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ABSTRACT

Purpose: Astigmatism is an important refractive condition in children. However, the functional impact of uncorrected astigmatism in this population is not well established, particularly with regard to academic performance. This study investigated the impact of simulated bilateral astigmatism on academic-related tasks before and after sustained near work in children.

Methods: Twenty visually normal children (mean age: 10.8 ± 0.7 years; 6 males and 14 females) completed a range of standardised academic-related tests with and without 1.50 D of simulated bilateral astigmatism (with both academic-related tests and the visual condition administered in a randomised order). The simulated astigmatism was induced using a positive cylindrical lens while maintaining a plano spherical equivalent. Performance was assessed before and after 20 minutes of sustained near work, during two separate testing sessions. Academic-related measures included a standardised reading test (the Neale Analysis of Reading Ability), visual information processing tests (Coding and Symbol Search subtests from the Wechsler Intelligence Scale for Children) and a reading-related eye movement test (the Developmental Eye Movement test). Each participant was systematically assigned either with-the-rule (WTR, axis 180°) or against-the-rule (ATR, axis 90°) simulated astigmatism to evaluate the influence of axis orientation on any decrements in performance.

Results: Reading, visual information processing and reading-related eye movement performance were all significantly impaired by both simulated bilateral astigmatism ($p<0.001$) and sustained near work ($p<0.001$), however, there was no significant interaction between these factors ($p>0.05$). Simulated astigmatism led to a reduction of between 5% and 12% in performance across the academic-related outcome measures, but there was no significant effect of the axis (WTR or ATR) of astigmatism ($p>0.05$).

Conclusion: Simulated bilateral astigmatism impaired children's performance on a range of academic–related outcome measures irrespective of the orientation of the astigmatism. These

findings have implications for the clinical management of non-amblyogenic levels of astigmatism in relation to academic performance in children. Correction of low to moderate levels of astigmatism may improve the functional performance of children in the classroom.

INTRODUCTION

Moderate to high levels of uncorrected astigmatism (2.00 – 3.00 D) which persist throughout the plastic period of visual development (up to approximately 7 years of age)[1] can lead to permanent visual impairment, such as meridional amblyopia.[2, 3] Lower levels of uncorrected astigmatism (as low as 0.75 D) can also impact negatively upon functional performance such as reading ability in adults.[4-6] However, the empirical evidence concerning the relationship between uncorrected astigmatism and academic performance in children is limited. This is surprising since astigmatism is a relatively common refractive error in primary school children. A population based survey of 6-year-old Australian children revealed that 24% of correctable visual impairment in this population was associated with uncorrected astigmatism ≥1.00 D alone or 46% when considered in combination with spherical refractive errors.[7] The prevalence of astigmatism varies considerably with age[8] and ethnicity,[9, 10] and is typically classified according to the orientation of the negative correcting cylinder axis as being either with-the-rule (WTR, axis 0 or 180 ± 30°), against-the-rule (ATR, axis 90 ± 30°) or oblique (axis between 30-60 or 120-150°),[11] with WTR (40%) and ATR (44%) astigmatism being more common in school children than oblique astigmatism (16%).[12]

Although a number of published prescribing guidelines discuss the magnitude of astigmatism that requires refractive correction in childhood, the levels specified are primarily designed to prevent the development of meridional amblyopia.[13-15] For lower levels of astigmatism, which are common in children, there is no consensus regarding the minimum level that requires correction to ensure optimal visual performance. This may be due to variability in the extent to which uncorrected astigmatism impacts on functional performance, which depends upon both the magnitude and axis of astigmatism.[4, 11] Some authors recommend that astigmatism as low as 0.50 D should be corrected, particularly if oblique or ATR in orientation,[16] or if asthenopic symptoms are present,[17] while Congdon et al.[18] and Leat[19] both suggest that astigmatism ≥0.75 D should always be corrected in school children irrespective of symptoms. However, other published guidelines suggest that prescription for astigmatic refractive errors ≥1.00 D may benefit school aged children.[20] Importantly, these prescribing guidelines that target non-amblyogenic, lower levels of astigmatism in children[16-20] are largely based on practitioner clinical experience rather than empirical evidence.

The evidence that does exist regarding the impact of uncorrected astigmatism on the academic performance of children is mixed and is derived from a range of study designs. Eames[21] found no significant difference in the prevalence of astigmatism (>1.00 D) in "reading disabled" children and an age and IQ matched control group (7% and 5% respectively) but did not elaborate on the specific criteria used to classify children as "reading disabled". In contrast, Garber[22] observed significantly lower reading scores (17% lower) in uncorrected astigmatic (≥2.00 D) Navajo Indian school children, a population known to have a high prevalence of astigmatism, compared to non-astigmatic children of the same ethnic group. A significant limitation of the latter study was the use of the teacher's subjective grading as a measure of reading ability, which is non-standardised and potentially subject to bias. In addition, the cross sectional nature of this study limits the ability to draw conclusions regarding the causal nature of the relationship between uncorrected astigmatism and academic performance.

A number of studies have attempted to investigate the minimum level of astigmatism that significantly degrades visual or functional performance in adults. Schubert and Walton[23] examined the effect of simulated astigmatism on visual symptoms in adults and showed that lower levels of astigmatism (1.00 D) produced asthenopic symptoms during a 30 minute near task, which the authors suggest could potentially lead to a reduction in sustained reading ability. Sixty-three percent of their participants reported subjective blur and spatial distortion while 69% reported headaches following the astigmatic simulation. Similarly, in a study of older adults (50-69 years), Wolffsohn et al.[4] reported that simulated astigmatism as low as 1.00 D significantly reduced high and low contrast visual acuity and impaired functional performance measures including reading speed and the ability to read text on mobile phones or computer screens. In another study, Wills et al.[6] investigated the impact of simulated astigmatic refractive errors of 1.00 D and 2.00 D on reading performance of young adults (18 to 33 years), using the Discrete Reading Rate test. Simulated astigmatism significantly reduced reading speed even at the lower level of astigmatism (1.00 D) and it was hypothesised that the decrease in reading performance may be a consequence of the reduced resolution resulting from the simulated astigmatism. In a more recent study, Casagrande et al.[5] showed that 0.75 D of simulated astigmatism impaired reading performance in adults.

In addition to the magnitude of astigmatism, the impact of both uncorrected and simulated astigmatism on visual and functional performance differs depending on axis orientation.[4-6, 11] However, the evidence is conflicting; some studies have reported that ATR astigmatism results in a greater reduction in performance (for both visual acuity and reading parameters),[4, 6] others suggest that WTR is more detrimental[5, 24] and further studies revealed equivalent performance with WTR and ATR astigmatic simulations.[11, 25, 26] These differences between studies may be a result of differences in the specific methodologies employed. These include factors such as the method of astigmatic simulation (cylindrical lenses with or without spherical equivalent compensation), the functional assessments used as outcome measures (visual acuity, reading or driving performance), the age of participants (young or older adults), pupil size (natural or artificial) and accommodative control (with or without cycloplegia).

Although several authors have investigated the impact of simulated astigmatism on visual performance,[4, 6, 11, 23, 27] these studies have been limited to adults. The impact of simulated astigmatism on standardised measures that are related to academic performance in children has not been investigated. Children spend 4 to 5 hours each day on academic activities and have been shown to maintain constant near fixation for up to 16 minutes;[28] however, the impact of uncorrected astigmatism on sustained school-based near tasks has not been established. The aim of the current study was thus to investigate the impact of simulated bilateral astigmatism, combined with sustained near work, on a range of standardised academic-related measures in children. The influence of the axis of the astigmatic simulation (WTR or ATR) on performance was also investigated, along with the association between the reduction in distance and near visual acuity during simulated astigmatism and the observed changes in academic-related performance. A repeated measures design was used to control for potential differences between participants (such as socioeconomic status and IQ) and a range of standardised academic-related tasks that are representative of activities commonly conducted in school classrooms were included as outcome measures.

METHODS

Recruitment flyers were sent to academic and professional staff of Queensland University of Technology (QUT), as well as to parents of children from Years 5 to 7 at local primary schools. Twenty children (mean age 10.8 ± 0.7 years) consisting of 6 males and 14 females, participated in this study. The participants were all of Caucasian ethnicity and spoke English as their first language. The study was conducted in accordance with the Declaration of Helsinki and was approved by the QUT Human Research Ethics Committee. Written informed consent was obtained from the participants and their parents following a full explanation of the experimental procedures. Participants had the option to withdraw from the study at any time.

Each participant underwent a visual screening examination to determine their eligibility for inclusion in the study. Exclusion criteria for participants included best corrected distance visual acuity worse than 0.00 logMAR in either eye, any significant refractive error (defined as spherical equivalent refraction < -0.75D or > +0.75D, spherical equivalent anisometropia > 0.25 D and astigmatism > 0.25 D), stereoacuity worse than 60 seconds of arc, any evidence of strabismus or amblyopia, any history of ocular disease or surgery or any known binocular vision abnormality. The screening examination included measurement of refractive status, which included non-cycloplegic retinoscopy (which has been shown to be accurate and suitable for refractive error screening in children of this age)[29] and subjective refraction. During non-cycloplegic retinoscopy, pupil size and the movement and brightness of the reflex were also monitored for fluctuations suggestive of accommodative control difficulties, latent hyperopia, attentional or fixation changes. A fogging test with +1.50 D lenses in addition to the optimal sphero-cylindrical refraction was also performed and binocular distance visual acuity was re-measured. None of the participants showed any evidence of significant latent hyperopia. Binocular vision status was determined by assessing monocular and binocular amplitudes of accommodation (push-up method), near point of convergence, stereopsis (TNO test) and near dissociated horizontal heterophoria (Howell-Dwyer card, Cyclopean Design, Heathmont, Australia).

Assessments of visual acuity and academic-related performance were conducted binocularly with either the participant's optimal refractive correction or the bilateral astigmatic simulation (added to the optimal refractive correction), at two separate time points. The order of the visual conditions (optimal refractive correction or astigmatic simulation condition) was randomised between participants. Measurements were conducted immediately following the introduction of each visual condition (using full aperture trial lenses placed in a trial frame), and repeated again after 20 minutes of sustained near work (with the optimal refraction or the simulation lenses in place). Testing was conducted during two separate sessions, controlling for time of the day, with participants being assessed under only one visual condition during each visit. Pen and paper puzzles, comprised of N10 print at a working distance of 40cm, were performed by each participant during the 20 minute near task. This task duration was selected based on a previous study which reported that, on average, school children engage in near point tasks continuously in approximately 15 minute intervals.[28] A reading board was used throughout each near task to ensure a constant working distance of 40cm between participants and across experimental sessions. The assessment of all of the outcome measures was performed under photopic illumination conditions (680 lux) and the order in which the academic-related outcome measures were administered was randomised between participants to minimise potential order effects. Published guidelines for the correction of childhood refractive errors recommend prescribing for uncorrected astigmatism between 1.00 to 2.00 D.[20, 30] Therefore, 1.50 D, the intermediate level of this range, was selected for this study. The orientation of the axis of astigmatism was systematically varied between participants, with half receiving a WTR simulation and the other half receiving an ATR astigmatic simulation. These orientations were chosen since WTR and ATR astigmatism are more common in children compared to oblique astigmatism.[12, 31] Bilateral astigmatism was simulated using positive cylindrical lenses (i.e. +1.50 D oriented at either 90 or 180 degrees in addition to the optimal sphero-cylindrical refraction) with the inclusion of a compensating negative spherical lens to ensure the simulation condition maintained a plano spherical equivalent (i.e. -0.75 DS/ +1.50 DC x 90 or 180). This resulted in a 1.50 D simulated astigmatic interval, with +0.75 D and -0.75 D of imposed defocus along each principal meridian, and the circle of least confusion positioned at the retinal plane.

Outcome measures

Reading performance

The Neale Analysis of Reading Ability test (https://shop.acer.edu.au/acer-shop/group/NEA) was selected to assess reading performance. This test evaluates three main components of reading performance (rate, accuracy and comprehension) and is one of the most widely used standardised measures of reading performance with published normative data available for Australian children.[32] The test is made up of four individual forms, with each form consisting of six passages of increasing reading difficulty. One form was used during each assessment (two for each visit – before and after the sustained near task). Participants read aloud each passage, each of which was followed by a series of comprehension questions. Once the specified number of pronunciation errors was reached, testing was terminated. Reading rate (words per minute) was derived from the time taken to complete all of the individual passages using the following formula: (total words read/total time taken) x 60. For each passage, the total number of reading errors was subtracted from the maximum permissible errors for that particular passage and these values were summed for the six passages to provide the reading accuracy score. Reading comprehension was quantified in terms of the total number of questions answered correctly.[33]

Visual Information Processing (VIP) performance

The processing speed domain of the Wechsler Intelligence Scale for Children - Australian Standardised Edition (WISC-IV) (https://www.pearsonclinical.com.au/products/view/46) was used to assess VIP performance. This is a widely used test for assessing the intellectual ability of children aged 6 to 16 years old with published normative data available for Australian children.[34] The processing speed domain includes two subtests, Coding and Symbol Search, which closely mirror copying tasks that are commonly performed in classrooms.

The Coding subtest provides a measure of speed and accuracy of visual motor coordination, attention skills, visual scanning and tracking. Participants were presented with a rectangular grid of digits and instructed to substitute the appropriate symbol for each of the digits, using a code that appears at the top of the page. Participants were required to complete as many items as possible within 120 seconds, with their score being the number of correct responses recorded within that time period.

The Symbol Search subtest is a measure of perceptual discrimination, speed, accuracy, visual scanning and visual motor coordination. Participants were presented with a series of horizontal arrays of symbols, which were divided into a target and a search group. For each array, participants were instructed to scan the two groups and tick a box to indicate whether the symbols in the target group also appeared in the search group. As for the Coding subtest, participants were required to complete as many items as possible within 120 seconds, with the score being the number of correct responses recorded within that time period.

Reading-related eye movement performance

Reading-related eye movement performance was evaluated using the Developmental Eye Movement (DEM) test (https://www.bernell.com/product/DEM/417), which is designed to control for rapid automatised naming (RAN) skills.[35] While DEM scores do not correlate with quantitative measures of eye movements, DEM performance is associated with reading performance and speed of visual processing.[36] Based on this relationship, and the fact that the construct of the DEM accounts for verbalisation speed, the DEM test has been suggested to be suitable for identifying children at risk of delayed academic progress.[36] This test consists of a pre-test, two subtests with 40 numbers arranged in vertical columns (subtests A and B) and a subtest with 16 horizontal rows consisting of 80 irregularly spaced numbers (subtest C). The vertical subtest is designed to measure RAN ability while the ratio of horizontal to vertical subtest times (after adjustment for errors), provides a measure of reading-related saccadic eye movements (RSEM), by factoring out the effect of RAN.[35] This test was administered according to the standard procedure.[35]

Distance and near visual acuity

Distance visual acuity (VA) was measured and recorded binocularly using a standard high contrast Bailey-Lovie logMAR chart (http://precision-vision.com/products.html) at a distance of 6 metres.[37] Participants read each letter commencing from the top line of the chart and were encouraged to read letters when unsure. The measurement was terminated once four letters were reported incorrectly on a line.[38] Visual acuity was scored on a letter by letter basis with each correctly identified letter representing a score of -0.02 log units.[39] The same procedure was used to measure near visual acuity using a high contrast near Bailey-Lovie logMAR letter chart (http://precision-vision.com/products.html) at 40 cm.

STATISTICAL ANALYSIS

Statistical analysis was performed using SPSS 21.0 (www.ibm.com/software/au/analytics/spss/). Normality of data was determined using the Shapiro-Wilk test, which revealed that all data were normally distributed. A three way repeated measures analysis of variance (ANOVA) was used to examine the influence of refractive error simulation (with or without 1.50 D of bilateral astigmatism) and sustained near work (before and after the 20 minute near task) on the various academic-related outcome measures. The orientation of the cylinder axis during the simulation (ATR or WTR) was included as a between-subjects factor. All two-way and three-way interactions were examined. Pearson's correlation analysis was conducted to investigate if the reduction in distance or near visual acuity resulting from the simulated astigmatism was associated with any of the reductions in the academic-related outcome measures. A p value of < 0.05 was considered statistically significant.

RESULTS

All participants had minimal refractive error with a group mean spherical component of +0.23 ± 0.45 D (range: -0.75 to +0.75 D) and -0.08 ± 0.12 D of astigmatism (range: 0.00 to -0.25 D). The mean reduction in binocular best corrected visual acuity with the +1.50 D fogging lens was 0.65 ± 0.02 logMAR as would be expected for this magnitude of imposed defocus if participants were optimally corrected.[40] Binocular vision parameters were within clinically normal limits for children in this age group, with group mean values of; binocular amplitude of accommodation: 14.95 ± 0.89 D, near point of convergence: 4.70 ± 0.80 cm, stereoacuity: 28.50 ± 12.78 seconds of arc and near horizontal heterophoria: 1.10 ± 1.45 Δ exophoria.[41, 42] Data collected with the optimal refractive correction prior to the sustained near work task also indicated that more than 85% of the participants had an above average score (greater than the 50^{th} percentile) for their age on all the academic-related outcome measures, with a group mean equal to the 70^{th} percentile.

Reading performance

Reading rate, accuracy and comprehension were all significantly reduced by simulated bilateral astigmatism (rate: $F_{1,18}$ = 138.16, p<0.0001; accuracy: $F_{1,18}$ = 119.56, p<0.0001; comprehension: $F_{1,18}$ = 89.44, p<0.0001) and sustained near work (rate: $F_{1,18}$ = 37.42, p<0.0001; accuracy: $F_{1,18}$ = 16.20, p = 0.001; comprehension: $F_{1,18}$ = 29.60, p<0.0001). However, there was no significant interaction between these factors for any of the reading performance components (rate: $F_{1,18}$ = 2.53, p = 0.13, accuracy: $F_{1,18}$ = 3.36, p = 0.08, comprehension: $F_{1,18}$ = 1.99, p = 0.18) (Figure 1). There was also no significant between group effect of axis of astigmatism, and no other significant two-way or three-way interactions. Bilateral astigmatic simulation alone resulted in a reduction in each of the reading components examined with 6.2% for rate, 5.2% for accuracy and 8.8% for comprehension. These reductions increased slightly following sustained near work; 6.7% (rate), 5.6% (accuracy) and 10.8% (comprehension), but this additional reduction (interaction) did not reach statistical significance.

Visual information processing performance

Performance on the Coding and Symbol Search subtests was significantly reduced by simulated bilateral astigmatism (Coding: $F_{1,18}$ = 69.57, p<0.0001 and Symbol Search: $F_{1,18}$ =192.49 , p<0.0001) and sustained near work (Coding: $F_{1,18}$ = 13.92, p = 0.002 and Symbol Search $F_{1,18}$ = 43.46, p<0.0001). However, there was no significant interaction between the astigmatic simulation and sustained near work for either of the VIP subtests (Coding: $F_{1,18}$ = 0.53, p = 0.48 and Symbol Search: $F_{1,18}$ = 2.10, p = 0.16) (Figure 2). There was also no significant between group effect of astigmatic axis, and no other significant two-way or three-way interactions. The astigmatic simulation reduced Coding and Symbol Search scores by 8.7% and 11.8% respectively which were further impaired following sustained near work (Coding 9.8% and Symbol Search 12.9%), but this small additive effect was not statistically significant.

Reading-related eye movement performance

Vertical and horizontal time components of the DEM test were significantly increased by both the bilateral astigmatic simulation ($F_{1,18}$ = 218.40, p<0.0001 and $F_{1,19}$ = 156.90, p<0.0001 respectively) and sustained near work ($F_{1,18}$ = 161.04, p<0.0001 and $F_{1,18}$ = 53.30, p<0.0001 respectively). The DEM ratio increased significantly only in the presence of the simulated astigmatism ($F_{1,18}$ = 38.58, p<0.0001) (Figure 3). As for the other outcome measures, no significant interaction was observed between bilateral simulated astigmatism and near work for any DEM parameter (vertical: $F_{1,18}$ = 0.01, p = 0.95, horizontal: $F_{1,18}$ = 1.73, p = 0.21, ratio $F_{1,18}$ = 0.25, p = 0.62). There was also no significant between group effect of astigmatism axis, and no other significant two-way or three-way interactions. Slower vertical (5.9%) and horizontal (7.9%) times, and an increased ratio (1.8%) were observed for the astigmatism simulation. However, the additional reductions in performance that were observed in the presence of sustained near work were not significant; 7.2% for vertical time, 9.5% for horizontal time and 1.8% for ratio.

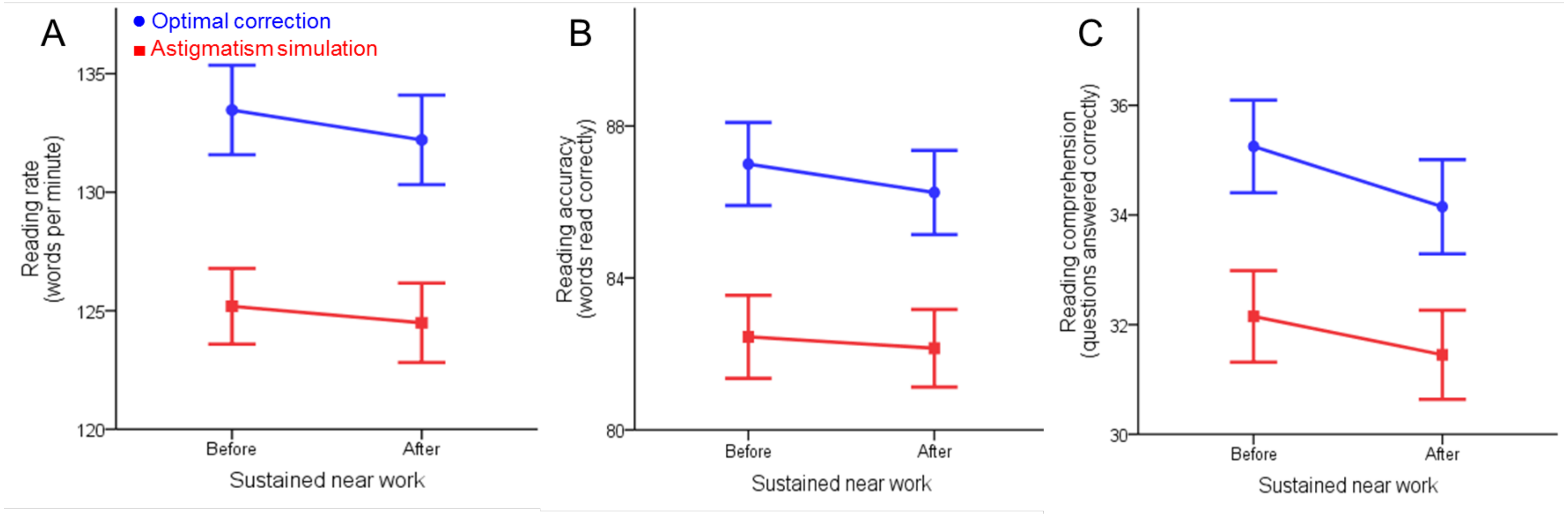

Figure 1: Mean reading performance (Neale Analysis of Reading Ability Test: higher score indicates better performance); rate (A), accuracy (B) and comprehension (C) before and after the 20 minute sustained near work task with and without the 1.50 D bilateral astigmatic simulation (error bars represent standard error of the mean).

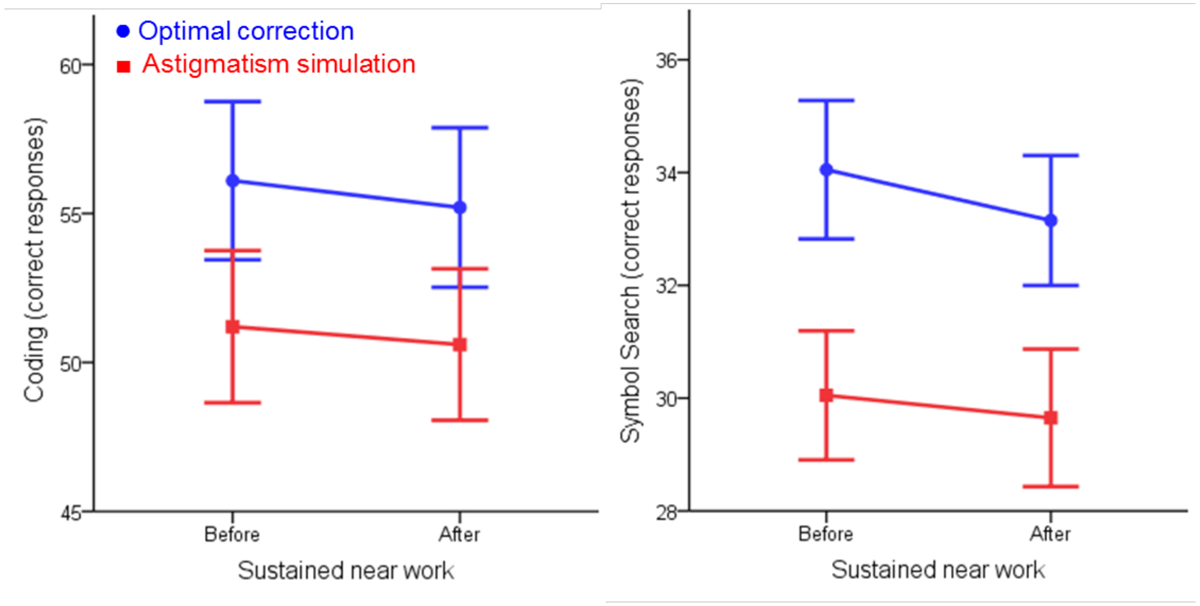

Figure 2: Mean VIP performance (WISC subtests: higher score indicates better performance); Coding (A) and Symbol Search (B) before and after the 20 minute sustained near work task with and without the 1.50 D bilateral astigmatic simulation (error bars represent standard error of the mean).

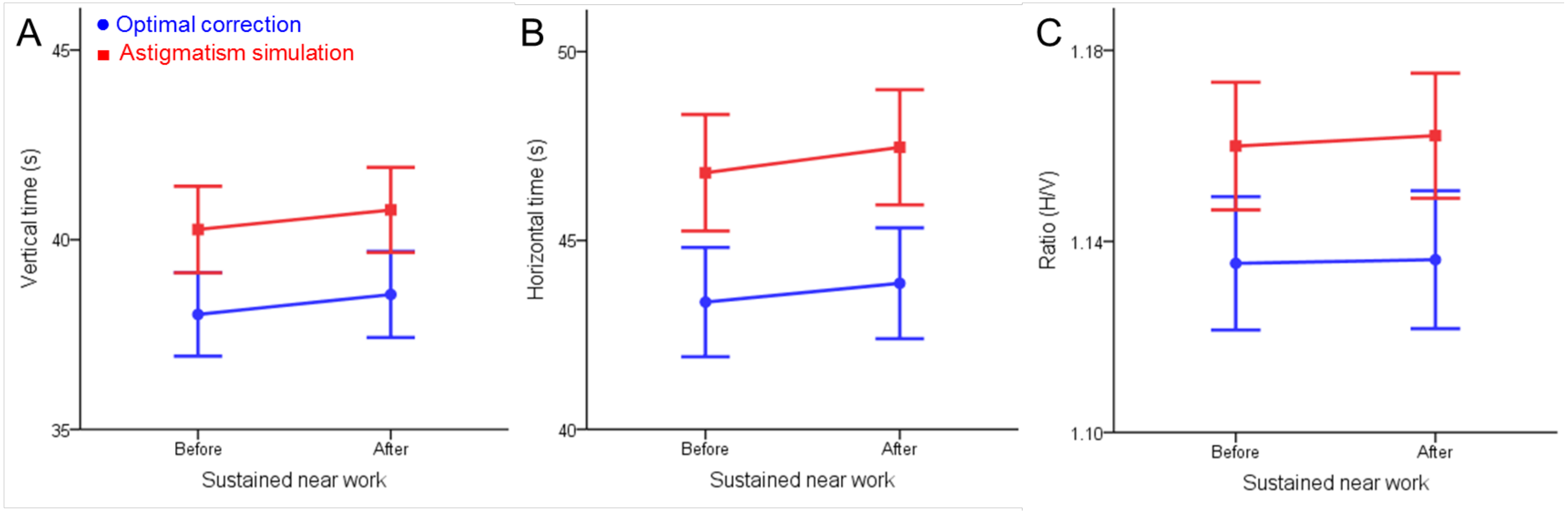

Figure 3: Mean DEM test performance (higher score indicates poorer performance); vertical time (A), horizontal time (B) and ratio (C) before and after the 20 minute sustained near work task with and without the 1.50 D bilateral astigmatic simulation (error bars represent standard error of the mean).

Distance and near visual acuity

As expected, both distance and near visual acuity were significantly impaired in the presence of simulated bilateral astigmatism, with reductions of 0.18 ± 0.05 ($F_{1,18}$ = 343.82, $p<0.0001$) and 0.16 ± 0.05 ($F_{1,18}$ = 264.76, $p<0.0001$) logMAR respectively. However, sustained near work in isolation (without astigmatic simulation) did not influence visual acuity at distance or near; 0.02 ± 0.03 ($F_{1,18}$ = 4.16, p = 0.06) and 0.01 ± 0.02 ($F_{1,18}$ = 2.98, p = 0.10) logMAR reductions respectively. There was also no significant interaction between simulated astigmatism and sustained near work for either of these measures of visual acuity ($F_{1,18}$ = 1.77, p = 0.20 and $F_{1,18}$ = 2.16, p = 0.16).

While there was no significant effect of axis orientation, larger reductions in performance were observed with the ATR simulation compared to WTR astigmatism for the majority of the outcome measures (relative to optimal correction before sustained near work), as shown in Table 1.

Table 1: Reduction in performance (relative to optimal refractive correction before sustained near work) for WTR and ATR astigmatic simulation.

Academic-related outcome measures	WTR (%)	ATR (%)
Reading performance[a]		
Rate (words per minute)	-6.00	-6.40
Accuracy (words read correctly)	-4.92	-5.54
Comprehension (questions answered correctly)	-9.63	-7.95
VIP performance[a]		
Coding (correct responses)	-7.65	-9.82
Symbol Search (correct responses)	-11.14	-12.32
DEM performance[b]		
Adjusted vertical time (s)	5.40	6.34
Adjusted horizontal time (s)	7.30	8.47
Ratio	1.74	2.68

[a] Higher score indicates better performance
[b] Higher score indicates poorer performance

There were also no significant correlations between the change in either distance or near visual acuity and the observed changes in any of the academic-related outcome measures (Table 2).

Table 2: Pearson's correlation coefficients for the change in academic-related outcome measures in relation to the change in distance and near visual acuity in the presence of the bilateral 1.50 D astigmatic simulation (without sustained near work).

Academic-related outcome measures	**Distance VA r (p value)**	**Near VA r (p value)**
Reading performance		
Rate	0.25 (0.29)	0.12 (0.62)
Accuracy	0.001 (0.99)	0.02 (0.92)
Comprehension	-0.10 (0.67)	0.06 (0.81)
VIP performance		
Coding	-0.04 (0.85)	0.13 (0.57)
Symbol Search	0.35 (0.13)	0.12 (0.60)
DEM performance		
Adjusted vertical time	-0.20 (0.39)	-0.42 (0.16)
Adjusted horizontal time	-0.04 (0.87)	-0.38 (0.10)
Ratio	0.12 (0.61)	0.04 (0.87)

DISCUSSION

This is the first study to examine the impact of simulated bilateral astigmatism on standardised academic-related measures in children before and after a period of sustained near work, and to examine whether ATR or WTR astigmatism had a differential impact on performance. A repeated measures design was used to control for potential confounding factors and a plano spherical equivalent was maintained during the simulation to isolate the influence of astigmatic defocus. Simulated astigmatism, independent of the orientation, resulted in impairment of reading, visual information processing and reading-related eye movement performance. These findings are in general accord with several studies that have investigated the functional impact of astigmatism in adults (ages 18-69 years).[4-6]

Simulated bilateral astigmatism resulted in a significant reduction in reading performance with the Neale test of reading comprehension showing the highest decrement (8.8%) compared to rate (6.2%) and accuracy (5.2%). These findings, particularly with respect to reading comprehension, have important implications for children in the ‘reading to learn’ stage, during which reading is the fundamental mechanism used to obtain and interpret new knowledge.[43, 44] Therefore, uncorrected astigmatism in children may be detrimental to comprehension of written information, which may subsequently impact on their overall academic performance. The impaired reading performance, in particular, the reduction in reading speeds evident in the presence of the astigmatic simulation is consistent with previous studies of adults.[4-6, 11] Casagrande et al.[5] used a similar magnitude of astigmatism (1.50 D) in their recent simulation study, and observed a slightly greater decrement in the reading speed of their adult participants (9%) compared to the 6% decrease observed in this current study of children. This slight discrepancy between studies may be a result of the differences in the methodologies employed; Casagrande et al.[5] imposed astigmatic blur in their study participants using cylindrical lenses alone without compensating for the induced spherical equivalent blur and used the Salzburg Reading Desk test (with reading materials that were displayed on a computer screen), while in the current study, the spherical equivalent was always plano during the astigmatic simulation and a standardised (paper based) test for Australian children was used to assess reading performance. The difference may also be a consequence of the naturally faster reading rates of an average, visually normal adult when compared with a child.

The current study also found a significant reduction in performance of both VIP subtests in the presence of the bilateral astigmatic simulation. Visual information processing is considered an important skill for children to perform well in school.[45] The impaired performance on both the Coding and Symbol Search subtests, which mirror visual analysis and copying tasks frequently performed in classrooms, suggests that children with uncorrected astigmatism of 1.50 D or more may face difficulty in efficiently interpreting visually presented information. This might be a disadvantage for children when undertaking time-based tasks, such as exams, which need to be completed within a specified duration.

The astigmatic simulation also resulted in slower vertical (5.9%) and horizontal (7.9%) DEM times and an increase in the ratio component (1.8%). This finding is in agreement with Wills et al.,[6] who observed a similar effect of astigmatic blur on DEM test performance in adult participants, but to a lesser extent compared to this study of children. Given that both RAN and RSEM skills are linked with certain aspects of reading and visual processing,[36, 46] these findings further imply that uncorrected astigmatism may impact negatively on reading and visual information processing ability in children. This is consistent with the decrement in performance observed in both the Neale and VIP tests in this study.

We also observed a small but significant decrease in performance in almost all of the academic-related measures (except the DEM ratio) following prolonged near work in the absence of the astigmatic simulation. While sustained near work activities constitute a significant proportion of classroom tasks, very few studies have investigated the impact of prolonged near fixation, with or without simulated visual impairments, on the functional performance of children. This finding has important implications for teachers in terms of planning and managing daily classroom activities. Frequent short breaks should be incorporated between continuous near work activities to minimise visual fatigue, as this may impact on a child's ability to perform optimally in school, irrespective of their refractive status.

No significant interaction was observed between astigmatic defocus and sustained near work. That is, the decrease in performance observed as a result of the astigmatic simulation was not significantly exacerbated when combined with sustained near work, which was a consistent finding across all academic-related outcome measures included in this study. The lack of an additive effect between imposed astigmatic defocus and near work could be a result of short-term adaptation to meridional blur[47-50] during the 20 minute near task (i.e. any detrimental effect of sustained near work may have been masked by an improvement in visual performance due to adaptation to the astigmatic blur). There is some evidence to suggest that the visual system can adapt rapidly (within 2 minutes) to imposed lower-order astigmatism.[49] While the exact mechanism underlying this process remains unclear, evidence suggests the adaptation is cortical in origin.[50, 51] In addition, the magnitude (greater adaptation for larger magnitudes of blur) and orientation (adaptation to horizontally imposed astigmatism resulted in images appearing more blurred vertically and vice versa) of the imposed blur appears to influence the capacity of the visual system to adapt,[49] as well as the magnitude and orientation of the individuals habitual astigmatism.[47] The potential confounding influence of any longer-term adaptations to habitual astigmatism (corrected or uncorrected) in this study was minimised by imposing a strict inclusion criteria with respect to habitual refractive astigmatism (≤0.25 D).[47]

Surprisingly, the orientation of the imposed astigmatic simulation did not significantly influence academic-related performance despite having a sufficient number of participants to detect a statistically significant difference in outcome measures for a between subject factor. This is in contrast to the majority of previous studies which show that the impact of astigmatic blur on visual or functional performance varies depending on the axis.[4-6, 24] Some studies have shown that ATR astigmatism is more detrimental,[4, 6, 52] while others report that WTR astigmatism has the greatest impact.[5, 24] These differences could be attributed to the variation in methodologies employed. All of these previous studies have been performed on young or older adults and included different functional measures compared to the current study. Some of these studies also cyclopleged their participants (accommodation control is completely inhibited and a larger pupil size may result in an increase in higher order aberrations) or used different methods of simulating the astigmatic refractive error (without compensating for spherical defocus). Another potential confounding variable which has not been considered in previous simulation studies is the participant's habitual astigmatism, which has been suggested to impact on the short term adaptation to imposed astigmatic blur.[47, 48] While not reaching statistical significance, there was a trend for larger reductions in performance to result from ATR astigmatic simulation compared to WTR in the majority of the outcome measures in this study, which is consistent with the findings of previous studies.[4, 6, 11]

The exact mechanism underlying the impaired performance of the academic-related outcome measures in this study remains unclear. Wills et al.[6] suggested that reduced resolution due to meridional blur may account for impaired reading performance; however, in the current study, there were no significant associations between the reduction in distance or near visual acuity resulting from the simulated astigmatic blur and the reduction in reading, VIP or eye movement performance. This is most likely due to the fact that the print sizes of the outcome measures had a substantially lower visual acuity demand (calculated based on the critical resolution of the targets and a working distance of 40 cm) than the participants' acuity threshold in the presence of simulated astigmatic blur; Neale test (0.5 - 0.6 logMAR), VIP test (0.8 - 0.9 logMAR), DEM test (0.6 logMAR).

Overall, the bilateral astigmatic simulation of 1.50 D resulted in a significant decrement in performance for a range of academic-related measures. On average (for all the academic-related measures examined; Neale, VIP and DEM tests), children's performance decreased from the 70th percentile during optimal refractive correction prior to sustained near work to the 59th percentile during the astigmatic simulation and remained relatively stable (at the 58th percentile) following the sustained near task in addition to the refractive error simulation. Even though this level of performance is not typically considered as a low level of functioning, these results do indicate that children may perform below their full potential in the presence of uncorrected astigmatism. Therefore, refractive correction for this level of astigmatic error would be of potential benefit for children in regard to academic performance.

The results of this study should be considered in light of some potential limitations. The use of a simulation approach may have resulted in a sudden change in the visual environment in this sample of children with minimal refractive error and normal binocular vision; thus potentially overestimating the effects observed across the different outcome measures compared to children with actual uncorrected astigmatism who may have partially adapted to their refractive error.[47] However, the repeated measures design allowed for control of potential factors that may vary between participants as well as inter-individual variations in performance. An additional limitation is that only WTR and ATR astigmatic simulations were included in this study; this is justified by the fact that these are more commonly found in the paediatric population than oblique astigmatism.[12, 31] It would nonetheless be of interest to investigate the impact of oblique astigmatism on functional performance in children, given that some studies have shown that oblique orientations result in the greatest reductions in acuity and reading measures in adults.[4, 11] The use of non-cycloplegic refraction to determine the refractive status of participants is another possible limitation, which may have underestimated the magnitude of any latent hyperopia to a small degree. However, the results of the +1.50 D fogging test and the normal accommodative/vergence profile support our assertion that the participants included in the current study had minimal latent hyperopia. The prolonged wearing of a trial frame throughout the experimental session may have been uncomfortable for the participants and could have contributed to the reduction in performance observed following sustained near work. Therefore, future studies should address this issue by including the astigmatic lenses in comfortable children's spectacle frames.

In summary, the findings of this study demonstrated that simulated astigmatism in children resulted in impaired performance on a range of academic-related measures. These results suggest that refractive correction for low to moderate levels of uncorrected astigmatism in children is important in order to minimise potential functional disadvantage at school. Future studies should explore the impact of different magnitudes of both simulated and habitual uncorrected astigmatism in children, especially those who have below average academic performance.

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Supplementary information:

Group mean data (standard deviation) for all the visual conditions before and after 20 minutes of sustained near work.

Academic-related outcome measures	Mean Performance (SD)			
	Optimal refractive correction		1.50 D astigmatism simulation	
	Before 20 minutes near work	After 20 minutes near work	Before 20 minutes near work	After 20 minutes near work
Reading performance[a]				
Rate (words per minute)	133 (8)	132 (8)	125 (7)	124 (8)
Accuracy (words read correctly)	87 (5)	86 (5)	82 (5)	82 (6)
Comprehension (questions answered correctly)	35 (4)	34 (4)	32 (4)	31 (4)
Visual Information Processing (VIP) (WISC subtests)[a]				
Coding (correct responses)	56 (12)	55 (12)	51 (11)	51 (11)
Symbol Search (correct responses)	34 (6)	33 (5)	30 (5)	30 (5)
Developmental Eye Movement test (DEM)[b]				
Adjusted vertical time (s)	38.03 (4.92)	38.56 (5.07)	40.27 (5.10)	40.78 (5.02)
Adjusted horizontal time (s)	43.37 (6.48)	43.87 (6.56)	46.79 (6.90)	47.47 (6.82)
DEM ratio	1.14 (0.08)	1.14 (0.06)	1.16 (0.06)	1.16 (0.06)
Visual acuity[b]				
Distance (logMAR)	-0.12 (0.06)	-0.11 (0.06)	0.06 (0.05)	0.06 (0.05)
Near (logMAR)	-0.10 (0.06)	-0.09 (0.05)	0.07 (0.06)	0.07 (0.05)

[a] Higher score indicates better performance, [b] Higher score indicates poorer performance

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