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FEATURE ARTICLE - PUBLIC ACCESS

Reading Fluency in School-Aged Children with Bilateral Astigmatism

Erin M. Harvey*, Joseph M. Miller†, J. Daniel Twelker‡, and Amy L. Davis§

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 third- to eighth-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 [cylinder < 1.00 both eyes, no significant myopia/hyperopia], moderate [cylinder ≥ 1.00 D both eyes, mean ≥ 1.00 D and < 3.00 D], or high astigmatism group [cylinder ≥ 1.00 D both eyes, mean ≥ 3.00 D]) were excluded. Oral reading fluency was tested with a modified version of the Dynamic Indicators of Basic Early Literacy Skills (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 between 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) but not in moderate astigmats ($p = 0.193$; mean improvement, 1.87 words per minute). 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 with their nonastigmatic 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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Key Words: 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 although 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 because of the presence of amblyopia[1] or because of 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]

*PhD
†MD, MPH
‡OD, PhD
§OD
Department of Ophthalmology and Vision Science (EMH, JMM, JDT, ALD), College of Public Health (EMH, JMM, JDT), and College of Optical Sciences (JMM), The University of Arizona, Tucson, Arizona.

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

METHODS

Subjects

Subjects were third- through eighth-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 to 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 before testing.

Procedures

Eye Examination

Uncorrected monocular and binocular visual acuity was measured at a distance of 3 m 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 of 5 letters. Students then completed a cycloplegic eye examination 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 min after one drop of 0.5% proparacaine followed by one drop of 1% tropicamide and one drop of 1% cyclopentolate were 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 1.00D or higher in either eye, myopia 0.75D or higher on any meridian in either eye, hyperopia 2.50D or higher on any meridian in either eye, spherical equivalent (SE) anisometropia 1.50D or higher. For astigmatism and myopia, the full correction was prescribed. For hyperopia, the sphere correction was reduced by one-third or by 1.00D, whichever was greater.

Assessment of Best-Corrected Acuity and Spectacle Dispensing

Two pairs of spectacles were ordered for students who met prescribing criteria. One pair was dispensed, and the second pair was 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 m 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,[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 of 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 two 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 noncycloplegic 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 the 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 were conducted at least 2 weeks after spectacle dispensing for students who were prescribed spectacles and were conducted on a date after the eye examination 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 (NPC), positive (PFV) and negative fusional vergence (NFV) 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 Δ greater than at far, a receded NPC break ($\geq$6 cm), insufficient PFV at near (convergence amplitudes) (i.e., failing Sheard's criterion [PFV less than twice the near phoria] or minimum PFV of $<$15 Δ base-out blur or break), and a CISS score of 16 or higher were classified as having symptomatic convergence insufficiency. Students with accommodative amplitude at least 2D below Hofstetter's formula for minimum amplitude for the child's age (15 to 0.25 [age]) and an elevated CISS score ($\geq$16) were classified as having symptomatic accommodative insufficiency.[18] Students with esophoria at near at least 3 Δ greater than at far and failed Sheard's criterion or a NFV 7 Δ or less base-in blur or break at near (40 cm) in addition to an elevated CISS score ($\geq$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 Dynamic Indicators of Basic Early Literacy Skills (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 vary with grade level. Materials for grades 1 and 2 use Report School, a san-serif font, in 16.5 point.[20] Times New Roman, a serif font, was used for grade 3

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(size 16 point) and grades 4 to 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 materials.[20] At a distance of 25 cm, 12 point font is equivalent to 20/120 and 16 point font is equivalent to 20/160.[21] At a distance of 40 cm, 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 40 cm was 20/100 (fifth 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 before 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 s, the tester read the word for the child and marked the word as incorrect. At the end of 1 min, 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 six times (using six 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 three 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 three 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 six passages without spectacle correction. All students were tested binocularly and completed all six 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 two 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 has 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) that typically follows ORF. This was eliminated for 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 that amblyopic and fellow eyes were similar in terms of reading comprehension but differed in terms of rate, accuracy, and fluency.[7] Second, students read six 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, that is, ORF scores were not analyzed relative to the DIBELS published norms. Because of the above noted changes to the standard testing protocol, use of published norms for transforming the raw scores was not appropriate. Because raw scores are not age/grade normed, students' grades were included in analyses as a covariate.

Data Analysis

Data from students with ocular abnormalities, anisometropia (>1.50D SE or >1.50D cylinder), 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 less than 1.00D and do not meet any criteria for spectacle prescription.
- Moderate/high astigmatism: Astigmatism in both eyes 1.00D or higher.
  - Moderate astigmats: Mean astigmatism 1.00D or higher and less than 3.00D.
  - High astigmats: Mean astigmatism 3.00D or higher.

Preliminary Analyses

Test order effects were assessed before 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 three passages compared to the second three passages was conducted. For students in the astigmatic group, who were tested with and without correction, ANCOVA were conducted to determine if there were significant effects of test order (best-corrected first vs. uncorrected first) on median reading. In both analyses, grade was included as a covariate.

ORF in Astigmatic Students Compared with ORF in Students with No/Low Astigmatism

ANCOVA was used to compare mean ORF for students with no/low astigmatism to students with astigmatism, including grade as a covariate.

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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 (χ^2, p = 0.481), sex (χ^2, p = 0.770), or mean age (analysis of variance [ANOVA], p = 0.521).

The three groups did not significantly differ on mean 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, χ^2, $p < 0.001$): a significantly greater percentage of students with no/low astigmatism had a hyperopic SE compared with the moderate (p = 0.009) and high astigmats ($p < 0.001$), but moderate and high astigmats did not significantly differ (p = 0.218). Because of the difference across groups in the percentage of students with hyperopic SE, SE refractive error (hyperopic vs. not hyperopic) was included in analyses comparing students with no/low astigmatism 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) (ANCOVA with age as covariate, $p < 0.001$; 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 ($p < 0.001$) 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, three highly astigmatic students). The poorest uncorrected acuity was 0.80 LogMAR (20/125, two 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 ($p < 0.001$ for no/low vs. moderate and high astigmats, p = 0.022 for moderate vs. high astigmats), with the greatest improvement seen in students with high astigmatism and the 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

TABLE 1.
Summary of sample characteristics by group

Variable		No/low astigmatism	Moderate astigmatism	High astigmatism	Total
Sample size		130	67	76	273
Age, yr	Mean	11.45	11.46	11.72	11.53
p = 0.521	SD	1.72	1.68	1.89	1.76
Right eye SE, D	Mean	+0.29	−0.07	+0.03	+0.13
p = 0.233	SD	0.52	2.06	2.04	1.53
Left eye SE, D	Mean	+0.31	−0.05	+0.15	+0.18
p = 0.277	SD	0.52	2.03	1.98	1.49
SE category*, N (%)	Not hyperopic (≤0)	36 (28)	31 (46)	43 (57)	110 (40)
p < 0.001	Hyperopic (>0)	94 (72)	36 (54)	33 (43)	163 (60)
Sex, N (%)	Female	57 (44)	33 (49)	35 (46)	125 (46)
p = 0.770	Male	73 (56)	34 (51)	41 (54)	148 (54)
Grade, N (%)	3	18 (13)	13 (19)	14 (18)	45 (17)
p = 0.481	4	22 (17)	8 (12)	9 (12)	39 (14)
	5	21 (16)	12 (18)	8 (11)	41 (15)
	6	34 (26)	15 (22)	18 (24)	67 (25)
	7	11 (9)	11 (16)	14 (18)	36 (13)
	8	24 (19)	8 (12)	13 (17)	45 (17)
Uncorrected acuity (LogMAR)	Mean	−0.10	0.21	0.32	0.09
p < 0.001	SD	0.11	0.19	0.16	0.24
Best-corrected acuity (LogMAR)	Mean	−0.13	−0.03	0.02	−0.06
p < 0.001	SD	0.08	0.09	0.11	0.11
Acuity change with correction	Mean	0.02	0.24	0.31	0.15
(LogMAR) p < 0.001	SD	0.10	0.18	0.19	0.20
Compliance, N (%) p = 0.020	Compliant	—	33 (49)	52 (68)	85 (59)
	Not compliant	—	34 (51)	24 (32)	58 (41)

Values of p represent results of comparisons across groups.
*If mean of right and left eye SE ≤ 0, it was classified as not hyperopic; if mean > 0, it was classified as hyperopic.

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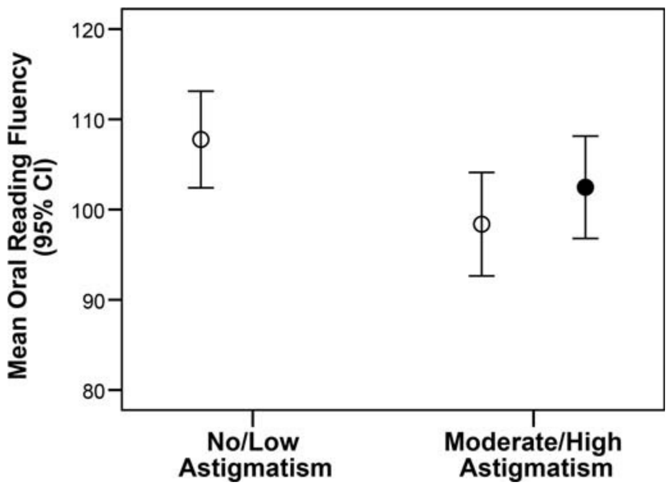

FIGURE 1.

Mean oral reading fluency (ORF) scores for nonastigmatic students and for astigmatic students. Open symbols represent uncorrected ORF, and closed symbol represents best-corrected ORF. Mean ORF was significantly poorer in astigmats than in nonastigmats only when astigmatic students were uncorrected. 95% CI, 95% confidence interval.

moderate astigmats (49.3%) arrived at the reading assessment wearing their spectacles (p = 0.020). Therefore, compliance was included in the analyses comparing moderate and high astigmats.

DIBELS Next reading materials are based on the student's grade placement rather than age; therefore, student grade was included in analyses as a covariate. One-way ANOVA, conducted separately for each grade, yielded no significant differences in mean age across astigmatism groups (all $p \geq 0.136$).

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 scores for the first three passages compared to the second 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, the median of all six passages was determined for each student in the no/low astigmatism group and was used as their representative reading score in primary analyses.

For students in the astigmatic group, who were tested with and without correction, preliminary ANCOVA 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.

ORF in Astigmatic Students Compared with ORF in Students with No/Low Astigmatism

Analysis of covariance compared mean ORF in no/low astigmats with moderate/high astigmats, controlling for SE refractive error (hyperopic or not hyperopic) and grade. Results are illustrated in Fig. 1. When uncorrected, mean ORF was poorer in astigmats than in nonastigmats (p = 0.011). Secondary ANCOVA 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) (Fig. 2).

Analysis of covariance 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 Fig. 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 ORF and bilateral astigmatism magnitude (no/low, moderate, or high) and

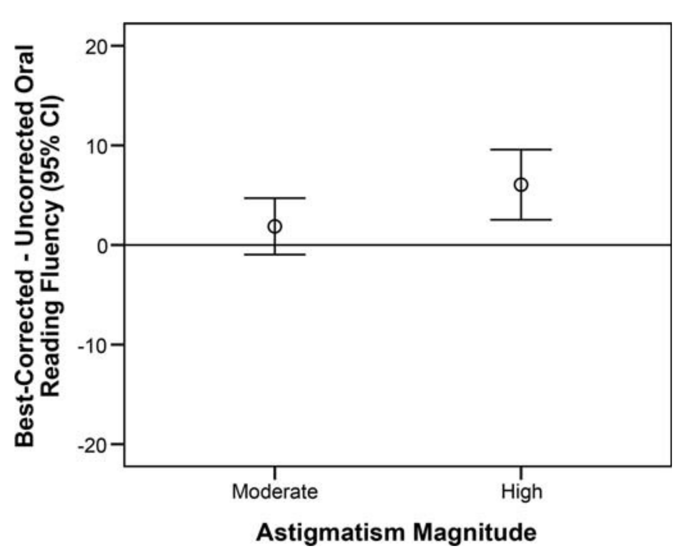

FIGURE 2.

Improvement in oral reading fluency (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 (95% CI). The horizontal line represents no improvement (difference of 0), and positive values represent improvement with correction.

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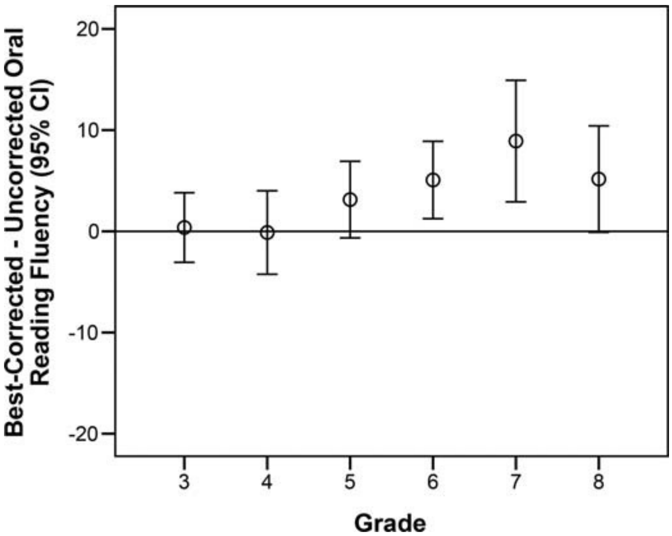

FIGURE 3.

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

the impact of spectacle correction on ORF 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 on 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. Oral reading fluency improvement with spectacle correction in astigmatic students was dependent on 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-aged children: children referred because of 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 schoolchildren, who have a high prevalence of astigmatism, Garber[27] reported that uncorrected astigmatic fifth- and sixth-grade students (≥2.00D) had poorer teacher-assigned reading scores than nonastigmatic students but found no significant effect of astigmatism on reading scores from standardized tests in second-grade students. Orlansky et al.[28] compared measures of early academic readiness for preschoolers (3- to 5-year-olds enrolled in Head Start) with no astigmatism with those for preschoolers with astigmatism (≥0.50D in either eye) and found that the presence of astigmatism was associated with lower scores on several measures of academic readiness. 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 with ORF in 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 versus 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.[4] assessed reading performance with no astigmatism and with 1.50D of simulated astigmatism in a sample of 20 schoolchildren (mean age, 10 years) and observed a significant reduction in reading performance (rate, accuracy, and comprehension) with simulated astigmatism. Wolffsohn et al.[2] reported that simulated astigmatism in 21 adult subjects was associated with decreased reading speed but only at high levels of astigmatism (≥3.00D). Wills et al.[3] assessed the impact of 1.00 and 2.00D of simulated 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. For larger print sizes (16 and 20 point), reading speed was only reduced with 2.00D ATR astigmatism.

Previous results indicating that the effects of simulated astigmatism are dependent on astigmatism magnitude are consistent with our finding that spectacle correction improves ORF in students with high (≥3.00D) but not moderate astigmatism (1.00 to <3.00D). However, the magnitude of astigmatism necessary to significantly reduce reading speed varies across studies. Our results are consistent with those of Wolffsohn et al.[2] who observed a decrease in reading speed only with 3.00D or higher of simulated astigmatism (in the range of our high astigmats) but are not consistent with those of Wills et al.[3] who reported reduced reading speed with lower levels of simulated astigmatism (in the range of our moderate astigmats). In our study, the sample size in the high astigmatism group was larger than that in the moderate astigmatism group. It is possible that a lower statistical power may have contributed to 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 astigmatism[3] and estimates that reading speeds increase about 14 words per minute each year from first grade through college,[23] suggesting that 7 words per minute represents the approximate expected gain for one-half year. We use this estimate cautiously in interpreting our data because 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

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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 caused by 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 on print size.[3,31] Chung et al.[31] 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. 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 ORF 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 to 5, 16 to 16.5 point) than the older grades (grades 6 to 8, 12 point). Fig. 3 indicates larger ORF improvement with 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 a 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 with 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 caused by 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.[31] 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. This is consistent with our finding of no significant improvement in ORF with correction in moderate astigmats. The absence of an effect of spectacle wear on ORF in moderate astigmats may be caused by 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 children with convergence insufficiency and accommodative insufficiency have a higher rate of reading/near vision symptoms compared with 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 caused in part by 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 the student's grade, rather than age, to control for developmental differences across groups. It was necessary to use grade because 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 because those students would be compared with nonastigmatic 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 with 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 suggests 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, because of the cross-sectional study design, this study cannot determine whether or not spectacle correction of astigmatism helps astigmatic students show faster reading improvement rates across time compared with no spectacle correction. Although this would be an important topic for further study, randomization to spectacles versus no spectacles would be difficult to justify because 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 noncompliant 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.

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REFERENCES

1. Harvey EM. Development and treatment of astigmatism-related amblyopia. Optom Vis Sci 2009;86:634–9.
2. Wolffsohn JS, Bhogal G, Shah S. Effect of uncorrected astigmatism on vision. J Cataract Refract Surg 2011;37:454–60.
3. Wills J, Gillett R, Eastwell E, Abraham R, Coffey K, Webber A, Wood J. Effect of simulated astigmatic refractive error on reading performance in the young. Optom Vis Sci 2012;89:271–6.
4. Narayanasamy S, Vincent SJ, Sampson GP, Wood JM. Simulated astigmatism impairs academic-related performance in children. Ophthalmic Physiol Opt 2015;35:8–18.
5. Harvey EM, Miller JM, Apple HP, Parashar P, Twelker JD, Crescioni M, Davis AL, Leonard-Green TK, Campus I, Sherrill DL. Accommodation in astigmatic children during visual task performance. Invest Ophthalmol Vis Sci 2014;55:5420–30.
6. Guyton DL. Prescribing cylinders: the problem of distortion. Surv Ophthalmol 1977;22:177–88.
7. Repka MX, Kraker RT, Beck RW, Cotter SA, Holmes JM, Arnold RW, Astle WF, Sala NA, Tien DR; Pediatric Eye Disease Investigator Group. Monocular oral reading performance after amblyopia treatment in children. Am J Ophthalmol 2008;146:942–7.
8. Stifter E, Burggasser G, Hirmann E, Thaler A, Radner W. Monocular and binocular reading performance in children with microstrabismic amblyopia. Br J Ophthalmol 2005;89:1324–9.
9. Stifter E, Burggasser G, Hirmann E, Thaler A, Radner W. Evaluating reading acuity and speed in children with microstrabismic amblyopia using a standardized reading chart system. Graefes Arch Clin Exp Ophthalmol 2005;243:1228–35.
10. Kanonidou E, Proudlock FA, Gottlob I. Reading strategies in mild to moderate strabismic amblyopia: an eye movement investigation. Invest Ophthalmol Vis Sci 2010;51:3502–8.
11. Koklanis K, Georgievski Z, Brassington K, Bretherton L. The prevalence of specific reading disability in an amblyopic population. A preliminary report. Binocul Vis Strabismus Q 2006;21:27–32.
12. Zürcher B, Lang J. Reading capacity in cases of 'cured' strabismic amblyopia. Trans Ophthalmol Soc U K 1980;100:501–3.
13. Dobson V, Miller JM, Harvey EM. Corneal and refractive astigmatism in a sample of 3- to 5-year-old children with a high prevalence of astigmatism. Optom Vis Sci 1999;76:855–60.
14. Harvey EM, Dobson V, Clifford-Donaldson CE, Green TK, Messer DH, Miller JM. Prevalence of astigmatism in Native American infants and children. Optom Vis Sci 2010;87:400–405.
15. Harvey EM, Dobson V, Miller JM. Prevalence of high astigmatism, eyeglass wear, and poor visual acuity among Native American grade school children. Optom Vis Sci 2006;83:206–12.
16. Miller JM. Clinical applications of power vectors. Optom Vis Sci 2009;86:599–602.
17. Convergence Insufficiency Treatment Trial (CITT) Study Group. The convergence insufficiency treatment trial: design, methods, and baseline data. Ophthalmic Epidemiol 2008;15:24–36.
18. Hofstetter HW. Useful age-amplitude formula. Optom World 1950; 38:42–5.
19. Good RH, Kaminski RA. DIBELS Next Assessment Manual. Eugene, OR: Dynamic Measurement Group; 2011.
20. Good RH, Kaminski RA, Dewey EN, Wallin J, Powell-Smith KA, Latimer RJ. DIBELS Next Technical Manual. Eugene, OR: Dynamic Measurement Group; 2013.
21. Bailey IL, Lovie JE. The design and use of a new near-vision chart. Am J Optom Physiol Opt 1980;57:378–87.
22. Langford A, Hug T. Visual demands in elementary school. J Pediatr Ophthalmol Strabismus 2010;47:152–6.
23. Carver RP. Reading Rate: A Review of Research and Theory. San Diego, CA: Academic Press; 1990.
24. Legge GE. Psychophysics of Reading in Normal and Low Vision. Mahwah, NJ: Lawrence Erlbaum Associates; 2007.
25. Dusek W, Pierscionek BK, McClelland JF. A survey of visual function in an Austrian population of school-age children with reading and writing difficulties. BMC Ophthalmol 2010;10:16.
26. Quaid P, Simpson T. Association between reading speed, cycloplegic refractive error, and oculomotor function in reading disabled children versus controls. Graefes Arch Clin Exp Ophthalmol 2013;251: 169–87.
27. Garber JM. High corneal astigmatism in Navajo school children and its effect on classroom performance. J Am Optom Assoc 1981; 52:583–6.
28. Orlansky G, Wilmer J, Taub MB, Rutner D, Ciner E, Gryczynski J. Astigmatism and early academic readiness in preschool children. Optom Vis Sci 2015;92:279–85.
29. de Gracia P, Dorronsoro C, Marin G, Hernández M, Marcos S. Visual acuity under combined astigmatism and coma: optical and neural adaptation effects. J Vis 2011;11:pii: 5.
30. Vinas M, Sawides L, de Gracia P, Marcos S. Perceptual adaptation to the correction of natural astigmatism. PLoS One 2012;7:e46361.
31. Chung ST, Jarvis SH, Cheung SH. The effect of dioptric blur on reading performance. Vision Res 2007;47:1584–94.
32. Kulp MT, Schmidt PP. Visual predictors of reading performance in kindergarten and first grade children. Optom Vis Sci 1996;73: 255–62.
33. Borsting E, Rouse MW, Deland PN, Hovett S, Kimura D, Park M, Stephens B. Association of symptoms and convergence and accommodative insufficiency in school-age children. Optometry 2003;74:25–34.
34. Davis A, Twelker JD, Miller JM, Harvey EM. The relation between convergence insufficiency and astigmatism. Invest Ophthalmol Vis Sci 2015;56:E-Abstract 532.

Erin M. Harvey
The University of Arizona
Department of Ophthalmology and Vision Science
655 N. Alvernon Way Suite 108
Tucson, AZ 85711
e-mail: emharvey@email.arizona.edu

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