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MEDICAL OPHTHALMOLOGY

Association between reading speed, cycloplegic refractive error, and oculomotor function in reading disabled children versus controls

Patrick Quaid · Trefford Simpson

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Abstract
Background Approximately one in ten students aged 6 to 16 in Ontario (Canada) school boards have an individual education plan (IEP) in place due to various learning disabilities, many of which are specific to reading difficulties. The relationship between reading (specifically objectively determined reading speed and eye movement data), refractive error, and binocular vision related clinical measurements remain elusive.
Methods One hundred patients were examined in this study (50 IEP and 50 controls, age range 6 to 16 years). IEP patients were referred by three local school boards, with controls being recruited from the routine clinic population (non-IEP patients in the same age group). A comprehensive eye examination was performed on all subjects, in addition to a full binocular vision work-up and cycloplegic refraction. In addition to the cycloplegic refractive error, the following binocular vision related data was also acquired: vergence facility, vergence amplitudes, accommodative facility, accommodative amplitudes, near point of convergence, stereopsis, and a standardized symptom scoring scale. Both the IEP and control groups were also examined using the Visagraph III system, which permits recording of the following reading parameters objectively: (i) reading speed, both raw values and values compared to grade normative data, and (ii) the number of eye movements made per 100 words read. Comprehension was assessed via a questionnaire administered at the end of the reading task, with each subject requiring 80% or greater comprehension.
Results The IEP group had significantly greater hyperopia compared to the control group on cycloplegic examination. Vergence facility was significantly correlated to (i) reading speed, (ii) number of eye movements made when reading, and (iii) a standardized symptom scoring system. Vergence facility was also significantly reduced in the IEP group versus controls. Significant differences in several other binocular vision related scores were also found.
Conclusion This research indicates there are significant associations between reading speed, refractive error, and in particular vergence facility. It appears sensible that students being considered for reading specific IEP status should have a full eye examination (including cycloplegia), in addition to a comprehensive binocular vision evaluation.

Keywords Binocular vision · Reading · Visagraph · Vergence · Accommodation

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P. Quaid
IRIS The Visual Group,
Guelph, Ontario, Canada

P. Quaid (✉)
Adjunct Clinic Faculty, University of Waterloo School of Optometry & Vision Science,
200 University Avenue West,
Waterloo, Ontario N2L 3G1, Canada
e-mail: ptquaid@sciborg.uwaterloo.ca

T. Simpson
Faculty, University of Waterloo School of Optometry & Vision Science,
Waterloo, Canada

Introduction

The term “binocular vision dysfunction” is a broad term, and can be used for manifest eye turns (i.e., heterotropias) or latent eye turns (i.e., heterophorias) in addition to accommodative and vergence disorders. The relationship between reading and oculomotor status is an intriguing area but also a challenging one. Whilst binocular vision has been shown to be desirable over monocular vision in a number of skills [1, 2], the relationship of binocular visual skills and reading ability remains difficult to ascertain. A relationship between reading skills and oculomotor efficiency has been shown in the literature, with accommodative facility specifically being suggested as predictive of reading performance in kindergarten and grade one children [3, 4]. In addition, a longitudinal study of 144 beginning readers in public school, using 25 measures of visual efficiency concluded that visual factors were a *primary cause* for beginning reading failure in children [5].

Numerous research papers have suggested a link between oculomotor efficiency, refractive error (specifically hyperopia) and reading ability [6–11], and the obvious use of vision in reading warrants these investigations. However, other areas of interest outside of reading difficulties have also been raised with respect to binocular vision dysfunction. One such study [12] dealt with the challenging topic of the potential link between attentional issues and binocular vision dysfunction, specifically convergence insufficiency. This study looked at 266 ADHD cases, and found a three times higher prevalence of binocular vision dysfunction (convergence insufficiency) in the ADHD group compared to population normal values. Of particular interest was the observation that five out of the nine DSM-IV criteria required for the diagnosis of ADHD overlapped with symptoms of binocular vision dysfunction [12]. The potential for diagnostic confusion was discussed, and it was suggested that whilst there are cases of ADHD with no binocular vision dysfunction present, due to the increased incidence in the ADHD population, binocular vision issues should be ruled out.

Another binocular vision related topic discussed in reading impairment literature is Irlen coloured filters for "scotopic sensitivity syndrome". These custom-tinted lenses are proposed to result in higher levels of efficiency when reading. Schiemann et al. [13], however, have shown that the majority (approximately 95%) of such Irlen cases potentially have unresolved binocular vision and refractive anomalies. Given the significant overlap in symptoms between the two conditions (including double vision and headaches), the authors expressed concern that binocular vision dysfunction issues were being under-detected, and concluded that although all Irlen centres require a normal result from a routine eye examination prior to referral, routine exams may not necessarily include a cycloplegic examination or accommodative and/or vergence testing [13].

When taken together, the above constellation of research suggests that although vision is playing at least a moderate role in reading-based learning disabilities, visual dysfunction beyond reduced visual acuity does not appear to be emphasized in the work-up of students with reading-based learning disabilities. On a related note, it is also somewhat surprising, given the evidence of increased prevalence of binocular vision dysfunction in the ADHD population [12], that current published ADHD guidelines [14] make no recommendation in terms of even basic vision requirements. It appears that the role of vision in attentional disorders and learning disabilities, whilst certainly not being the only factor in many cases, is nonetheless being under-emphasized. Given that an increased mis-classification of ADHD has also been documented in confirmed binocular vision dysfunction subjects [15], it is important to clarifying how much impact binocular vision dysfunction has on tasks related to attention (such as reading).

The aim of this study was to examine 50 students with an IEP (individual educational plan) in place and 50 control students, in order to compare vision-related clinical outcome data specifically to reading speed and eye movement data attained using the Visagraph eye-tracking system, an instrument which has been shown to give reliable and objective data in terms of quantitative eye movement data and reading speed [16, 17]. An IEP within the school boards we dealt with was defined as "any form of documented accommodation or help put in place which has been deemed necessary as result of academic or environmental challenges in the school environment specifically". The IEPs in place for our experimental group were specific for reading difficulties, with the most common "accommodation" being the use of a laptop to enlarge print or to allow the student to have text read to them rather than the student having to read the text themselves.

It is conservatively estimated that between one in ten to one in fifteen students within the school boards we worked with have a reading specific IEP in place. The average student with a reading-based IEP in place within these school boards were reported to be approximately two grade levels behind their grade level in reading ability. In addition to the obvious psychological consequences of learning disabilities (LD) to the student and their family, there is also a significant economic cost. The average yearly cost of educating in mainstream schooling in Canada is approximately doubled in LD children ($12,000 per year as opposed to $6,000 per year approximately) with the simple incremental cost of LD from birth to retirement being conservatively estimated at $1.98 million dollars per LD individual [18]. It should be noted that 61.4% of these costs are borne by the families, with 38.5% being borne by public programs and 0.1% by private sector insurance [18]. Thus, it is clear that research efforts to determine underlying causes of all LD issues (not just reading-based) are certainly justified from both an economic and social responsibility standpoint.

Materials and methods

Subjects examined consisted of 50 IEP students (31 male) and 50 control students (27 male). There was no significant age difference between the two groups (p=0.64, Fig. 1), with the mean age in the IEP group being 10.34 years (SD 2.96) and the mean age in the control group being 10.60 years (SD 2.68). The IEP group consisted of referrals from three local school boards for evaluations, with the control group being assessed from the routine patient base of the first author's optometric clinic. All legal guardians gave signed informed consent for their children's clinical data to be used for research purposes consistent with the 1964 Declaration of Helsinki. The only requirement for IEP students to enter to the study was that a reading-specific IEP status had been granted by the school board. Any patients currently taking any form of stimulant medications for ADHD or ADD were specifically excluded from the study. None of the IEP cases were reported to have a diagnosis of dyslexia or significant phonological issues at the time of the study, following the standardized psychological evaluation process required to attain IEP status in Ontario (Canada) Schools. The control group was selected from new pediatric patients. Only patients with no chief complaint and no academic issues reported on the intake form were used. Pediatric eye exams in Ontario are government-insured by the Ontario Health Insurance Program (OHIP) annually. All controls gave informed consent prior to examination to be part of this study, as extra tests were performed over and above what OHIP covers, with all testing for the purposes of this study being done at no cost. The first 50 patients to meet these criteria were selected as controls for this study. At the completion of the study, the sample size of 50 for each group was deemed adequate and not increased due to the moderate difference in outcome measures attained (i.e., low potential for Type II error).

All subjects were seen for a binocular vision work-up following a comprehensive eye examination which included a cycloplegic refraction. This binocular vision work-up generally followed a pyramidal approach (Fig. 2), with initial testing at the most fundamental level of the pyramid (i.e., visual acuity) and subsequent testing working upwards towards stereopsis and recording clinical data for each level of the pyramid on a clinical template. This approach has been published elsewhere [19], and is shown solely to explain the sequence in which clinical testing was done and not as representation of the hierarchy of the binocular vision system.

Clinical data attained considered part of a routine eye examination

In all vergence-based testing, if the subjective response did not agree with the objective observation, the objective end point was taken as the outcome measure:

Refractive error Both the spherical and cylindrical dioptric powers were noted for the right and left eye, following a dry subjective refraction (with binocular balancing) in addition to a cycloplegic refraction (autorefractor result followed by a subjective refraction), using a single drop of 0.5% proparacaine in each eye followed 5 min later by two drops of cyclopentolate 1% ophthalmic solution in each eye. Cycloplegic refraction was performed after 30 min. The cycloplegic refraction result was used for the purposes of this paper.

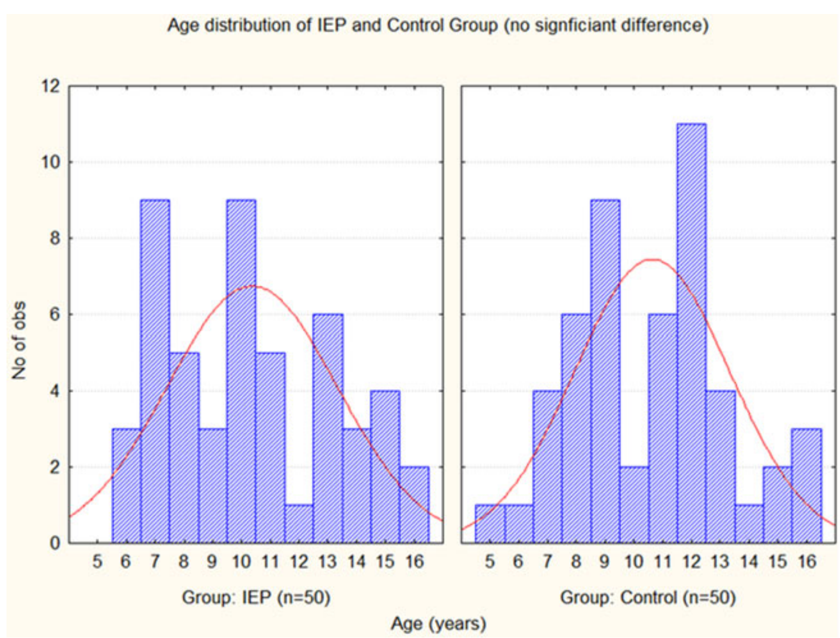


Fig. 1 Age distribution of the IEP group versus the control group. No significant age difference was present between the groups

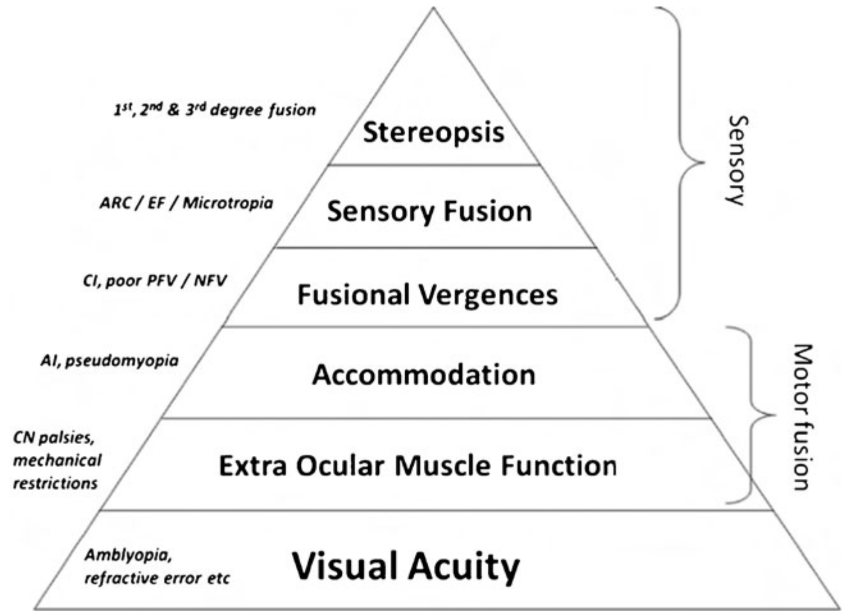


Fig. 2 Pyramid of binocular vision used as work-up template on new referrals[19]. Schematic shows sequence of testing as being from the bottom upward (published elsewhere)

Stereopsis Depth perception was recorded in seconds of arc using the Titmus stereotest, which can measure stereopsis from 800” arc to 20” arc. This measurement was made on presentation (i.e., unaided or with habitual correction in place) and not with the optimal correction place per se, as the presenting ocular status was also used to assess reading skills. This test is primarily subjective in nature.

Near point of convergence (NPC) This was assessed using an accommodative target (letter E on a “budgie stick” with VA equivalent to 20/30), with the measurement being recorded as the average distance in centimetres from the bridge of the nose at which the patient reported double vision after three successive measurements. If no diplopia was reported, the distance in centimetres at which one eye drifted was recorded. As the eyes can be seen converging, there is an objective and subjective endpoint to this test.

Amplitudes of accommodation (monocular and binocular) This measurement was assessed using 20/20 acuity print, and was recorded as the dioptric equivalent of the distance at which sustained near-point blur was reported. This was also taken as the average of three measurements. This test is primarily subjective in nature.

Clinical data selected for the study generally considered binocular vision specific

The following clinical tests of vergence and accommodative status were performed on the same day, but are generally *not* considered part of a routine eye examination, and are considered clinical tests that are more specific to detecting binocular vision dysfunction.

Vergence facility (cycles per minute) This measurement has been described elsewhere, with the normal clinical value being accepted as approximately 15 cycles per minute at 40 cm [20]. In our study, a 12 base out/3 base in flipper (Fig. 3) was used over the right eye, with both eyes open during testing. The subject was asked to fuse a 20/30 acuity letter while the examiner changed the flipper position from 12 prism dioptres base out to 3 prism dioptres base in. The number of cycles fused in 1 min was recorded. If the patient stayed diplopic at any point (i.e., fusion broke down) the number of cycles to that point was noted. This test is both subjective and objective, as the responses of the patient are listened to, but given the prism power used the eyes can also be seen to converge and diverge, permitting objective verification of the subjective response.

Convergence amplitude (base out break and base out recovery) Also known as positive fusional vergences or PFVs. Convergent “step vergence” was determined at near using a prism bar in free space using a 20/30 acuity target (i.e., the budgie stick). The “break point” was the prism value at which subject saw double and could not re-fuse, with the “recovery” being the prism value at which the letter could be re-fused. The eyes can be seen to move inwards with increasing prism demand, although the patient is required to state when diplopia is reported, and objective confirmation of this report can be seen as the eyes will be noted to “break” in terms of fusion and drift outward. Conversely, when re-fusing on base out recovery, the eyes will be seen to re-fuse and recover to a convergent state.

Divergence amplitude (base in break and base in recovery) Also known as negative fusional vergences or NFVs.

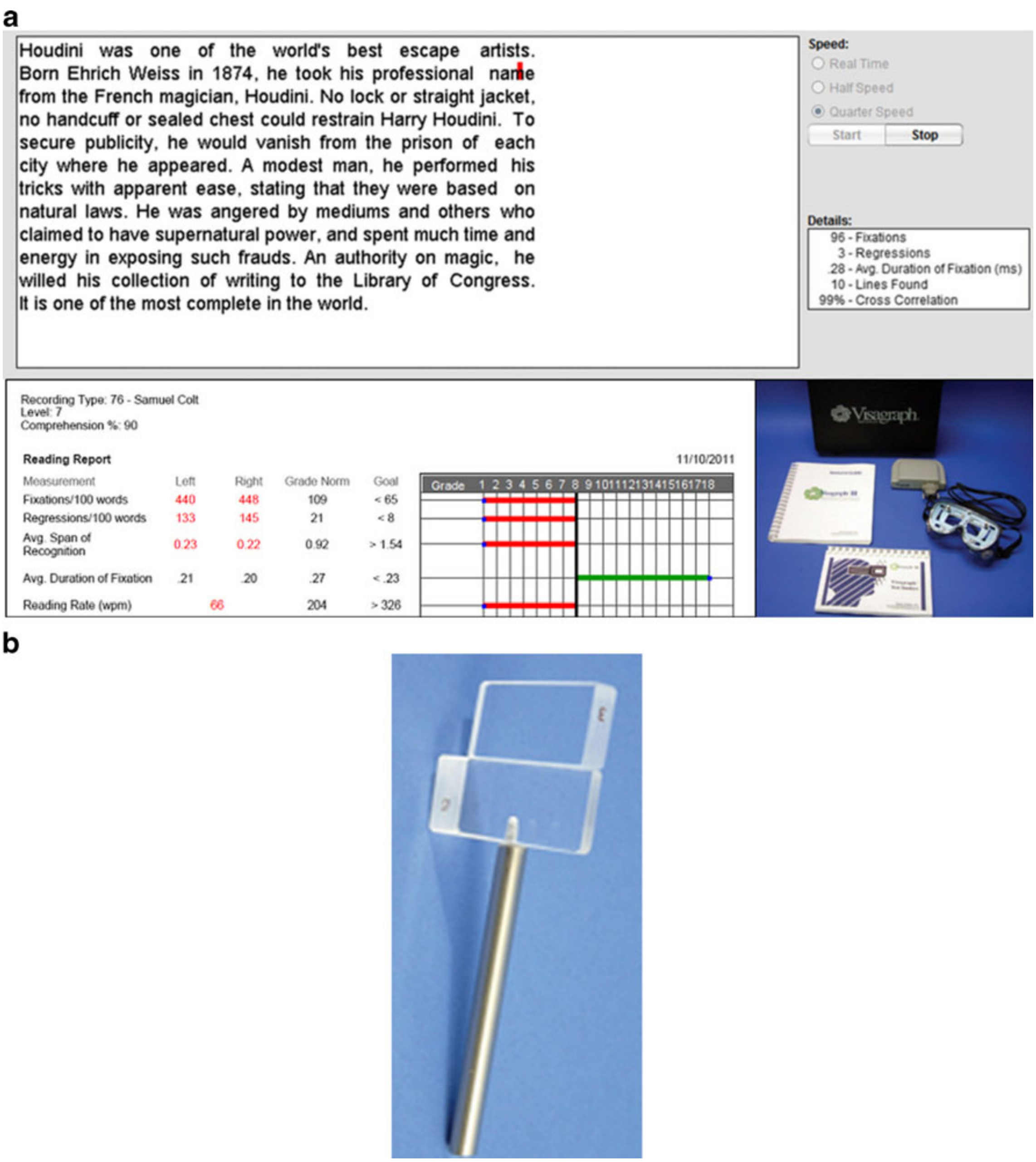


Fig. 3 **a** The Visagraph III system with infra-red photo-detectors and standardized reading test booklets (*red mark* moves to show where the subject was looking when reading in real time). The printout produced shows the number of eye movements made to read 100 words and the reading speed in words per minute. Other measures such as regressions (i.e., back-tracking) are also tracked. For the purposes of this study, only reading speed and eye movements per 100 words read were examined. **b** The 12BO/3BI prism flipper used to measure vergence facility. The patient is required to report near target fusion when the flipper is switch from 12 base out demand to three base in demand. The test is both subjective (as the patient responds) and objective (as the examiner can see if the eye moves in or out) in nature. A result of 15 cycles per minute or more is considered normal (i.e., one cycle is from base out to base in back to base out) [20]

Divergent "step vergence" was determined at near using a prism bar in free space using a 20/30 acuity target (i.e., the budgie stick). The "break point" was the prism value at which the subject saw double, and could not re-fuse and the "recovery point" was the prism value at which the letter could be re-fused. It should be noted that, consistent with published research, NFVs were measured prior to PFVs [21]. The eyes can be seen to move outwards with increasing prism demand, although the patient is required to state when diplopia is reported, and objective confirmation of this report can be seen as the eyes will be noted to "break" in terms of fusion and drift inward. Conversely, when re-fusing on base in recovery, the eyes will be seen to re-fuse and recover to a divergent state.

Monocular accommodative facility (MAF) Recorded as cycles per minute (cpm), ±2DS flippers at near were used *monocularly* to determine how many times the patient could clear the 20/20 line of text at 40 cm. The patient was instructed to clear the text with one lens in place and to report the word "clear", at which point the examiner (not the patient) changed the flipper to the other side. This process was done monocularly and the number of cycles per minute recorded. If the patient was unable to clear the text, the number of complete cycles up to that point was noted. MAF testing is considered a reflection of the integrity of the accommodative system in isolation, with little to no influence of the vergence system (as the subject is tested monocularly). This test by design is primarily subjective in nature.

Binocular accommodative facility (BAF) Recorded as cycles per minute (cpm), ±2DS flippers were used *binocularly* to determine how many times the patient could clear the target (20/20 line at 40 cm). The patient was instructed to clear the text with one lens in place and to report the word "clear", at which point the examiner (not the patient) changed the flipper to the other side. The number of complete cycles per minute was recorded. If the patient was unable to clear the text, the number of complete cycles up to that point was noted. BAF testing is considered a reflection of the integrity of the accommodative system and the vergence system *together*. Thus, for example, if a patient primarily has an accommodative issue with relatively normal vergences, MAF performance will be reduced compared to BAF performance, whereas if there is *also* a vergence issue, both MAF and BAF are usually reduced. Looking at this relationship clinically is of great use in determining whether a patient has primarily an accommodative issue or a vergence-based issue. This test by design is primarily subjective in nature.

CITT symptom questionnaire (0–60 scale) A questionnaire was administered to all patients using an iPad app ("NuBV", available from NuVision Systems Inc.). This questionnaire was validated as part of the Convergence Insufficiency Treatment Trial or CITT [22]. This questionnaire contains 15 questions, each of which has five answers (never, infrequently, sometimes, fairly often, always) which are totalled with the ultimate symptom score, which therefore varies from 0 to 60. Any score over 15 is considered a "fail", and is indicative of a significantly symptomatic patient from a binocular vision dysfunction perspective in convergence insufficiency cases [22]. The questionnaire was filled out prior to the initial case history.

Visagraph III (Fig. 3) eye movement recordings Eye movement and reading speed data were collected on all 100 subjects (50 IEP and 50 controls) using the same instrument under the same testing conditions by the same examiner (first author). Subjects were seated in good lighting, with their presenting correction (if present) being worn. The Visagraph III was used with the pupillary distance (PD) of the tracking system adjusted to the patients PD for the reading distance. The Visagraph III system is a commercially available eye-tracking system (Fig. 3) which enables the recording of eye movements in real time while the patient is reading standardized text. Infrared photo-detectors are mounted inside the goggles, and tracings are recorded for each eye, allowing a variety of data to be recorded and quantified. Data may also be compared to an age-matched normative database maintained by the manufacturers of the system. Reading rate information recorded using this system has been shown to relate reasonably to standardized reading achievement scores, and produces data that are reliable measures of reading skills [16, 17].

In addition to recording the eye movements (which can be saved as a movie file) a printout of the results and a comparison to age-matched normative data are provided (Fig. 3). One practice session was administered to the patient prior to the study recording, and a minimum of an 80% comprehension score was required for the data to be accepted as baseline data. The IEP group's reading level was set at the recommended level by the school board and IEP assessment protocol (which included a psychological–educational assessment). If the comprehension of the IEP patient was below 80%, the grade level was dropped until this was achieved. The control group had grade appropriate text shown to them initially, and the grade level dropped (if required) until the desired comprehension level of 80% was attained. The requirement of a minimum of 80% comprehension on the story (questionnaire built in to the Visagraph III system) was taken to ensure that "understanding from reading" was present and that the child did not simply "skim read".

All IEP and control subjects were instructed to only move their eyes during the recording (and not their head), and were observed for compliance during the recording. Subjects were not shown the text prior to the recording to avoid artificial inflation of the comprehension scores, with subjects being required to close their eyes whilst the examiner set up the Visagraph apparatus. When the subject opened their eyes prior to the recording, they were instructed to only look at a fixation target (an "O" on the top of the page of the standardized Visagraph III test booklet) until the examiner told them to start reading. Subjects were instructed to "read for comprehension" and were informed that they would be asked ten questions (with binary Y/N answers) after the grade appropriate text was read. Subjects were instructed to read "in their head" and not out loud, and to close their eyes when done reading and tell the examiner they are finished. The examination was conducted in a quiet, well-lit room with good lighting on the page. Parents were allowed to observe the procedure, but not to interfere or make any sounds during the recording.

The Visagraph III system was relatively easily administered to patients, and well-accepted. No subjects reported any confusion with instructions and "very good" quality recordings were obtained following one training session. Each recording session required on average 20 min of time from the examiner, with the actual text used consisting of one page of reading material (which translated into approximately 2 minutes of reading). After the recording is completed, the Visagraph III instrument reports whether the recording is "very good" or "low reliability". Whilst the exact cut-off percentages are not reported in the literature and are probably proprietary information, the determination of the quality of the recording is based on a number of features. The first feature is the percentage of time that the instrument was able to pick up valid eye movement data (i.e., low percentage can be due to, for example, occlusion of one infra-red sensor by a thick frame or excessive blinking). The second feature examined is the cross-correlation of the data, which is mainly determined using three factors: (i) the number of right eye movements made without the left eye moving, (ii) the number of left eye movements made without the right eye moving, and (iii) the number of opposite eye movements made. When these percentages are minimal, a low error score is attained and a high-quality output is reported.

Potential for selection bias was a concern in this study, as subjects were not masked in terms of group, given the clinical environment. This selection bias was minimized by taking data on the *first* 50 referred IEP students and the *first* 50 controls that presented to the clinic, regardless of the findings. A reassuring finding in this regard was the observation that the median cycloplegic refractive error of our IEP group was found to be very similar to the minimum hyperopic refractive error associated with decreased academic performance in a larger scale study using 782 subjects [8], whilst the median refractive error of the control group was found to be closer to emmetropia, as one would expect in a non-IEP control group. The refractive error range found in the control group was comparable to large-scale published normative data for the age range examined [23, 24]; thus, we believe that any selection bias inherent in this type of study design was not a significant factor.

The following two outcome measures using the Visagraph III were examined in this study:

1. *Fixations per 100 words:* Refers to the number of eye movements made to read 100 words of text. The data printout shows the results for the subject in addition to the expected age-matched normal results. Eye movement data reported were *extra* eye movements per 100 words read.
2. *Reading Rate (words per minute):* The number of complete words read per minute taken as an average of the entire text. The reported reading values in this research were the grade normal expected reading rate minus the actual reading rate recorded. This gives reading speed relative to the grade expected normal values.

Statistical analysis

Data were analyzed using Statistica 7 (StatSoft Inc.) and R (Development Core Team, 2011), a language and environment for statistical computing. (R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/). The Student's *t*-test was used in addition to correlation co-efficient testing to compare groups: discriminant analysis, hierarchical cluster analysis, regression trees, logistic analysis, and ROC curve analysis were the exploratory techniques used.

Results

A tabulated overview of all data attained by group is presented in Table 1, and a correlation matrix between all variables is shown in Table 2. The results will initially be presented in terms of the data that gave the best separation of the two groups (i.e., IEP versus controls). The relationship of these factors to both reading speed and the number of eye movements made when reading will then be presented, in addition to the most clinically relevant differences between the two groups in terms of binocular vision testing (i.e., clinical outcome measures).

Figures 4 and 5 below show the relationship between vergence facility and reading speed (specifically "words per minute below reading level" as determined by the Visagraph system). Vergence facility was related to the reading level in both groups, with the stronger correlation being in the IEP group ($p<0.001$ in IEP group versus $p=0.046$ in the control group). Although there were significant differences between the IEP group and the control group in almost all vision outcome scores tested (apart from astigmatic refractive error and inter-eye refractive difference), this study was designed to particularly examine which factors were associated with reading speed. In addition to the reading speed, the number of physical eye movements made when reading was also examined, to determine if this could be correlated to any of the oculomotor clinical outcome measures.

The difference in vergence facility between the IEP group and the controls was significant ($p<0.001$), as was the

Table 1 Reading performance scores and oculomotor measurements examined in this study (n=100). Analysis was performed using Statistica 7.0 software, with results from the IEP and control group being compared using the 2-tailed Student's t-test

Clinical test performed	Mean (SD) IEP (n=50)	Mean (SD) control (n=50)	Significance level
WPM below age normal	54.92 (32.87) wpm	8.62 (8.93) wpm	$p<0.001$
# of extra eye movements[a]	90.24 (62.52)	11.74 (12.14)	$p<0.001$
Questionnaire (0–60 score)	26.82 (13.91)	5.38 (3.58)	$p<0.001$
12BO / 3BI vergence facility	7.31 (3.37) cpm	14.48 (2.03) cpm	$p<0.001$
Spherical Rx (average Rx)	+1.37 (1.92) DS	−0.66 (1.62) DS	$p<0.001$
Astigmatic Rx	−0.82 (0.68) DC	−0.78 (0.59) DC	$p=0.69$
MAF (+/−2DS)	8.24 (3.58) cpm	12.81 (1.57) cpm	$p<0.001$
BAF (+/−2DS)	9.14 (3.44) cpm	13.52 (1.61) cpm	$p<0.001$
Amplitudes of accommodation	10.44 (2.13) D	12.86 (1.31) D	$p<0.05$
Base out break (near)	15.88 (6.95) PD	25.58 (5.67) PD	$p<0.001$
Base out recovery (near)	12.56 (6.21) PD	21.05 (4.41) PD	$p<0.001$
Base in break (near)	9.21 (4.37) PD	13.28 (2.87) PD	$p<0.001$
Base in recovery (near)	7.02 (4.07) PD	11.21 (2.59) PD	$p<0.001$
Stereopsis (seconds of arc)	65.20 (41.36)	32.40 (12.04)	$p<0.001$
Near point of convergence	10.76 (4.03) cm	7.48 (2.27) cm	$p<0.001$

[a]This number is the difference in the number of extra eye movements made versus the number of eye movements expected based on grade level (determined from the normative data provided by the Visagraph)

difference in reading speed between the two groups ($p<0.001$). Looking at the two groups combined (Fig. 5 below), there is also a significant correlation between vergence facility and reading speed (co-efficient of determination= 0.65, $p<0.001$).

Specifically examining test combinations that effectively separated IEP and control groups, Fig. 6 (below) shows that using both vergence facility and the symptom score appears to classify subjects in the correct group with a high degree of accuracy with very few false classifications. These data, when taken with the finding of a significant correlation in reading speed with vergence facility present a promising tool in predicting reading speed and likelihood of reading impairment.

Looking at the other main factor that separated experimental and control groups reasonably well (i.e., the standardized questionnaire), we note that there is an interesting relationship between the symptom score (0–60 scale) and both the "number of fixations" made and the "reading speed below grade level" outcomes. Looking at "number of fixations" (per 100 words read) as recorded by the Visagraph III system, there is a significant difference noted between the IEP and control groups (Fig. 7a). In addition, looking at Fig. 7b, there is a significant correlation between the number of excessive eye movements made (per 100 words read) and the level of symptoms present using the standardized questionnaire (r^2=0.643, $p<0.001$), in addition to being correlated to the reading speed (Fig. 7c).

Although the main focus of this paper was on the relationship between binocular vision clinical measures and reading speed between the IEP group and the control group, differences in numerous other refractive and oculomotor measurements were also apparent between the groups. Although the levels of astigmatic correction were not significantly different between the two groups, spherical refractive error was significantly more hyperopic (i.e., long-sighted) in the IEP versus the control group on cycloplegic refraction (Fig. 8), with the more hyperopic subjects also tending to have higher symptom scores (Fig. 9) and a slower reading speed (Fig. 10). Given that there was a significantly higher amount of hyperopia in the IEP group overall, which was for the most part uncorrected, the increased symptomatology in this group is not surprising. It should be noted that as there was no statistically significant difference (p=0.59) between the right and left eye spherical data in this study, the spherical data from the right and left eye *for each subject* was averaged and used to compare against the Visagraph III outcomes. It should be noted that 21 of the 50 IEP students had never had a routine eye examination prior to the study visit, with no subject in either group (with a history of prior examinations) reporting ever being cyclopleged. Five out of the 50 IEP students presented with correction, with seven out of the 50 controls presenting with correction. Thus, in both groups, more than 85% of subjects had no corrective ophthalmic lenses in use when examined for the purposes of this study.

It can be seen that as the hyperopic spherical error increases, the reading speed deteriorates (Fig. 10). This is noteworthy, as the IEP group as a whole was significantly more hyperopic than the control group, with most of the IEP group presenting uncorrected (only five out of 50 IEP subjects presented corrected, four of which were myopes). All subjects were correctable to 20/20 visual acuity in each eye with optimal correction, with 93% of IEP subjects and 87% of controls presenting with 20/25 acuity or better.

Table 2 Correlation matrix showing the correlation co-efficient and 95% co-efficient confidence interval (100 subjects). A pie-chart visual interpretation option is also presented. Red indicates an inverse relationship and blue indicates a direct relationship. The higher the correlation the more complete the pie and the darker the colour of the pie. As an example, if one looks at "Vergence facility" and "WPM below" (i.e., words per minute below normative data) and vectors the resultant correlation co-efficient, the correlation is seen to be −0.81 (95% confidence interval of −0.73 to −0.87). This example highlights that vergence facility was in fact the highest inversely correlated clinical outcome measure to reading speed (i.e., as vergence facility decreased, the WPM below expected normal levels increased). All correlations shown are significant to at least the $p<0.05$ level (the only clinical outcome measures found not to be significantly different between the groups were age and astigmatic refractive error)

BIR												
0.99 (0.98,0.99)	BIB											
0.74 (0.63,0.81)	0.74 (0.64,0.82)	BOB										
0.73 (0.63,0.81)	0.73 (0.63,0.81)	0.96 (0.94,0.97)	BOR									
0.60 (0.46,0.72)	0.61 (0.47,0.72)	0.73 (0.62,0.81)	0.77 (0.68,0.84)	BAF								
0.64 (0.51,0.75)	0.63 (0.50,0.74)	0.74 (0.64,0.82)	0.78 (0.69,0.85)	0.79 (0.70,0.86)	VergFac							
0.65 (0.52,0.75)	0.66 (0.53,0.76)	0.66 (0.53,0.76)	0.68 (0.56,0.77)	0.79 (0.71,0.86)	0.78 (0.69,0.85)	MAF						
0.54 (0.38,0.67)	0.54 (0.38,0.66)	0.57 (0.42,0.69)	0.60 (0.46,0.71)	0.63 (0.49,0.73)	0.63 (0.50,0.74)	0.62 (0.49,0.73)	Amps					
-0.47 (-0.61,-0.30)	-0.46 (-0.61,-0.29)	-0.59 (-0.70,-0.44)	-0.59 (-0.71,-0.45)	-0.62 (-0.73,-0.48)	-0.55 (-0.68,-0.40)	-0.49 (-0.62,-0.32)	-0.44 (-0.59,-0.27)	NPC				
-0.56 (-0.68,-0.40)	-0.56 (-0.68,-0.40)	-0.62 (-0.72,-0.48)	-0.66 (-0.76,-0.53)	-0.71 (-0.79,-0.59)	-0.72 (-0.80,-0.61)	-0.69 (-0.78,-0.58)	-0.71 (-0.80,-0.60)	0.54 (0.38,0.66)	Stereo			
-0.65 (-0.75,-0.52)	-0.66 (-0.76,-0.54)	-0.71 (-0.79,-0.60)	-0.72 (-0.80,-0.61)	-0.73 (-0.81,-0.62)	-0.79 (-0.85,-0.70)	-0.78 (-0.85,-0.69)	-0.64 (-0.75,-0.51)	0.53 (0.37,0.66)	0.76 (0.66,0.83)	ExtraMoves		
-0.61 (-0.72,-0.46)	-0.61 (-0.72,-0.47)	-0.68 (-0.77,-0.55)	-0.69 (-0.78,-0.57)	-0.76 (-0.83,-0.67)	-0.81 (-0.87,-0.73)	-0.76 (-0.84,-0.67)	-0.65 (-0.75,-0.51)	0.60 (0.46,0.72)	0.70 (0.59,0.79)	0.80 (0.72,0.86)	WPMbelow	
-0.62 (-0.73,-0.49)	-0.63 (-0.74,-0.49)	-0.67 (-0.77,-0.55)	-0.69 (-0.78,-0.57)	-0.67 (-0.77,-0.55)	-0.79 (-0.86,-0.71)	-0.78 (-0.85,-0.69)	-0.63 (-0.73,-0.49)	0.54 (0.39,0.67)	0.68 (0.56,0.77)	0.78 (0.69,0.85)	0.79 (0.71,0.86)	Sx

A receiver operating characteristic (ROC) curve of separation of experimental and control groups (Fig. 11) with vergence facility, number of extra eye movements made when reading, symptom score, and stereopsis confirmed that vergence facility has the highest area under the curve of all parameters examined (top three shown compared to stereopsis). As can be seen, the highest area under the ROC curve (0.97) was attained by vergence facility. Figures 12 and 13 show the IEP and control groups plotted separately, confirming that subjects from each group are indeed separated quite well by the use of vergence facility testing and a symptom scoring task. The ROC curve agrees well with the regression analysis, in that it confirms that the two best predictors of group are symptoms and vergence facility.

Discussion

Although reading difficulties can often be quite multifactorial, it seems intuitive that vision probably plays a major role in *reading-based* learning issues. The main aim of this study was to examine a moderate-sized group of both IEP and control subjects to determine whether any significant difference in eye movement and reading speed existed between the groups, as measured using the Visagraph III system. It is evident that not only are there significant differences in both the number of excessive eye movements and the reading speed between the two groups, but that there are also significant differences in oculomotor skills between the two groups, with vergence facility dysfunction in

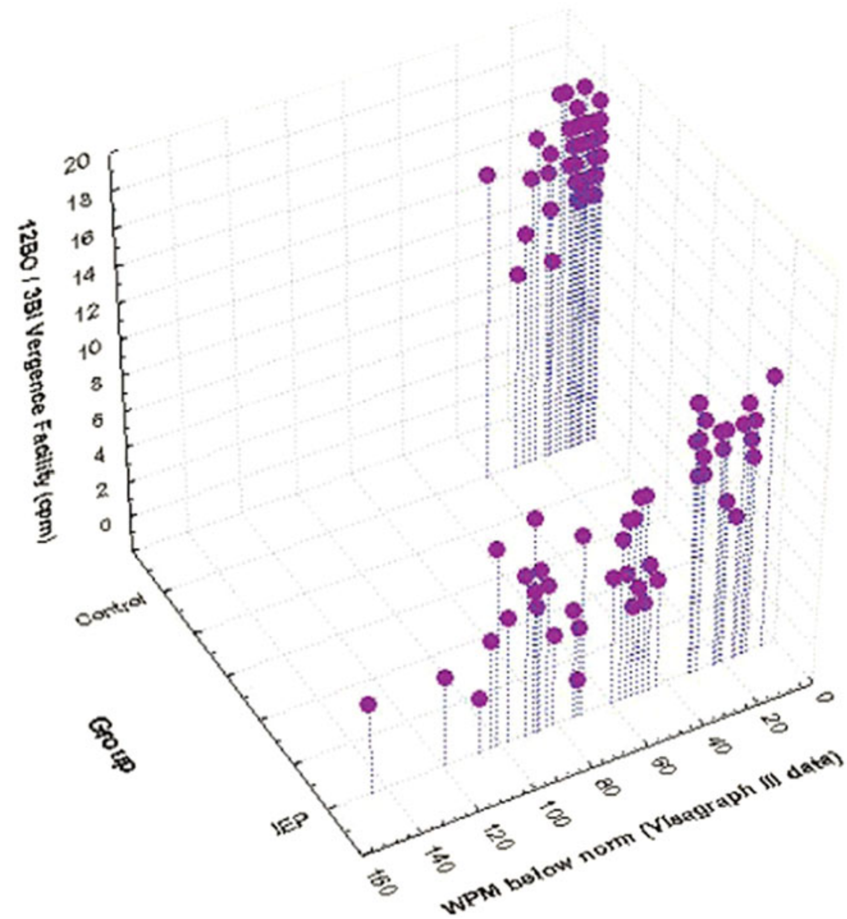


Fig. 4 Relationship between vergence facility and reading speed (words per minute below grade level expected values as determined by the normative database of the Visagraph III system). The difference in vergence facility between groups was highly significant ($p<0.001$), as was the difference in reading speed between the two groups ($p<0.001$)

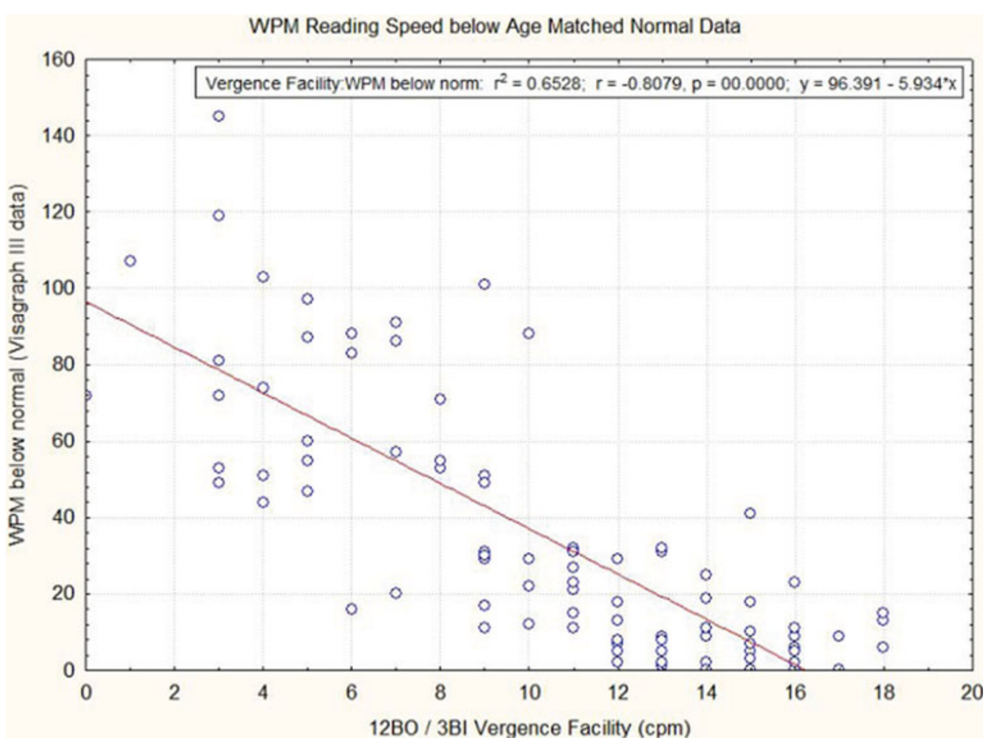


Fig. 5 Using all data ($n=100$) from both the IEP and control groups, a significant correlation is apparent between vergence facility and reading speed ($r^2=0.65$, $p<0.001$)

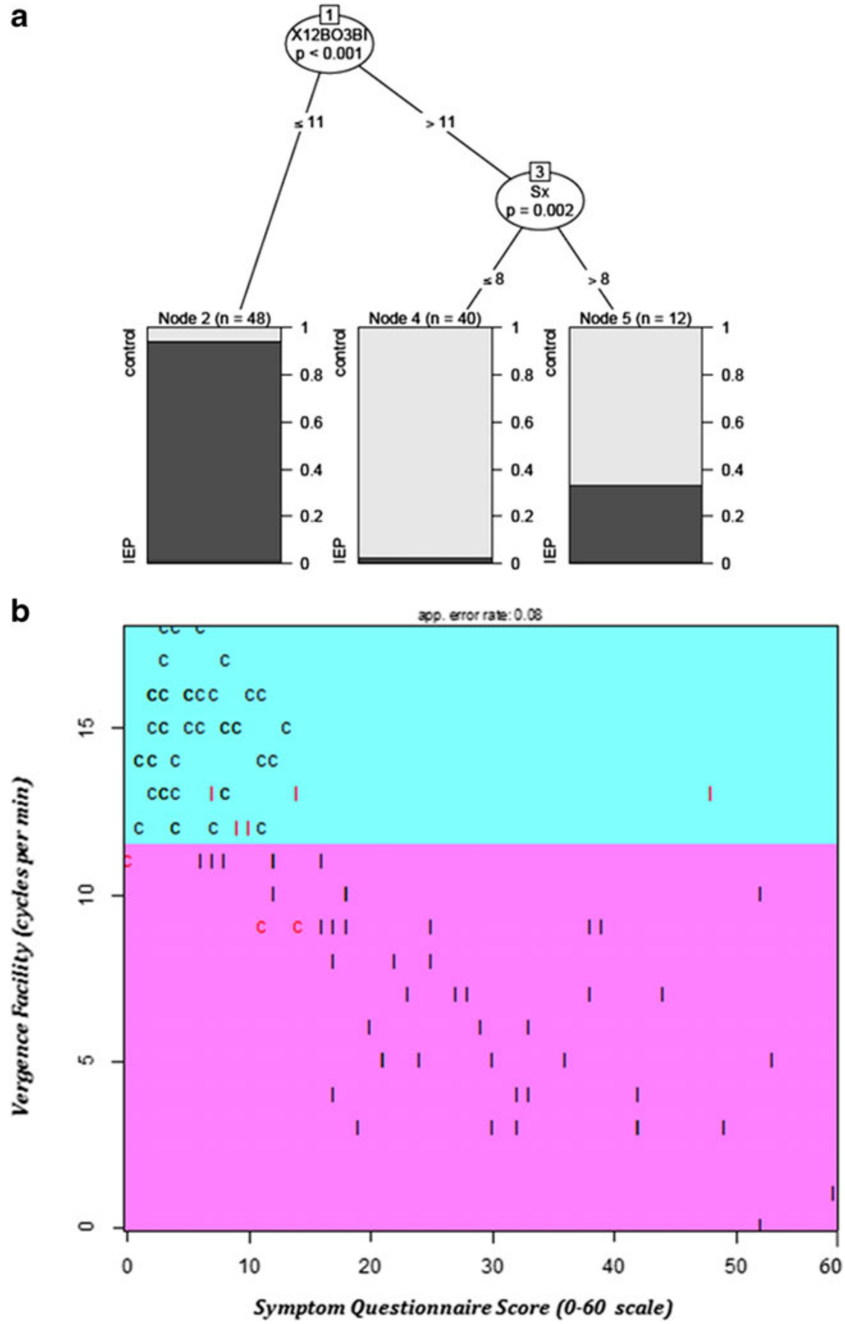


Fig. 6 **a** Regression tree analysis showing which outcome measures best predict the group with the least amount of mis-classifications. The analysis shows that using a cut-off value of 11 cpm or better only results in two cases being mis-classified out of 48 applicable cases (*left silo*). If the vergence facility is better equal to or better than 11 cpm with a symptom score of 8 or less, only one case is mis-classified out of 40 applicable cases. Only in 12 out of 100 cases was vergence facility 11 cpm or better with a symptom score of more than 8 (in which case, three patients are mis-classified). The vergence facility value of 11 cpm and the symptom score of 8 was determined by the regression analysis as being the optimal combination that produced the least amount of mis-classifications. **b** Linear discrimination of experimental and control groups (*blue and pink rectangles*) and the association between symptoms and vergence facility showing the rate of false classifications using a cut off 11 cycles per minute or higher (i.e., optimal cut-off as attained from analysis in **a**) for a normal result for vergence facility (*red letters* indicate mis-classifications, *C* = Control subject, *I* = IEP subject). It can be seen from the analysis that only eight out of 100 subjects would be mis-classified using a vergence facility cut-off of 11 cpm (which reduces to only six mis-classifications when combined with symptoms)

particular being noteworthy. Although excessive eye movements may be caused by other issues (i.e., decoding strategies), the differences in eye movement data between the groups are suggested to be primarily oculomotor-based, as the IEP subjects in this study did not have any have significant phonological issues identified on their psychological education assessments. In essence, no definitive reason for the reading disability was reported in the IEP cases used in this study. Although oculomotor/binocular vision dysfunction issues are probably not the only factors at play, they do appear to be playing a significant role, as evidenced by the association between reduced reading speed and several oculomotor outcome measurements.

It has been demonstrated elsewhere, using a large sample size of 782 first to fifth graders, that hyperopic refractive error of +1.25D or above is associated with lower academic achievement levels [8]. Interestingly, the median refractive error in the IEP group in this study was found to be close to this value (+1.37D), with the control group having a median refractive error closer to emmetropia (Table 1). The observation that more than 85% of the IEP group and control group saw 20/25 or better unaided despite significant

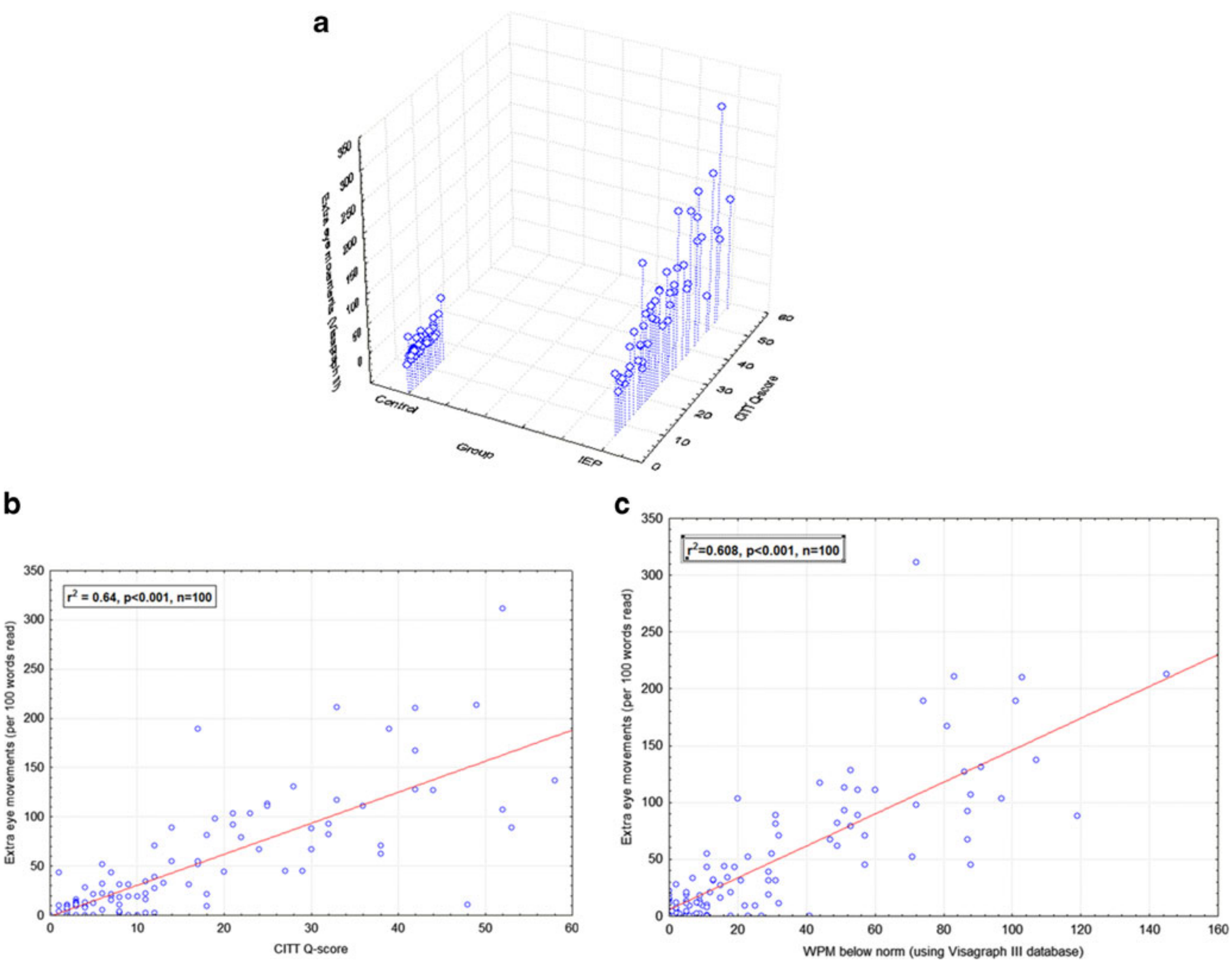


Fig. 7 **a** Graph showing the clustering of data points between the IEP and control group when specifically looking at the standardized symptom questionnaire and the number of extra eye movements made (per 100 words read) compared to grade normative data within the Visagraph III database. **b** Using all data from both IEP and control subjects from the above graph, this graph shows the relationship between the standardized symptom score and the number of extra eye movements made when reading (100 words). As can be seen, there is a significant correlation between the symptom score and excessive eye movements (i.e., moving from a normal reading pattern to a scanning pattern). **c** The relationship between WPM below grade level and the number of eye movements made per 100 words read. Although the scatter of the data increases as the reading performance worsens, there is nonetheless a significant correlation between the outcome variables (co-efficient of determination is 0.643, $p<0.001$)

amounts of hyperopia (in the IEP group in particular) agrees well with previous studies showing that visual acuity alone is a poor predictor of refractive error [25]. The findings in this study not only confirm that visual acuity is a poor predictor of refractive error, but that visual acuity is also a poor predictor of reading speed, and poorly discriminates between IEP and control subjects in this study. Given the correlation between reading speed and cycloplegic refractive error, it appears sensible that clinicians consider a cycloplegic examination in reading-impaired children even in the presence of good acuity. This approach appears justified, given that over 40% (20 out of 50) of the IEP group were under-plussed/over-minused by +1.25D or more in the habitual state, whereas only 4% (2 out of 50) of the control group were under-plussed/over-minused by this amount in their habitual state (whether corrected or uncorrected). Given the proximity of the results in this study to prior research showing poorer academic performance at +1.25D of hyperopia or greater [8], it also appears reasonable to consider prescribing for uncorrected hyperopia of +1.25D or greater when dealing specifically with reading-impaired children. The decision to ultimately prescribe, however, should as always take vergence and accommodation amplitudes and facility into account, in addition to presenting symptoms using a standardized questionnaire.

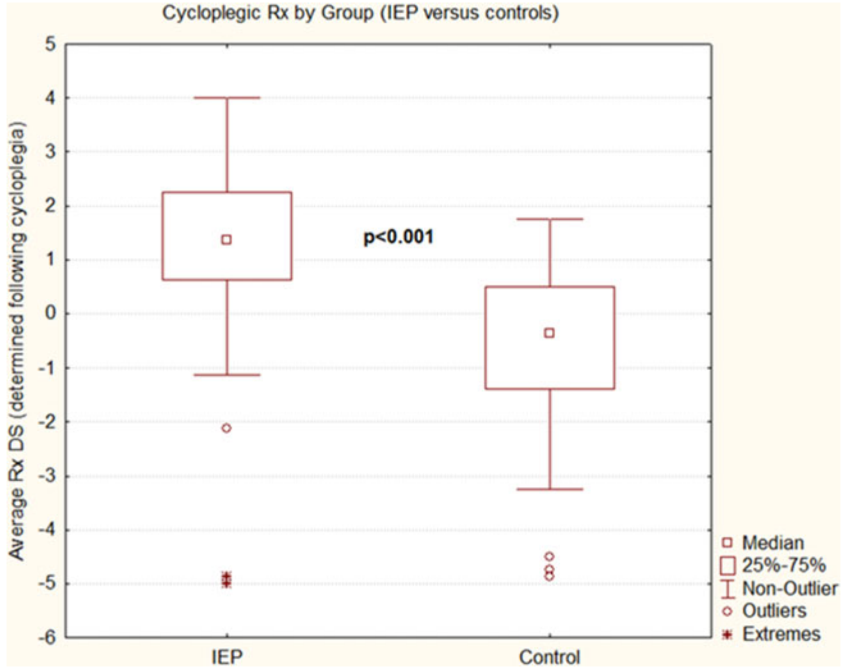


Fig. 8 Cycloplegic refractive error in the IEP group versus the control group following cycloplegic refraction (cyclopentolate 1% for 30 min duration prior to refraction). It can be seen that the IEP group has significantly more hyperopic refractive error than the control group, even taking into account outliers

Although there is evidence that fluency in reading and reading comprehension uses skills other than visual/oculomotor skills, the notion that oculomotor skills are inherently vital to proper reading ability is not new [8–10]. The importance of an efficiently functioning visual system over and above visual acuity appears under-emphasized. For example, 21 out of the 50 IEP group had never had a comprehensive eye examination, with most reporting only visual acuity based vision screenings. In the geographical areas from which the IEP subjects were recruited, before IEP status is approved, a full psychological–educational assessment is usually required. Given that a fair proportion of these psychological assessments are visually based (i.e., test of visual perceptual skills or visual motor integration testing), the results of these tests appear to be based on a working assumption of a normal oculomotor system. Based on the results of this study, it appears as though the assumption of visual normality from good acuity alone is unwise. It appears sensible that the oculomotor system of any child suspected of a reading-based learning disability should be tested and corrected prior to any such vision-based psychological testing, to remove confounding oculomotor factors. The results from this study strongly suggest that visual acuity testing should be avoided as a sole measure of visual normality.

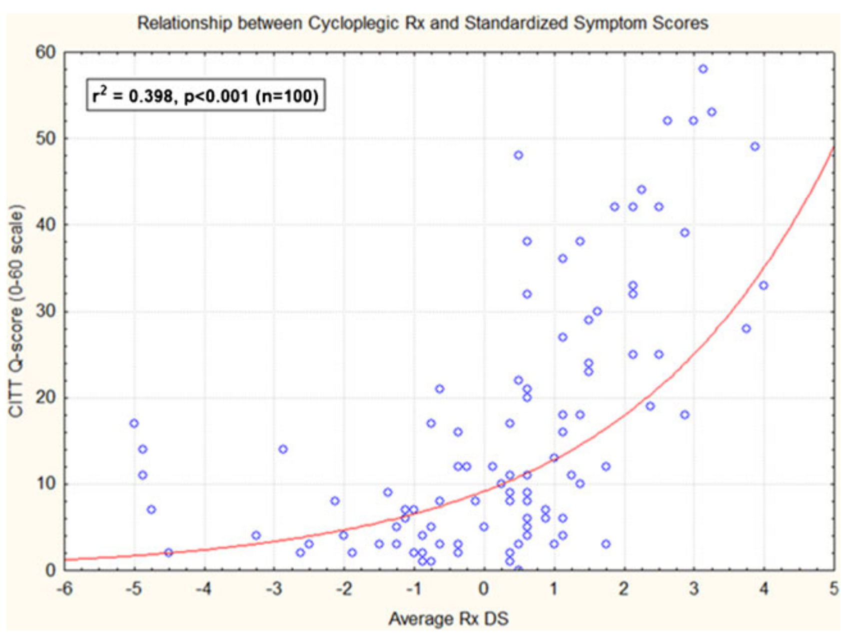


Fig. 9 Relationship between the cycloplegic Rx and the standardized symptom scoring system used in this study. As can be seen, the symptoms rise as one moves from the myopic spectrum to the hyperopic spectrum. All subjects (n=100) are shown

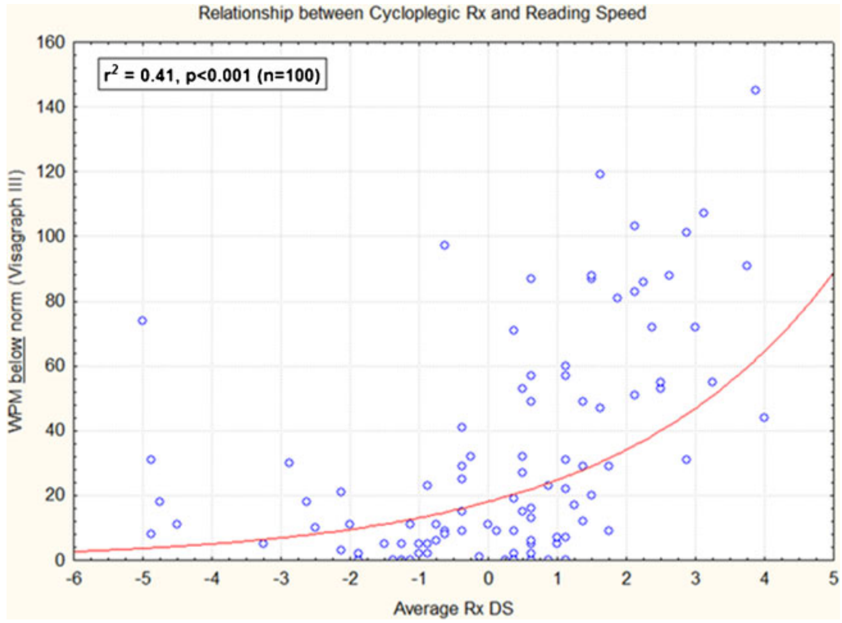


Fig. 10 Relationship between the cycloplegic Rx and reading speed. All subjects (n=100) are shown in this plot. As can be seen, reading speed is significantly correlated (p< 0.001) with the cycloplegic Rx, with the co-efficient of determination (r^2) in this analysis being 0.41

Given the often difficult and multi-disciplinary task of correctly determining the primary underlying issues in reading-based IEP cases, it appears logical in these cases that the basic ability to fuse one's eyes comfortably and efficiently should be evaluated, in addition to undertaking an objective evaluation of reading speed and eye movement patterns. The optimum approach appears to be a collaborative care model, whereby such ocular evaluations would take place in conjunction with other testing such as psychological educational assessments and auditory evaluations. This research is important, in that it confirms an association between cycloplegic refractive error, oculomotor integrity, symptoms, and an objective measure of reading performance. While association certainly does not necessarily imply causation, the numerous oculomotor and refractive results presented in this study that correlate significantly to reading speed and eye movement data certainly prompt assessment of the visual system beyond visual acuity in reading-based learning disabilities.

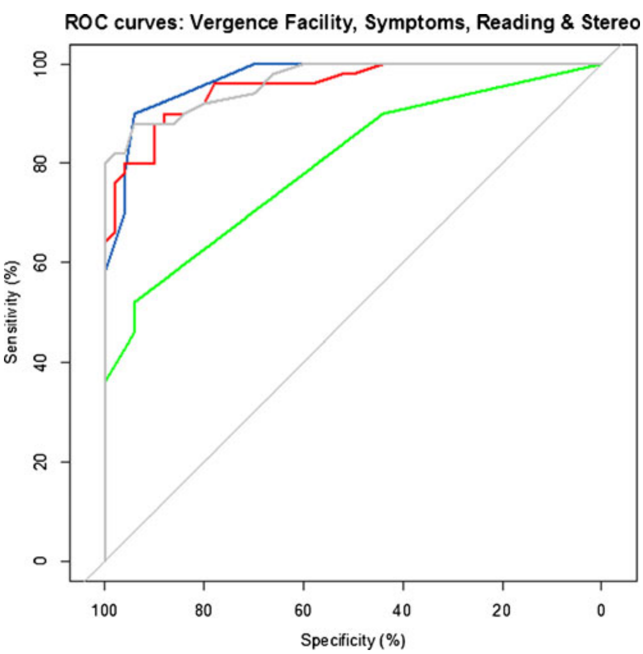


Fig. 11 Receiver operating characteristic curve showing the ability of the top differentiators of experimental and control group. In figure, *blue* (0.97)=vergence facility, *grey* (0.96)=symptom score, *red* (0.95)=extra eye movements, *green* (0.80)=stereopsis. It should be noted that presenting visual acuity (not shown) was very poor at differentiating group, with over 87% of both groups seeing 20/25 or better unaided. All subjects were correctable to 20/20 in each eye (i.e., no amblyopia was found); thus, both unaided and aided acuity are very poor predictors of group

In addition to cycloplegic examination, detection of binocular vision dysfunction in terms of vergence issues is especially important in light of evidence that these issues can be effectively treated, as shown in the Convergence Insufficiency Treatment Trial [22]. When one also looks at research confirming an overlap in symptoms between attentional disorders and binocular vision dysfunction [12], the importance of detecting and treating binocular vision dysfunction again becomes apparent. It should be noted that five out of the nine DSM-IV criteria for ADHD overlap with the symptoms of convergence insufficiency [12, 15], one of the most common binocular vision disorders and the main topic of the CITT study [22]. We chose to use the CITT symptom questionnaire (Convergence Insufficiency Symptom Survey or CISS), as it has been validated and confirmed as an acceptable outcome measure in research pertaining to children and convergence dysfunction. It has also been used as a relative measure of symptomatology in clinical research pertaining to both vergence and accommodative dysfunction [23]. It should be noted that although not specifically

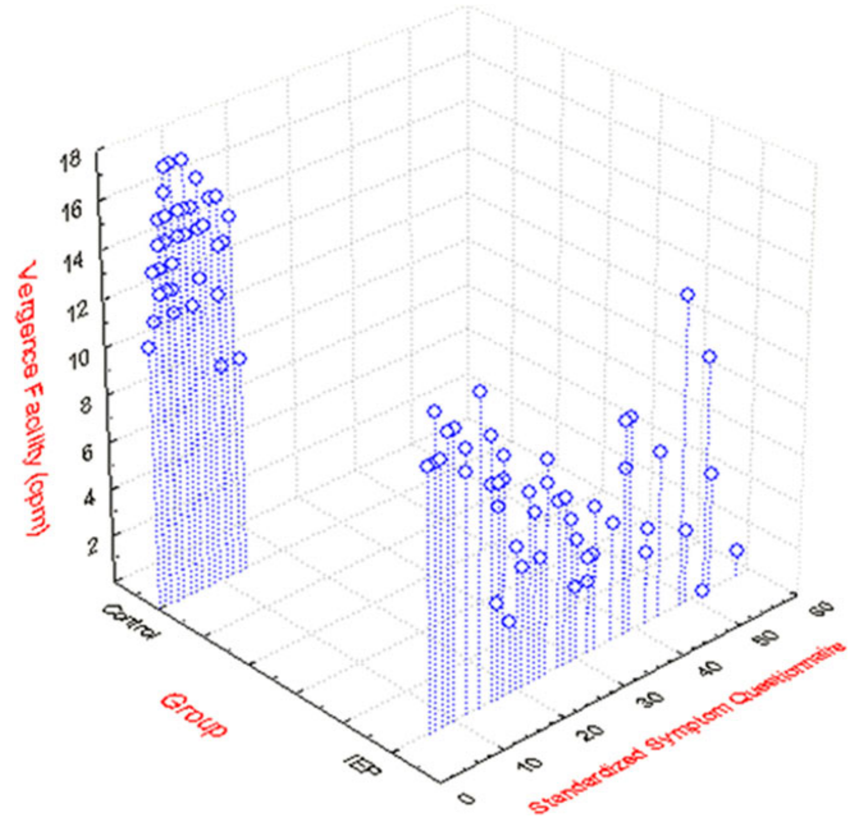


Fig. 12 3-axis plot showing the difference in clustering between the IEP and control group when looking specifically at the variables "Vergence Facility" and "Symptoms". It can be seen from the graph that there is a good separation between the IEP group and the control group both on the X-axis (symptoms) and the Y-axis (vergence facility)

labelled in this study, 18 out of the 50 IEP group patients in this study met the definition of CI as outlined in the CITT study. The association between reading impairment and convergence issues in children with no apparent

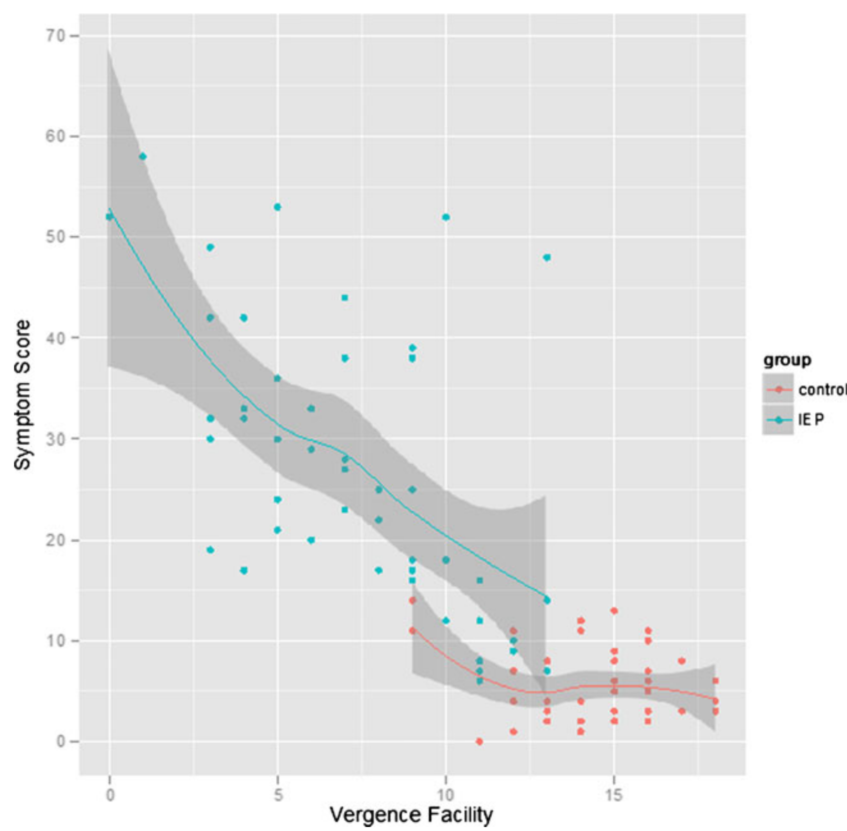


Fig. 13 Symptom score plotted against vergence facility, with 95% confidence interval data for both the IEP group and the control group. It can be seen that the IEP group has a much higher symptom score in addition to much lower vergence facility

psychological or intellectual issues has also been shown elsewhere [24, 25]. Given the relatively high prevalence of CI cases in the IEP group, we felt this symptomatology scoring methodology was valid. The influence of the uncorrected hyperopia on the symptom score is probably loosely additive, as both accommodative and vergence dysfunction have been associated with increased symptom scores [26], with some studies indicating that accommodative components probably play a role at least equal to if not greater than vergence dysfunction [23].

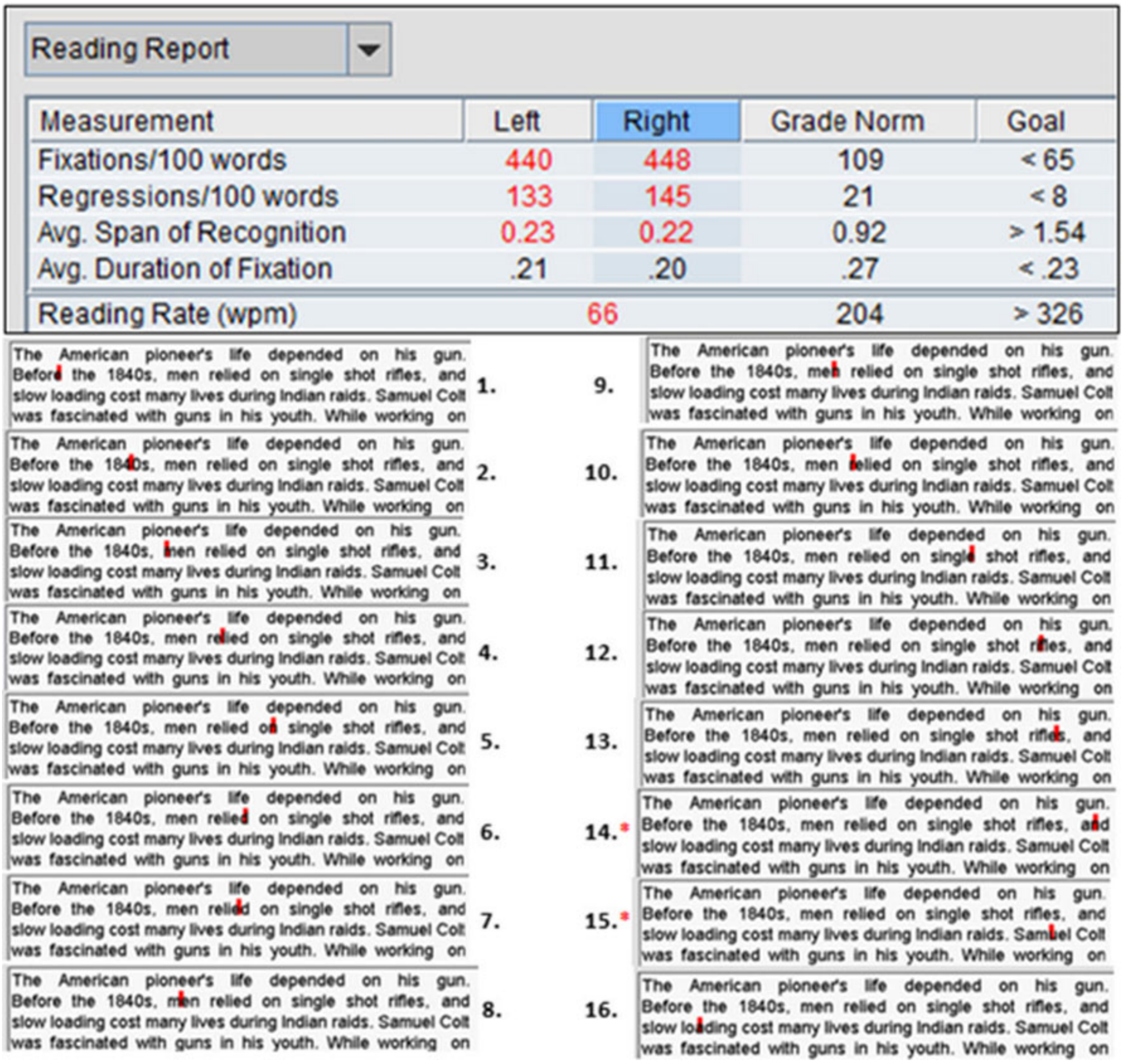
Vergence facility testing involves using a handheld prism flipper (Fig. 3b) used in front of one eye (with both eyes open). Binocular flippers are also available, but of course the overall vergence demand is identical, being 12 prism dioptres base out and 3 prism dioptres base in. The task is to fuse a near fixation target as many times as possible in a 1-min period, with the examiner changing from the 12BO component to the 3BI component rapidly when the subject reports fusion. This deceivingly simple task can be quite challenging, as one must have a very well developed oculomotor system in order to adjust to the rapidly changing demand. This is essentially a "stress test" for the oculomotor system. It is not difficult to hypothesise why this task may be strongly associated with reading speed, as found in this study. When we read, we are essentially making version movements whilst in a converged position, with the added task of maintaining accurate vergence and accommodative demand for the task distance whilst the eyes are in motion. To make matters more challenging, we also have to make a version/vergence movement whilst in a converged position, in order to move to the next line of text accurately.

To illustrate the point of how easily tracking can become affected in low-vergence-facility patients, an interesting phenomenon was noted on the Visagraph III recordings (control group, see Electronic Supplementary Material 1; IEP group, see Electronic Supplementary Material 2). When the vergence facility was extremely low (usually about 4 cpm or less), it was noted that when the child finished reading a line of text, they would move their eyes downward *directly to the end of the next line* and then proceed to "back track" to the start of the next line to be read (Fig. 14). Usually the parents reported the use of "tracking aids" in such cases, such as a ruler or the child using their finger to track. These subjects also tended to be the patients with uncorrected hyperopia of +1.50D or more. One possible explanation for the trend of going diplopic on the base in component is that the subject will habitually be over-accommodating due to the uncorrected hyperopia at near. This habitual over-accommodation, therefore, could quite conceivably result in the inability (or at least difficulty) to diverge rapidly *from* a converged position. Given the high demand on the vergence system when reading, we propose that it is expected that there would be an expected increase in tracking issues with both increasing hyperopia and decreased vergence facility, a trend that was indeed noted in this study.

The significantly increased number of physical eye movements in the IEP group lends credence to this notion. Our results suggest that the more eye movements are required when reading, the more symptomatic the patient becomes (Fig. 7b). This in turn should mean that an *increase* in excessive eye movements will perhaps lead to a somewhat counter-intuitive *decrease* in reading speed, as presumably the subject moves from a normal tracking pattern to an erratic "scanning" pattern. This trend was indeed observed in the IEP group (Fig. 7c).

Clinical application in terms of diagnosing oculomotor dysfunction using 12 base out/3 base in vergence facility [19] and correlating clinical symptoms to vergence facility [25] have been published elsewhere. However, to our knowledge this is the first paper to specifically examine the relationship between vergence facility and an objective outcome measure of reading speed. The findings presented in this paper agree well with published vergence facility research, in that we confirm that a normative value of approximately 15 cpm is sensible in both clinical terms and in terms of predicting grade appropriate reading speed. This conclusion is based on Fig. 5 showing that normal reading speed (i.e., the zero mark on the *Y*-axis, representing "at grade level") occurs when vergence facility approaches 15 cpm, which is reasonably close to the slightly lower value of 11 cpm suggested by our regression analysis to result in the least mis-classifications (Fig. 6a and b). The normative value for vergence facility is thus likely within this 11–15 cpm range.

Although hyperopia is implicated as an important issue to address in IEP subjects, the complex effect of refractive error on oculomotor mechanisms should be discussed. We will omit astigmatism from this discussion, as there was no difference between the control and IEP group in this regard, and astigmatism has not been implicated in reading ability [27, 28]. If we consider the standard definition of emmetropia (between +1.00D and −1.00D) and consider only the spherical refractive error range attained in this study, the mean refractive error of the control group was "emmetropic" (with 54% of refractive errors between +1.00D and −1.00D) and the IEP group was "hyperopic" (with 28% of refractive errors between −1.00D and +1.00D). It should be noted that the refractive error range in the control group in this study agrees well with larger-scale published normative data in this age range [24, 25], which is reassuring from a selection bias standpoint. When one also considers that 87% of the control group and 93% of the IEP group saw 20/25 or better on presentation and that less than 15% of both groups were corrected, the effect of uncorrected myopia in the control group is probably not significant. There were, however, two patients in the IEP group who



Reading Report

Measurement	Left	Right	Grade Norm	Goal
Fixations/100 words	440	448	109	< 65
Regressions/100 words	133	145	21	< 8
Avg. Span of Recognition	0.23	0.22	0.92	> 1.54
Avg. Duration of Fixation	.21	.20	.27	< .23
Reading Rate (wpm)	66		204	> 326

Fig. 14 Tracking pattern and Visagraph data in the presence of impaired vergence facility (16 sequential snapshots from the Visagraph recording of one such subject in the IEP group). This particular subject had a cycloplegic refractive error of +1.75DS OD and +2.25DS OS, with significantly impaired vergence facility (three cycles per minute to diplopia on the base in component, i.e., inability to diverge from a converged position). Looking at snapshot 14 and 15 above (*red asterisk*) it can be seen that the subject "dropped down to the end of the next line" rather than moving their fixation to the proper location to start reading the next line. This trend was particularly noticed in cases of impaired vergence facility, and possibly represents a compensatory adaptation

had moderate to high myopia (see outliers, Fig. 8) who also had impaired reading speed on the Visagraph (see Fig. 11). Interestingly, these myopic patients also had impaired vergence facility (4 cpm), but were also over-corrected by approximately 1.00D–1.25D in the spectacle Rx compared to the cycloplegic result. This may, of course, be logical, as over-correction of myopia probably creates a similar scenario to uncorrected hyperopia. However, it is interesting to note that the vergence facility prism side failed in these cases was base out, whereas in the uncorrected hyperopes it was typically the base in component that was failed. It is thus important to acknowledge that there may well be effects of low uncorrected myopia on the oculomotor system that have been under-estimated in this study due to the relatively small sample size. We hope to address these issues further in a subsequent publication examining the effects of correction alone, and subsequently with therapy in applicable cases.

Research in the area specific to reading ability and binocular vision and refractive data is sparse. The results from this study confirm a link between hyperopia and poorer reading skills in line with several other papers [7–11]. There have been reports, however, failing to show such an association. Looking at research published previously using non-dyslexic learning impaired subjects and controls in a Spanish sample [29], no difference in refractive error was found between the reading-impaired group and controls, but notably cycloplegia was not used nor was vergence facility examined. It is important to note that children can mask hyperopia quite well given their sizable amplitudes of accommodation, as evidenced in papers confirming poor correlation between unaided visual acuity and refractive error [30]. In addition, no objective or quantitative data in terms of reading ability was presented in this research.

In this study, we opted to evaluate all data *as the patient presented*, and to use an objective measurement of both reading speed and number of eye movements made when reading. The rationale behind this approach was that it would give a more accurate reflection of the habitual classroom performance of each student, and to see any correlations, one must assess all baseline data *in the habitual state* before applying any form of therapy or refractive correction. Therefore, the methodology in this study was essentially cross-sectional in nature. To answer the obvious question as to how much improvement in reading speed is attained longitudinally with (i) refractive correction alone, and (ii) subsequently with vision therapy (in appropriate cases), we will be following all subjects who were treated with either spectacle therapy, vision therapy, or both in a subsequent publication.

In summary, this research confirms an association between uncorrected refractive error (particularly hyperopia), impaired vergence facility and reduced reading speed, as determined objectively with an infra-red eye tracking system. This research suggests that students with reading-based learning difficulties that fail either the questionnaire or vergence facility testing should have an objective measure of reading speed, a cycloplegic refraction, and specific examination of vergence and accommodative amplitude and facility performed. Given that there is ample evidence (including a large-scale randomized controlled trial) as to the effectiveness of rehabilitation strategies for binocular vision dysfunction [22, 31] in addition to numerous studies confirming an association between reading-based outcome scores and oculomotor-based outcome scores [7–11, 32, 33], this approach appears justified.

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