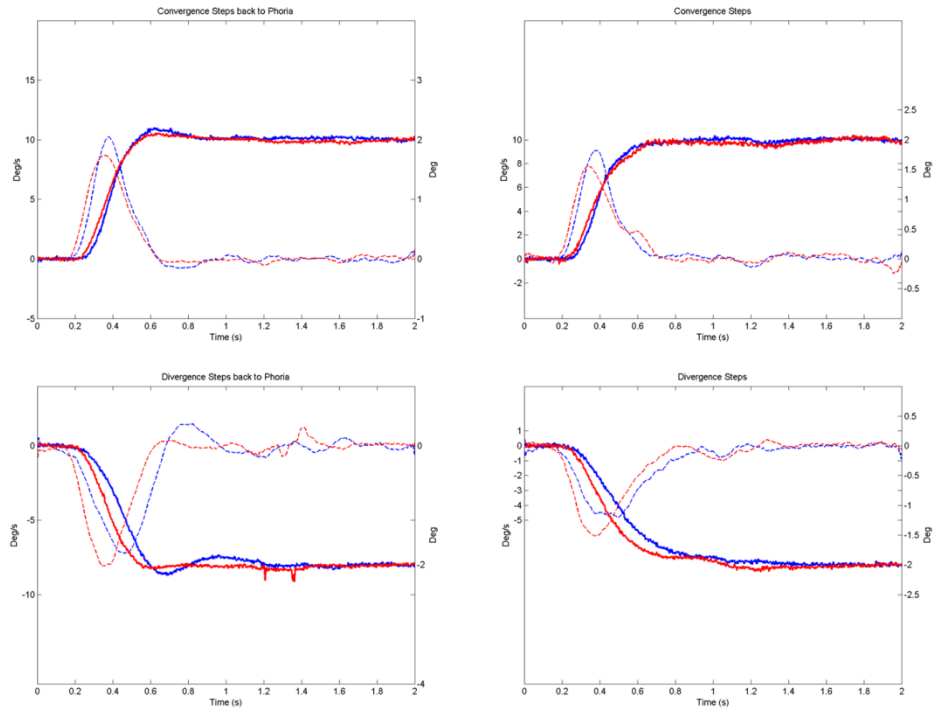
Subject 9 – SRC 20/M

| | Before | After |
|---------------------|--------|--------|
| Phoria (Δ) | ORTHO | ORTHO |
| NPC (cm) | 2 | 2 |
| Blur/Break/Recovery | 8/2/2 | 7/2/2 |
| | Fine | Coarse |
| Stereopsis (sec) | 25 | 250 |

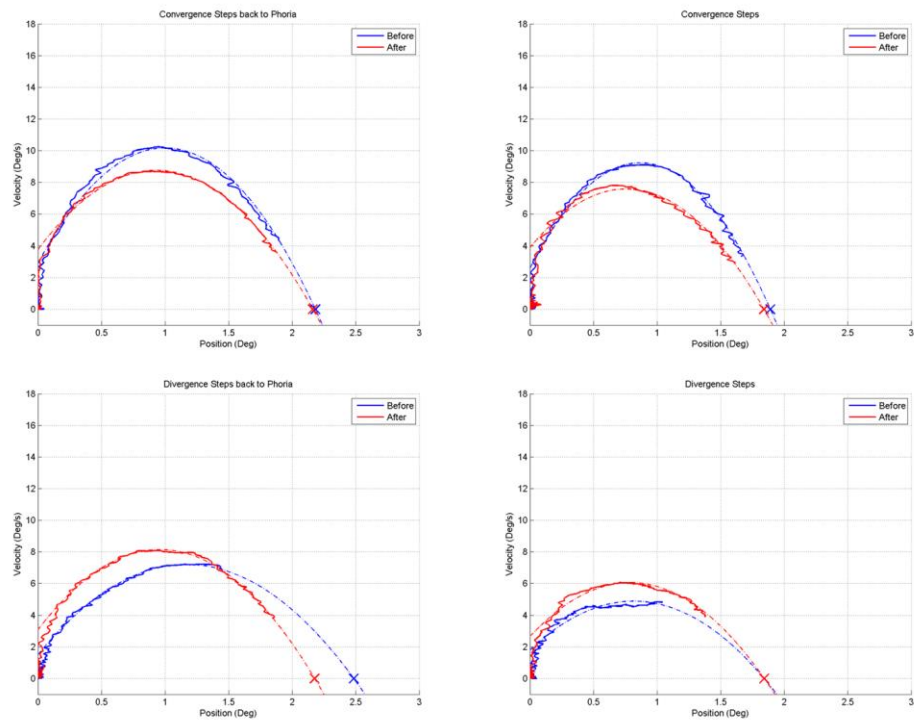
Position and Velocity Traces



Before/After Plots



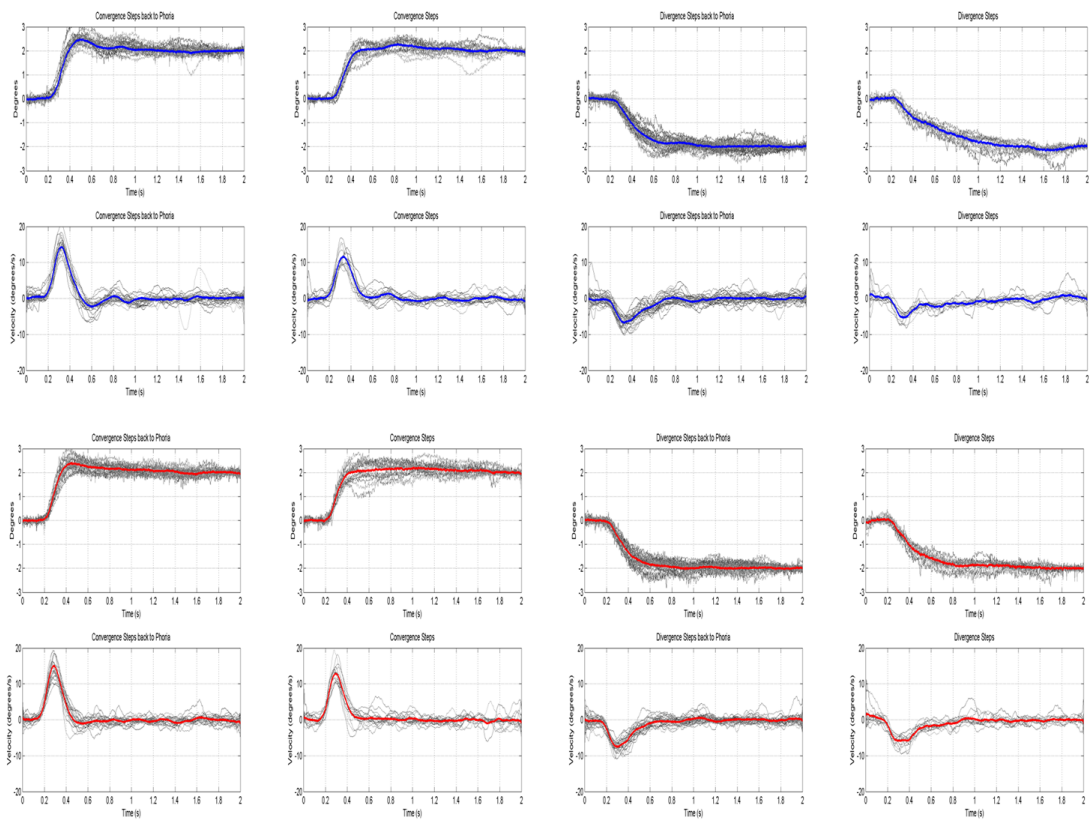
Phase Plots



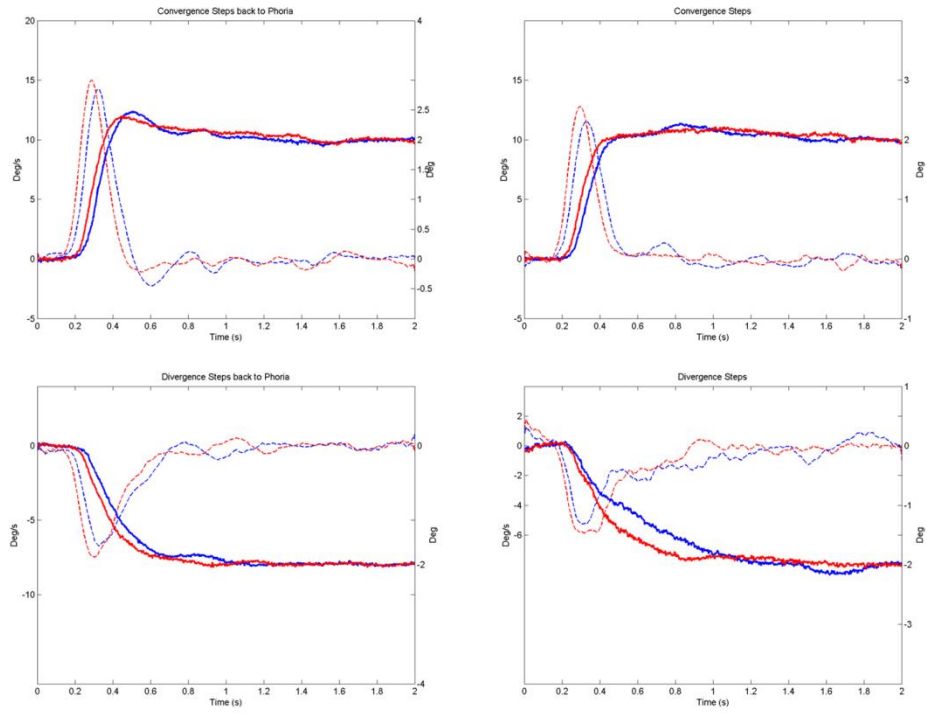
Subject 10 – TAC 18/M

| | Before | After |
|---------------------|--------|--------|
| Phoria (Δ) | ORTHO | ORTHO |
| NPC (cm) | 3 | 3 |
| Blur/Break/Recovery | 7/3/5 | 5/3/5 |
| | Fine | Coarse |
| Stereopsis (sec) | 30 | 250 |

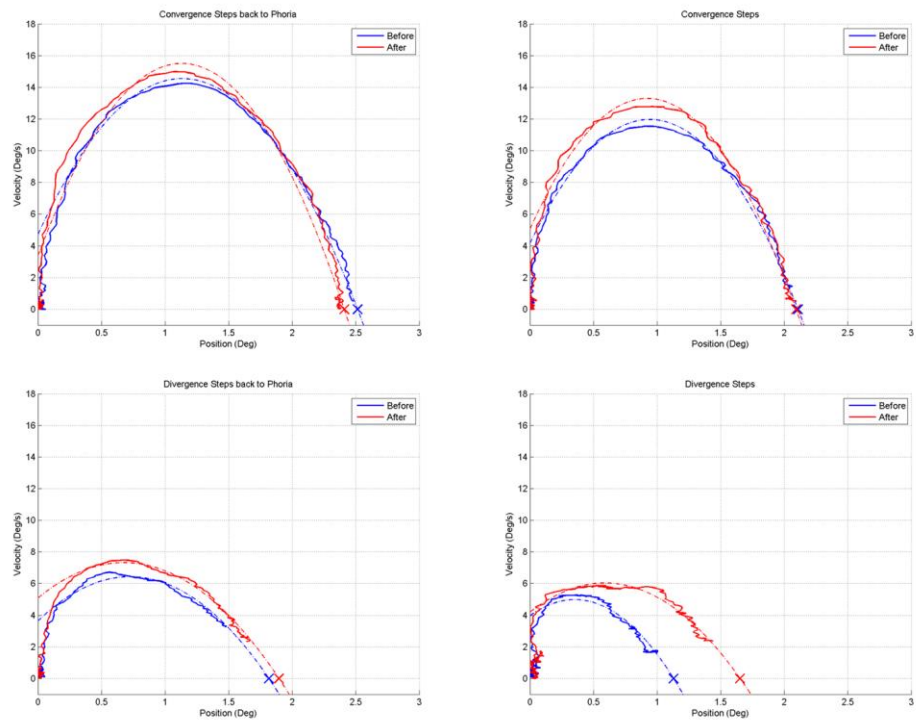
Position and Velocity Traces



Before/After Plots



Phase Plots



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