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Reduced vergence adaptation is associated with a prolonged output of convergence accommodation in convergence insufficiency

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ABSTRACT

Convergence insufficiency (CI) is a developmental visual anomaly defined clinically by a reduced near point of convergence, a reduced capacity to view through base-out prisms (fusional convergence); coupled with asthenopic symptoms typically blur and diplopia. Experimental studies show reduced vergence parameters and tonic adaptation. Based upon current models of accommodation and vergence, we hypothesize that the reduced vergence adaptation in CI leads to excessive amounts of convergence accommodation (CA). Eleven CI participants (mean age = 17.4 ± 2.3 years) were recruited with reduced capacity to view through increasing magnitudes of base out (BO) prisms (mean fusional convergence at 40 cm = 12 ± 0.9Δ). Testing followed our previous experimental design for (n = 11) binocularly normal adults. Binocular fixation of a difference of Gaussian (DoG) target (0.2 cpd) elicited CA responses during vergence adaptation to a 12Δ BO. Vergence and CA responses were obtained at 3 min intervals over a 15 min period and time course were quantified using exponential decay functions. Results were compared to previously published data on eleven binocular normals. Eight participants completed the study. CI's showed significantly reduced magnitude of vergence adaptation (CI: 2.9Δ vs. normals: 6.6Δ; p = 0.01) and CA reduction (CI = 0.21D, Normals = 0.55D; p = 0.03). However, the decay time constants for adaptation and CA responses were not significantly different. CA changes were not confounded by changes in tonic accommodation (Change in TA = 0.01 ± 0.2D; p = 0.8). The reduced magnitude of vergence adaptation found in CI patients resulting in higher levels of CA may potentially explain their clinical findings of reduced positive fusional vergence (PFV) and the common symptom of blur.

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1. Introduction

1.1. Linkages between vergence and accommodation

The near triad defines a reflex system (synkinesis), which links convergence with accommodation and pupil constriction (Westheimer & Blair, 1973). It is well known that this synkinesis is achieved by two reciprocal cross links, accommodative convergence which can be quantified as the AC/A ratio (Alpern & Ellen, 1956) and convergence accommodation which can be quantified as the CA/C ratio (Fincham & Walton, 1957). As their names indicate, stimulation of one leads to a linked output of the other. Individuals can show mismatches between the cross links of accommodation and vergence (AC/A and CA/C) which typically leads to the well-known developmental anomalies of convergence insufficiency and convergence excess (Scheiman & Wick, 2002). Convergence insufficiency (CI) is one of the most common of these anomalies with a prevalence of 5% in school aged children (Cooper, Schulman, & Jamal, 2013; Scheiman & Wick, 2002). The condition has been long recognized since the 1850s by both von Graefe and Duane (Cooper, Schulman, & Jamal, 2013). CI defines a pattern of near point clinical findings which include an exophoria greater at near than at distance; a remote near point of convergence (NPC); and reduced capacity to "hold" a near target clear and single while viewing through a range of base out prisms (convergence amplitudes also called as positive fusional vergence or PFV) (Borish, 1975; Cooper & Duckman, 1978; Scheiman & Wick, 2002). It should be noted that positive fusional vergence requires more than the ability to converge the eyes. There is a need for convergence to dissociate from accommodation. Current models (Schor & Kotulak, 1986) and empirical evidence (Thiagarajan, Lakshminarayanan, & Bobier, 2010) indicates that this

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independence results from vergence adaptation (Schor, 1986). Adaptation provides the opportunity to dissociate the near triad driven cross talk between vergence and accommodation.

Ophthalmic treatment for CI has considered prescribing base-in relieving prisms to reduce the exophoria and increase the positive fusional vergence. Several studies have shown that this has not proven effective (Cooper, Schulman, & Jamal, 2013; Scheiman et al., 2005). Instead, vision-training (orthoptic) activities have proven more successful (Scheiman et al., 2005). Traditionally, pencil push-ups have been the most commonly prescribed (Cooper, Schulman, & Jamal, 2013; Scheiman & Wick, 2002; Scheiman et al., 2002). The task is essentially similar to that of measuring the near point of convergence (NPC). The patient converges to a pencil, which she/he moves as close as possible before it doubles. Studies have shown this technique to be very limited in its success (Cooper, Schulman, & Jamal, 2013; Scheiman & Wick, 2002; Scheiman et al., 2008). More effective outcomes are found when a battery of techniques that emphasize not only convergence but its dissociation from accommodation are provided (Cooper, Schulman, & Jamal, 2013; Scheiman & Wick, 2002; Scheiman et al., 2008); Thus these techniques are similar to viewing through a base-out prism where there is a demand to converge the eyes but without increasing accommodation. This is then similar to the clinical measure of positive fusional vergence limits (Thiagarajan, Lakshminarayanan, & Bobier, 2010).

Experimental studies have found that CI is associated with reduced vergence amplitudes (van Leeuwen et al., 1999) coupled with reduced peak velocity (Alvarez et al., 2010) and a high degree of saccadic response mixed with the attenuated vergence response in CI's (Alvarez & Kim, 2013). These reduced parameters showed significant improvement with vergence training (Alvarez & Kim, 2013; Alvarez et al., 2010; van Leeuwen et al., 1999).

1.2. Vergence adaptation and convergence insufficiency

It has long been recognized, that patients wearing prismatic corrections with the purpose of reducing large phorias often adapted to them over time (Carter, 1963) meaning that the original phoria slowly reappeared through the prismatic correction. Prism adaptation was found to be a normal adaptive response of the vergence system (Henson & North, 1980; Schor, 1979). Currently both vergence and accommodative systems have been modelled as having adaptive elements which reduce the output of the initial reflex or phasic systems leading to reduced output of the AC/A and CA/C cross couplings (see Fig. 1).

Given that convergence insufficiency shows a reduction in fusional vergence limits (Convergence Insufficiency Treatment Trial Study Group, 2009; Grisham, 1988; Scheiman & Wick, 2002), and that vergence adaptation underlies fusional vergence measures (Thiagarajan, Lakshminarayanan, & Bobier, 2010), it would be logical to hypothesize that these individuals may have reduced adaptive capacity. Early experimental work by Henson and North (1981) has shown that vergence adaptation is reduced in CI and improves with training (Henson & North, 1982) with no change in the CA/C cross link gain (Brautaset & Jennings, 2006). Considering these empirical studies along with the current models of vergence and accommodation (Schor & Kotulak, 1986), we hypothesize that the major disadvantage of the reduced vergence adaptation is that it results in excessive convergence accommodation. This would be consistent with clinical finding of a reduced capacity to clearly view through base out converging prisms (PFV limit) and complaints of blur. Excessive convergence accommodative levels would also explain the clinical observations that CIs show higher than normal accommodative levels at 40 cm (Scheiman & Wick, 2002).

The hypothesis will be tested by measuring vergence adaptation and convergence accommodation under conditions of open-loop accommodation and closed-loop vergence in participants with convergence insufficiency and compare them with visually normal participants tested previously under the same experimental design (Thiagarajan, Lakshminarayanan, & Bobier, 2010).

2. Methods

The overall experimental design for the measurement of vergence adaptation and convergence accommodation was similar to a previous study performed on binocularly normal adults (Thiagarajan, Lakshminarayanan, & Bobier, 2010). Pre-training data from these binocular normals constitute the "control group" for the present data on convergence insufficiency.

The study protocol received approval from the University of Waterloo ethics review board and followed the tenets of

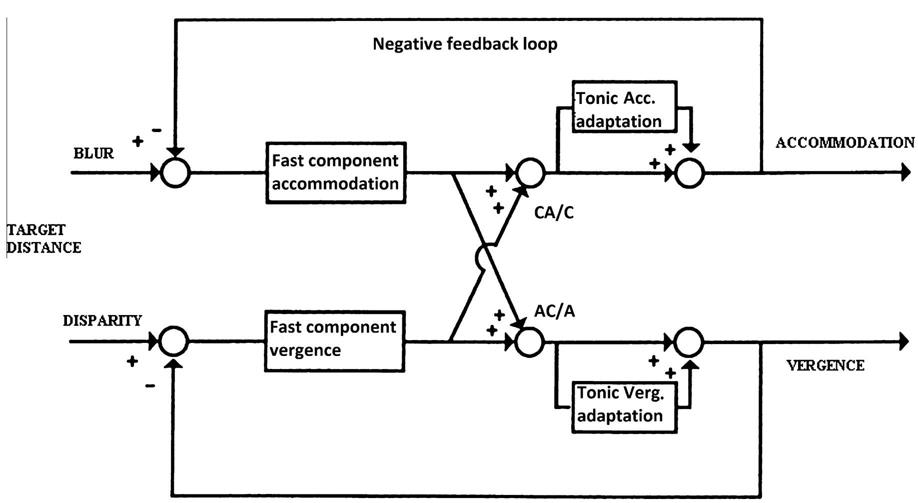

Fig. 1. Negative feedback diagram of the linkage between accommodation and vergence based upon investigations by Schor and associates (Schor, 2009). If a target is moved closer to the eye, a symmetrical change to both accommodation and vergence occurs simultaneously as a result of increased blur and crossed disparity. This is handled initially by the fast (reflex) component of the controllers of accommodation and vergence along with cross coupling between the two system driven by AC/A and CA/C. However if a prism is used, since only disparity is changed, then only fast (reflex) vergence and the cross coupled CA/C will occur. The excessive CA/C innervation can only be attenuated when the tonic vergence adaptation reduces the fast vergence component output and that of the CA/C.

Declaration of Helsinki. Informed consent was obtained after verbal and written explanation of the nature of the study.

2.1. Study participants

We recruited CI participants based upon insufficient convergence amplitudes at near OR, decompensated near phoria (i.e. inadequate levels of convergence amplitude (PFV) to compensate for their high exophoria – Sheard's criteria (Sheard, 1930). The cut-off for insufficient fusional amplitudes were set at 12 base-out (BO) and 15 BO break which are values less than the accepted (Morgan) norms of 17 ± 5 (base-out to blur) and 21 ± 6 for BO-break (Morgan, 1944; Scheiman & Wick, 2002). These values appear to fall well within a range of what has been described by various investigators as low fusional limits (Cooper, Schulman, & Jamal, 2013; Scheiman et al., 2008). To ensure that their visual problems were limited to CI, other eligibility criteria included: best corrected visual acuity of ⩾6/9 in each eye; normal amplitudes of accommodation for age- (18.5-age/3) (Hofstetter, 1944; Scheiman & Wick, 2002); vertical phoria < 1Δ; non-strabismic; astigmatism < 1D; anisometropia < 1D; no history of past vision therapy; absence of secondary CI (e.g. acquired brain injury). Potential participants between the ages of 7–30 years were recruited from the clinic database at the School of Optometry, University of Waterloo. Patients whose clinical files suggested that they met the above CI criteria were contacted by clinical staff. Nineteen patients agreed to have their key clinical findings confirmed and level of asthenopia defined by a questionnaire (convergence insufficiency symptom survey or CISS) designed and validated for CI (Scheiman et al., 2008). Eleven (mean age = 17.4 ± 2.3 years) who were confirmed to meet the eligibility criteria, agreed to participate. The degree of symptoms experienced by the study participants were assessed using the revised convergence insufficiency symptom survey (Borsting & The Convergence Insufficiency Treatment Trial Group, 2003). The mean CISS score for the entire CI group (n = 11) was 28.4 ± 3.3 and the range of scores observed in our sample fell within the ranges reported in the literature (Borsting & The Convergence Insufficiency Treatment Trial Group, 2003; Rouse et al., 2004) for 9 out of 11 subjects.

2.2. Measurement of phoria and convergence accommodation during prism adaptation

2.2.1. Overview

The experiment was conducted under conditions that rendered accommodation virtually open loop (absence of a stimulus to blur-driven accommodation) and closed-loop vergence, achieved by binocularly fixating a 0.2 cpd difference of Gaussian (DoG) target (Kotulak & Schor, 1987) at 0.4 m in an otherwise dark room. The adapting stimulus was a wedge prism of 12Δ BO placed in front of the left eye.

The instrumentation used for measuring vergence adaptation and accommodation was similar to several previous studies from our lab (Sreenivasan, Irving, & Bobier, 2009; Thiagarajan, Lakshminarayanan, & Bobier, 2010). Briefly, vergence adaptation was quantified by measuring changes in near phoria using the modified Thorington technique (MTT). This technique has been shown to be repeatable and valid in adults and in children (Casillas & Rosenfield, 2006; Rainey et al., 1998; Schroeder et al., 1996; Sreenivasan, Irving, & Bobier, 2008). We have also confirmed this in our lab studies where we have found the 95% limits of agreement with cover-test to be ±1.02Δ (Sreenivasan, Irving, & Bobier, 2008, 2009). The co-efficient of repeatability between measures taken on two different days was observed to be 1.98Δ (1.96 * standard deviation of difference). We have shown previously that children between 7 and 15 years of age were able to achieve standard deviation of less than 1.5Δ (range 0–1.25Δ; mean = 0.51 ± 0.43) when near phoria was measured 5 times within the experimental session (Sreenivasan, Irving, & Bobier, 2009). For this study, measurement was repeated thrice and the near phoria was defined as the average of the three responses. Accommodative responses were measured at 25 Hz using a PowerRefractor (Multichannel System, Reutlingen, Germany), and averaged over 5-s intervals following individual calibrations which have been described elsewhere (Sreenivasan, Irving, & Bobier, 2008, 2009). Briefly, the responses obtained from the PowerRefractor were calibrated for each subject using a two-step protocol to ensure relative accuracy (obtained by measuring the slope of change in PowerRefractor response to induced lenses) and absolute accuracy of accommodation (comparison with retinoscopy) similar to previous studies (Sreenivasan, Irving, & Bobier, 2008, 2009). While the slope of the calibration function matched with the instruments default for some participants, others needed separate calibration functions, possibly due to differences in fundal reflectance (Schaeffel, Wilhelm, & Zrenner, 1993).

2.2.2. Experimental procedure

Prior to the start of the study session, participants sat in total darkness for 3 min in order to dissipate any effects of previous work and allow the accommodation and vergence system to return to their resting states (Wolf, Ciuffreda, & Jacobs, 1987).

Baseline near phorias (0.4 m) and open-loop binocular accommodation (using the DoG target) were then recorded for 5 s without any prism through best corrective lenses (if any). The DoG target was generated on a laptop and projected onto a 7 in. wide TFT (thin-film transmitter) LCD monitor (Pyle Co, USA) at 0.4 M. Subsequent to baseline measures, a 12Δ BO prism was added in front of the occluded left eye. A baseline phoria was measured prior to any binocular viewing through the prism and this represented the induced phoria for which adaptation was to be quantified. Prior to adaptation, an increase of 12Δ exophoria resulted over the subjećts habitual phoria. Binocular fusion/suppression through the prism was then evaluated by presenting polarizing targets. Participants who were unable to binocularly fuse through the prism, resulting in suppression or diplopia were identified. Several practices were attempted. However, in 3 cases participants with CI were unable to reliably gain fusion through the prisms and were excluded from the study. Experimental testing began with the subject viewing through the prism for 15 min. Complete data sets were taken for the remaining eight participants and formed the basis of the analysis. Measures of binocular open-loop accommodation were then taken through the prism and the induced change in accommodation was considered as convergence-accommodation (because other components of accommodation were either eliminated (blur) or kept constant, (proximity)). Phoria and open-loop accommodative measures were repeated in 3 min intervals for 15 min while the participants binocularly fixated the DoG target at 0.4 M. Phoria and open-loop accommodation responses measured during the adaptation period were fitted using an exponential decay function using Graphpad Prism (GraphPad Software Inc., USA). The exponential curves depicting the magnitude of change in vergence adaptation and convergence accommodation were then compared between the CI group and the control group. Data analysis was performed using Graphpad Prism (GraphPad Software Inc., USA) and STATISTICA 7.0 (StatSoft, Inc., USA).

Further, since tonic changes in accommodation (accommodative adaptation) could influence open loop accommodative measures and therefore confound the CA measures, we also measured tonic accommodation before and after sustained fixation. These measurements were performed by instructing participants to monocularly fixate a low spatial frequency

(0.2 cpd) difference of Gaussian target at 4 M (left eye occluded) which rendered the accommodative and vergence system virtually open-loop.

2.3. Control group

Data for the control group were taken from an earlier study as discussed above. This group consisted of 11 binocular normal adults between the ages of 19 and 30 years (mean 24.63 ± 2.8 years) (Thiagarajan, Lakshminarayanan, & Bobier, 2010). Binocular normals adults had best corrected visual acuity of 20/20 in each eye and were confirmed to have accommodative and binocular functions that fell within Morgan's normal limits. The following functions were assessed: distance and near phorias, near point of convergence, fusional vergence limits, negative and positive relative accommodation and monocular and binocular near point of accommodation.

3. Results

Out of the 11 CI's examined in the study, only eight participants could maintain fusion through the 12Δ BO prism for the duration of the study. The three excluded participants had very low PFV limits (4, 6 and 8Δ BO respectively). The mean convergence insufficiency treatment score (CISS score) for the eight remaining subjects did not change significantly (27.3 ± 3.8) from the entire group consisting of 11 subjects (28.45 ± 3.3).

The positive fusional vergence (PFV) limit for CIs was significantly less (BO to blur) in comparison with binocular normals (Fig. 2; $t = 3.527$; $p = 0.0026$).

3.1. Changes to phoria and CA over time

The addition of 12Δ BO significantly increased the exophoria ($p < 0.001$) which then showed an exponential decay function over 15 min in both normal and CI subjects. The prism-induced exophoria declined significantly over time ($p < 0.001$). This was infact, similar to earlier investigations with both CI subjects and controls (Henson & North, 1980). This pattern of exophoria reduction is taken to be indicative of a change in tonic vergence to a more convergent position (Henson & North, 1980) which is referred to as vergence adaptation (Schor, 2009). The average magnitude and rate of vergence adaptation and the output of convergence accommodation is described by exponential decay curves averaged across all subjects in the CI and control group (Figs. 3 and 4), Two parameters were compared between subjects within the two groups from the exponential fits: the magnitude of adaptation (total span of change in the response from start through to the asymptotic plateau defined as the ordinate (Y axis) value in diopters) and the time constant of the function defined as the time at which the response reached 63% of the final value.

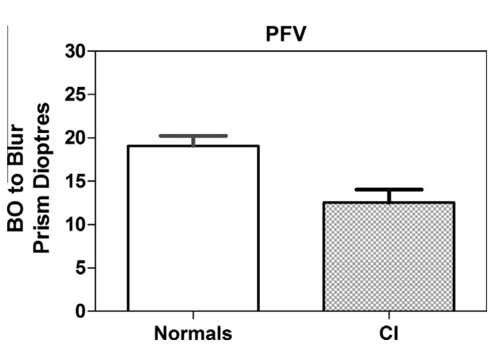

Fig. 2. CI's show significantly reduced PFV (BO to blur) compared to normals.

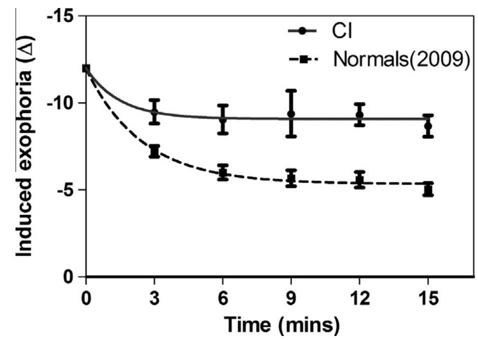

Fig. 3. Exponential decay function shows significantly less vergence adaptation in CI's compared to normals. Phorias were normalized and signed with exophoria being negative. Error bars indicate mean ± SEM.

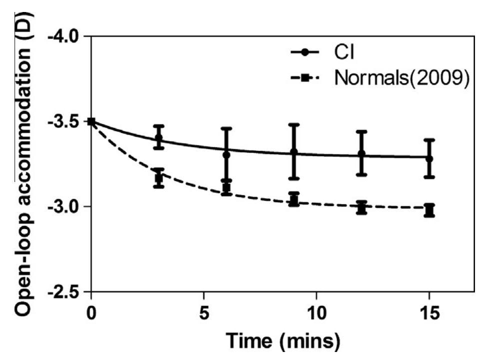

Fig. 4. Binocular normals show greater reduction in the CA (normalized open-loop accommodative response) over time (during adaptation) than CI. Open-loop accommodation was negatively signed to be consistent with the direction of reduction in exophoria. Error bars indicate mean ± SEM.

Decay functions fitted to the change in phoria over 15 min (Fig. 3) were significantly more shallow (less change) for the CI's compared to the controls ($p < 0.001$) Fig. 3. Individual analyses showed the effect to result from differences in the magnitude of vergence (phoria) adaptation which was significantly reduced ($p = 0.01$) in the CI group (2.9Δ) compared to the normal group (6.6Δ). However, there was no statistically significant difference in the time constants ($p = 0.5$) between the two groups (CI: 1.48 min vs. Normals 2.45 min).

Similarly, the introduction of 12Δ BO significantly increased the binocular open loop accommodative response in both groups ($p < 0.005$). This change in open-loop accommodation was considered to represent changes in convergence accommodation (CA); since other components such as proximal and tonic were constant (tonic accommodation results in Section 3.2). This prism-induced CA response decreased significantly ($p < 0.0001$) concurrent with the reduction in exophoria in binocular normals alone. The CI's showed a non-significant effect of time (Fig. 4; $p = 0.14$), suggesting that the prism induced CA remained high even with prolonged fixation.

The averaged exponential decay curves were again significantly ($p < 0.005$) shallower in the case of the CI group compared to the normals (Fig. 4), Comparisons of individual parameters, indicated that the amplitude or rate of adaptation was significantly reduced in CI vs. normals (CI = 0.21D; Normals = 0.5D, $p = 0.03$) but the difference in time constants (CI = 4 min; Normals = 3.6 min, $p = 0.9$) did not reach statistical significance.

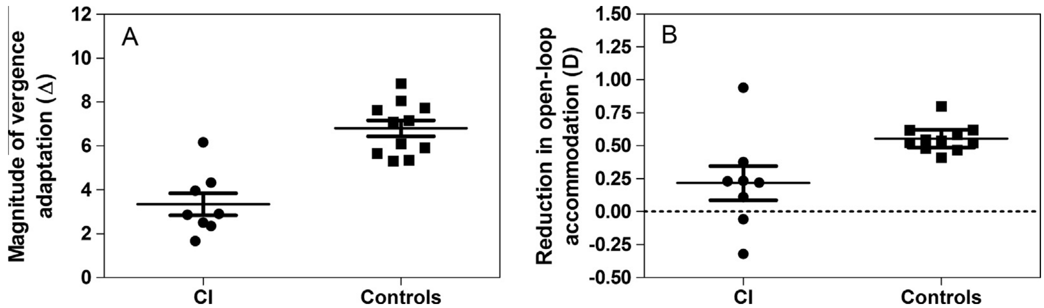

Fig. 5. Individual magnitudes of reduction in phoria (A) and CA (B) for both study groups. It is evident that majority of CI's exhibit reduced adaptation and less change in CA after 15 min of sustained fixation. Error bars indicate mean ± SEM.

Fig. 5A and B shows a scatter plot of the differences between the magnitudes of vergence adaptation and CA, derived from individual exponential decay functions in the two study groups. It is clear that the majority of the CI's show a significantly reduced magnitude of vergence adaptation (CI = $p = 0.01$) and CA reduction (CI = 0.21D, Normals = 0.55D; $p = 0.03$) compared to the normals. Inspection of Fig. 5B shows one CI subject exhibiting reduction in CA (0.9D) that was substantially different from the mean. The magnitude of convergence accommodation elicited would be affected not only by vergence adaptation but also by the CA/C ratio. We have confirmed that this individual had a higher than average vergence adaptation which was augmented by a very high CA/C value that was close to twice the mean value.

3.2. Accommodative adaptation

Since tonic changes in accommodation could confound the CA measures over time, we measured tonic accommodation before and after the sustained task. The difference between pre and post task tonic accommodation (i.e. accommodative adaptation) was not significantly different from zero in either study group ($p = 0.36$). Further, the magnitude of tonic accommodation adaptation was not significantly different between the study groups (CI = 0.08 ± 0.19D; Normals: −0.01 ± 0.05D; $p = 0.65$).

3.3. Missing data

Three subjects were unable to fuse the 12Δ BO prism as identified above. As might be expected, their clinical findings showed very low PFV limits (4, 6 and 8Δ BO prism). Given the low PFV correlates with reduced vergence adaptation (Thiagarajan, Lakshminarayanan, & Bobier, 2010) we predict that their omission would not affect the conclusion of the study. Their omission may underestimate the magnitude of the difference in vergence adaptation and CA output between the CI group and controls.

4. Discussion

The vergence adaptation response in CI subjects following fixation through a base out prism (12 BO) was more sluggish and smaller in amplitude compared with normals. This finding has been reported previously in CIs (Brautaset & Jennings, 2005; Henson & North, 1981). Open loop accommodation which has not been measured previously in this context, did not reduce over time to the same degree in CIs as in the normals. Given that tonic accommodation did not change significantly, the failure for open loop accommodation to change must reflect the lack of attenuation of CA, due to the reduced vergence adaptation. This allows the retention of the hypothesis that individuals with CI show a reduced vergence adaptation, which then attenuates the reduction of CA with prolonged viewing through a prism.

Current models of accommodation and vergence (Judge, Miles, & Optican, 1987; Schor, 2009) predict that excessive CA would result from the reduced vergence adaptation. Since the "blur" value in clinical positive fusional vergence testing corresponds to the output of CA (Semmlow & Heerema, 1979), the elevated levels of CA are consistent with a number of clinical findings in individuals with CI. The reduced base-out to blur response observed during clinical positive vergence testing; the finding of increased accommodation found in binocular tests of "dynamic retinoscopy" at near and the common complaint of blurry vision after 20–30 min of close work, all support these results. A recent study (Momeni-Moghaddam, Goss, & Sobhani, 2014) suggests that higher amounts of vergence accommodation is a factor in asthenopia. Furthermore, if an individual with CI accommodated accurately at a near target, then any excessive accommodation found from binocular accommodative measures would not likely arise from the longstanding view of the over use of accommodative convergence (Fry, 1937, 1982; Hofstetter, 1945) but, more likely results from the excessive convergence driven accommodation due to weak vergence adaptation.

The prescribing of exercises ("pencil push ups") that force convergence to an object slowly moved toward the eyes have been used in the past. Recently, they have been down graded as a sole means to train convergence insufficiency as they were not found to be statistically different than placebo interventions (Convergence Insufficiency Treatment Trial Study Group, 2009). Perhaps their limitation is that unlike other orthoptics methods, converging to a pencil provides a congruent stimulus to both accommodation and vergence and thus may be less effective in changing vergence adaptation than methods that induce an asymmetry between the demand on vergence compared to that for accommodation. Only in this way are the cross links required to alter their outputs.

4.1. Basic mechanisms underlying CI

The results of this investigation coupled with other studies showing reduced vergence adaptation (Brautaset & Jennings, 2006; Henson & North, 1981) and reduced reflex properties of vergence (Alvarez & Kim, 2013; Alvarez et al., 2010; van Leeuwen et al., 1999) allow CI to be understood conceptually. Consistent with basic models (Schor & Kotulak, 1986) reflex properties of convergence are reduced resulting in a reduced input to vergence adaptation, which in turn reduces the attenuation of convergence accommodation. Clinical findings can be put into context: The reduced near point of convergence (NPC) would most likely be based upon the reduced amplitude of vergence. The reduced amplitude of "fusion limits" tested by base out prisms would be based upon the reduced tonic adaptation and high levels of CA. Perhaps put another way, investigations into the basic mechanisms of CI support models of accommodation and vergence that predict that when viewing is prolonged, reflex vergence is replaced by tonic changes which in turn reduce the output of the cross links between vergence and accommodation.

We would hypothesize that vision training should not only improve reflex vergence and improve vergence adaptation as has been noted (Brautaset & Jennings, 2006; Henson & North, 1982) but also should reduce the resulting CA output over time, resulting in less subjective complaints of blur.

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References

Alpern, M., & Ellen, P. (1956). A quantitative analysis of the horizontal movements of the eyes in the experiment of Johannes Mueller: I. Methods and results. *American Journal of Ophthalmology, 42*, 289–303.

Alvarez, T. L., & Kim, E. H. (2013). Analysis of saccades and peak velocity to symmetrical convergence stimuli: Binocularly normal controls compared to convergence insufficiency patients. *Investigative Ophthalmology and Visual Science, 54*, 4122–4135.

Alvarez, T. L., Vicci, V. R., Alkan, Y., Kim, E. H., Gohel, S., Barrett, A. M., et al. (2010). Vision therapy in adults with convergence insufficiency: Clinical and functional magnetic resonance imaging measures. *Optometry and Vision Science, 87*, 985–1002.

Borish, I. M. (1975). *Clinical refraction*. Chicago: Professional Press.

Borsting, E. J., & The Convergence Insufficiency Treatment Trial Group (2003). Validity and reliability of the revised convergence insufficiency symptom survey in children aged 9 to 18 years. *Optometry and Vision Science, 80*, 832–838.

Brautaset, R. L., & Jennings, J. A. M. (2005). Distance vergence adaptation is abnormal in subjects with convergence insufficiency. *Ophthalmic and Physiological Optics, 25*, 211–214.

Brautaset, R. L., & Jennings, A. J. M. (2006). Effects of orthoptic treatment on the CA/C and AC/A ratios in convergence insufficiency. *Investigative Ophthalmology and Visual Science, 47*, 2876–2880.

Carter, D. B. (1963). Effects of prolonged wearing of prism. *American Journal of Optometry, 40*, 265–273.

Casillas, E., & Rosenfield, M. (2006). Comparison of subjective heterophoria testing with a phoropter and trial frame. *Optometry and Vision Science: Official Publication of the American Academy of Optometry, 83*, 237–241.

Convergence Insufficiency Treatment Trial Study Group (2009). Long-term effectiveness of treatments for symptomatic convergence insufficiency in children. *Optometry and Vision Science, 86*, 1096–1103.

Cooper, J., & Duckman, R. (1978). Convergence insufficiency: Incidence, diagnosis, and treatment. *Journal of American Optometric Association, 49*, 673–680.

Cooper, J., Schulman, E., & Jamal, N., 2013. *Convergence insufficiency – A major review. Optometry online.* American Optometric Association. 16-1-2013.

Fincham, E. F., & Walton, J. (1957). The reciprocal actions of accommodation and convergence. *Journal of Physiology, 237*, 488–508.

Fry, G. A. (1937). An experimental analysis of the accommodation-convergence relation. *American Journal of Optometry, 14*, 402–414.

Fry, G. A. (1982). Basic concepts underlying graphical analysis. In C. M. Schor & K. J. Ciuffreda (Eds.), *Vergence eye movements. Basic and clinical aspects* (pp. 403–437). Boston: Butterworths.

Grisham, J. D. (1988). Visual therapy results for convergence insufficiency: A literature review. *American Journal of Optometry and Physiological Optics, 65*(6), 448–454.

Henson, D. B., & North, R. (1980). Adaptation to prism-induced heterophoria. *American Journal of Optometry and Physiological Optics, 57*(3), 129–137.

Henson, D. B., & North, R. (1981). Adaptation to prism induced heterophoria in subjects with abnormal binocular vision or asthenopia. *American Journal of Optometry and Physiological Optics, 58*, 746–752.

Henson, D. B., & North, R. (1982). Effect of orthoptics upon the ability of patients to adapt to prism-induced heterophoria. *American Journal of Optometry and Physiological Optics, 59*(12), 983–986.

Hofstetter, H. W. (1944). A comparison of Duane's and Donder's tables of the amplitude of accommodation. *American Journal of Optometry and Archives of American Academy of Optometry, 21*, 345–362.

Hofstetter, H. W. (1945). The zone of clear single binocular vision. *American Journal of Optometry and Archives of the American Academy of Optometry, 22*(7), 301–333.

Judge, S. J., Miles, F. A., & Optican, L. M. (1987). Optically induced changes in the couplings between vergence and accommodation. *The Journal of Neuroscience, 7*(8), 2576–2589.

Kotulak, J. C., & Schor, C. M. (1987). The effects of optical vergence, contrast, and luminance on the accommodative response to spatially bandpass filtered targets. *Vision Research, 27*, 1797–1806.

Momeni-Moghaddam, H., Goss, D. A., & Sobhani, M. (2014). Accommodative response under monocular and binocular conditions as a function of phoria in symptomatic and asymptomatic subjects. *Clinical and Experimental Optometry, 97*, 36–42.

Morgan, M. W. (1944). The clinical aspects of accommodation and convergence. *American Journal of Optometry and Archives of the American Academy of Optometry, 21*(8), 301–313.

Rainey, B. B., Schroeder, T. L., Goss, D. A., & Grosvenor, T. P. (1998). Inter-examiner repeatability of heterophoria tests. *Optometry and Vision Science, 75*, 719–726.

Rouse, M. W., Borsting, E. J., Lynn Mitchell, G., Scheiman, M., Cotter, S. A., Cooper, J., et al. (2004). Validity and reliability of the revised convergence insufficiency symptom survey in adults. *Ophthalmic and Physiological Optics, 24*, 384–390.

Schaeffel, F., Wilhelm, H., & Zrenner, E. (1993). Inter-individual variability in the dynamics of natural accommodation in humans: Relation to age and refractive errors. *Journal of Physiology, 461*, 301–320.

Scheiman, M., Cooper, J., Mitchell, G. L., DeLand, P., Cotter, S., Borsting, E., et al. (2002). A survey of treatment modalities for convergence insufficiency. *Optometry and Vision Science: Official Publication of the American Academy of Optometry, 79*, 151–157.

Scheiman, M., Cotter, S., Mitchell, G. L., Kulp, M., Rouse, M., Hertle, R., et al. (2008). Randomized clinical trial of treatments for symptomatic convergence insufficiency in children. *Archives of Ophthalmology, 126*, 1336–1349.

Scheiman, M., Cotter, S., Rouse, M., Mitchell, G. L., Kulp, M., Cooper, J., et al. (2005). Randomised clinical trial of the effectiveness of base-in prism reading glasses versus placebo reading glasses for symptomatic convergence insufficiency in children. *British Journal of Ophthalmology, 89*, 1318–1323.

Scheiman, M., & Wick, B. (2002). *Clinical management of binocular vision: Heterophoric, accommodative and eye movement disorders*. Philadelphia: Lippincott Williams & Wilkins.

Schor, C. M. (1979). The influence of rapid prism adaptation upon fixation disparity. *Vision Research, 19*, 757–765.

Schor, C. M. (1986). The Glenn A. Fry award lecture: Adaptive regulation of accommodative vergence and vergence accommodation. *American Journal of Optometry and Physiological Optics, 63*(8), 587–609.

Schor, C. M. (2009). Neuromuscular plasticity and rehabilitation of the ocular near response. *Optometry and Vision Science, 86*, 1788–1802.

Schor, C. M., & Kotulak, J. C. (1986). Dynamic interactions between accommodation and convergence are velocity sensitive. *Vision Research, 26*, 927–942.

Schroeder, T. L., Rainey, B. B., Goss, D. A., & Grosvenor, T. P. (1996). Reliability of and comparisons among methods of measuring dissociated phoria. *Optometry and Vision Science, 73*, 389–397.

Semmlow, J. L., & Heerema, D. (1979). The role of accommodative convergence at the limits of fusional vergence. *Investigative Ophthalmology Visual Science, 18*, 970–976.

Sheard, C. (1930). Zones of ocular comfort. *American Journal of Optometry, 7*, 9–25.

Sreenivasan, V., Irving, E. L., & Bobier, W. R. (2008). Binocular adaptation to near addition lenses in emmetropic adults. *Vision Research, 48*, 1262–1269.

Sreenivasan, V., Irving, E. L., & Bobier, W. R. (2009). Binocular adaptation to +2D lenses differs between myopic and emmetropic school aged children. *Optometry and Vision Science, 86*, 731–740.

Thiagarajan, P., Lakshminarayanan, V., & Bobier, W. R. (2010). Effect of vergence adaptation and positive fusional vergence training on oculomotor parameters. *Optometry and Vision Science, 87*, 487–493.

van Leeuwen, A. F., Westen, M. J., Van der Steen, J., de Faber, J. T. H. N., & Collewijn, H. (1999). Gaze-shift dynamics in subjects with and without symptoms of convergence insufficiency: Influence of monocular preference and the effect of training. *Vision Research, 39*, 3095–3107.

Westheimer, G., & Blair, S. M. (1973). The parasympathetic pathways to internal eye muscles. *Investigative Ophthalmology, 12*(3), 193–197.

Wolf, K. S., Ciuffreda, K. J., & Jacobs, S. E. (1987). Time course and decay of effects of near work on tonic accommodation and tonic vergence. *Ophthalmic and Physiological Optics, 7*, 131–135.