

Article: Confusion Inside Panum's Area and Symptomatic Convergence Insufficiency

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ABSTRACT

In the present study we compared the ability of commonly used diagnostic criteria for CI to discriminate between symptomatic pediatric patients and normal controls with corresponding sensitivity and specificity parameters of a novel test of Near Point of Fixation Disparity (NPF_D) and a measure of Associated Positive Fusional Convergence (APFC). The results yielded 95% sensitivity and 100% specificity for the NPF_D-based criteria, while common Near Point of Convergence and Positive Fusional Convergence criteria were no better than chance. Supplemental use of NPF_D and APFC are expected to increase the sensitivity of optometric evaluation to CI without compromising its specificity.

Convergence Insufficiency (CI) is a binocular vision disorder that represents a specific type of decompensated heterophoria. Evans¹ classified the symptoms of decompensated heterophoria into three categories: visual symptoms (blur, diplopia, distorted vision); binocular difficulties and asthenopia. Convergence Insufficiency is typically characterized by exophoria that is greater at near than distance, a remote near point of convergence (NPC) or decreased

positive fusional convergence (PFC) at near.² It is often associated with symptoms such as double vision, eyestrain, headaches, blurred vision, and loss of place while reading or performing near work. Not all patients with CI, however, present with symptoms possibly due to either suppression, avoidance of near visual tasks, high pain threshold or monocular occlusion.² Yet symptoms associated with CI may negatively affect a person's quality of life by interfering with school, work, and leisure activities performed at near. The presence of CI may contribute to parental reports of difficulty with their child's ability to complete schoolwork efficiently,³ whereas a successful or improved outcome after CI treatment has been shown to be associated with a reduction in the frequency of adverse academic behaviors and parental concern associated with reading and school work as reported by parents⁴.

The diagnostic criteria for CI have been neither consistently applied by investigators and clinicians nor have been particularly accurate in identification of CI in the presence of asthenopia. For example, Rouse⁵ reported that 93.8% of the optometrist's surveyed in their study used reduced NPC for the diagnosis of convergence insufficiency. Others believe that an exophoria

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greater at near must be present, along with either a reduced NPC or PFC. Yet there are many who believe that all three criteria need to be satisfied (both the NPC and PFC should be reduced in the presence of an exophoria) before CI can be diagnosed.⁶

On the other hand, in some cases, none of the 3 criteria may be abnormal, yet CI may be diagnosed in the presence of asthenopia associated with convergence.^{2,7,8} Rouse et al.⁶ further reported that out of 206 children between 8 and 12 years of age whose records showed none of the 3 classic signs of CI (were classified as "no CI"), 25% had symptoms consistent with Convergence Insufficiency including the presence of symptoms when reading or writing, such as headache, diplopia, eye fatigue, or print running together when reading. Furthermore, because convergence in the pre-presbyopic population is never independent of the accommodative system, due to the interactive negative feedback loop between accommodation and vergence, a convergence problem may be secondary to a primary accommodative problem, and vice versa.⁹ These issues of inconsistency and inaccuracy of CI diagnosis continue to thwart attempts to estimate CI prevalence in pediatric and adult populations, impede development of effective treatment strategies and interfere with evaluation of treatment outcomes.

Another reason for difficulty in establishing clear diagnostic criteria for convergence insufficiency may be related to the fact that classic vergence and near point of convergence measures used by clinicians can underestimate binocular dysfunction. The classic Divergence-to-Convergence Recovery range (VRR) and Near Point of Convergence (NPC) measures evaluate when the burden of fusion demand placed upon binocular vision becomes too great and diplopia becomes manifest as fusion limits are exceeded (break point) and when fusion recovers (recovery point). In its turn diplopia occurs when retinal fixation disparity falls outside of Panum's area. In 1858 Panum described Panum's fusional area

defined for a stimulus at a fixed retinal locus as the retinal area, upon which a target can be imaged in the other eye and appears fused.¹⁰ Disparities that exceed this limit result in diplopia or binocular rivalry. Hence Panum's area is also a threshold measure of diplopia.¹¹

Within Panum's area, however, double vision is not experienced, and yet a significant binocular disparity dysfunction can be present and can manifest itself as asthenopia.¹² In a review of literature on visual discomfort and visual fatigue Lambooj and Ijsselsteijn¹³ contend that under natural viewing conditions retinal disparities within Panum's fusion area beyond 1° are assumed to cause visual discomfort. The authors equate this 1° area around Donder's line with Percival's zone of comfort defined as the middle third of the amount of binocular vergence with almost no change in accommodation, i.e., the middle third of "the zone of clear, single binocular vision."

At the same time while NPC and VRR measures may not be sensitive to asthenopia-inducing vergence issues occurring within Panum's fusion area, traditional measures of fixation disparity using dichoptic targets and binocular fusion locks are assumed to address retinal disparity within PFA, when the object is still seen singly.^{14,12} The angular value of fixation disparity is a measure of the degree to which the images have slipped.¹⁵ The conventional view is that fixation disparity typically measures between 5 and 10 min of arc and rarely exceeds 10 min of arc.¹⁶

Yekta and Pickwell¹⁷ investigated fixation disparity in relation to symptomatic convergence insufficiency using the Mallett fixation disparity unit, in which at near the central fixation target OXO is seen with both eyes and the two monocular markers (nonius strips) in line with the 'X' are seen one with each eye using cross polarizing filters. Symptomatic participants had significantly higher degrees of fixation disparity than asymptomatic ones. This finding was consistent with Mallett's¹⁸ and later Sheedy and Saladin's¹⁹ suggestion that fixation disparity is a

better indicator of decompensated heterophoria than the degree of heterophoria. Similar findings were reported by Yekta et al.²⁰ and Pickwell et al.²¹ for decompensated heterophoria at near. Jenkins et al.²² also reported that the sensitivity of the Mallett's test to decompensated heterophoria in pre-presbyopes was 75% with specificity of 78%, if an aligning prism at near of 1 Δ or greater was used as a cutoff for failing the test.

The location of the fusion lock in a clinical target may be an important factor in the measurement of fixation disparity. Because it is important to orient the fusion lock to be most sensitive to such "stressful" near tasks as reading, it is important to make this central target contain a letter in order to help draw one's attention toward letter identification. Ciuffreda²³ demonstrated that in visually normal individuals, accommodative interactions with vergence accounted for up to 50% of the measured fixation disparity found under normal viewing conditions. He also found that the use of an accommodative target, such as a letter, showed less vergence variability as compared to a penlight stimulus. Therefore, attention to the clarity of the accommodative target facilitates a better evaluation of focal binocular fusion as target identification is now more intimately involved with its orientation.

Similarly with the use of the same central fusion lock, measures of associated vergence can be evaluated by recording reported fixation disparity that is induced when vergence eye movements lag behind a changing vergence demand, either by moving the target inward and outward or by creating gradual increases in convergence (BO prism) or divergence (BI prism), respectively. These measures of associated vergence responses may be more sensitive to thresholds of binocular dysfunction than classic vergence measures and can thus complement diagnostic criteria for CI. For example Yekta et al.²⁰ investigated phoria, associated phoria, fixation disparity and stereopsis for near vision in a sample of 187 subjects ranging in age

from 10 to 65 years. The authors reported a statistically significant relationship between visual symptoms for near and the magnitude of fixation disparity and associated phoria for all age groups. They did not, however, find any relationship between the presence of symptoms and phoria measurement. Similarly, exo fixation disparity (FD) (or the related associated phoria) at 40 cm indicated visual symptoms in the studies of Sheedy and Saladin^{24,19,25} and the of Pickwell group.^{26,22,17,21} Additionally Jaschinski²⁷ also reported that in nonpresbyopic subjects with normal vision but who differed in near vision fatigue at a 50cm viewing distance, higher fatigue was significantly associated with a steeper proximity-FD curve (more exo FD and near vision).

The additional use of associated vergence measurements in nearpoint binocular assessment will determine how well an individual's vergence response may keep up with a changing vergence demand (prism adaptation time). The traditional "blur", "break" and "recovery" patient responses created when classic vergence measurements alone are performed may now reveal, under associated measurements, when a vergence demand-response mismatch occurs, characterized by misalignment of the vertical nonius lines. In addition, the larger the difference between the classic and associated vergence findings, the more these patients can encounter visual stress without the presence of double vision.

In the present study we evaluated a novel test of near point fixation disparity used in two ways:

1. as a relatively quick and easy assessment of fixation disparity to an incoming and outgoing dichoptic target, similar to NPC, where an exo fixation disparity was induced as the target approached a patient's nose and a reduction in exo fixation disparity occurred as it receded. This is called the Nearpoint of Fixation Disparity Test (NPDFD) and is a measure of vergence response to the combined

changes in proximal, accommodation and fusional vergence demand.

2. As a test, where the NPDF target remained at a fixed nearpoint (40 cm.) distance while associated vergence ranges were measured with prism. This is called the Associated Vergence Ranges, which measures vergence response to changes in fusional vergence demand alone, with no direct changes in accommodative vergence or proximal vergence.

We compared these measurements made under associated, dichoptic conditions to classic measures of near point of convergence (NPC) and positive fusional convergence at near (PFC). We then evaluated the sensitivity of the diagnostic criteria using traditional NPC and PFC measures to the symptoms of CI with the corresponding sensitivity of the statistically derived criteria for NPDF and associated measures. We hypothesized that the latter would show much greater sensitivity to CI as these measures would not only capture those patients whose symptoms are driven by binocular dysfunction measured outside of Panum's area, but also those whose binocular deficits could be measured as occurring within PFA.

METHODS

Participants

This was a retrospective study using records of 60 pediatric patients between 6 and 17 years of age ($M=10.56$, $SD=3.61$), who were seen as part of a normal private practice in a Midwestern optometric clinic. Thirty-five of the patients did not report any symptoms of convergence insufficiency and had normal binocular vision, while 25 of them reported significant asthenopia consistent with symptoms of some binocular disorders including convergence insufficiency. Specific symptoms included unusual visual fatigue during near-work tasks such as reading, slow and inaccurate reading and poor comprehension, loss of focus and concentration, limited visual attention

span for critical visual activities at near point, intermittent blurring and double vision, loss of place during sustained near visual tasks and ocular headaches following sustained near visual tasks, well as motion sickness. Symptom reports were obtained from an entrance history form and from the Doctor's interview.

In their review of Convergence Insufficiency Cooper and Jamal² noted that up to 18% of patients with CI may be asymptomatic because of either suppression, avoidance of near visual tasks, high pain threshold, or monocular occlusion. For this reason during the selection special attention was also paid to those patients who reported avoiding near work (especially reading) and, therefore, originally did not report any symptoms. For many, symptoms were present but revealed through follow-up questions that were specifically aimed at situations, which required sustained visual performance. This is well represented by the standardized testing often experienced in school. It is their adaptation to this challenge or conflict to stay in visual focus despite the presence of increasing symptoms, which can be insightful regarding their visual history. Other probing questions relate to their having to read out loud as they begin to show an increasing trend toward the misreading or substituting of primarily the small words. The reading out loud of unfamiliar material presents a situation that makes their visual issue public and embarrassing. As a result they develop behavioral adaptations of avoidance regarding reading out loud and often tend to do the minimal amount of near work (i.e. reading) required. These characteristics complicate the process of discovery when investigating clinical history. They also reflect the emotional collateral damage that often occurs as a result of Convergence Insufficiency going undiagnosed and untreated. When questioning these patients the first author (Lederer) often indicated to them that he could attempt to get them accommodations that would provide extended time on those tests and asked them whether they would use the extended time

if they had it. Their answer was often “NO”. These types of questions are clinically insightful and provide additional clues to the performance for those who have made avoidance adaptations to their visual dysfunction. These behavioral avoidance characteristics can make the presence of symptoms more difficult to reveal. In contrast, those who tend to fight against visual stress to perform well typically reveal symptoms more overtly,

Exclusionary criteria included presence of amblyopia, convergence excess, divergence excess exotropia, constant strabismus and accommodative insufficiency as defined by a reduction in accommodative amplitude during monocular minus lens bar amplitude assessment done at 13” using a .62M acuity target.

Similarly case histories for the control group were selected from the pool of pediatric patients who were not identified as having any oculomotor problems, who did not report any symptoms of asthenopia and typically reported being good readers and liking near work (computer work, reading etc). Patient histories were thus assigned to either symptomatic or asymptomatic groups. Furthermore, this was a single-blind design as the data analyst was unaware of the association between symptoms (group membership was coded with either 1 or 2) and test values until all analyses were completed.

The likelihood of CI was estimated using some of the well-established conservative diagnostic criteria for CI as well as estimates of fixation disparity and associated phoria. The former included presence of both reduced NPC (break \geq 5cm and recovery \geq 7) and PFC (less than 15 Δ BO break). These criteria were based on a number of previous research reports. Specifically, Maples and Hoenes²⁸ suggested that the criterion for the NPC break score to differentiate symptomatic from less symptomatic elementary school children should be 5 cm or greater. We chose this cut-off instead of 6 cm used by the CITT group with children between 9 and 18 years of age (see Scheiman et al.²⁹)

to increase sensitivity of the NPC-based criteria to symptomatic CI (easier to classify someone as having CI). Consistent with other CITT group’s eligibility criteria for their CI treatment trial, we used a 7cm clinical cutoff for NPC recovery and a PFC criterion of 15 Δ BO break when establishing diagnostic criteria for CI in their study of school-aged children between 9 and 18.

Diagnostic criteria for fixation disparity and associated phoria were statistically derived (see results section below) and included reduced NPDF (\geq 5cm break and \geq 6cm recovery) and reduced associated vergence ($<$ 16 Δ BO break).

In our study we did not look at exophoria at near as a predictor of asthenopia as in their review Cooper and Jamal² did not consider presence of abnormal exophoria at near a necessary condition for the diagnosis of common CI. In research studies presence of exophoria at near in patients with CI ranges between 63% 30 and 79%.³¹

MATERIALS

Near Point of Convergence (NPC)

The near point of convergence (NPC) measure has been shown to be a useful tool in assessing convergence insufficiency.³² The fixated target is gradually moved toward the patient until it becomes double. The target is then moved back until it has become single again. The break and recovery findings are recorded. The repetition of this test is a useful modification to the single measure and can reveal more subtle diagnostic issues regarding reduced stamina.³² A variety of targets have been used such as a penlight, a penlight with red/green glasses, and an identification target to engage accommodation. Ciuffreda³³ and later Scheiman et al.³² showed that an accommodative target showed less variability as compared to the penlight stimuli. This type of target (a single 20/30 letter) was used in the present study. The Bernell Accommodative Rule (Bernell Corp., Mishawaka, IN) was placed just above the nose at the brow between the two eyes of the participant. The target was then



Figure 1: Near Point of Fixation Disparity (NPF) test (reproduced with permission from Vision Assessment Corporation).

moved toward the participant at a rate of about 1 to 2 cm/s. Subjects were encouraged to try to keep the target single. The subjective break and recovery values were measured and recorded in centimeters. If there was no subjective report of diplopia, the points at which the patient objectively lost and regained ocular alignment were recorded as the break and recovery. The NPC was measured twice for each subject and average values for break and recovery were then used in the analyses.

Fusional Vergence at Near

Positive and Negative fusional vergence at near were measured using a hand-held Risley prism in free space. With the patient seated and wearing their refractive correction, he/she was instructed to view the same accommodative target that was used in the NPC (i.e. a single 20/30 letter) displayed on a near card and held before the eyes at a distance of 40 cm. The patient was then instructed to inform the examiner when the print was seen to blur and/or become double as the examiner slowly introduced an increasing amount of base-out [BO] prism in front of either eye. When/if blur was reported, the amount of base-out prisms was smoothly and continuously increased until the break-point (double) was reported (positive

fusional convergence-PFC). The patient was then instructed to report the recovery of single vision (fusion) as the prism direction was reversed, and the amount of prism was decreased by the examiner. A similar procedure was used with base-in (BI) prisms to determine negative fusional vergence (NFV) at near.

Near Point of Fixation Disparity (NPF)

The NPF test and its target have been originally developed and tested by the first author of this study (Lederer). When administering the NPF, the target represents a fixation disparity cross [Figure 1] that is mounted on a hard board with a silvered background. The circle that surrounds the E represents part of the fusion lock. The central E target is equivalent to a 20/100 sized reduced Snellen letter, which subtends the eye at 25' of arc. The circle surround is equivalent to a 20/200 sized reduced Snellen letter, which subtends the eye at 50' of arc. The E and circle are solid and are seen by both eyes. The circle's spherical shape steers attention toward its perceptual center, which supports the judgment involved in aligning the arrows. The NPF Card was placed on the moveable rod of the Bernell Accommodation Rule while the subject wore polaroid vectograph glasses as a way to dichoptically view nonius lines (right eye seeing top the line, left eye seeing the bottom line) while both eyes fused the central E target and circle surround. The center of the forehead at the level of the brow was used as the zero measure point from which the NPF was taken. With the end of the ruler placed against the forehead, the target was moved slowly toward the subject at approximately one to two centimeters per second until the subject reported that the vertical nonius lines began to move out of alignment, at which point the distance from the zero measure point was read off the ruler. The ability to observe offset is very sensitive especially if a patient (even a young pediatric patient) is instructed to report when the arrows "begin sliding". The presence of an unresolved fixation slip, without diplopia,

represents the associated phoria for that specific distance. Disparity break and recovery findings were recorded as the break/recovery of the NPDF. While viewing the target the patient was asked to maintain the fusion lock clear and as the target is moved from a far point distance (often started outside 50") toward the patient they were to indicate when a fixation disparity slip developed and could not be resolved in the time it took to ask "Is it still sliding?". Other diagnostic questions commonly used during the administration of the NPDF include: "Is it shifting?"; "Is it still off or did it line up again?"; "Is it blurring?"; "Is either of the arrows fading out?" Once there is a better understanding of test parameters that are to be attended to, it then becomes easier to just integrate these questions into: "Is it breaking up?"; "Did it come back together or is it still breaking up?" The term "breaking up" represents a disruption to binocular vision that is reflected as a fixation disparity, or a blurring of the letter "E" fusion lock or suppression.

The target was then moved back to the distance until the nonius lines appeared to be both aligned and clear. While the NPC evaluates the distance at which double vision is seen as fusion breaks and when single vision is seen as fusion recovers, the NPDF evaluates when the two eyes, prior to separating, begin to "argue" and misalign due to the increased vergence and accommodative demand and then become re-aligned as the vergence and accommodative demand is gradually reduced and the binocular argument is resolved. Although both of the measures involve a significant degree of proximal, accommodative and fusional vergence responses, the NPDF yields a more sensitive perceptual indication of the breakdown of one or more of these mechanisms.

Associated Vergence

Associated vergence was measured with the fixation disparity target as used for NPDF (Figure 1) and rotary Risley prism. This testing can be done in free space or in the phoropter. In the

present study all testing was done in free space. The patient was instructed to maintain clarity of the central fusion lock "E" during testing and to indicate when an unresolved fixation disparity became apparent as the convergence (BO) or divergence (BI) prism demand was gradually increased at a rate of approximately 1 second/ 5pd. During this testing the patient was asked "are they still straight and clear?" This question was meant to aid arousal and visual discrimination. The prism demand was increased until the patient reported that the arrows were "sliding." They were then immediately asked "are they STILL sliding?" The time necessary for recovery is the time it took to ask this question. When the patient indicated that the arrows were still offset, the prism demand was rapidly increased another 5pd and then gradually decreased until the patient recovered both alignment and clarity. This information provided measures of associated BO and BI vergence break and recovery recorded in prism diopters.

Statistical Analyses

To determine the best cutoff values for break and recovery points on the NPDF test as well as the BO break point for the associated convergence measure we first calculated 25th, 50th, and 75th percentiles for each measure and then used each of the percentile scores to discriminate between patients with symptoms of CI and asymptomatic control patients using a series of Receiver Operating Characteristic (ROC) Curves. ROC curves are graphs of sensitivity of a particular measure to CI symptoms plotted against the false positive rate of CI diagnosis (1 – specificity). Specificity refers to the measure's ability to identify patients, who do not have a target characteristic (i.e. CI symptoms). The ability of two or more variables to diagnose an outcome can be compared using ROC curves and their associated areas under the curve (AUROCs) that the ROC tests also provide. The ideal test would have an AUROC of 1, whereas a random guess would have an AUROC of 0.5. According to Hoshmer and Lemeshow's

Table 1: Receiver Operating Characteristic (ROC) Curves' Area Under the Curve (AUC), 95% Confidence Intervals (CI) of AUC, Sensitivity and Specificity and the resultant Youden's index for each traditional and associated test of vergence and CI diagnosis.

Measure	AUC	95% CI	Sensitivity	Specificity	Youden's index
NPDF break point					
>50th pcntl (4cm)	0.885*	0.79-0.98	0.91	0.86	0.77
>75th pcntl (14.25cm)	0.804*	0.67-0.94	0.61	1.00	0.61
NPDF recovery point					
>50th pcntl (5cm)	0.893*	0.80-0.98	0.96	0.83	0.79
>75th pcntl (18.25cm)	0.804*	0.67-0.94	0.61	1.00	0.61
APFC break point (BO)					
<25th pcntl (3.5)	0.813*	0.68-0.93	0.63	1.00	0.63
<50th pcntl (16)	0.971*	0.92-1.00	1.00	0.94	0.94
<75th pcntl (17)	0.714*	0.58-0.84	1.00	0.43	0.43
CI according to NPDF break >4 cm and NPDF recovery > 5 cm and APFC break BO <16	0.98*	0.92-1.00	0.95	1.00	0.95
CI according to NPC break ≥ 5cm and recovery ≥ 7and PFC BO break < 15	0.59	0.43-0.75	0.19	1.00	0.19

36 criteria AUCs between 0.7 and 0.8 indicate acceptable discrimination, AUCs between 0.8 and 0.9 show excellent discrimination with values equal to or above 0.9 reflecting the test's outstanding discrimination ability. We thus utilized these guidelines to select the best cutoff scores for each measure and in cases of similar AUCs we further calculated Youden's index (J) and selected values with the highest J. Youden's index is represented by the following formula:

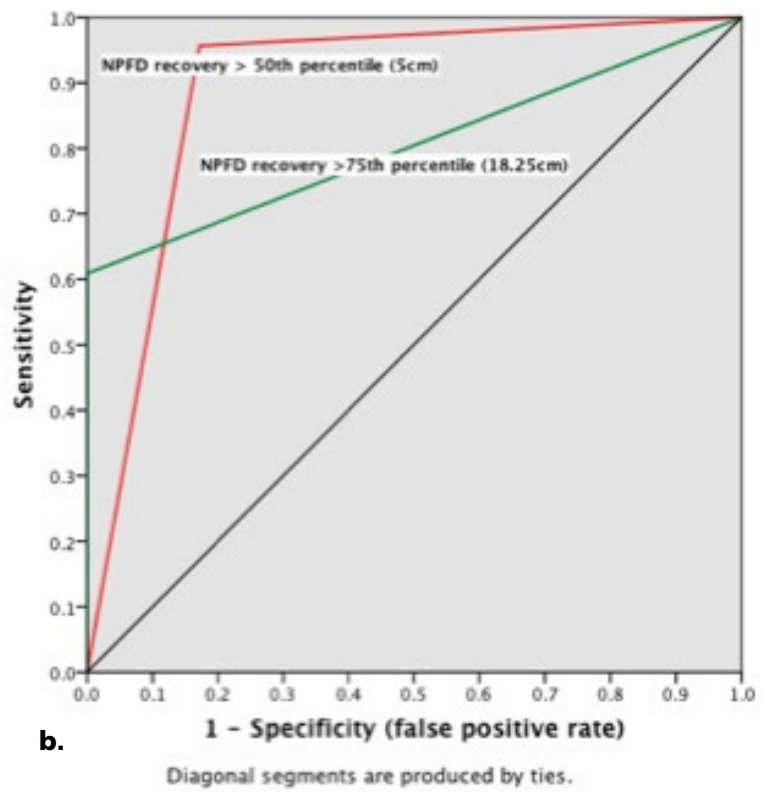
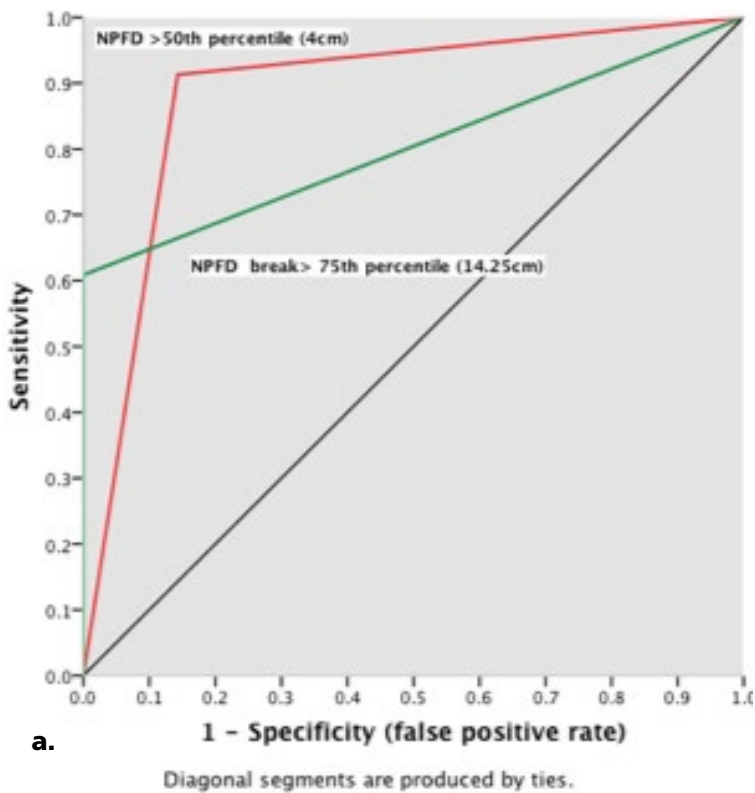
$$J = \text{sensitivity} + \text{specificity} - 1$$

According to Bewick, Cheek and Ball³⁷ in instances where both sensitivity and specificity of a diagnostic test are equally important, cutoff values with the highest Youden's index should be used.

Since the likelihood of CI is traditionally estimated using conservative diagnostic criteria such as the presence of both reduced NPC (break ≥ 5cm and recovery ≥ 7) and PFC (<15 Δ BO break;^{38,2}), we similarly utilized identified cutoff values for the NPDF and the BO break point of associated convergence to arrive at an algorithm for CI diagnosis using the latter measures.

Finally we directly compared the sensitivity of traditional CI diagnostic criteria and those utilizing NPDF and APFC values to symptoms of CI using ROC curves.

We also conducted a series of independent sample t-tests comparing traditional and associated measures between the symptomatic CI and non-symptomatic normal groups and calculated the magnitude of effect size for each comparison using Hedges' g.³⁹ This index is similar to Cohen's d but instead of using the population standard deviation it utilizes pooled standard deviation for the comparison groups. According to Ferguson⁴⁰ g values around 0.4 indicate a recommended minimum effect size, values around 1.15 are considered moderate, while anything equal to or greater than 2.7 should be considered a 'strong' effect. This effect size estimate evaluates the magnitude of group differences on a particular measure and is an indirect index of the likelihood that the observed values on a given measure belong to representatives from two different populations (i.e. CI vs. no CI). So the greater is the magnitude of the effect size, the higher is the probability that the observed means describe two different populations.



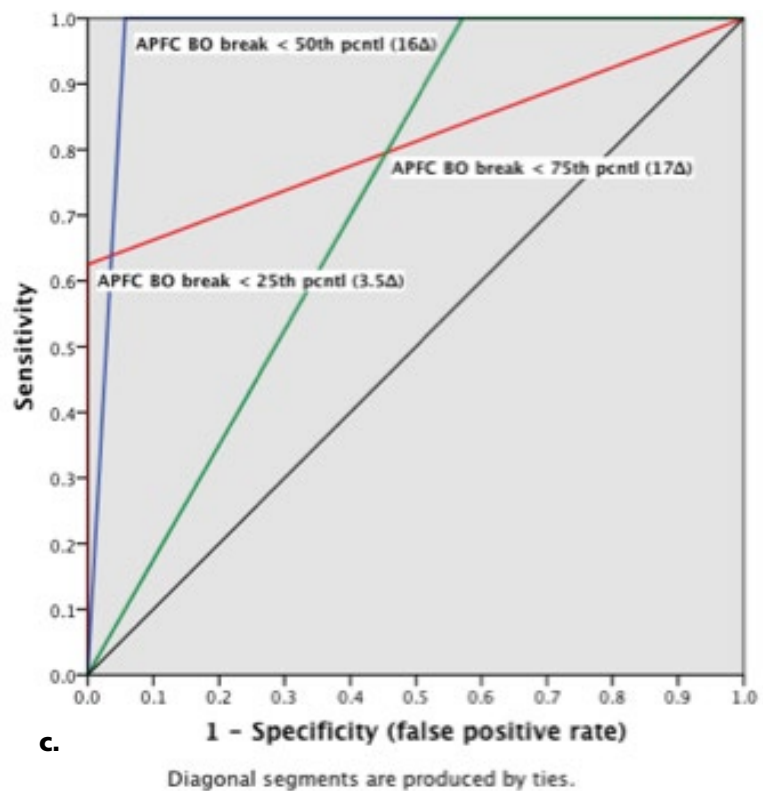
Figures 2a, 2b, 2c: Receiver Operating Characteristic (ROC) Curves for the 50th and 75th percentiles of the NPDF break (a) and recovery (b) and the 25th, 50th, and 75th percentile of Associated Vergence BO break (APFC; c) in relation to presence of CI symptoms (sensitivity).

RESULTS

ROC Curves

Percentile scores for the NPDF break point for the entire sample showed that both the 25th and 50th percentiles were equal to 4 cm while the 75th percentile for the sample was 14.25 cm. ROC curves on these percentile scores discriminating between symptomatic and asymptomatic patients showed that both NPDF break values above 4 cm and 14.25 cm significantly predicted CI symptoms (AUC=0.885 and AUC=0.804, respectively). The Youden's index, however, was greater for the 50th percentile (J=0.77) than for the 75th percentile (J=0.61), thus the value of 4cm was selected as a diagnostic cutoff for the NPDF break with values higher than 4cm indicating probability of CI. These results are summarized in Table 1 and Figure 2a.

Similarly, although both the 50th and the 75th percentiles for the NPDF recovery had significant AUCs, which according to Hoshmer



and Lemeshow's36 criteria provided excellent discrimination (>0.80), scores above the 50th percentile (5cm) provided much greater sensitivity to CI (0.96) and a correspondingly much higher Youden's index (J=0.79) compared to NPDF recovery values above the 75th

Table 2: Independent-sample t-tests comparing NPC / PFC and NFPD /APFC measures of the CI-symptomatic group (n=25) with corresponding measures of the non-symptomatic normal patient group (n=35).

Measure	Symptomatic CI		No CI		t	Hedges' g
	Mean (SD)	95% confidence interval for mean	Mean (SD)	95% confidence interval for mean		
NPC Break (cm)	6.04 (4.63)	3.56-7.57	3.37 (0.60)	3.16 – 3.57	2.81**	1.02
NPC Recovery (cm)	8.43 (4.94)	5.91-10.19	4.45 (0.74)	4.20-4.71	3.83**	1.40
PFC Break (BO)	14.16 (7.67)	10.08-16.58	21.17 (3.65)	19.91-22.42	-4.15**	1.24
NFPD Break (cm)	20.30 (12.99)	15.21-27.08	3.85 (0.84)	3.57-4.14	6.02**	2.38
NFPD Recovery (cm)	23.56 (11.74)	18.87-29.61	5.02 (0.82)	4.75-5.31	7.56**	2.95
APFC Break (BO)	0.88 (5.09)	-1.81-2.86	16.94 (1.92)	16.28-17.60	-14.75**	4.58

*-significant at alpha=0.05; equal variances are NOT assumed.

** -significant at alpha=0.01; equal variances are NOT assumed.

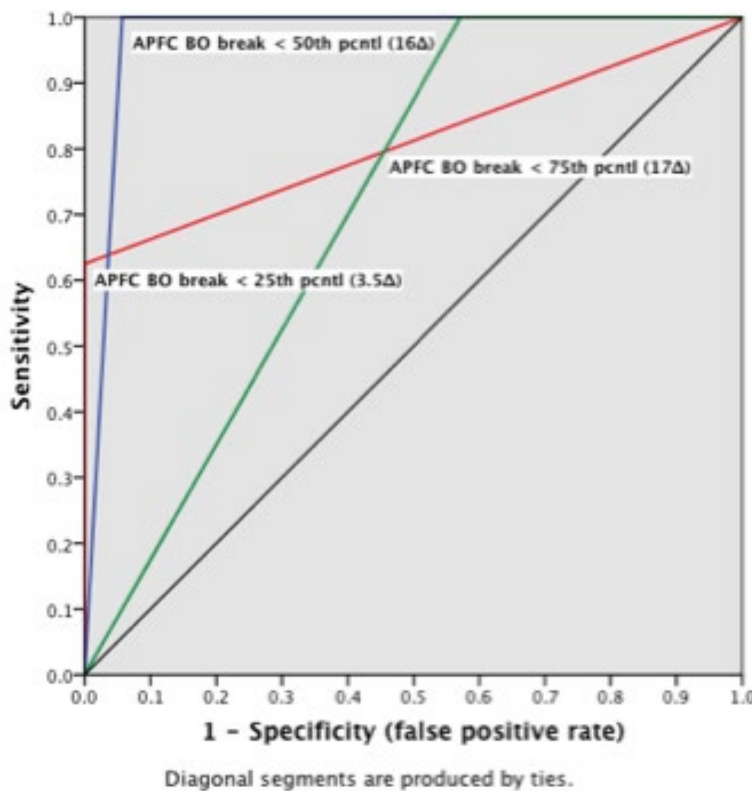


Figure 3: Receiver Operating Characteristic (ROC) curves for NFPD with APFC-based diagnosis of CI and NPC with PFC-based CI diagnosis in relation to the actual presence of CI symptoms (sensitivity).

percentile (18.25 cm) and Youden's index of 0.61 (refer to table 1 and Figure 2b for details). The 50th percentile for the NFPD recovery was thus selected as another cut-off criterion in CI diagnosis.

Finally the ROC curves for the 25th, 50th, and 75th percentiles of associated fusional convergence (BO break point for associated vergence) showed the highest Youden's index

(J=0.94) for the 50th percentile (15Δ). The values below the 50th percentile on the APFC were thus used for CI diagnosis (see Table 1 and Figure 2c for details).

ROC curves were then generated for the combined probability of CI diagnosis according to NFPD break values greater than 4cm, recovery values greater than 5cm and APFC less than 15Δ BO break and commonly accepted NPC-based criteria (NPC break \geq 5cm and recovery \geq 7; and PFC < 15 Δ BO break). The results showed that NFPD-based discrimination among CI-symptomatic and asymptomatic patients was almost perfect (AUC=0.98), while similar NPC-based diagnostic criteria were no better than flipping a coin (AUC=0.56). Furthermore, while both types of criteria reliably identified asymptomatic patients (specificity for both = 1.0), sensitivity to CI symptoms was 0.95 for the NFPD-based criteria and only 0.19 for the NPC-based criteria (see table 1 and Figure 3 for details). Essentially in the present study 81% of symptomatic patients were overlooked by the standard diagnostic criteria and classified as NOT having CI, while NFPD-based criteria identified 95% of the symptomatic patients.

Independent group t-tests also supported these findings. Although the CI and non-CI groups were significantly different on all of the traditional and associated measures of Convergence Insufficiency, the magnitude of the effect sizes for the associated measures

was large using Ferguson's criteria,⁴⁰ while the corresponding effect sizes for the traditional measures were moderate (see Table 2 for details). This suggests a greater likelihood that on the measures of Near Point of Fixation Disparity and Associated Positive Fusional convergence any two randomly sampled individuals from CI and normal populations are going to be different (greater sensitivity of NPFD and APFC) compared to the probability of observing such difference with traditional measures of NPC and PFC.

DISCUSSION

Consistent with the original hypotheses the results of the study have shown that receded Near Point of Convergence and reduced Positive Fusional Convergence amplitude at near in many cases was not sufficiently sensitive to the symptoms of Convergence Insufficiency. The sensitivity of the combined diagnostic criteria for these measures in our study was only 19%, with 81% of the pediatric CI-patients classified as having no CI. At the same time diagnostic criteria based on the NPFD and APFC identified 95% of the patients with CI symptoms and did not misclassify any of the asymptomatic controls with normal binocular function.

Part of the issue here may have to do with the fact that our cut-off values based on fixation disparity and associated phoria were derived directly from the sample measurements, while similar criteria based on the receded NPC and reduced PFC were based on the reported pediatric norms.^{38,2} For convergence insufficiency the NPC is almost always closer to the patient (inside) than the NPFD measure, as the former is supposed to occur outside of PFA while fixation disparity takes place within PFA12. It is thus almost counterintuitive why in the present study the NPFD break point greater than 4cm, NPFD recovery point greater than 5 cm and APFC BO break less than 16 Δ in combination resulted in a much better diagnostic algorithm identifying patients with asthenopia than very similar criteria used for NPC (≥ 5 cm break and ≥ 7 cm recovery) and PFC ($< 15\Delta$).

The inspection of the group means in Table 2, however, explains these findings. The NPC break for the asymptomatic control group was 3.37 cm while the corresponding mean for the symptomatic group was 6.04 cm. This difference was statistically significant ($t=2.81$, $p<0.01$). Yet for the NPC break only values lower than 5 cm were considered asymptomatic, which created an overlap with the 95% confidence interval for the symptomatic group mean of 6.04 cm (95%CI= 3.56 cm-7.58cm, see Table 2). Similarly while the NPC recovery for the control group was 4.45 cm, which was significantly better than the corresponding mean for the symptomatic group ($M=8.43$), the selection of values below 7cm as indicative of the normal population was again too liberal for the present sample making it fall within the 95%CI for the mean of the symptomatic group (5.91cm-10.19cm). Finally, the mean PFC BO break for the control group ($M=21.17\Delta$) was significantly better than for the symptomatic group ($M=14.16\Delta$), but inclusion of values above 15 Δ as the criterion of normal convergence at near was again overly permissive as it fell within the 95%CI for the mean of the symptomatic group (95%CI= 10.08 Δ -16.58 Δ).

It is thus very likely that in a much larger sample the variability around the mean for symptomatic and asymptomatic patients is going to decrease (greater confidence that the means reflect true population means), which would increase the sensitivity of NPC and PFC-based criteria with cutoffs used. It is also likely that the sensitivity of the NPFD and APFC-based measures will decrease somewhat. Based on the first author's clinical practice with over 1000 pediatric patients with convergence insufficiency the diagnostic criteria for CI derived from fixation disparity and associated phoria are somewhat more liberal: NPFD break >8 cm, recovery >12 cm and APFC BO break $<16\Delta$. Applying these criteria to the sample in the present study we were still able to obtain 70% sensitivity and 100% specificity (see

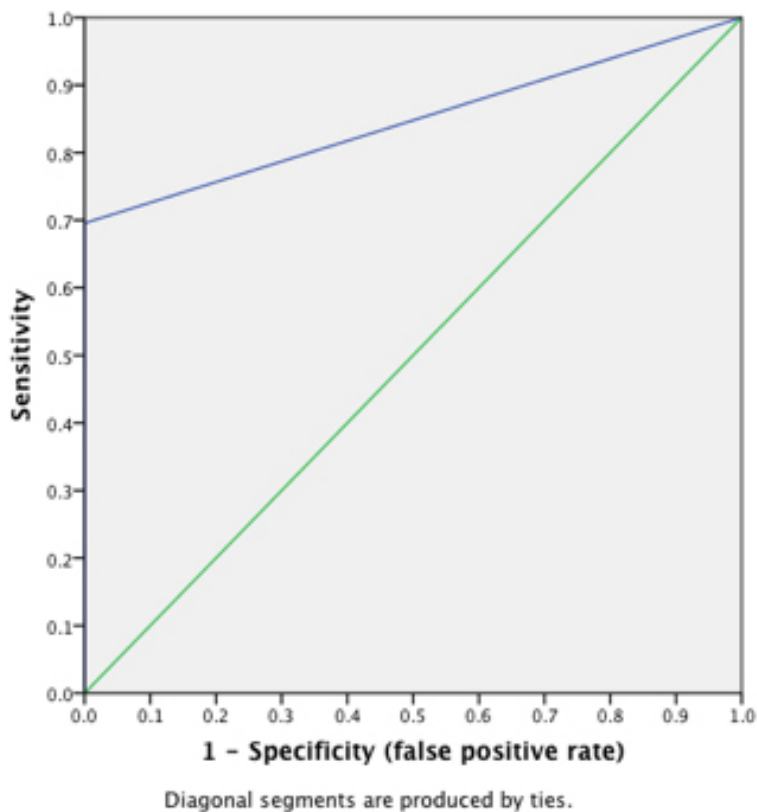


Figure 4: ROC curve for clinically derived diagnostic criteria for CI with NPF break > 8 cm, NPF recovery > 12cm, and APFC < 16 Δ.

Figure 4 for details). The area under the curve for the generated ROC curve was 0.848, which indicates 'excellent' discrimination according to Hoshmer and Lemeshow's³⁶ criteria.

Additionally the observed mean NPC and PFC values in the symptomatic CI group in the present study did not correspond to what Rouse et al.⁶ determined to be "definite CI" in a pediatric sample of 620 patients. In their study this CI classification was characterized by the mean NPC break of 11.8 cm (+/-6.0) and recovery of 16.9 cm (+/-5.7) with corresponding PVC BO break and recovery values of 12.1Δ (+/-4.3) and 3.7Δ (+/-4.8), respectively. Our CI group values (see table 2 for details) on these measures fell somewhere between 'low' and 'high suspect CI', according to the classification of the Rouse et al.⁶ study. It is, therefore, likely that the use of measures of Near Point of Fixation Disparity and Associated Positive Fusional Convergence in conjunction with traditional diagnostic tests of CI may be particularly useful in cases of milder CI with concurrent symptoms of asthenopia

or behavioral avoidance /adaptation to the demands of near work.

Overall our finding of greater sensitivity of tests of fixation disparity to symptoms of convergence insufficiency is supported by previous research. Yekta and Pickwell¹⁷ reported that symptomatic participants had significantly higher degrees of fixation disparity than asymptomatic ones in their study using the Mallett fixation disparity unit. Jenkins et al.²² also reported that the sensitivity of the Mallett's test to decompensated heterophoria in pre-presbyopes was 75% with specificity of 78%, if an aligning prism at near of 1Δ or greater was used as a cutoff for failing the test.

The Mallet Unit Fixation Disparity Test, however, measures associated phoria as it does not measure angular fixation disparity but instead measures the prismatic power that eliminates the fixation disparity. In the present study we did both and used combined statistically derived criteria to predict symptoms of convergence insufficiency. On the NPF test we also used a central fixation disparity lock in the form of accommodative binocularly viewed 'E' target, which is intended to maximally simulate the visual demands of reading. The circle or ring, that surrounds the E, frames the identification target to support the perceptual judgment of the shape's center of symmetry. This symmetrical shape facilitates judging alignment. Attention to the clarity of the accommodative target ('E') facilitates better evaluation of focal binocular fusion. Identification is now intimately involved with orientation. This corroborates the theory that measurements of vergence that are made when targets exceed or enter the outer limits of Panum's region are not as sensitive as associative vergence measurements that reveal how centralized the dichoptic targets are within Panum's region.

Sensitive measurement of fixation disparity in combination with specific instructions,¹² thus, becomes a useful clinical tool for evaluating binocular alignment inside Panum's area. As the cone density is greatest at the

fovea, there is likely to be little room for error of fixation and, consequently, Panum's areas are likely to be small⁴¹. Beyond a visual angle of five degrees from the macula, Panum's areas measure approximately 6% to 7% of the angle of eccentricity.⁴² This increase in the dimensions of Panum's areas is in direct relation to the decreasing cone density in the more peripheral regions of the retina. The larger extent of Panum's area in the periphery makes the peripheral visual field more tolerant of larger degrees of disparity and less likely to undergo adaptations to avoid diplopia, such as suppression.⁴³ Thus the use of a peripheral fusion lock in some devices such as the Disparometer and the Wesson unit destabilizes⁴⁴ and increases⁴⁵ fixation disparity and under these unnatural conditions fixation disparity may, therefore, be a less useful indicator of visual stress and subsequent asthenopia,¹ than if the fusion lock were located centrally. According to Ukwade⁴⁶ fixation disparity is approximately 1.5 to 3 times smaller when a combined central-plus-peripheral fusion lock is used, compared with a peripheral lock alone. More specifically, Carter¹⁵ reported forced vergence fixation disparity values of 10 to 30 min arc with only a peripheral fusion lock and values that rarely exceeded 6 min arc with a foveal fusion lock. The inclusion of a central fusion lock has also been shown to result in less variability in the measured values of fixation disparity.⁴⁷

Study Limitations

In the present study we did not use the Convergence Insufficiency Symptom Survey (CISS) that has previously been shown to have 96% sensitivity and 88% specificity in clinical trials of children and adults by the Convergence Insufficiency Treatment Trial Study Group (CITT Study Group: Borsting et al.^{48,49,50}). It would thus be of interest to investigate the relationship between CISS scores (pre and post-CI treatment) with corresponding measures of fixation disparity and associated positive fusional convergence. Based on the results of

the present study this correlation should be larger for the NPDF and APFC than for the NPC and PFC.

For the purposes of statistical analyses our sample size with 25 CI and 35 control patients was adequately powered to detect medium-to-large effect sizes ($d=0.65$) for independent-group t-tests.⁵¹ Moreover, Borsting et al.⁴⁹ reported their sensitivity of 95.7% and specificity of 87.5% for the CISS with only 47 children with CI and 56 controls. We do, however, feel that clinical trials on a much larger scale are in order to stabilize the proposed cutoffs and maximize the sensitivity and specificity of NPDF and APFC-based diagnosis. Due to the recent development of the NPDF target, normative data and reliability indices have yet to be established.

CONCLUSIONS

The present study showed that the use of the Near Point of Fixation Disparity test in combination with measurement of Associated Positive Fusional Convergence at near provides a viable tool in diagnosis of symptomatic Convergence Insufficiency in children that can be used in conjunction with traditional tests of binocular function. This recommendation is also supported by recent findings of Poltavski and Biberdorf⁵² who showed that the NPDF break equal to or greater than 15cm was significantly predictive of lifetime history of concussion in elite hockey players. At the same time the CISS scores in that study were not significantly different for concussed and non-concussed players. Thus the use of the NPDF and measurement of APFC are expected to increase the sensitivity of optometric evaluation to CI without compromising its specificity. Future investigations may also compare Classical and Associated Positive and Negative Relative Accommodation. Such studies are expected to improve our understanding regarding the relationship of clarity to alignment, especially when measured inside Panum's area.

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