Study of Eye Convergence

Thesis

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By

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Abstract

Purpose: Convergence Insufficiency (CI) is a common binocular vision disorder that frequently results in symptoms with near work. The purpose of this study was to evaluate the proportion of subjects who could voluntarily converge with and without a target. A second purpose of this study was to determine the sensitivity and specificity of the inability to voluntarily converge for detection of convergence insufficiency and other binocular vision disorders. An additional objective was to compare mean values for NPC, PFV in adults to the limited normative data in the current literature. Methods: Subjects ages 8 years and older with 20/32 or better visual acuity were recruited from visitors at the Center of Science and Industry in Columbus, Ohio. Testing involved administration of the Convergence Insufficiency Symptom Survey (CISS) and evaluation of phoria (Modified Thorington), near point of convergence, positive and negative fusional vergences, accommodative amplitude, visual acuity, and dry autorefraction. Results: Sixty-five participants were enrolled (mean age = 22.3 ± 15.5). Among all participants assessed in this study, 85% were able to voluntarily converge with a target held at 6 cm, while only 55% were able to voluntarily converge their eyes without a target. The majority of participants without signs of CI, AI or significant esophoria were able to converge either voluntarily (75%) or with a target at 6cm (90%). On the other hand, the majority of participants with 2-3 signs of CI were unable to converge voluntarily (38%),

but 71% could converge to a target at 6cm. The inability to converge to a target at 6cm was associated with identifying a patient with a 3 sign CI with sensitivity of 0.67 and specificity of 0.89. Conclusion: Inability to converge either voluntarily or to a target at 6cm was associated with signs of CI. Inability to converge to a target identified 2/3 of those with 3 signs of CI.

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Table of Contents

List of Tables

List of Figures

Chapter 1. Literature Review

Definition of Convergence

Convergence is a disjunctive eye movement meaning both eyes rotate in opposite directions inward, about their corresponding vertical axes, in order to gaze at near object. There are four components of horizontal ocular vergence involved: proximal, fusional, accommodative, and tonic [1]. Proximal vergence is associated with perceived distance. Proximal convergence can occur when a patient senses a near object such as being behind a phoropter. There is some evidence that by a person imagining a target being very near they will stimulate proximal convergence and contribute to voluntary convergence [2]. Maddox referred to voluntary vergence as the "knowledge of nearness", suggesting that proximal and voluntary convergence may be interchangeable concepts [3]. Fusional vergence is driven by binocular retinal disparity which occurs when the image of a real object falls on non-corresponding retinal points. Disparity stimulates the eyes to either convergence or diverge in order to place image of the object of regard on the fovea of each eye. Fusional vergence is made of two components: dynamic, which is used to change vergence position due to retinal disparity, and static, which functions to hold a vergence posture in place in the presence of a phoria. Accommodative vergence is coupled with accommodation. A blurred retinal image is the stimulus to accommodation which will drive accommodative convergence. The rate at which an individual will

convergence per diopter of accommodation is termed the accommodative convergence/accommodation (AC/A) ratio. On average, individuals have an AC/A ratio of 4^{Δ}/D. Lastly, tonic vergence describes the vergence position in the absence of the other three types of vergence. When the stimuli of proximal, fusional and accommodative vergence is zero, the amount of vergence left over is described as tonic vergence [1]. Proximal convergence has also been suggested to include voluntarily convergence [2], which is convergence due to voluntary effort that occurs without a proximal, fusional or accommodative stimulus [5]. The idea of voluntary convergence and the training of this ability began in 1943 [4]. Although not extensively studied, voluntary accommodation has been suggested to be the driving force behind voluntary convergence with the amount of accommodation exerted closely linked to a person's AC/A ratio [5]. Morgan summarized Maddox and reported that accommodation relates to the magnitude of voluntary convergence that will occur [3]. Anomalies of the vergence system can occur, resulting in disorders such as convergence or divergence insufficiency or convergence or divergence excess. The most common of these is convergence insufficiency (CI), or the inability of the eyes to convergence in an appropriate manner.

The Convergence Insufficiency Treatment Trial (CITT) study group defined the three signs of convergence insufficiency as follows: a near exophoria of at least 4 prism diopters or more than the phoria at distance, a receded near point of convergence of 6 cm or more, and insufficient positive fusional vergences (either failing to meet Sheard's criterion (defined below) or less than 15^{Δ} Base out to break) [6]. Sheard's criterion was developed to distinguish patients who were suspected to be symptomatic due to a

binocular vision anomaly; It states that the patient's phoria should be less than half of their compensating vergence ability [7].

Prevalence of Convergence Insufficiency

Considered to be the most common binocular vision disorder, convergence insufficiency has received a lot of attention in the scientific community. The precise prevalence of CI has been difficult to determine due to varying defining criteria of studies, and infrequent population-based screenings or testing to detect it but is often estimated to be between 2 and 36% of the population. The type of study can also impact the prevalence. Clinic-based studies often over-estimates the prevalence since the population is one that is already seeking eye care. For this reason, population-based studies like school screenings often provide a more accurate representation of the prevalence in the population. In 1980, some of the pioneers in studying convergence insufficiency, Pickwell and Hampshire conducted a clinic-based study on the prevalence and significance of CI. They collected and analyzed data from 455 participants to compare the prevalence and associated symptoms of CI between two methods for determining CI: 1) NPC > 10 cm, finding a prevalence of 12% and 2) inadequate jump vergences, finding a prevalence of 20% [8]. In a large population-based study of 2,045 elementary-aged students, Letourneau and Ducic used a different determinant to evaluate prevalence of CI. For their study in 1988, CI was defined as an NPC break greater than 10 cm with a penlight as a target. Using this criterion, they found a prevalence of 8.3%. They then evaluated the addition of a second factor of a greater exophoria at near

compared to distance. The prevalence of CI defined as having both NPC greater than 10 cm with a penlight and exophoria greater at near was 2.25% among the elementary-aged children [9]. In attempt to evaluate the prevalence of CI using more specific criteria, Rouse, et al. first performed a clinic-based study in 1998 investigating 620 total patients aged 8 to 12 in an optometry practice. Eligibility criteria to continue in the study included: established (more than 1 month) glasses or contact lens wearer or no glasses/contacts, a visual acuity of 20/30 or better with habitual correction, an uncorrected refractive error of between -0.50 to +1.00 as well as less than 1 D astigmatism and less than 1 D anisometropia, and no strabismus, resulting in 415 eligible participants. To meet criteria of suspected CI, participants had to have an exophoria and at least two of the following: 1) a near exophoria of at least 4^{Δ} or more than the phoria at distance, 2) insufficient positive fusional vergences, or 3) a receded near point of convergence of 6 cm or more. With these criteria, he found a prevalence of clinically significant (2 or 3 signs) CI to be 17.6%. The prevalence of patients with 2 sign CI was 12%, and the prevalence of 3 sign CI was 6% [10]. To further investigate the prevalence of CI, Rouse, et al. conducted a population-based study in 1999 by screening 5^{th} and 6^{th} grade students using the same diagnostic criteria for CI as used in his 1998 study. Eligibility criteria for inclusion in this study was identical to Rouse's previous study in 1998 listed above. Of the 453 eligible participants screened, highly suspected (2 signs of CI, one being 4^{Δ} greater exophoria at near) or definite (3 signs of CI: 4^{Δ} greater exophoria at near, insufficient PFV by failing Sheard's or less than 15^{Δ} BO to break, and receded NPC of 7.5 cm or more to break) CI was found in 13% of participants. The prevalence of

2 sign CI was 8.8%, and the prevalence of 3 sign CI was 4.2% [11]. In a recent population-based study of 282 school-aged participants evaluating screening methods for indentifying CI, Menjivar found a prevalence of 2-3 sign CI to be 20% and a prevalence of 3 sign CI to be 6% using similar diagnostic criteria [12]. Based upon these studies it's evident that the prevalence of CI varies depending on the population and the definition of CI.

Symptoms of Convergence Insufficiency

Symptoms associated with convergence insufficiency vary in type and severity between patients. Common symptoms reported with convergence insufficiency include headaches or eye strain with near work, intermittent blurred vision or diplopia, frequent loss of place when reading, difficulty concentrating when reading, feeling tired when reading and burning or tearing sensations [6,8,13,29,30]. In 1984, Daum et al. surveyed 110 symptomatic subjects (mean age 19.9 years) who had previously been diagnosed with convergence insufficiency to assess the prevalence of symptoms and the effect of current treatment options. The presenting symptoms in order of most to least common were headache, diplopia, blur, asthenopia, fatigue, and problems with reading [13]. In 2015, Vilela, et. al. performed a study investigating asthenopia, or eyestrain in school-aged students. The questionnaire given to 964 students aged 6-16 asked if their eyes felt tired or heavy during the previous school week. After completing additional binocular vision testing, the investigators determined an overall prevalence of asthenopic complaints to be 24.7%. Further, they determined age to be directly associated with risk of having asthenopia; the authors reported a prevalence of 18.6% in 6- to 9-year-olds,

28% in 10- to 14-year-olds and 31.3% in 15- to 16-year-olds. Students ages 10 to 14 years had a 51% risk and students ages 15 to 16 years had a 69% risk of having asthenopic complaints as compared to children who were aged 6 to 9 years [14].

Conditions Associated with Convergence Insufficiency

Accommodation is linked with convergence through the near triad of convergence, accommodation and pupillary miosis. The AC/A ratio describes the amount of convergence in prism diopters associated with each diopter of accommodation exerted. A normal value for an AC/A ratio is $4^{\Delta}/1.00$ Diopter. One of the most common co-morbidities associated with convergence insufficiency is accommodative dysfunction and the two conditions have increased associated symptoms [16]. A recent study published in 2019 by Nunes, et al. set out to determine the prevalence of CI and accommodative insufficiency (AI) in 5^{th} and 6^{th} grade children in Portugal. This cross-sectional study collected data from 292 children and classified accommodative insufficiency as an amplitude of accommodation 2D less than the minimum expected. This is calculated based on Hofstetter's equation (minimum amplitude of accommodation = 15-0.25*age). They defined CI with the same three criteria used by Rouse et al, indicating that a participant with only an exophoria at near was a low suspect CI, while a participant with an exophoria and NPC greater than 6 cm or inadequate positive fusional vergences was a high suspect CI. They found the prevalence of high suspect or definite CI to be 6.8% and the prevalence of AI was 10%. Combining the two conditions, they found that 3% of the participant population presented with both CI and AI [17]. Rouse et al. also evaluated the

prevalence of CI and AI in 5th and 6th grade American students. The research team used the same 3 criteria to diagnose CI and determined AI by the participants' accommodative amplitude or MEM. They found a significant trend of increased prevalence of AI with increasing number of signs of CI. More specifically, an AI prevalence of 21% was found in low suspect or one sign CI. For two and three sign CI participants the prevalence of AI increased to 55% and 79%, respectively [11]. Similarly, Scheiman et al. found associated accommodative dysfunction in 74% of participants with three signs of CI in a randomized clinical trial to investigate the effectiveness of vergence/accommodative therapy for the treatment of symptomatic convergence insufficiency [18].

Recently, researchers have studied the ways in which symptoms and behavior patterns of convergence and accommodative disorders are similar to those with Attention Deficit Hyperactivity Disorder (ADHD). In 2005 Granet et al. initiated a retrospective review of 266 charts of patients in an ophthalmology practice and investigated the connection between convergence insufficiency and ADHD. Using a CI definition of NPC >6 cm or positive fusional vergence $\leq 15^{\Delta}$ and symptoms (e.g. headache, asthenopia, and difficulty reading), they found a 15.9% incidence of CI among patients with ADHD. Additionally, they found a 3 times increased incidence of ADHD among patients with CI compared to the incidence of ADHD in the general population [19]. Borsting et al. evaluated the presence of ADHD-like behavior in 24 children (8 to 15 years old) with symptomatic CI or AI but without ADHD. CI was defined using the CITT definition; AI was defined as 2 diopters less than Hofstetter's minimum expected [20]. The parents of the children were asked to complete the Connors Parent Rating Scale Revised Short Form

(CPRS-R.S.), a 27-element questionnaire assessing the frequency of school behaviors relating to four major categories: oppositional, cognitive/inattention, hyperactivity, and ADHD index. The Connors test compares results to its normative database of 2,426 children aged 3-17. The test involves parents answering the various questions on behavior of their child on four levels: “not true at all”, “just a little true”, “pretty much true”, and “very much true”. The scored results of each test administered are converted into T-scores which are compared to the normative CPRS-R.S. scores; a score greater than 50 indicates an increase in the given behavior. The one sample t-test in Borsting’s study showed significantly higher T-scores in the study’s population as compared to the normative data for three out of the four CPRS-R.S. categories (cognitive problems/inattention, hyperactivity, and ADHD index). The findings suggested that that children with a symptomatic accommodative dysfunction or CI may have behaviors of inattention and learning problems in school similar to those with ADHD [21]. More recently, Varela et al. compared eye vergence during attention-related tasks between clinical controls (N=30) who were healthy patients showing no signs of attention deficits or issues with conduct and 62 children with diagnosed ADHD (N=43) or attention difficulties (N=19). The investigators found that participants with ADHD had poorer eye movement control and reduced abilities to converge during the attention-related tasks. Furthermore, they determined that vergence ability could correctly identify ADHD patients from healthy patients with 96.3% accuracy. This study did not rule out participants with CI but was able to control for CI by using testing distances that were all well outside the range of near distances that are problematic for CI patients [22].

Studying the correlation between ADHD and CI as well as identifying those patients with ADHD who also show signs of CI is important because there is an established method to treat the signs and symptoms associated with convergence insufficiency [23].

Another condition associated with convergence insufficiency is Parkinson's Disease. In 2017 Irving, et al. completed a study to investigate the prevalence of CI among 80 patients with Parkinson's Disease and 80 patients without Parkinson's Disease. They found a higher prevalence of CI and symptoms due to CI in the patients with Parkinson's. While the prevalence of CI among controls was 16.3%, she found the prevalence of CI among Parkinson's Disease patients to be 43.8%. She also found increased symptoms and more receded NPC in Parkinson's Disease patients as compared to controls [24].

Among adult-onset convergence insufficiency, researchers have found that CI is frequently observed after traumatic brain injury. Cohen measured vergence ability in 72 individuals who had suffered a traumatic brain injury and discovered a prevalence of CI of 42%. Even years after the trauma, they discovered that a defective vergence ability was a permanent result of the brain injury [25]. In a retrospective study of 270 athletes who had experienced a concussion due to sports, researchers Duprey et al. looked into the relationship between the athlete's concussion and presence of CI. A few days after the injury, 50.4% of the athletes were determined to have CI, defined as an NPC > 6 cm. Additionally, the researchers determined that presence of CI after concussion greatly increased the athletes' recovery time; those with CI or NPC > 6 cm required an average of 51.6 days whereas athletes without post-concussion CI and NPC of ≤6 cm required an

average of 19.2 days to recover. These findings suggest that a simple screening test such as NPC could be administered to athletes following traumatic brain injury to identify at least one sign of CI and therefore help tailor treatment and referral for vision therapy to potentially aid in recovery time [26].

Effects of Convergence Insufficiency in Academia

A binocular vison disorder such as convergence insufficiency has the potential to negatively impact academic behaviors. The Convergence Insufficiency Treatment Trial study group developed the Academic Behavior Survey (ABS) to investigate the impact of convergence insufficiency on the academic behavior of children ages 9 to 17 years. Parents of children with (n=210) and without (n=49) CI filled out the survey questions regarding the presence of adverse academic behaviors in their child, such as difficulty or distraction while completing homework or reading and the child's avoidance of reading and studying. On average, children with signs and symptoms of CI were determined to have a significantly higher ABS score as compared to children with normal binocular vision, meaning children with CI display more adverse academic behaviors. This study concluded that the presence of CI in a child may contribute to the parents' reports of their child having difficulty completing schoolwork [27]. The CITT group also investigated the effect of treatment on these negative academic behaviors. The ABS score for the children with symptomatic CI was 12.85 prior to vergence/accommodative therapy and decreased, or improved, to 10.6 after treatment. The group broke down this data further by dividing the treatment outcome of the participants into 'successful', 'improved' and

'non-responders' to treatment. They determined the ABS score improved by 4.01 points for 'successful', 2.94 points for 'improved' and 1.27 points for 'non-responders' which demonstrated that the success of treatment outcome correlated with improvement in ABS score. Additionally, they found that an improvement of the ABS score significantly correlated with a decrease in symptoms of the participants. A 15-point lower score on the CISS indicated an average reduction or improvement of the ABS score by 2.1. Overall Borsting et al found that parents reported fewer adverse academic behaviors following treatment of their child's symptomatic CI [28].

As part of an open trial, the CITT-Reading Study group compared parental reports of behavior of 44 school-aged children with symptomatic CI before and after treatment for their convergence insufficiency using the Conners 3 ADHD index and the Child Behavior Checklist (CBCL). After 16 weeks of office-based vergence accommodative therapy (OBVAT) with home reinforcement and 8 additional weeks of home reinforcement therapy for CI, significant improvements were observed in three scales of the Child Behavior Checklist, anxious/depressed, somatic, and internalizing problems (in order from least to greatest). Overall, parents of children with symptomatic CI reported more ADHD-like behavior problems as compared to the test's normative values, but these behaviors improved with OBVAT [29].

Treatment of Convergence Insufficiency

Common treatments for convergence insufficiency that have been researched over the past decade include pencil push-ups, base-in prism in glasses, and

vergence/accommodative therapy. Pencil push-ups require a patient to binocularly focus on a small target on a pencil (e.g. small letters printed on a pencil). The patient is instructed to bring the target toward the eyes until the letters double or split into two, attempt to fuse the target, then slowly back the target away until the letters become single. Patients are often prescribed 15 minutes a day of this activity.

The goal of ground base-in prism in glasses for patients with CI is to reduce the convergence demand when looking at near targets. The CITT Study Group investigated the benefit of adding base-in (BI) prism to glasses compared to placebo reading glasses in the randomized clinical trial. The amount of prism added was determined by the necessary amount to meet Sheard's criterion using the formula: prism to be prescribed = 2/3 phoria – 1/3 compensating fusional vergence. The placebo glasses only corrected the participant's refractive error and were instructed to wear for any near work lasting more than 5 minutes. They found no significant difference in symptom score, NPC and PFV in the patients with BI prism as compared to placebo. The symptom level according to CISS of both BI and placebo group did show a statistically significant decrease, but neither group significantly dropped below the standard symptom level for normal binocular vision of 16 or less [30] and there was no significant difference between groups in signs and symptoms.

Vergence/accommodative therapy involves activities that require the patient to stimulate and relax their accommodation and vergence. The goal of vergence and accommodative therapy is to improve the convergence and accommodative amplitudes as well as facility and control of vergence and accommodative abilities. The Convergence

Insufficiency Treatment Trial (CITT) study group completed a randomized clinical trial to evaluate the effectiveness of various treatment options for convergence insufficiency. Scheiman et al. randomly assigned 221 children aged 9 to 17 years with symptomatic CI into one of four of the following treatment groups: home-based pencil push-ups (HBPP), home-based computer /vergence/accommodative therapy and pencil push-ups (HBCVAT+), office-based vergence/accommodative therapy with home reinforcement (OBVAT), and office-based placebo therapy with home reinforcement (OBPT). The findings showed that only those in the OBVAT had a statistically significant improvement in their CISS symptom score. After 12 weeks of therapy, the average symptom score for the OBVAT participants was 6.9 points lower than in OBPT, 7.9 points lower than HBPP, 8.5 points less than HBCVAT+. In addition, only those in the OBVAT group had a significantly improved NPC to <6cm on average. The NPC among the HBPP and HBVAT+ improved somewhat more than the OBPT but NPC remained receded on average. The OBVAT also displayed a significantly improved positive fusional vergence range compared to the HBPP, HBCVAT+, and OBPT groups. The CITT group also determined the percentages of participants in each group who had had achieved normal NPC and PFV values. The proportion of patients in the OBVAT, HBPP, HBCVAT+, and OBPT to achieve a normal NPC and PFV outcome was 73%, 40%, 37%, and 22%, respectively. These data demonstrated that office-based vergence/accommodative therapy was the most effective treatment to reduce signs and symptoms associated with CI [31]. The research by the CITT group confirmed that office-based vision therapy was a highly effective method to treat signs and symptoms

associated with CI. This conclusion suggests that eye care providers have the opportunity to positively impact the visual system, resulting in vision that is comfortable for the patient.

The effectiveness of non-surgical treatments (base-in prism, in-office vision therapy, home-based pencil push-ups, and home-based computer therapy) for improving the signs and symptoms of convergence insufficiency has been compared using Cochrane systematic review. The Cochrane Review found three main results regarding non-surgical treatment of CI. First, the use of base-in prism in reading glasses was no better than placebo at improving signs or symptoms of CI in children. Second, in-office vision therapy was more effective than home-based orthoptic vergence exercises or computer-based vision therapy. Lastly, the Cochrane Review concluded that the outcomes of vision therapy techniques analyzed in this review were not consistent for the adult population [32].

Identification of CI

Despite the high prevalence of CI among school-aged children, frequently associated near work symptoms, and the availability of effective treatment, the majority of vision screenings do not include testing that would identify convergence insufficiency. In order to investigate screening measures, Menjivar et al. performed thorough screenings in 282 children and evaluated the ability of several common binocular vision tests such as NPC and PFV to correctly identify CI. The vision testing included CISS, visual acuity, retinoscopy, cover test, Modified Thorington, NPC, fusional vergence ranges, monocular

amplitude of accommodation, monocular accommodative facility, and binocular accommodative facility. Receiver Operating Characteristic Curves (ROC) were created to compare the various procedures and identify tests that screened for CI with the greatest sensitivity and specificity. The near point of convergence break was identified to be the test best at identifying CI. Menjivar et al. determined an NPC measurement of 6 cm or more was highly indicative of CI, while an NPC break of 7 cm or more was sensitive for a symptomatic CI [12].

Rouse et al. evaluated the repeatability of some common binocular vision measures (von Graefe near heterophoria, positive fusional vergences in the phoropter, near point of convergence (NPC), and monocular accommodative amplitude push-ups) on a cohort of twenty 5th and 6th grade students. Two examiners performed the four tests three separate times on each participant. Testing was also repeated approximately one week later to investigate between session repeatability. Rouse et al. found that positive fusional vergence measured through the phoropter was less reliable; whereas the other tests had good reliability between investigators as well as consistently reliable measures across different days.

A simple test that could be parent-, teacher-, nurse- or self-administered may further facilitate identification of those with convergence insufficiency. McLin and Schor proposed that most individuals are able to voluntarily converge [5]. It could be theorized that those without convergence insufficiency should have the ability to voluntarily converge, while those with convergence insufficiency would lack that ability. However, prior studies have not reported the percentages of individuals who can voluntarily

converge among those with and without convergence insufficiency. Therefore, the purpose of this study was to investigate the proportion of those with and without convergence insufficiency who can voluntarily converge their eyes. A second aim was to determine the association between the ability of a person to voluntarily converge their eyes, either with or without a target, and the signs and/or symptoms of CI in order to determine whether inability to voluntarily converge could be useful as a simple screening test for convergence insufficiency. A final purpose of the study was to compare normative values for NPC, PFV, and distance and near phoria to the present study's population.

Chapter 2. Methods

IRB approval

The Ohio State University Institutional Review Board (IRB) approved the study protocol and verbal assent documents used for this study. We enrolled participants who were museum goers at the COSI science museum in Columbus, Ohio. All subject testing and data collection took place in a glass-walled enclosed room of the "Labs in Life" exhibit within the museum.

Inclusion/Exclusion Criteria

Major eligibility criteria for participation in the study included age 8 or older and visual acuity of at least 20/32. A brief overview of the study was explained and provided to each participant. Verbal assent was obtained according to the protocol approved by the institutional review board of The Ohio State University. Demographic information was obtained from the participants which included: date of birth, race, and sex. No identifiable information was recorded. The same researcher (NM) performed all vision tests and the Convergence Insufficiency Symptom Survey (CISS) (described below). All vision testing was performed through the participant's optical correction, if applicable.

Procedures

Visual acuity and dry refraction: First, the participant's visual acuities were measured. Monocular visual acuities at distance were measured using a lighted LogMAR Early Treatment Diabetic Retinopathy Study (ETDRS) chart placed at 20 feet. Participants' near visual acuity was measured binocularly with an HOTV eye chart at 40cm. Participation was complete for those with a corrected visual acuity of 20/40 or worse at either distance or near in order to exclude participants with significant uncorrected refractive error or amblyopia. Next, dry autorefraction was performed using a Grand Seiko WAM-5500, and the subjects' refractive error was recorded.

Symptom survey: The CISS was administered to assess each participant's symptom level. The participant was given a card to hold which contained the five response options (i.e. Never, Infrequently, Sometimes, Fairly Often and Always). Each question was read verbatim, slowly and clearly and without examples of the symptoms to the participant. The participant was only allowed to respond with one of the five response options listed above. The investigator recorded and scored the participant's responses as '0' to '4' for responses of 'never' to 'always', respectively. Then the total symptom score was calculated. The total CISS score could range from 0 to 60. A copy of the CISS questionnaire can be found in the appendix.

Ocular Alignment: Each participant's eye alignment or phoria was measured using the Modified Thorington (Bernell Corporation Muscle Imbalance Measure (MIM) card;

Bernell Corp., South Bend, Indiana). A Maddox rod was held with the striations oriented horizontally over the participant's right eye as they observed a vertical red line on the Modified Thorington card. Instructions were presented to the participant to identify where the vertical red line crossed the number line. The dissociated heterophoria amount was measured and recorded for both distance at 10 feet and near at 16 inches.

Near Point of Convergence: Each participant's near point of convergence (NPC) was measured using Gulden's Near Point Rule (Gulden Ophthalmics, #15150) with the printed Gulden fixation target consisting of a single column of 20/30 letters (Figure 1). The Convergence Rule was held against the participant's forehead so that the participant looked at the vertical column of letters in a slight downgaze position. Beginning at 40 cm the participant was instructed to look at the letters and report when they became double or broke into two as the target was slowly (1-2cm/sec) moved toward the participant. When the participant reported that the column of letters doubled or split into two, the participant was asked if the letters came back to one. If the letters remained double, the point at which the participant reported double was recorded as the NPC break. If the letters became single, the target was moved closer until double was reported. If the examiner observed that the participant was no longer converging (e.g. one eye turned out), the point at which that occurred was recorded as the "break" even if the participant never reported a doubling of the letters. Next, the participant was asked to report when the letters became single, as the target was slowly moved away from the participant. This distance was recorded as the NPC recovery. If the participant didn't report a break value

and converged to the nose, one eye was covered for 3-5 seconds to break fusion so that recovery could be measured.

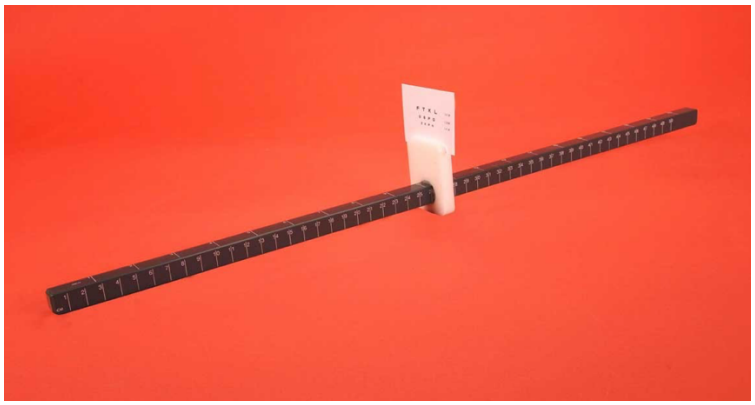

Figure 1: Gulden's Near Point Rule

Image from http://www.guldenophthalmics.com

Vergence Ranges: The fusional vergence ranges were measured using an LB-15 Horizontal Prism Bar ("Long Bar") (Gulden Ophthalmics, #11112) with a range of 1-40 prism diopters (Figure 2). The target used was a Gulden fixation target with single column of 20/30 letters (Gulden Ophthalmics, #15302) and was held in the participant's primary gaze at 40 cm (Figure 3). The horizontal prism bar was first held in base-in orientation to measure the participant's negative fusional vergences. The participant was asked to report when the letters became blurred or double as the amount of BI prism was increased slowly (beginning with 1^{Δ} and increasing prism by approximately 2^{Δ}/sec), pausing at each prism amount to confirm the letters were "clear and single". The prism through which the letters were reported to be blurred was recorded as the "blur" finding,

and the prism amount was increased further. If blur was not reported, "X" was recorded on the data sheet. When the line of letters doubled or split into two, the participant was asked if the letters came back to one or remained double. If the letters remained double that prism amount was recorded as the "break" finding. If the letters came back into one, the amount of prism was increased again until double was reported. The participant's eyes were watched closely to ensure that both eyes stayed aligned on the target. If one of the participant's eyes turned out, the prism value would be recorded as the "break" even if the participant never reported a doubling of the letters. After the letters split, 5^{Δ} was added, and the amount of prism was slowly decreased (approximately 2^{Δ}/sec), and the participant was told to report when the doubled line came back to one. The amount of prism at which re-fusion of the doubled lines occurred was recorded as the "recovery" finding. This procedure was then repeated with the bar prism held in the base-out orientation to measure the participant's positive fusional vergence ranges. The blur, break and recovery were measured and recorded for both base-in and base-out directions at near only.

Figure 2: LB-15 Horizontal Prism Bar (“Long Bar”)

Image from http://www.guldenophthalmics.com

Figure 3: Gulden Fixation Sticks (4 pack)

Image from http://www.guldenophthalmics.com

Accommodation: If the participant was 30 years old or younger, accommodative amplitude was also measured on the subject’s right eye. The left eye was covered and Gulden’s Near Point Rule with the printed Gulden fixation target with single column of

20/30 letters was slowly (1-2cm/sec) moved toward the participant. The participant was asked to report when the column of letters first started to blur. The participant was then asked if the blurred letters became clear or stayed blurred. The accommodative amplitude was measured (in centimeters) and recorded as the point at which the participant reported the first sustained blur.

Convergence: Lastly, the participant was asked by the researcher if he or she could converge or cross his/her eyes voluntarily without a target. The ability was marked as either "able" or "unable". Then the researcher asked if the participant could convergence his or her eyes to look at a target placed at a distance of 6 cm from the eyes. Again, ability was marked as "able" or "unable". The convergence ability was considered "unable" if the participant could not converge their eyes or if their eyes weren't aligned. Testing for voluntary convergence was performed last so the investigator would be masked to the participant's ability to voluntarily converge their eyes.

Classification of CI, State of Symptoms, and Binocular Dysfunction

Participants were classified as having 1, 2 or 3 signs of convergence insufficiency based on the definition used by Convergence Insufficiency Treatment Trial (CITT) investigator group. The signs included 1) an exophoria of at least 4^{Δ} more at near than distance, 2) insufficient positive fusional vergences (failing Sheard's criterion or near PFV $\leq 15^{\Delta}$ base-out blur), and 3) a receded NPC of ≥ 6.0 cm [6].

Subjects also were classified as being symptomatic or asymptomatic based on the CISS symptom score using the criteria for symptomatic of ≥ 16 for children and ≥ 21 for adults. For children, a score of 8 or 9 has been reported in those with normal binocular vision while scores of 16 or more indicate symptomatic. For adults, a score of 11 has been reported in those with normal binocular vision while a score of 21 or more indicates the patient is symptomatic. In 2003 Borsting, et al. investigated the validity of an updated version of the convergence insufficiency symptom survey on 106 children aged 9-18. They found the CISS to be an accurate measure of symptoms of children aged 9-18 and determined a score of 16 or more to be considered symptomatic [33]. Following this study, in 2004 they investigated the validity of the CISS on 19-30 year old adults. Of the 92 participants investigated, they found the CISS to be an appropriate measure of symptom level, and they considered a score of 21 or greater to by symptomatic [34].

Additionally, participants were considered to have a binocular vision disorder if they had 2 or 3 signs of CI or an esophoria ≥ 3^{Δ} at near [35]. Participants less than 30 years of age were considered to have accommodative insufficiency if their amplitude of accommodation was ≥2D less than the minimum expected (15 – [age*0.25]) [36].

Statistical Analysis

All subject data was transferred onto an electronic database on a secure computer. Analysis of the data was performed with the Statistical Package for the Social Sciences (version 25, SPSS Inc., Chicago, Illinois, USA) software. Descriptive analysis of the data

was performed to find the mean, standard deviation, median and range of the data. The frequency of the number of participants who were and were not able to voluntarily cross their eyes was determined. In order to determine if the inability to voluntarily converge was an indication that patient was likely to have convergence insufficiency, be symptomatic, have accommodative insufficiency or have binocular dysfunction, crosstabulation tables were created to compare the ability to cross one's eyes against the presence of CI or binocular dysfunction.

Sensitivity, specificity, positive predictive value, and negative predictive value of each measure were also determined. The validity of a test refers to its ability to accurately measure the presence or absence an indicated disease [37]. Validity is determined by measuring sensitivity and specificity and is often depicted in a 2x2 table comparing the presence of disease in a given population to a test's detection of the disease in the same population. In the 2x2 table, box A is the 'true positives' or those participants who were correctly referred based on the screening test. Box B is the 'false positives' and includes the participants who were referred based on the screening test even though they didn't have the disease. Box C includes the 'false negatives' or participants who had the disease but weren't detected by the screening test. Box D is the 'true negative' or the portion of the individuals who were correctly identified by the test as being free of disease (Table 1).

		Presence of Disease		
		Yes	No	
Test Result	+	**A** True Positive (TP)	**B** False Positive (FP)	Total test positive (A+B)
	-	**C** False Negative (FN)	**D** True Negative (TN)	Total test negative (C+D)
		Total Diseased (A+C)	Total Disease-free (B+D)	Total population (A+B+C+D)

Table 1: 2x2 table displaying the portion of population with disease and result of test

Sensitivity is defined as the ability of a test to correctly identify that a person has a given disease or condition. Sensitivity is calculated by dividing the true positive (TP) by the portion of the population that had the disease (formula 1). In Formula 1, 'A' is the number of correct referrals and 'A+C' is the total number of persons with the disease. Sensitivity determines the probability that a test will be positive in the presence of disease [37].

$$\text{Sensitivity} = \frac{A}{A + C}$$

Formula 1: Calculation of sensitivity based on the 2x2 table

Specificity is defined as the ability of a test to identify an individual as being free of disease. Specificity is calculated by dividing the true negative (TN) by the portion of

the population that is disease-free (formula 2). In formula 2, 'D' is the number of correct non-referrals and 'B+D' is the total number of persons without the disease. Specificity is the probability that a test will be negative in the absence of disease, or a test's ability to identify those without a condition or disease [37].

$$\text{Specificity} = \frac{D}{B + D}$$

Formula 2: Calculation of specificity based on the 2x2 table

The higher the sensitivity and/or specificity is, the closer the value will be to 1.00. The higher sensitivity is, the better a given test will be at identifying disease, and the number of under-referrals will be minimized. The higher the specificity is, the better the given test is at identifying those without disease, and the number of over-referrals of those without disease would be minimized [37]. In general, as a test's criteria is adjusted to increase its sensitivity, the specificity of the test will decrease.

The positive predictive value (PPV) is the percentage of the population with a positive test result who do have the disease. PPV is calculated by dividing the true positive (TP) (A) by all participants with a positive test result (A+B) (formula 3) [37].

$$\text{Positive predictive value} = \frac{A}{A + B}$$

Formula 3: Calculation of positive predictive value based on 2x2 table

The negative predictive value (NPV) is the percentage of the population with a negative test result who are indeed disease-free. NPV is calculated by dividing the true negative (TN) (D) by all participants with a negative test result (C+D) (formula 4) [37].

$$\text{Negative predictive value} = \frac{D}{C + D}$$

Formula 4: Calculation of negative predictive value based on 2x2 table

Chapter 3. Results

Sixty-five healthy participants between the ages of 8 to 64 years were enrolled in the study. 10 participants were excluded due to visual acuity worse than 20/32 at distance. Of the sixty-five subjects, 73% identified themselves as white, 13% as African American, 6% as American Indian, 3% as Asian, and 3% were unsure of their race. Sixty percent of the participants were female. Additionally, 100% of subjects considered themselves to be non-hispanic.

Descriptive statistics for symptom level (as measured by the CISS symptom survey) as well as each test of binocular and accommodative function are listed in Table 2. Based on visual acuity and dry autorefraction, no subjects were suspected to have significant uncorrected refractive error expected to affect amplitudes of accommodation or convergence.

Characteristic	N	Range	Minimum	Maximum	Mean	Std. Dev
CISS symptom score	65	48	1	49	15.92	10.43
Modified Thorington (distance)[1]	65	7	-4	3	-0.15	1.07
Modified Thorington (near)[1]	65	29	-13	16	-2.31	4.531
NPC[2] Break	65	22.5	0.5	23	4.87	3.66
NPC Recovery	63[3]	25	1	26	7.22	4.44
NFV[4] Blur	65	43	2	45	13.06	6.72
NFV Recovery	65	29	6	35	13.05	4.99
PFV[5] Blur	65	41	4	45	19.57	10.36
PFV Recovery[6]	64[7]	36	4	40	19.98	8.14
Accommodative Amplitude (cm)	23[8]	13	1	14	5.94	2.59

Table 2: Descriptive statistics for measures of binocular and accommodative function

[1] A negative number indicates an exophoria
[2] NPC: near point of convergence
[3] NPC recover was not recorded for 2 participants
[4] NFV: negative fusional vergence
[5] PFV: positive fusional vergence
[6] If no blur was reported, the 'break' was recorded
[7] PFV recovery was not recorded for 1 participant
[8] Accommodative amplitude was not measured for the 42 participants who were 30 or older

The percentage of subjects determined to have zero, one, two and three signs of CI are listed in Table 3. Approximately 29% of the participants had no signs of CI, 39% had one sign of CI, 28% had two signs of CI, and about 5% had three signs of CI. Table 3 also shows the percentages of participants with esophoria greater than 3^{Δ} at near (9%) or accommodative insufficiency (AI) (accommodative amplitude 2 D less than minimum expected) (28%). Subjects classified as having binocular dysfunction (two to three signs of CI, esophoria > 3^{Δ}, or AI) (56.9%) are also shown in Table 3.

Classification	n	Percentage
0 signs CI	19	29.2
1 sign CI	25	38.5
2 sign CI	18	27.7
3 sign CI	3	4.6
2-3 sign CI	21	32.3
Esophoria	6	9.2
AI	18	27.7
Binocular Dysfunction	37	56.9
Symptomatic per CISS	23	35.4
Symptomatic BD[1]	9	13.8
Symptomatic 2-3 sign CI	8	12.3
Symptomatic 3 sign CI	1	1.5
Symptomatic BD	17	26.2
None of the conditions listed above	12	18.5

Table 3: Percentages of subjects classified as 0, 1, 2 or 3 sign CI, esophoria, AI, BD and the proportion of symptomatic participants classified with those conditions

[1] BD: binocular dysfunction

The proportion of the participant cohort determined to be able to cross their eyes voluntarily with or without a target is listed in Table 4. Overall, fifty-five percent (36/65) of the participants were able to voluntarily convergence their eyes without a target. This number improved to 75 percent (9/12) among participants without any signs of CI, AI or esophoria > 3^{Δ}. This percentage decreased to 38 percent (8/21) in those participants with 2-3 signs of CI. Eighty-five percent (55/65) of the participants demonstrated an ability to converge their eyes to a target at 6cm. This number improved to 90 percent (11/12) among participants without signs of CI, AI or esophoria > 3^{Δ}. This percentage decreased to 71 percent (15/21) in those participants with 2-3 signs of CI.

	All Participants		Participants without signs of CI, AI or esophoria > 3Δ		Participants with 2-3 signs CI	
Convergence	**N**	**Percentage (Std. Deviation)**	**N**	**Percentage (Std. Deviation)**	**N**	**Percentage (Std. Deviation)**
Voluntary Convergence without a target	65	55 (0.501)	9	75 (0.45)	8	38 (0.498)
Convergence with a target	64[1]	85 (0.35)	11	90 (0.30)	15	71 (0.463)

Table 4: Ability to voluntarily converge with and without a target

[1] The ability to converge with a target was not recorded for 1 participant

Crosstabulation tables were created to determine agreement between ability of the participants to voluntarily converge their eyes and performance on each test of binocular vision or diagnostic classification. This was done to identify the signs of CI or binocular dysfunction that could be predicted by the ability to cross one's eyes voluntarily. Tables 8-27 list the crosstabs for each of the 14 conditions both with and without a target. Table 28 lists a summary of the sensitivities and specificities as well as the calculated positive predictive value (PPV) and negative predictive value (NPV) of the tests analyzed.

		RECEDED NPC (≥ 6CM)		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	11	18	29
	Able	8	28	36
	Total	19	46	65

Table 5: Agreement between receded NPC and voluntary convergence without a target

		RECEDED NPC (≥ 6CM)		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	6	3	9
	Able	13	42	55
	Total	19	45	64

Table 6: Agreement between receded NPC and voluntary convergence with a target

		INSUFFICIENT PFV (BLUR[1] ≤ 15Δ)		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	13	16	29
	Able	14	22	36
	Total	27	38	65

Table 7: Crosstab of insufficient PFV and voluntary convergence without a target

[1] Or break if a blur point was not reported by the participant

		INSUFFICIENT PFV (BLUR[1] ≤ 15Δ)		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	7	2	9
	Able	20	35	55
	Total	27	37	64

Table 8: Agreement between insufficient PFV and voluntary convergence with a target

[1] Or break if a blur point was not reported by the participant

		EXOPHORIA 4Δ GREATER AT NEAR		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	15	14	29
	Able	9	27	36
	Total	24	41	65

Table 9: Agreement between exophoria greater at near and voluntary convergence without a target

		EXOPHORIA 4Δ GREATER AT NEAR		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	3	6	9
	Able	21	34	55
	Total	24	40	64

Table 10: Agreement between exophoria greater at near and voluntary convergence with a target

		SYMPTOMATIC		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	11	18	29
	Able	13	23	36
	Total	24	41	65

Table 11: Agreement between symptoms and voluntary convergence without a target

		SYMPTOMATIC		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	4	5	9
	Able	20	35	55
	Total	24	40	64

Table 12: Agreement between symptoms and voluntary convergence with a target

		2-3 SIGN CI		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	13	16	29
	Able	8	28	36
	Total	21	44	65

Table 13: Agreement between 2-3 sign CI and voluntary convergence without a target

		2-3 SIGN CI		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	6	3	9
	Able	15	40	55
	Total	21	43	64

Table 14: Agreement between 2-3 sign CI and voluntary convergence with a target

		3 SIGN CI		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	3	26	29
	Able	0	36	36
	Total	3	62	65

Table 15: Agreement between 3 sign CI and voluntary convergence without a target

		3 SIGN CI		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	2	7	9
	Able	1	54	55
	Total	3	61	64

Table 16: Agreement between 3 sign CI and voluntary convergence with a target

		SYMPTOMATIC 2-3 SIGN CI		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	5	24	29
	Able	3	33	36
	Total	8	57	65

Table 17: Agreement between symptomatic 2-3 sign CI and voluntary convergence without a target

		SYMPTOMATIC 2-3 SIGN CI		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	2	7	9
	Able	6	49	55
	Total	8	56	64

Table 18: Agreement between symptomatic 2-3 sign CI and voluntary convergence with a target

		ACCOMMODATIVE INSUFFICIENCY		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	10	19	29
	Able	8	28	36
	Total	18	47	65

Table 19: Agreement between accommodative insufficiency (AI) and voluntary convergence without a target

		ACCOMMODATIVE INSUFFICIENCY		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	2	7	9
	Able	16	39	55
	Total	18	46	64

Table 20: Agreement between accommodative insufficiency (AI) and voluntary convergence with a target

		BINOCULAR DYSFUNCTION		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	12	17	29
	Able	12	24	36
	Total	24	41	65

Table 21: Agreement between binocular dysfunction and voluntary convergence without a target

		BINOCULAR DYSFUNCTION		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	5	4	9
	Able	19	36	55
	Total	24	40	64

Table 22: Agreement between binocular dysfunction and voluntary convergence with a target

		SYMPTOMATIC BINOCULAR DYSFUNCTION		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITHOUT A TARGET	Not able	5	24	29
	Able	4	32	36
	Total	9	56	65

Table 23: Agreement between binocular dysfunction and symptomatic and voluntary convergence without a target

		SYMPTOMATIC BINOCULAR DYSFUNCTION		
		Yes	No	Total
VOLUNTARY CONVERGENCE WITH A TARGET	Not able	2	7	9
	Able	7	48	55
	Total	9	55	64

Table 24: Agreement between binocular dysfunction and symptomatic and voluntary convergence with a target

Binocular Vision Classification	Condition	Sensitivity	Specificity	PPV	NPV
Receded NPC	no target	0.58	0.61	0.38	0.78
Receded NPC	with target	0.32	0.93	0.67	0.76
Insufficient PFV	no target	0.48	0.58	0.45	0.61
Insufficient PFV	with target	0.26	0.95	0.78	0.64
Exophoria	no target	0.63	0.66	0.52	0.75
Exophoria	with target	0.13	0.85	0.33	0.62
Symptomatic	no target	0.46	0.56	0.34	0.64
Symptomatic	with target	0.17	0.89	0.44	0.64
2-3 sign CI	no target	0.62	0.64	0.45	0.78
2-3 sign CI	with target	0.28	0.93	0.67	0.72
3 sign CI	no target	1	0.58	0.10	1
3 sign CI	with target	0.67	0.89	0.22	0.98
2-3 sign CI + symptoms	no target	0.63	0.58	0.17	0.92
2-3 sign CI + symptoms	with target	0.25	0.88	0.22	0.89
AI[1]	no target	0.56	0.59	0.34	0.78
AI	with target	0.11	0.85	0.22	0.71
BD[2]	no target	0.5	0.59	0.41	0.67
BD	with target	0.21	0.9	0.56	0.66
BD + symptomatic	no target	0.56	0.57	0.17	0.89
BD + symptomatic	with target	0.22	0.87	0.22	0.87

Table 25: Summary of sensitivities and specificities of the agreement between voluntary convergence ability with and without a target and binocular vision classifications

[1] AI: accommodative insufficiency
[2] BD: binocular dysfunction

Table 26 lists the mean NPC observed in this study as well as several normative values for NPC break in children and adults, all of which used accommodative targets to measure.

	NPC break Adults (age >19)	*NPC break Children (age <19)*	*Target used*
Scheiman, et. al [38]	2.5 ± 1.74		accommodative
Abraham [39]	8 ± 3.39	6.3 ± 2.8	accommodative
Ostadimoghaddam, et al. [40]	7.59 ± 3.95	6.95 ± 3.87	accommodative
Yekta, et al. [41]	6.33 ± 4.28	5.2 ± 3.52	accommodative
Borish [45]	-	3 ± 4	
Jiménez R, et al [46]		5.2 ± 4.4	penlight
Current study (0 signs CI)	3 ± 0.82	2.97 ± 1.56	accommodative
Current study (0 or 1 signs)	3.59 ± 1.94	3.32 ± 1.74	accommodative

Table 26: Normative values for NPC break

Table 27 lists normative values and averages for the present study for positive fusional vergence ranges.

	Adults (age >19)	*Children (age <19)*
Yekta, et al. [41]	20.5 ± 5.59; 20.96 ± 5.64	20.46 ± 6.48; 22.92 ± 6.44
Morgan [43]	17 ± 5; 11 ± 7	17 ± 5; 11 ± 7
Fray, et al. [44]	33.5[1]; 28.1	-
Jiménez R, et al [46]		18 ± 8; 13 ± 6
Current study (0 signs CI)	22.25 ± 8.7; 21.0 ± 6.2	27.5 ± 8.8; 25.7 ± 6.96
Current study (0 or 1 signs)	22.0 ± 8.3; 23.44 ± 6.39	22.11 ± 9.51; 22.70 ± 7.16

Table 27: Normative values for PFV (blur, recovery)

[1] First value listed by Fray, et al. is the break finding

Table 28 lists normative values as well as values of the current study of mean phoria at distance and near for children and adults.

	Adults (age >19)	*Children (age <19)*
Abraham [39]	-0.55 ± 2.12; -0.74 ± 3.58	0 ± 1.2; -1.2 ± 2.63
Yekta, et al. [41]	-1.62 ± 3.63; -5.54 ± 5.81	-1.03 ±1.32; -4.74 ± 4.24
Jiménez R, et al [46]		0.6 ± 1.7; -0.4 ± 3.1
Current study (0 signs CI)	0.5 ± 0.7; 4.0 ± 8.52	0.23 ± 0.62; -0.67 ± 1.5
Current study (0 or 1 signs)	-0.16 ± 0.65, -1.69 ± 5.85	0.13 ± 0.91; -1.07± 2.98

Table 28: Normative values for phoria measurement (distance, near)

Lastly, table 29 lists the proportion of the participants with the ability to converge with and without a target divided by age.

	< 18		18-30		> 30	
Number	N =	Percentage	N =	Percentage	N =	Percentage
Voluntary convergence without target	17/33	51.5	12/18	66.7	7/14	50.0
Voluntary convergence with a target	28/32	84.4	17/18	94.4	10/14	71.4

Table 29: Voluntary convergence ability categorized by age

Chapter 4. Discussion

This study found that 27.7% of participants were determined to be a 2 sign CI, and 4.6% of participants were a 3 sign CI. These values are similar to those found by Menjivar et al, who found 20% of subject to have a 2 or 3 sign CI and 6% of subjects to have a 3 sign CI [12]. These values are also similar to what Rouse et al. determined, finding a prevalence of 2 sign CI to be between 8.8%-12%, and a prevalence of 3 sign CI to be between 4.2%-6% [11].

This study found that 85% of participants overall were able to converge with a target placed at 6 cm, while only 55% of participants were able to voluntarily converge without a target. Among those with 2-3 signs of CI, 71% of participants could converge to a target at 6 cm while only 38% could voluntarily converge without a target. The greatest proportion having the ability to converge was among participants without any signs of CI, AI or esophoria > 3^{Δ}, with 90% being able to converge with a target and 75% able to converge without a target. Thus, those with 2-3 signs of CI were more likely to be unable to voluntarily converge in addition to having reduced positive fusional vergence and/or receded near point of convergence. Instructions to participants for voluntary convergence without a target was limited to asking if the participant could cross their eyes. Participants were not coached to imagine a near object, and the proportional of

individuals with voluntary convergence ability may have been different if this had been stated.

Inability to voluntarily converge with a target was related to classification of 3 sign CI. With a sensitivity of 0.67, the inability to voluntarily converge to a target at 6 cm identified 2/3 of individuals with 3 signs of CI. Specificity is the ability of a test to correctly identify a participant as being free of disease. The ability to voluntarily converge to a target at 6 cm correctly identified 89% of participants as not having 3 signs of CI, which equates to an over-referral of 11%. The inability to voluntarily converge without a target had a sensitivity of 100% for identification of participants with 3 sign CI. However, the specificity was only 58%. Sensitivity and/or specificity of ability to voluntarily converge or converge to a target were low for other binocular vision findings and classifications. It is surprising that the ability to voluntarily converge to a target held at 6 cm didn't match the NPC sign of greater than 6 cm more closely. A majority (13/16) of participants with a receded NPC of more than 6 cm were able to voluntarily convergence to a target at 6 cm. This variation may be due to a fatiguing effect of NPC testing and/or the fact that a target stimulates disparity and proximal vergence while the NPC testing procedure stimulates disparity, proximal and accommodative vergence.

Participating adults with 0 or 1 signs of CI were found to have an NPC of 3.59cm, while participating children with 0 or 1 signs of CI were found to have an NPC of 3.32cm. This is comparable to the NPC reported for adults by Scheiman and to the NPC reported for children by Borish. Other reported normative values in the literature were higher. The NPC break of 2.5 ± 1.74 listed by Scheiman below was determined using the

standard push-up technique with a Bernell accommodative rule with a single 20/30 letter on 175 participants with normal binocular vision. This value increased to 9.34 ± 6.74 among participants with 3 signs of CI which was defined as exophoria greater at near, receded NPC of 5 cm or more, and reduced PFV (>1 SD from Morgan's expected) [38]. The NPC break values reported by Abraham were averages for 50 adults and 50 children using an accommodative target or Beren's ruler [39]. The NPC break measures recorded by Ostadimoghaddam used a single 20/40 letter on a Gulden fixation stick [40]. Yekta et al. used a single letter for the NPC break that was one line above the participant's corrected visual acuity [41]. Thus, all but one used an accommodative target to assess the NPC. The results by Jiménez were determined using the push-up technique with a penlight to evaluate NPC and were more receded than the present study. However, the studies by Abraham, Ostadimoghaddam and Yekta did not exclude participants with CI, so the values listed likely include participants with signs of CI, esophoria, or accommodative dysfunction. Additionally, the study performed by Ostadimoghaddam used an average of 5 NPC measurements while the current study only measured the NPC once. Measuring NPC several times in a row could fatigue a participant, and result in the higher or more receded NPC values reported by Ostadimoghaddam for both children and adults. The study methodology and findings by Scheiman most closely resemble the present study which used the same target and method for measuring NPC. Additionally, the NPC value reported by Scheiman included only subjects with 2 or fewer signs of CI.

Participating adults with 0 or 1 signs of CI were found to have a PFV blur and break of 22.0 and 23.44, respectively, while participating children with 0 or 1 signs of CI

were found to have a PFV blur or break of 22.11 or 22.70, respectively. These values are comparable to values for PFV blur and recovery reported in the literature. The vergence ranges reported by Yekta and Jiménez were measured using a prism bar in a step-wise manner to measure the points of blur, break and recovery [41,46]. Morgan's values were also measured using prisms [43]. Fray et al. measured the vergence ranges of participants with the prism bar held over the non-dominant eye [44]. However, the finding by Fray et al. for PFV were greater that the present study because the study by Fray only used the break and recovery values while the present study used the blur and recovery.

The mean phoria observed in the current study using the Modified Thorington procedure was comparable to phoria values reported previously in the literature. Phoria measurements reported by Abraham also were measured using the Modified Thorington technique [39] while the phoria measurements by Yekta were measured by the alternate cover test with a prism bar using a letter target one line larger than the participant's best corrected visual acuity [41]. These findings suggest that phoria measures are stable across the populations assessed in these studies and may not vary based on number of signs of CI among the populations. The studies by Abraham and Yekta did not exclude participants with CI and those studies found phoria measures similar to the present study of participants with 0-1 sign of CI.

The Study of Voluntary Converge is the first study to assess the proportion of individuals with the ability to voluntarily converge as well as whether the ability to voluntarily convergence could be a useful screening test to identify convergence insufficiency. One strength of this study was the population-based recruitment. One

limitation of this study was the small number of subjects. Recruitment for this study was restricted to weekends during the school year and may have been better if more recruitment had been done during the summer months when children are out of school.

Future research should investigate whether successfully learning to voluntarily converge during vergence therapy is associated with successful treatment of the signs and symptoms of CI. A current end-of-therapy goal is for the patient to be able to voluntarily converge [6].

Chapter 5. Conclusion

The majority of participants without signs of CI, AI or significant esophoria were able to converge either voluntarily or with a target. On the other hand, the majority of participants with 2-3 signs of CI were unable to converge voluntarily, but 71% could converge to a target at 6cm. Thus, inability to converge either voluntarily or to a target at 6cm was associated with signs of CI. Inability to converge to a target identified about 2/3 of those with 3 signs of CI.

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Appendix. Convergence Insufficiency Symptom Survey

SYMPTOM QUESTIONNAIRE

Subject #:_____ Date:____/____/_____

Clinician instructions: Read the following subject instructions and then each item exactly as written. If subject responds with "yes" - please qualify with frequency choices. **Do not give examples.**

Subject instructions: Please answer the following questions about how your eyes feel when reading or doing close work. First think about whether or not you have the symptom. If you do, please tell me whether the problem occurs: Infrequently (not very often), Sometimes, Fairly Often, or Always."

		Never	Not very often	Sometimes	Fairly often	Always
1.	Do your eyes feel tired when reading or doing close work?					
2.	Do your eyes feel uncomfortable when reading or doing close work?					
3.	Do you have headaches when reading or doing close work?					
4.	Do you feel sleepy when reading or doing close work?					
5.	Do you lose concentration when reading or doing close work?					
6.	Do you have trouble remembering what you have read?					
7.	Do you have double vision when reading or doing close work?					
8.	Do you see the words move, jump, swim or appear to float on the page when reading or doing close work?					
9.	Do you feel like you read slowly?					
10.	Do your eyes ever hurt when reading or doing close work?					
11.	Do your eyes ever feel sore when reading or doing close work?					
12.	Do you feel a "pulling" feeling around your eyes when reading or doing close work?					
13.	Do you notice the words blurring or coming in and out of focus when reading or doing close work?					
14.	Do you lose your place while reading or doing close work?					
15.	Do you have to re-read the same line of words when reading?					
To obtain score, total the number of "X"s in each column						
Multiply by the column value		x0	x1	x2	x3	x4
Sum 5 values						

Score_____ Examiner_____