Published in final edited form as:

Optom Vis Sci. 2016 February ; 93(2): 118–125. doi:10.1097/OPX.0000000000000779.

Reading Fluency in School-Age Children with Bilateral Astigmatism

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Abstract

Purpose—To compare oral reading fluency (ORF) in students with no/low astigmatism and moderate/high astigmatism and to assess the impact of spectacle correction on ORF in moderate and high astigmats.

Methods—Subjects were 3rd–8th grade students from a highly astigmatic population. Refractive error was determined through subjectively refined cycloplegic autorefraction. Data from students with ocular abnormalities, anisometropia, symptomatic binocular vision disorders, or refractive error that did not meet study criteria (no/low (cyl < 1.00 both eyes, no significant myopia/hyperopia), moderate (cyl 1.00 D both eyes, mean 1.00 D and < 3.00 D), or high astigmatism group (cyl 1.00 D both eyes, mean 3.00 D)) were excluded. ORF was tested with a modified version of the DIBELS Next test of ORF. No/low astigmats were tested without spectacles; astigmats were tested with and without spectacles. Mean ORF was compared in no/low astigmats and astigmats (with and without correction). Improvement in ORF with spectacles was compared for moderate and high astigmats.

Results—The sample included 130 no/low, 67 moderate, and 76 high astigmats. ORF was lower in uncorrected astigmats than in no/low astigmats ($p=0.011$). ORF did not significantly differ in no/low astigmats and corrected astigmats ($p=0.10$). ORF significantly improved with spectacle correction in high astigmats ($p=0.001$, mean improvement 6.55 words per minute (WPM)), but not in moderate astigmats ($p=0.193$, mean improvement 1.87 WPM). Effects of spectacle wear were observed in students who read smaller text stimuli (older grades).

Conclusions—ORF is significantly reduced in students with bilateral astigmatism (> 1.00D) when uncorrected, but not when best-corrected, compared to their non-astigmatic peers. Improvement in ORF with spectacle correction is seen in high astigmats, but not in moderate astigmats. These data support the recommendation for full-time spectacle wear in astigmatic students, particularly those with high astigmatism.

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These data were presented in part at the Annual Meeting of the Association for Research in Vision and Ophthalmology, May 5–9, 2013, Seattle WA.

Conflicts of interest/commercial relationships: none.

Keywords

reading; astigmatism; children; spectacles; refractive error

Astigmatism has been associated with reduced performance on low level visual tasks, such as grating acuity and contrast sensitivity for grating stimuli, as well as visual tasks that require higher level functioning, such as vernier acuity, stereo acuity, and recognition (letter) acuity.¹

There are several reasons to hypothesize that astigmatism may also be associated with reduced performance on more complex visual and cognitive tasks, such as reading fluency. Uncorrected astigmatism causes blur, and while most uncorrected astigmats can bring all aspects of a visual stimulus into focus through accommodation or changes in viewing distance, they cannot bring all aspects of a stimulus fully into focus at once. Previous studies have reported that simulated astigmatic blur can reduce reading speed.^{2–4} Recent evidence also suggests that uncorrected astigmatic children have reduced accuracy of accommodation (relative to the circle of least confusion) and increased variability of accommodation.⁵ Even with spectacle correction, reading fluently may be a challenge for some astigmatic children due to the presence of amblyopia¹ or to optical distortion caused by their spectacle correction,⁶ although with consistent spectacle wear children will adapt to the optical distortion. Most previous studies of the relation between amblyopia and reading have reported significantly reduced reading performance in amblyopes, but these studies focused on unilateral (anisometropic and/or strabismic) amblyopia.^{7–12}

The aims of the present study are to (1) compare reading fluency in children with bilateral astigmatism to reading fluency in children with no or low astigmatism from the same cohort and (2) to assess the impact of spectacle correction on reading fluency in children with moderate and high bilateral astigmatism.

METHODS

Subjects

Subjects were 3rd through 8th grade students from schools on the Tohono O'odham reservation who were participants in a study of astigmatism and amblyopia. All students in grades 3–8 were eligible to participate. The Tohono O'odham have a high prevalence of with-the-rule (WTR) astigmatism.^{13–15} This research complied with the Declaration of Helsinki and was approved by the Tohono O'odham Nation and by the Institutional Review Board of the University of Arizona. Parents provided written informed consent and children provided written assent prior to testing.

Procedures

Eye Examination—Uncorrected monocular and binocular visual acuity was measured at a distance of 3 meters using an ETDRS LogMAR letter chart (Precision Vision, LaSalle, IL). Visual acuity was scored as the smallest LogMAR line on which the student was able to correctly identify at least 3/5 letters. Students then completed a cycloplegic eye examination

in order to determine a best estimate of refractive error and to determine if spectacles were required. Cycloplegic autorefraction was performed with the Retinomax KPlus2 (Nikon, Inc. Melville NY) at least 30 minutes after one drop of 0.5% proparacaine followed by a drop of 1% tropicamide and one drop of 1% cyclopentolate was administered. A best estimate of refractive error was determined through subjectively refined autorefraction. Students who met any of the following criteria were prescribed spectacles for full-time wear: astigmatism

1.00 D in either eye, myopia: 0.75 D on any meridian in either eye, hyperopia: 2.50 D on any meridian in either eye, anisometropia 1.50 D spherical equivalent (SE). For astigmatism and myopia, the full correction was prescribed. For hyperopia, the sphere correction was reduced by 1/3 or by 1.00 D, whichever is greater.

Assessment of Best-Corrected Acuity and Spectacle Dispensing—Two pair of spectacles were ordered for students who met prescribing criteria. One pair was dispensed and the second pair were kept for later testing (to be used if the student lost his/her spectacles).

Best-corrected monocular and binocular visual acuity was measured at a distance of 3 meters using an ETDRS LogMAR letter chart (Precision Vision, LaSalle, IL). Students prescribed spectacles were tested with their spectacles. Students who were not prescribed spectacles were tested with their best-spectacle correction from a set of stock spectacles that contained correction of their right and left eye refractive error within 0.50 vector difference in diopters (VDD),¹⁶ as this was the protocol for a longitudinal study of astigmatism and amblyopia in this sample. Visual acuity was scored as the smallest LogMAR line on which the student was able to correctly identify at least 3/5 letters.

If a student who was prescribed spectacles had best-corrected monocular acuity worse than 20/32 in either eye or if there was a 2 or more line difference in acuity between eyes, spectacles were dispensed and acuity was rechecked at a later date after a period of adjustment. If poor acuity persisted on the second test, the prescription was rechecked by a study optometrist who conducted non-cycloplegic subjective refinement. If a change was required, new spectacles were ordered and dispensed, and acuity was checked with the new prescription as described above. This prescription recheck protocol was conducted to verify accuracy of prescriptions. Students were not excluded on the basis of best-corrected acuity.

Reading Assessment and Binocular Vision Testing—Reading assessment and binocular vision testing was conducted at least 2 weeks after spectacle dispensing for students who were prescribed spectacles, and was conducted on a date after the eye exam for students who were not prescribed spectacles. This allowed students who were prescribed spectacles time to adapt to their new spectacles. The students did not know in advance which day reading would be tested. When students arrived for testing, experimenters recorded whether or not they arrived wearing their spectacles. Students who did not arrive with their spectacles were tested with their spare spectacles.

Binocular vision testing was conducted with best correction for students prescribed spectacles and without correction for students who were not prescribed spectacles. Testing was conducted per Convergence Insufficiency Treatment Trial (CITT)¹⁷ protocol and

included: cover testing at distance and near, measurements of near point of convergence, positive and negative fusional vergence at near (fusional convergence and divergence amplitudes), accommodative amplitude (Donder's pushup method), and symptoms (Convergence Insufficiency Symptom Survey (CISS)). Students with an exodeviation at near at least 4° greater than at far, a receded NPC break (6 cm or greater), and insufficient positive fusional vergence at near (PFV) (convergence amplitudes) (i.e., failing Sheard's criterion (PFV less than twice the near phoria) or minimum PFV of < 15° base-out blur or break), and a CISS score of ≥ 16 were classified as having symptomatic convergence insufficiency. Students with accommodative amplitude at least 2D below Hofstetter's formula for minimum amplitude for the child's age ($15 - 0.25(\text{age})$) and an elevated CISS score (≥ 16) were classified as having symptomatic accommodative insufficiency.¹⁸ Students with esophoria at near at least 3° greater than at far and failed Sheard's criterion or have a NFV 7° or less base-in blur or break at near (40 cm) in addition to an elevated CISS score (≥ 16) were classified as having convergence excess. Study optometrists were trained on the CITT testing procedures by a CITT investigator.

A modified version of the DIBELS Next test of Oral Reading Fluency (ORF) was administered.¹⁹ This test was chosen because it is widely used and validated, and because it has many stimuli (reading passages) for each grade level, which allowed for repeated measurements on each student without content repetition. The font and type size used in the DIBELS reading passages varies with grade level. Materials for grades 1 and 2 use Report School, a sans-serif font, in 16.5 point.²⁰ Times New Roman, a serif font, was used for grade 3 (size 16 point) and grades 4–6 (size 12 point) passages.²⁰ Report School was used for the lower grade level passages because those letter forms would likely be more familiar to younger students.²⁰ Times New Roman was used in older grade level passages because it is similar to the fonts used in most books and other reading material.²⁰ At a distance of 25cm, 12 point font is equivalent to 20/120 and 16 point font is equivalent to 20/160.²¹ At a distance of 40cm, 12 point font is equivalent to 20/80 and 16 point font is equivalent to 20/100.²¹ These values are consistent with results of a survey of reading materials from kindergarten to grade 5 classrooms indicating that the minimum near visual acuity demand at 40cm was 20/100 (5th grade).²² Reading distance was not controlled, however, so these Snellen equivalent values are provided as a general reference with regard to stimulus sizes used and required acuity.

Study staff completed DIBELS online training (Dynamic Measurement Group, Eugene OR) and were certified in DIBELS testing prior to the start of study data collection. Testing proceeded according to the DIBELS Next Assessment Manual,¹⁹ with the exceptions listed below (see *Variations from DIBELS procedures*). Briefly, the procedure is as follows: The tester placed a reading passage in front of the student and instructed the child to “*Please read this out loud. If you get stuck, I will tell you the word so you can keep reading. Start here* (point to the first word of the passage). *Begin.*” The tester started a stopwatch when the student said the first word of the passage, and marked with a slash on the tester's copy of the reading text which words were read incorrectly. If the child hesitated on a word for more than 3 seconds, the tester read the word for the child, and marked the word as incorrect. At the end of 1 minute, the tester placed a bracket (]) after the last word read, and asked the

child to stop reading. The tester recorded the total number of words read *correctly* for each passage.

This procedure was performed 6 times (using 6 different reading passages) with each student. Six passages per grade were selected from DIBELS Next progress monitoring materials. To control for any differences in difficulty of passages, the passages for each grade were assembled into two groups (A passages and B passages), and the 3 passages in each group were always read in the same order. The passage group (A or B) tested first was counterbalanced across subjects. Students who were prescribed spectacles completed one group of 3 passages while uncorrected and one group of passages while best-corrected with testing order counterbalanced across subjects. Students who were not prescribed spectacles completed all 6 passages without spectacle correction. All students were tested binocularly and completed all 6 passages on the same day.

Variations from DIBELS Procedures—For the purposes of the study, we made three modifications to the DIBELS Next procedures:

1. Students read materials that were 2 grade levels below their current grade so that most students, including those who have difficulty with reading, would be comfortable and confident reading the passages. Previous research as shown that reading at a lower grade level reduces variation in reading speed across text difficulty.^{23,24}
2. Students completed the ORF portion of the DIBELS test but did not complete the Retell Fluency portion of the test (an assessment of reading comprehension) which typically follows ORF. This was eliminated two reasons. First, it is likely that improvements in reading as a result of correction will impact speed and accuracy (measured in ORF), rather than comprehension (measured in Retell Fluency). PEDIG found amblyopic and fellow eyes were similar in terms of reading comprehension, but differed in terms of rate, accuracy, and fluency.⁷ Second, students read 6 passages in a single session. Including the Retell Fluency portion of the test would have significantly increased the length of the testing session, introduced additional risk for losing the student's attention, and caused students to miss additional class time.
3. The data were scored using the DIBELS scoring method,¹⁹ but raw scores were used for data analysis, i.e., ORF scores were not analyzed relative to the DIBELS published norms. Due to the above noted changes to the standard testing protocol, use of published norms for transforming the raw scores was not appropriate. Since raw scores are not age/grade normed, students' grade was included in analyses as a covariate.

Data Analysis

Data from students with ocular abnormalities, anisometropia (> 1.50 D SE or >1.50 D cylinder), or symptomatic convergence insufficiency, accommodative insufficiency or convergence excess (as defined above) were excluded from analyses. In addition, data from

students who did not meet the criteria for inclusion in one of the groups below, based on cycloplegic refractive error measurements, were also excluded:

- No/low astigmatism: Astigmatism in both eyes < 1.00 D and do not meet any criteria for spectacle prescription.
- Moderate/high Astigmatism: Astigmatism in both eyes ≥ 1.00 D.
 - Moderate astigmats: Mean astigmatism ≥ 1.00 D and < 3.00 D.
 - High astigmats: Mean astigmatism ≥ 3.00 D.

Preliminary Analyses—Test order effects were assessed prior to primary analyses. For the no/low astigmatism group students, who were tested without correction, a repeated measures analysis of covariance (ANCOVA) comparison of median raw score for the first 3 passages compared to the 2nd three passages was conducted. For students in the astigmatic group, who were tested with and without correction, ANCOVA analyses were conducted to determine if there were significant effects of test order (best-corrected first vs. uncorrected first) on median reading scores while controlling for students' grade. In both analyses, grade was included as a covariate.

ORF in Astigmatic Students Compared to ORF in Students with Low/No Astigmatism—ANCOVA was used to compare mean ORF for students with no/low astigmatism to students with astigmatism, including students' grade as a covariate.

Effects of Spectacle Correction on ORF in Moderate and High Astigmats—Separate T-test analyses for moderate and high astigmats were used to compare mean improvement in ORF with spectacle correction to 0 to determine if improvement was statistically significant. An ANCOVA was used to compare change in ORF with spectacle correction (best-corrected – uncorrected ORF) in moderately and highly astigmatic students. Analyses controlled for student grade.

RESULTS

Study Sample

A total of 273 students met inclusion criteria: 130 with no/low astigmatism, 67 with moderate astigmatism, and 76 with high astigmatism. A sample summary by group is provided in Table 1. The three groups did not significantly differ on student grade level (X^2 , $p=0.481$), sex (X^2 , $p=0.770$), or mean age (ANOVA, $p=0.521$).

The three groups did not significantly differ on mean spherical equivalent (SE) (ANOVA, $p=0.233$ for right eye, $p=0.277$ for left eye). However, they did significantly differ on the percentage of students with a hyperopic SE (mean of RE and LE SE > 0, X^2 , $p<0.001$): a significantly greater percentage of students with no/low astigmatism had a hyperopic SE compared to the moderate ($p=0.009$) and high astigmats ($p<0.001$), but moderate and high astigmats did not significantly differ ($p=0.218$). Due to the difference across groups in the number of students with hyperopic SE, SE refractive error (hyperopic vs not hyperopic) was

included in analyses comparing students with no/low astigmats and moderate/high astigmatism.

The three groups significantly differed on mean binocular best-corrected visual acuity, mean binocular uncorrected acuity, and on the difference between best-corrected and uncorrected binocular acuity (i.e., LogMAR improvement with spectacle wear)(ANCOVAs with age as covariate, p values < 0.001 , see Table 1). Post hoc comparisons (t-tests with bonferroni correction) indicated that both best-corrected and uncorrected acuity in the no/low astigmatism group was significantly better than in the moderate and high astigmatism groups (p values < 0.001), and were significantly better in the moderate than in the high astigmatism group ($p = 0.02$ for best-corrected, $p < 0.001$ for uncorrected acuity)). The poorest best-corrected acuity measured was 0.30 LogMAR (20/40, 3 highly astigmatic students). The poorest uncorrected acuity was 0.80 LogMAR (20/125, 2 highly astigmatic students, one with myopic SE and one with hyperopic SE). Pairwise comparisons indicated significant differences across groups in the amount of acuity improvement with correction (p values < 0.001 for no/low vs. moderate and high astigmats, $p = 0.022$ for moderate vs. high astigmats), with greatest improvement seen in students with high astigmatism, and least improvement seen in students with no/low astigmatism.

Moderate and high astigmats significantly differed on spectacle compliance: significantly more high astigmats (68.4%) than moderate astigmats (49.3%) arrived at the reading assessment wearing their spectacles ($p = 0.020$). Therefore, compliance was included in analyses comparing moderate and high astigmats.

DIBELS NEXT reading materials are based on the student's grade placement rather than age, and therefore student grade was included in analyses as a covariate. One-way ANOVAs, conducted separately for each grade, yielded no significant difference in mean age across groups (all p values > 0.136).

Preliminary Analyses: Assessment of Test Order Effects—For the no/low astigmatism group students, who were tested without correction, a repeated measures ANCOVA comparison of median raw score for the first 3 passages compared to the 2nd three passages yielded no significant difference ($p = 0.146$). The effect of grade ($p = 0.145$) and the interaction between test order and grade were not significant ($p = 0.263$). Therefore in primary analyses, the median of all 6 passages was used as the representative reading score for the no/low astigmatism group.

For students in the astigmatic group, who were tested with and without correction, preliminary ANCOVA analyses were conducted to determine if there were significant effects of test order (best-corrected tested first vs. uncorrected tested first) on median reading scores (one analysis for best corrected medians, another for uncorrected medians) while controlling for grade. The effect of test order was not significant for either best-corrected measurements ($p = 0.731$) or uncorrected measurements ($p = 0.795$). Effects of grade were significant (best-corrected $p = 0.002$, uncorrected $p = 0.042$). Therefore, in primary analyses, grade was included as a covariate but test order was not.

Comparison of ORF in Students with No/Low Astigmatism vs. Students with Moderate/High Astigmatism—ANCOVA compared mean ORF in no/low astigmats vs. moderate/high astigmats, controlling for SE refractive error (hyperopic or not hyperopic) and grade. Results are illustrated in Figure 1. When uncorrected, mean ORF was poorer in astigmats than in non-astigmats ($p=0.011$). Secondary ANCOVA analyses examining the effect of astigmatism magnitude indicated that moderate ($p=0.016$) but not high astigmats ($p=0.202$) had significantly poorer mean ORF than students with no/low astigmatism (p values reflect correction for multiple comparisons). When corrected, mean ORF did not significantly differ in no/low astigmats and astigmats ($p=0.100$). The main effect of grade was significant in both analyses ($p=0.016$ for uncorrected, $p=0.001$ for corrected). Effect of SE refractive error was not significant in either analysis.

Effects of Spectacle Correction on ORF in Moderate and High Astigmats—T-test analyses comparing mean improvement in ORF with spectacle correction to 0 indicated that high astigmats showed significant improvement with spectacle correction (mean improvement 6.05 words per minute, $p=0.001$), but moderate astigmats did not (mean improvement 1.87 words per minute, $p=0.193$) (see Figure 2).

ANCOVA comparing change in ORF with correction (best-corrected – uncorrected ORF) across moderate and high astigmatic groups while controlling for grade and compliance yielded a significant main effect of grade ($p=0.008$), and a significant interaction between correction (change in ORF with correction) and grade ($p=0.010$). No other effects (including astigmatism magnitude) were statistically significant. Improvement in ORF with correction by grade is illustrated in Figure 3. Post-hoc analyses comparing mean improvement in ORF with spectacle correction across grade yielded no statistically significant effects after bonferroni correction for multiple comparisons.

DISCUSSION

The present study assessed the relation between oral reading fluency and bilateral astigmatism magnitude (no/low, moderate, or high), and the impact of spectacle correction on reading fluency in bilateral astigmatic children. The primary findings were:

1. When not wearing spectacle correction, astigmatic students had poorer ORF than students with no/low astigmatism.
2. When wearing spectacles, ORF in astigmatic students did not differ from ORF in students with no/low astigmatism.
3. ORF improvement with spectacle correction in astigmatic students was dependent upon astigmatism magnitude: High astigmats showed significant improvement in ORF with spectacle correction (mean improvement 6.05 words per minute, $p=0.001$), but moderate astigmats did not (mean improvement 1.87 words per minute, $p=0.193$).
4. ORF improvement with spectacle correction in astigmatic students was dependent upon grade, with students in higher grades showing greater improvement, and students in lower grades showing little improvement.

Few previous studies have focused specifically on the effect of astigmatism on reading, but several studies have assessed the impact of astigmatism along with other visual factors on reading. Two recent studies compared visual function in two clinical groups of school-age children: children referred due to reading difficulties and children referred for routine examination with no reported reading difficulties. In both studies, the group with reading difficulties had significantly reduced performance on several measures of binocular vision, but astigmatic refractive error did not differ between groups.^{25,26} In contrast, two studies using school-based samples found significant relations between astigmatism and academic performance and readiness in children.^{27,28} In a study of Navajo (Diné) Native American school children, who have a high prevalence of astigmatism, Garber reported that uncorrected astigmatic 5th and 6th grade students ($> 2.00\text{D}$) had poorer teacher-assigned reading scores than non-astigmatic students, but found no significant effect of astigmatism on reading scores from standardized tests in 2nd grade students.²⁷ Orlansky et al. compared measures of early academic readiness for preschool children (3 to 5 years olds enrolled in a Head Start) with no astigmatism to preschoolers with astigmatism ($> 0.50\text{D}$ in either eye) and found that the presence of astigmatism was associated with lower scores on several measures of academic readiness.²⁸ Our findings are consistent with results from studies of school based samples: ORF was significantly reduced in astigmatic students when they were not wearing their spectacle correction in comparison to students with little or no astigmatism.

Previous studies have examined the effects of simulated (lens induced) astigmatic blur on reading and other academic-related measures.²⁻⁴ Several studies compared reading performance under conditions of no astigmatism and simulated astigmatism in children or adults, a comparison roughly comparable to our within subjects comparison of ORF with vs. without spectacle correction for astigmatism. These studies found significant effects of astigmatism on reading speed,²⁻⁴ with some results indicating significant effects only with higher magnitudes of astigmatism,^{2,3} and only with smaller stimulus font sizes.³ Narayanasamy et al. assessed reading performance with no astigmatism and with 1.50D of simulated astigmatism in a sample of 20 school children (mean age 10 years) and observed a significant reduction in reading performance (rate, accuracy, and comprehension) with simulated astigmatism.⁴ Wolffsohn et al. reported that simulated astigmatism in 21 adult subjects was associated with decreased reading speed, but only at high levels of astigmatism (3.00D or more).² Wills et al. assessed the impact of 1.00 and 2.00D of astigmatism on reading performance in 30 young adults and observed reduced reading speed at small print sizes (10 and 12 point) for 2.00D of WTR and against-the-rule (ATR) astigmatism, and for 1.00D ATR astigmatism.³ For larger print sizes (16 and 20 point), reading speed was only reduced with 2.00D ATR astigmatism.

Previous results indicating that effects of simulated astigmatism are dependent upon astigmatism magnitude are consistent with our finding that spectacle correction improves ORF in students with high ($> 3.00\text{D}$), but not moderate astigmatism (1.00 to $< 3.00\text{D}$). However, the magnitude of astigmatism necessary to significantly reduce reading speed varies across studies. Our results are consistent with Wolffsohn et al. who observed decrease in reading speed only with $> 3.00\text{D}$ of simulated astigmatism (in the range of our high astigmatism),² but are not consistent with Willis et al. who reported reduced reading speed

with lower levels of simulated astigmatism (in the range of our moderate astigmats).³ In our study, the sample size in the high astigmatism group was larger than the moderate astigmatism group, suggesting lower statistical power may have influenced our finding of no significant increase in ORF with spectacles in the moderate group. We consider a change of 7 words per minute to be a meaningful change. This estimate is based on the finding that reading speed decreased 7.68 words per minute with 2.00D simulated WTR astigmatism³ and estimates that reading speeds increase about 14 words per minute each year from first grade through college²³ suggesting that 7 words per minute represents the approximate expected gain for ½ year. We use this estimate cautiously in interpreting our data, as our subjects were reading passages designed for students two grades lower than their current grade placement. Given our sample sizes and the SDs of the differences between best-corrected and uncorrected ORF measurements in the moderate (11.62) and high (15.41) astigmatism groups, we had sufficient power in both groups to detect at least a 7 word per minute improvement with spectacles (power = 1.00 and 0.97, respectively, for $\alpha = 0.05$), indicating that the absence of a significant effect in the moderate astigmats is not due to reduced statistical power. It is possible that differences across studies can be attributed to the many methodological differences in how reading was measured (e.g., stimulus font size, font type, reading task, testing environment). However, it is also possible that “natural” astigmatism may have a lesser impact on reading performance than simulated astigmatism, which is consistent with studies that indicate that natural astigmats perceptually adapt to their astigmatism.^{29,30}

Previous studies have noted that the effect of blur on reading speed is dependent upon print size.^{3,31} Chung et al. assessed the influence of stimulus font size and magnitude of lens induced blur (0, 0.5, 1.0, 2.0, and 3.0D) on reading performance.³¹ For all levels of blur, reading speed increased with print size up to a certain point (the maximum reading speed) and then remained constant. This finding is consistent with our finding of greater improvement in reading speed with correction in older grades. In our study, the effect of the student's grade is confounded with the visual demands of the DIBELS stimuli, with lower grades presented with larger stimuli (grades 3–5, 16–16.5 point) than the older grades (grades 6–8, 12 point). Figure 3 indicates larger ORF reduction without correction in grades in which smaller font sizes were used in reading passages. It is possible that students in grades 3 to 5 may have shown similar improvement in reading with spectacle correction as we observed in grades 6 to 8 if they were reading passages presented at a reduced font size. The fact that we observed no significant reduction in ORF in astigmatic students (compared to students with no/low astigmatism) when ORF was tested with spectacle correction suggests that the grade/text size effect we observed when students read without correction was due to the astigmatic blur and the visual demands of the stimulus (text size), rather than a developmental reading effect in which astigmatic students tend to gradually fall further behind their peers as they progress through school.

Chung et al. also reported that blur up to 2.00D did not affect the maximum reading speed, but there was a reduction in reading speed with 3.00D of blur.³¹ This is consistent with our finding of no significant improvement in ORF with correction in moderate astigmats. Absence of an effect of spectacle wear on ORF in moderate astigmats may be due to the fact that the stimuli were closer to uncorrected near acuity thresholds in the high astigmats than

in the moderate astigmats. The effect of astigmatism on ORF might become apparent in moderate astigmats with reading stimuli that is closer to their near acuity threshold.

Final considerations in interpreting our data are the potential effects of other vision problems, such as poor binocular vision, accommodation, or oculomotor skills.^{25,32} There is evidence that convergence insufficiency and accommodative insufficiency is associated with a higher rate of reading/near vision symptoms compared to children with normal binocular vision.³³ However, we observed no increased rate of convergence insufficiency in astigmatic students from our study sample,³⁴ and students with evidence of symptomatic binocular vision problems were excluded from our analyses. In a previous study we observed reduced accuracy and greater variability of accommodation in uncorrected students with high astigmatism, but also observed that accuracy improved with the increased visual task demand associated with reading.⁵ It is possible that the cause of the reduced ORF in astigmatic students when uncorrected may be due in part to reduced accuracy and increased variability in accommodation, in addition to blur associated with uncorrected astigmatism.

Our study has several strengths and limitations. Strengths include a large school-based sample of bilateral astigmatic students with WTR astigmatism, a comparison group of students with little or no astigmatism from the same cohort, and use of well validated reading stimuli and testing procedures for assessment of ORF.

One potential limitation of our study is the use of student's grade, rather than age, to control for developmental differences across groups. It was necessary to use grade, as the DIBELS materials are organized by grade level, not age. It is possible that *if* students with astigmatism have significant problems with reading and other school work, they may be more likely to be held back a grade, thus masking or reducing any observed effect on ORF as those students would be compared with non-astigmatic students from the same grade but of a younger age. If this were the case, we should see a higher mean age in each grade for the astigmatic groups compared to the no/low astigmatism group. This prediction was not supported by the data: mean age did not significantly differ across groups for any grade. This result justifies the use of grade as a covariate in analyses, and also suggest that astigmatic students from this population are *not* more likely to have trouble progressing in school, at least not to the extent that would warrant being held back a grade.

Other limitations are the absence of data on the effects of text size and near acuity on reading in our sample. However, the present study provides an indication of the effect of astigmatism on ORF using grade appropriate stimuli (in terms of font, text size, and reading difficulty) under somewhat typical reading conditions (e.g., uncontrolled viewing distance).^{20,22}

The results of our study suggest that with spectacle correction astigmatic children perform similarly on an ORF task to their peers with no/low astigmatism. However, due to the cross-sectional study design, this study cannot determine whether or not spectacle correction of astigmatism helps astigmatic students show faster reading improvement rates over time, compared to no spectacle correction. While this would be an important topic for further study, randomization to spectacle vs. no spectacles would be difficult to justify as our cross-

sectional data indicate that not wearing spectacles results in reduced ORF in astigmatic students. An alternative design would be to compare reading growth rates in spectacle compliant and non-compliant students, but this design introduces many possible confounding variables.

In summary, the data indicate that astigmatic students read less fluently when not wearing their spectacles than students with no/low astigmatism. However, with spectacle correction, astigmatic students performed similarly to students with no/low astigmatism. The data support the clinical recommendation for full-time spectacle wear in astigmatic students. These findings have important implications for the treatment of students with astigmatism and the impact of uncorrected astigmatism on school performance.

ACKNOWLEDGMENTS

This study was supported by National Institutes of Health/National Eye Institute (NIH/NEI grant EY13153 (EMH)) and by funding from Research to Prevent Blindness (grant to the University of Arizona Department of Ophthalmology and Vision Science (JMM), a Walt and Lilly Disney Award for Amblyopia Research (JMM), and a Career Development Award (EMH)).

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Figure 1.

Mean oral reading fluency (ORF) scores for non-astigmatic students and for astigmatic students. Open symbols represent uncorrected ORF, closed symbol represents best-corrected ORF. Mean ORF was significantly poorer in astigmats than in non-astigmats only when astigmatic students were uncorrected.

Figure 2.

Improvement in ORF with correction (calculated as the difference between corrected ORF and uncorrected ORF scores) by astigmatism magnitude (moderate, high). Error bars represent the 95% confidence interval. The horizontal line represents no improvement (difference of 0), positive values represent improvement with correction.

Figure 3.

Improvement in ORF with correction (calculated as the difference between corrected ORF and uncorrected ORF scores) by grade. Error bars represent the 95% confidence interval. The horizontal line represents no improvement (difference of 0), positive values represent improvement with correction.

Table 1
Summary of sample characteristics by group. P values represent results of comparisons across groups.

Variable	No/low Astigmatism	Moderate Astigmatism	High Astigmatism	Total
Sample Size	130	67	76	273
Age(Years) P=0.521	Mean SD	11.45 11.46 1.68	11.72 1.89	11.53 1.76
Right Eye SE (D) P=0.233	Mean SD	+0.29 0.52	-0.07 2.06 +0.03 2.04	+0.13 1.53
Left Eye SE (D) P=0.277	Mean SD	+0.31 0.52	-0.05 2.03 +0.15 1.98	+0.18 1.49
SE Category* (n, %) P < 0.001	Not Hyperopic (0) Hyperopic (>0)	36,28% 94,72%	31,46% 36,54% 43,57% 33,43%	110,40% 163,60%
Sex (n, %) p=0.770	Female Male	57,44% 73,56%	33,49% 34,51% 35,46% 41,54%	125,46% 148,54%
Grade (n, %) P=0.481	3 4 5 6 7 8	18, 13% 22, 17% 21, 16% 34, 26% 11, 9% 24, 19%	13,19% 8, 12% 12, 18% 15, 22% 11, 16% 8, 12% 14, 18% 13, 17%	45, 17% 39, 14% 41, 15% 67, 25% 36, 13% 45, 17%
Uncorrected Acuity (LogMAR) P<0.001	Mean SD	-0.10 0.11	0.21 0.19 0.32 0.16	0.09 0.24
Best-Corrected Acuity (LogMAR) P<0.001	Mean SD	-0.13 0.08	-0.03 0.09 0.02 0.11	-0.06 0.11
Acuity Change with correction (LogMAR) P<0.001	Mean SD	0.02 0.10	0.24 0.18 0.31 0.19	0.15 0.20

Variable	No/low Astigmatism	Moderate Astigmatism	High Astigmatism	Total
Sample Size	130	67	76	273
Compliance P=0.020	Compliant	33.49%	52.68%	85.59%
	Not Compliant	34.51%	24.32%	58.41%

* If mean of right and left eye SE is 0, classified as not hyperopic and if mean is > 0 classified as hyperopic.