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Title page

The effect of simulated astigmatic refractive error on reading performance in the young

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ABSTRACT

Background: Few studies have specifically investigated the functional effects of uncorrected astigmatism on measures of reading fluency. This information is important to provide evidence for the development of clinical guidelines for the correction of astigmatism.

Methods: Participants included 30 visually normal, young adults (mean age 21.7 ± 3.4 years). Distance and near visual acuity and reading fluency were assessed with optimal spectacle correction (baseline) and for two levels of astigmatism, 1.00DC and 2.00DC, at two axes (90° and 180°) to induce both against-the-rule (ATR) and with-the-rule (WTR) astigmatism. Reading and eye movement fluency were assessed using standardized clinical measures including the test of Discrete Reading Rate (DRR), the Developmental Eye Movement (DEM) test and by recording eye movement patterns with the Visagraph (III) during reading for comprehension.

Results: Both distance and near acuity were significantly decreased compared to baseline for all of the astigmatic lens conditions ($p < 0.001$). Reading speed with the DRR for N16 print size was significantly reduced for the 2.00DC ATR condition (a reduction of 10%), while for smaller text sizes reading speed was reduced by up to 24% for the 1.00DC ATR and 2.00DC condition in both axis directions ($p<0.05$). For the DEM, sub-test completion speeds were significantly impaired, with the 2.00DC condition affecting both vertical and horizontal times and the 1.00DC ATR condition affecting only horizontal times ($p<0.05$). Visagraph reading eye movements were not significantly affected by the induced astigmatism.

Conclusions: Induced astigmatism impaired performance on selected tests of reading fluency, with ATR astigmatism having significantly greater effects on performance than did WTR, even for relatively small amounts of astigmatic blur of 1.00DC. These findings have implications for the minimal prescribing criteria for astigmatic refractive errors.

Key Words: astigmatism, eye movements, reading speed, visual acuity

Astigmatism is a relatively common form of refractive error, affecting up to twenty percent of primary school children,[1, 2] depending on the refractive power used to define astigmatism. Higher levels of astigmatism are evident in some child populations including those with Native American or Asian ethnicity.[3-10]With-the-rule (WTR) astigmatism, where the steeper axis is vertical, is more common in school aged children than against-the-rule (ATR) where the steeper axis is horizontal, with oblique astigmatism being the least common.[11]Uncorrected astigmatic refractive errors, defined as ≥ 1.00 DC, account for up to 46.5% of correctable vision impairment in children.[12] What is not known is how uncorrected astigmatic refractive errors impact on visual tasks performed by children, such as reading, in the classroom.

An important question facing eye practitioners is the minimum level of astigmatic refractive error that should be prescribed for. This is complicated by the fact that the impact of uncorrected astigmatism on functional visual performance can vary both with the magnitude and the axis of astigmatism.[13] The majority of published guidelines for correcting astigmatism suggest that any astigmatism >1.00DC, or that which decreases visual acuity to <6/12, should be considered significant.[14-16] Conversely, other guidelines recommend correcting astigmatism as low as 0.50DC depending on the magnitude (diopters) and axis of astigmatism, along with the presence of asthenopic symptoms.[17, 18] Uncorrected astigmatism, as low as 1.00DC, has been reported to significantly decrease visual acuity and has been shown to impair performance on functional tests such as reading speed, and reading text on mobile phones and computer screens in studies of older adults.[13] Importantly, the effect of astigmatism on standardized tests of reading performance and fluency that are commonly used in the examination of children has not been previously assessed.

The purpose of our study was to assess the effect of induced astigmatic refractive error on a selection of standardized clinical measures of reading performance. The measures of reading performance were selected from those more commonly used in clinical practice and included a test of Discrete Reading Rate (DRR), the Developmental Eye Movement (DEM) test and the Visagraph. The DRR test provides a gross indication of fixation duration,[19] by recording the time taken to read aloud words of a given print size on standard Bailey-Lovie reading cards.[20] The DRR test was selected because the cards present unrelated words, rather than continuous text, thus removing contextual cues from the reading task that are found in other commonly used measures of reading performance, such as the MNRead and Radner tests. A change in DRR indicates a change in fixation duration and provides information regarding an individual's functional reading ability. The DEM test is used clinically to assess both poor automaticity in number naming and ocular motor fluency for reading horizontally and vertically arranged single digit numbers.[21] The time taken to read a series of single digit numbers arranged vertically is considered to be a measure of rapid automatic naming (RAN), while the ratio of the horizontal to vertical times is purported to provide a measure of saccadic eye movements that factors out RAN.[22] The Visagraph III Eye Movement system (Taylor Associates, NY) is a commercially available clinical method for directly recording eye movements during reading for comprehension.[23, 24] Outcome measures include number of fixations, regressions, return-sweep saccades, span of recognition, fixation duration and reading rate.[25]

Performance on these three standardized clinical measures of reading and eye movement fluency was determined for two levels of astigmatism, 1.00DC and

2.00DC, induced at both 90 and 180 degrees. These astigmatic conditions were selected based upon published surveys of eye care practitioners[14, 26] that indicate that the majority of eye care practitioners will consider prescribing corrective lenses at or between these levels of astigmatic refractive error, and that astigmatism is most commonly oriented along either the horizontal and vertical axes.

METHOD

<u>Participants</u>

Visually normal young adult subjects (n=30; mean age 21.7 ± 3.4 years; range 18 to 33 years) were recruited from students, staff and friends of the QUT School of Optometry. All participants had English as their first language and had completed at least six months tertiary education. Participants were emmetropic, or corrected to emmetropia with soft contact lenses (spherical refractive error ≥ -0.25 D to ≤ +0.50 D with ≤ 0.50 DC), with distance and near visual acuity (VA) of 0.00 logMAR or better in each eye. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Queensland University of Technology Human Research Ethics Committee. All participants were given a full explanation of the experimental procedures, and written informed consent was obtained with the option to withdraw from the study at any time.

<u>Induced astigmatic refractive error</u>

Using a repeated measures design, each participant's visual acuity and reading performance were measured binocularly under five lens conditions. The cylinder powers were matched with a balancing sphere to maintain a plano spherical equivalent.[18] The five visual conditions included the optimum spectacle refraction, with the addition of the following lens conditions: 1) 0.00D (baseline control condition), 2) -0.50DS/+1.00DC x 180 (induced WTR), 3) -0.50DS/+1.00DC x 90 (induced ATR), 4) -1.00DS/+2.00DC x 180 (induced WTR), 5) -1.00DS/+2.00DC x 90 (induced ATR). The order of lenses was randomized for each participant prior to the start of testing and a double-blind design was used such that neither the examiner nor the participant was aware of which lens was being used at any one time.

Visual Acuity

Each set of lens pairs for each of the five testing conditions were placed in a trial frame. Binocular distance and near visual acuity were measured and recorded using standard high contrast Bailey-Lovie distance and near charts at testing distances of 6m and 40 cm under the recommended illumination conditions. Participants were instructed to read the letters from left to right on the chart and were encouraged to guess letters when unsure until a line of errors was made. The participant was stopped once three or more letters were identified incorrectly on a single line. Visual acuity was scored on a letter by letter basis, where each correctly identified letter represented a score of 0.02 log units.

Discrete Reading Rate (DRR)

Reading speed was measured binocularly while participants read aloud words from Bailey-Lovie word charts viewed at 40cm. The DRR test uses non-continuous text charts containing six words per line for print sizes from N80 to N2 in 0.1 log unit steps. In this study, the DRR was recorded for font sizes N20 to N10 (2.5 M to 1.2 M respectively).[27] The DRR for smaller font sizes was also tested but most participants were not able to consistently read words smaller than N10 for all levels of astigmatic blur. Reading speeds were determined for each of the print sizes by using a stopwatch to record the time for the subject to read each line as quickly as possible. The times were subsequently converted to words per minute. Participants were required to attempt each word on a line, and were allowed to progress down the chart until they incorrectly reported three or more words on a line, at which point the test was terminated. A series of Bailey Lovie word cards for each font size were available allowing a different chart to be used for each lens condition to minimize familiarity effects.

Developmental Eye Movement (DEM) Test

The DEM test consists of a pre-test of number knowledge followed by two subtests, each with 40 numbers arranged in two vertical columns (Tests A and B), and a subtest with 80 irregularly spaced numbers arranged in 16 horizontal rows (Test C). Participants were asked to name aloud the single digit numbers as quickly and accurately as possible for each of the five lens pairs under binocular viewing conditions. The time taken to read aloud the 80 numbers in both the four vertical columns (test cards A and B - vertical time) and the sixteen line horizontal array (test card C - horizontal time) was recorded. The number of omission and addition errors was recorded and test times were adjusted for errors made. Both the vertical and horizontal times were adjusted to account for the number of digits actually named by the participant and subsequently a ratio score of horizontal to vertical time was calculated.[28] A total of six complete DEM charts were produced electronically from the original DEM with identical font and spacing, each number series was randomly generated. This allowed a different chart to be used for each lens condition.

Visagraph III

Eye movements were recorded binocularly with the Visagraph III recording system that uses goggles containing infra-red sensors to capture eye position information while the participants read a short paragraph of text. The test paragraphs employed were Taylor level 10, suggested for the assessment of college students. Each test paragraph was 10 lines long, typed double-spaced on white bond paper in 12-point Times bold font at an illumination level of 122cd/m^2. All paragraphs were read silently with no time limit. After reading, the participant was required to answer 10 standard true/false comprehension questions, presented orally by the examiner, regarding the content of the paragraph. The outcome measures calculated by the Visagraph software included the number of fixations per 100 words, number of regressions per 100 words, span of recognition, average duration of fixations and reading rate. The average span of recognition refers to the amount of print perceived and processed with each fixation. It is specified in units of "words" and calculated by dividing the number of words in the specified paragraph by the number of fixations. Fixation duration refers to the length of time that the eye pauses or remains fixated on a word. Reading rate refers to the number of words read per unit time and is specified in words per minute.

Lens pairs were fixed to the front surface of the Visagraph III goggles to avoid interference with the electronic sensing. The goggles were adjusted to the near inter-pupillary distance and were worn continuously for all near testing. The reading text was positioned in a text holder at a working distance of 40 cm and inclined back at an angle of 15 degrees from vertical. The text was positioned below the subject's horizontal line of sight, at the height preferred by the subject to simulate a normal reading posture. The order of Visagraph paragraphs was randomized for each participant to minimize practice effects.

Analysis

Each lens condition was initially compared against the baseline condition, for each dependent measure, to establish which of the lens conditions led to significant changes in performance. The effects of cylinder power versus axis direction were analyzed using a two-way repeated measures ANOVA with power and axis as the within subject factors.

RESULTS

Table 1 shows the group mean data and outcome of the statistical comparisons for each of the outcome measures for the baseline condition and the four induced astigmatic blur conditions. Both distance and near visual acuity were significantly decreased compared to baseline for all of the lens conditions. Reading speed was significantly impaired for N16 print only for the 2.00DC ATR condition while for smaller text sizes, reading speed was significantly reduced for the 1.00DC ATR and 2.00DC condition for both axis directions. For the DEM, only timed values were significantly impaired, with the 2.00DC condition affecting both vertical and horizontal times and the 1.00DC ATR condition affecting only horizontal times. None of the other DEM outcome measures, including the number of errors or ratios, were affected. Similarly, none of the Visagraph measures were affected by the lens conditions.

A series of two-way ANOVAs were conducted for the outcomes, represented as the difference in each of the conditions from the baseline, in order that the effects of cylinder power and axis could be considered separately (Table 1). Analysis revealed significant main effects of cylinder power for distance visual acuity and a marginally significant effect of axis. Near visual acuity was significantly affected by both cylinder power and axis. There was no significant interaction between cylinder power and axis.

Reading speed was significantly affected by cylinder power and axis for N10 text size, and by axis for N12and N10 text sizes. Horizontal and vertical times for the DEM were significantly associated with axis direction only, where reading times were significantly longer (worse performance) for induced ATR astigmatism than WTR. There were no effects of either cylinder power or axis on the Visagraph outcomes measures, however, there was a significant interaction between lens power and axis for fixations and the Visagraph measure of reading rate. For each of these measures, there was a significant effect of power for WTR astigmatism, where the larger power had the greater detrimental impact on performance, but with no significant effect of power for the ATR astigmatism.

To establish whether the observed changes in reading performance were a product of the changes in visual acuity, or might be attributable to other factors, a series of analyses of covariance (ANCOVAs) were conducted, examining each of the above significant differences between lens conditions on reading performance measures, controlling for visual acuity in each condition. None of these differences remained significant after controlling for changes in either distance or near visual acuity, suggesting that the changes in visual acuity fully mediated the observed changes in reading performance.

DISCUSSION

In this study we examined the impact of induced astigmatic refractive error on standardized measures of reading performance that are commonly employed in the optometric examination of children. Induced astigmatic refractive error was found to impair performance on these tests of reading function, with astigmatism of 1.00DC ATR or greater, or 2.00DC WTR found to reduce reading performance, particularly for the smaller font sizes of the DRR. The observed impairment in performance on these standardized functional reading tests can be attributed to the decrement in visual acuity created by the astigmatic refractive error conditions.

Astigmatic blur increased difficulty in identifying single words, letters, and numbers, and for smaller print sizes reduced reading rates. Against the rule astigmatism had more impact on both visual acuity and reading performance measures than did WTR astigmatism especially at smaller print sizes, which is in general agreement with previous studies.[13] Discrete Reading Rate (DRR) was significantly slower than baseline for the larger degree of ATR astigmatic blur for the larger print size (N16) (a reduction of 10%), while for smaller text sizes (N12 and N10) both the 1.00DC ATR and 2.00DC at either ATR or WTR reduced DRR (by up to 24%); reading performance for the N20 print size was not affected by any of the astigmatic conditions tested.

This effect of astigmatic blur on reading speed is consistent with findings from Chung et al,[29] who induced spherical dioptric blur and found that reading speed, as measured by the MNread acuity chart, was significantly related to reading acuity.[29] Reading speed appears to remain relatively constant until a critical print size (CPS) is reached,[19, 20] after which reading speed declines with decreasing print size.[19, 30]

Astigmatic blur also resulted in slower horizontal and vertical adjusted times on the DEM, but did not impact the DEM ratio. The astigmatic conditions resulted in increased difficulty recognizing and naming numbers but did not alter the ratio between horizontal and vertical times (which is purported to differentiate between poor saccadic function and a primary rapid naming deficit (RAN)) and did not result in additional errors. The slowing of horizontal and vertical times is in accord with our findings of reduced DRR for N10 font size, given that the DEM involves reading high contrast single digits (3 mm vertical extent), which are equivalent to N10, with 5 mm spacing between rows and 10 to 25 mm between numbers.

Conversely, the pattern of eye movements recorded by the Visagraph was not affected by the astigmatic conditions tested in this study. This is possibly because the text is larger than the critical print size sensitive to the effects of blur. The results from the DRR test showed that N12 was the first print size where a significant difference was found from baseline for both 1.00DC and 2.00DC levels of induced astigmatism. While the College reading task of the Visagraph uses N12 font, the paragraph is double-spaced and hence likely to be easier to read than Bailey-Lovie N12 which has increased crowding effects.[46] Unlike the DRR that requires reading of non-related words, the Visagraph reading task also has contextual cues that may have aided subjects in word identification, diminishing the impact of the astigmatic blur. For real world reading tasks such as reading newspapers, text size can be as small as N5, while recent studies that have assessed the visual demands of primary school have indicated that print sizes as small as N10 are involved in some classroom settings for Grades 3-5.[31] Thus assessing performance for print size of N12 is likely to underestimate the impact of astigmatic blur in the classroom. It is likely that if smaller print size had been available for this measure the impact of astigmatic blur would have been more apparent.

In clinical practice eye care practitioners make recommendations regarding whether an optical correction is required based upon the magnitude of refractive error, the presence of symptoms and, in early childhood, the risk or presence of amblyopia. O'Leary and Evans[14] reported that their sample of surveyed optometrists (n=38) would prescribe 1.50DC for 70% of the time in the absence of asthenopic symptoms, and that for symptomatic patients optometrists would prescribe 0.75DC for 60% of the time. Miller and Harvey[26] report that the majority of surveyed pediatric ophthalmologists (n=338) would prescribe to correct 2.00DC of astigmatism in children aged four to seven years. Our findings suggest that correction of WTR astigmatism is appropriate for powers above 1.00DC, however, for ATR astigmatism cylinder correction needs to be prescribed for values as low as 1.00DC, as both of the astigmatic powers included in this study affected reading speed, and ATR significantly decreased reading rates compared to WTR astigmatism. This finding provides support for the early prescribing guidelines of Gullstrand[32] which were based on clinical experience and suggested that ATR astigmatism should be corrected at values as low as 0.50DC, as it produced more asthenopic symptoms than twice the amount of WTR astigmatism.

Our findings suggest that the reductions in performance on reading tests found under the astigmatism conditions could be attributed to reduced resolution (decreased visual acuity). Reading rate decreased with increased astigmatic blur, particularly for font sizes below N16, while the pattern of eye movements recorded during reading for comprehension did not change under the astigmatism conditions, most likely because of the larger font size and the availability of contextual cues involved in the Visagraph test.

Our findings have implications for the correction of astigmatic refractive error in primary (elementary) school children. Robaei et al.[12] reported that, in their sample of six-year-old primary school children (n= 1738), astigmatism, defined as 1.00DC, was the main refractive error causing visual impairment and was frequently uncorrected. Younger children (kindergarten to grade 2) generally are required to read text of font size greater than N12, therefore may be less disadvantaged by the blur associated with uncorrected astigmatism, however as children progress through higher grades they are generally presented with printed material of decreasing font size that would be smaller than the critical print size of ≤ N12.[31] Children may not demonstrate the functional difficulties associated with reduced near acuity until the text has progressively decreased to the critical size during their schooling. In addition, poorer readers may be less able to take advantage of contextual cues in the text, which can counteract the degradation of legibility of print, increasing the need for correction of astigmatic refractive error in these children to maximize their reading performance.

The results of this study should be considered in light of some potential limitations. Simulating the effects of any type of visual impairment has inherent limitations in that the effects observed may be greater than for individuals with true visual impairment who have adapted to their condition. However, this approach does have the important advantage of making it possible to partial out the effects of astigmatic blur alone, without introducing inter-individual variations in performance. Further studies are planned to evaluate the effects of true uncorrected astigmatism for a range of powers and axes. A further limitation of this study is the potential for inflated experiment-wise error related to the number of statistical comparisons conducted. However, because of the number of independent comparisons it wasn't possible to control for all possible comparisons, as the resulting critical p-values would have been too small to enable meaningful analysis. Importantly, the differences observed across conditions were consistent between measures, which suggest that they were robust in this sample.

In summary, these findings provide important insight into the impact of uncorrected astigmatism on reading performance and demonstrate that ATR astigmatism has significantly greater effects on performance than does WTR, even for relatively small amounts of astigmatic blur of 1.00DC. Future studies are planned to quantify the impact of oblique astigmatic refractive error on reading rate, given that this is likely to have even greater effects on visual acuity and performance,[13] and to assess the impact of imposed astigmatic blur on the visual and functional performance of school-aged children.

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Table 1: Group mean data and outcomes of the statistical comparisons for the five testing conditions and the results of the two-way repeated ANOVAs with power and axis as the within subject factors

Measure		Mean (SD) for each of the lens conditions				$F_{(1,29)}$ and p values for results of 2-way repeated measures ANOVAs		
	Baseline	-0.50DS/+1.00DC x 180 (WTR)	0.50DS/+1.00DC x 90 (ATR)	1.00DS/+2.00DC x 180 (WTR)	-1.00DS/+2.00DC x 90 (ATR)	Power	Axis	Power x Axis
VA (logMAR)								
Distance	-0.19 (0.06)	-0.05 (0.08)***	0.00 (0.11)***	0.09 (0.17)***	0.17 (0.16)***	56.41***	3.94	0.70
Near	-0.04 (0.06)	0.04 (0.09)***	0.09 (0.13)***	0.14 (0.12)***	0.24 (0.14)***	29.84***	10.95**	3.54
Reading Speed (wpm)								
N20	156.88 (34.99)	151.29 (27.06)	148.68 (23.58)	151.12 (35.22)	149.84 (30.99)	0.02	0.37	0.03
N16	152.62 (36.15)	142.51 (29.15)	142.79 (29.63)	144.94 (36.41)	137.57 (33.09)*	0.05	0.64	0.82
N12	153.3 (30.45)	153.9 (27.51)	138.27 (26.90)*	141.84 (35.20)*	134.09 (29.58)***	3.54	11.49 **	1.06
N10	147.6 (31.49)	142.84 (36.80)	124.34 (29.28)**	128.95 (35.75)**	111.65 (37.23)***	6.06*	10.33 **	0.02
DEM								
Adj Vert Time (s)	24.69 (3.51)	24.73 (3.50)	26.01 (3.93)	25.42 (4.14)*	26.31 (4.68)*	1.01	5.25*	0.16
Adj Hor Time (s)	25.53 (4.38)	25.69 (4.35)	27.39 (4.73)*	26.39 (4.52)*	27.84 (5.02)***	1.90	7.76**	0.06
Adj Ratio (s)	1.03 (0.08)	1.04 (0.09)	1.05 (0.09)	1.04 (0.11)	1.07 (0.14)	0.40	1.51	0.21
Vert errors	0.37 (0.61)	0.2 (0.41)	0.41 (0.96)	0.47 (0.82)	0.67 (1.67)	1.97	1.17	0.00
Hor errors	0.4 (0.86)	0.37 (0.61)	0.48 (0.66)	0.4 (0.97)	0.53 (0.86)	0.09	0.96	0.01
Visagraph III								
RE Fixations	113.57 (28.92)	106.4 (23.48)	114.88 (26.12)	113.67 (22.87)	112.23 (25.47)	0.65	0.98	5.09*
RE Regressions	16.97 (10.69)	15 (9.13)	17.12 (9.66)	15.67 (7.34)	15.13 (9.35)	0.32	0.57	2.71
Reading rate (wpm)	221.03 (52.54)	232.23 (51.55)	215.88 (43.87)	213.43 (43.43)	218.17 (47.97)	2.19	0.94	6.16*

$p<0.05$*; $p<0.01$**; $p<0.001$***