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Do reduced visual acuity and refractive error affect classroom performance?

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The role of visual acuity and refractive errors in the academic performance of children is controversial due to the variable quality of the research in this area and the mixed findings reported. This review aims to provide clarity by reviewing and critiquing relevant peer-reviewed publications and also summarises what is known regarding the visual demands of modern classroom environments. The outcomes of this review suggest that while a number of studies have investigated the role of vision in relation to children's academic performances, the veracity of the evidence obtained from the majority of these studies is undermined by methodological limitations. Comparisons between studies are constrained by differences in experimental designs, instrumentation and sample characteristics. Despite these limitations, the weight of evidence suggests there is an association between academic performance and both visual acuity and refractive error in children. However, well-designed experimental studies are necessary to further understand the relationship between these parameters.

Key words: academic performance, children's vision, reading, refractive error, visual acuity

Refractive errors are common in children, with prevalence rates varying dependent on ethnicity.[1–5] When uncorrected, these refractive errors can cause symptoms of blurred vision, ghosting, headaches, asthenopia, and can also potentially have a negative impact on visual performance at near.

On a normal school day, almost half of academic-related tasks are conducted at near, and on average, it has been demonstrated that children typically engage in continuous near fixation tasks (such as continuous reading or undertaking tasks at near) for 23 (±5) minutes at a time.[6] This suggests that, in addition to the visual acuity demands imposed by many classroom activities, conditions that do not inherently impair vision quality, such as uncorrected hyperopia, are also important due to their capacity to impede comfortable access to visual information presented in the classroom.

Referral rates from school vision screenings in both Australia and the USA are typically around 20–30 per cent,[7–9] but vary depending on a number of factors. These factors include the prevalence of eye conditions in the population of interest, access to eye-care services, as well as the pass/fail criteria and the range of conditions targeted by the screening.[10] For example, screening for reduced visual acuity alone results in substantially fewer referrals compared to more comprehensive vision screenings designed to detect all refractive errors and a range of binocular vision conditions.[8] Nevertheless, these referral rates indicate that a number of children are potentially impacted by untreated visual conditions. The fact that many vision conditions go undetected in school-aged children[11] is highly relevant, given the functional impact that uncorrected eye conditions can theoretically have on a child's ability to achieve and maintain clear, comfortable vision. This is predicated on the widely, although not universally, held viewpoint that good vision more broadly (including visual acuity, as well as accommodative and binocular vision function, oculomotor and visual processing skills) plays an important role in academic-related performance.[12–14]

However, there is no consensus regarding precisely what level of refractive error and reduction in visual acuity negatively impact on a child's academic performance. This uncertainty has led to widespread discrepancies regarding the strategies adopted to clinically manage commonly presenting visual problems in children. Decisions regarding the correction of hyperopia to prevent strabismus and amblyopia development are largely evidence-based,[15] given the availability of research in this area. However, correction of hyperopia for the performance of near work tasks tends to be based on clinical experience, as the literature assessing the potential impact of the condition on these near tasks is limited (although there is growing research in this area).

This review aims to provide clarity regarding the strength or otherwise of current evidence by reviewing and critiquing peer-reviewed publications that have investigated the relationship between refractive error, visual acuity and academic-related measures in children. Additionally, this review summarises what is known regarding the visual demands of modern classroom environments.

The classroom

The physical characteristics of the individual classroom and associated learning materials, and the nature of the academic task, influence the demands placed on the visual system. In addition to sustained viewing at different distances, common classroom tasks include shifting between distance and near fixation, shifting between different tasks at near (copying tasks from page to page), and shifting between intermediate and near distances (between a workbook and a computer screen). This consequently has the potential to disadvantage children with untreated visual anomalies, including uncorrected refractive errors and accommodative and/or vergence dysfunctions.

An observational study assessing 11 classrooms from four North American schools showed that children in Grades 4 and 5 spend four to five hours per day on academic activities, including distance work (observing demonstrations by the teacher), near work (reading and writing) and successive alternations between distance and near work (copying from the blackboard).[16] Fifty-four per cent of learning activities involved reading and writing, with students engaging in continuous near and distance tasks for approximately 16 and seven minutes at a time, respectively. However, given the study was undertaken in the early 1990s, its applicability to current classroom environments and school curricula is limited, as modern technologies such as computers and smart boards were not commonly employed when this study was undertaken.

More recently in 2016, Narayanasamy et al.[6] studied children in 33 modern Australian primary school classrooms (Grades 5–6) from eight different schools and showed that in a typical school day, 56 per cent of students' time was spent on near tasks or computer-based activities and, on average, students were required to engage in continuous near fixation tasks for 23 minutes at a time. The mean estimated habitual near working distance was 23 cm, which corresponded to an approximate 4.00 D accommodative demand, and a 22^{Δ} vergence demand.[6] The amount of time spent on different activities during the school day from this study[6] is presented in Figure 1.

In the same study, classrooms and learning materials were evaluated to determine the demands that the physical characteristics of the classroom environment imposed on a child's visual system.[6] The mean visual acuity demand was 0.33 logMAR (6/12) for distance (range 0.06–0.64) and 0.72 logMAR (6/30) for near learning materials (range 0.48–0.87). More recently, a very similar mean distance visual acuity demand was observed in 33 Grade 4 to Grade 12 classrooms in India (0.31 ± 0.17 logMAR); however, a higher near visual acuity demand was observed (0.44 ± 0.14 logMAR), which is likely to reflect the older age group included (up to Grade 12) and hence the reduced print size of reading materials.[17]

In addition, Narayanasamy et al.[6] observed that illumination levels varied markedly between and within classrooms throughout the day (ranging from 130–1,224 lux), with up to 10 per cent of measurements falling below the minimum recommendations for classroom lighting (240 lux).[18] However, the mean contrast levels of learning materials at distance and near were greater than 70 per cent (which equates to a contrast reserve ratio larger than 35:1), which exceeded the recommended contrast reserve (for adults) of 20:1 for a range of spatial frequencies.[19]

The distance and near visual acuity demands in primary school classrooms in the USA were also examined in 2010 by Langford et al.[20] One classroom from each grade in a single school was evaluated, from kindergarten to Grade 5. An increase in the visual acuity demand (for both distance and near) was observed with increasing grade level, with the distance acuity demand always greater than at near. This increase in visual acuity demand as children progress through higher grade levels, is likely to reflect the increase in the average distance a student is seated from the board, along with the simultaneous decrease in text size of the learning materials. The average distance visual acuity thresholds for kindergarten to Grade 2 classrooms were 0.70 (6/30) to 1.18 (6/90) logMAR and 0.48 (6/18) to 0.70 (6/30) logMAR for Grade 3 to Grade 5 classrooms; average near visual acuity thresholds ranged from 0.70 (6/30) to 1.40 logMAR (6/150) at 40 cm across all classrooms.

The nature of the visual demands in school classrooms differs according to the grade level of the child.[12,21] Two different stages of learning have been proposed: 'learning to read' (up until Grade 3) and 'reading to learn' (Grade 3 onward).[22,23] The 'learning to read' stage involves larger print sizes and shorter words which are relatively widely spaced for younger children. During this early learning stage, reading is conducted for shorter periods of time.[24] Conversely, the 'reading to learn' stage focuses on prolonged text access, sustained

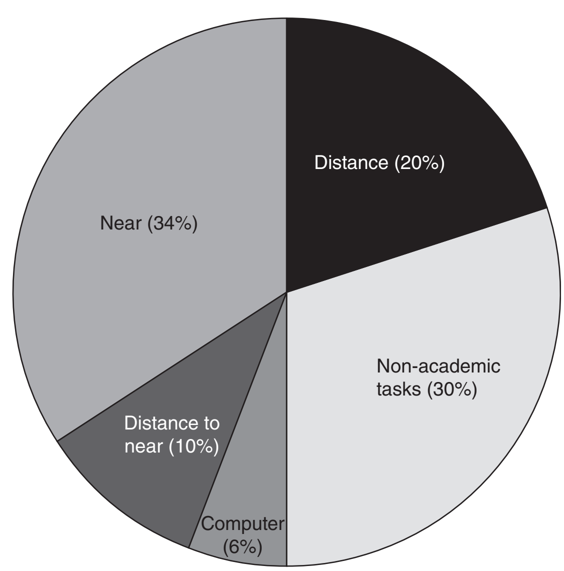

Figure 1. Proportion of the school day spent on different activities[6]

attention and increased comprehension demands in older children.[24] Surprisingly, given the broad interest in the link between vision and academic performance, only the limited number of studies described here have investigated the visual demands of primary school classrooms in this later 'reading to learn stage,' where more sustained visual effort is required.

Vision, refractive error and academic performance

The relationship between vision and academic achievement has long been debated, with a number of visual factors being associated with learning-related problems. These factors include reduced visual acuity, uncorrected refractive error, binocular vision dysfunction and delayed development of visual information processing skills.[25–31] In these studies, binocular vision dysfunction refers to anomalies affecting accommodation, vergence and ocular motility, while visual information processing refers to a wide range of perceptual skills such as visual spatial awareness, visual analysis and visual motor integration.[13] While numerous studies have been conducted in these areas, there have been a number of inconsistencies in the conclusions drawn, largely resulting from fundamental differences in study designs, populations of interest, and the outcome measures used to assess academic performance.[32]

One of the major limitations of previous studies has been in the definition and quantification of reading or academic performance. The terms 'learning disability' and 'dyslexia' are frequently used, yet inconsistently defined. This results in the recruitment of disparate samples representing poorly defined populations; consequently, study outcomes cannot be readily compared. Additional terms which have been used interchangeably include 'reading disability', 'poor readers' and 'slow readers', which typically are neither defined nor explained. This methodological limitation is further exacerbated by the use of non-standardised educational measures, such as subjective assessments by teachers, or school-based examinations, to classify students into different performance groups. The validity and reliability of these measures are undetermined, which further limits the strength of the conclusions that can be drawn. These non-standardised measures also have arbitrary criteria applied in order to classify normal versus abnormal performance. Table 1 presents a sample of some of the tests (both standardised and non-standardised) that have been used to measure academic performance in this area of vision research, as well as the cut-offs (where available) that are applied to these metrics to define reduced performance.

The majority of studies linking vision and academic achievement in children have used case control or correlational designs. In case control studies, the prevalence of visual dysfunction is compared between academically underachieving children and a control group.[25,35,37,51–53] This approach presumes, perhaps inappropriately, that a higher prevalence of visual dysfunction found among an underachieving group is indicative of the influence of the visual factor of interest on academic performance. In correlational studies, quantitative measures of visual function are related to measures of reading performance or academic ability.[26,28,39,41] The strength of the association between visual function skills and learning outcomes is quantified in terms of the correlation co-efficient (r) value. Again here, high r values can be misrepresented as indicating that one factor of interest is causally related to the other. Both of these designs can demonstrate an association between vision and academic achievement but cannot establish a causal nature for these relationships.

Experimental or intervention studies that can establish a cause–effect relationship are a more valid approach to investigating these issues. Several such studies have been reported, providing limited support for a causative role for uncorrected refractive error (or for convergence insufficiency in one study), in reduced academic achievement.[42–44,49,54] Recently, improvements in academic outcomes following spectacle intervention, have also been reported in a small number of studies.[55–57] In a US study, children who required (and received) spectacles displayed a significantly greater improvement in reading performance over a one year period, compared with children who did not receive spectacles. Interestingly, when the outcomes were evaluated with respect to refractive error, only children who received spectacles for myopia demonstrated significant improvements in reading performance (compared with emmetropic children); surprisingly, the reading performance of hyperopic children did not improve.[55] Common limitations with intervention studies include difficulties with ensuring compliance with spectacle wear, as well as agreement regarding the level of refractive error that warrants spectacle intervention (particularly low to moderate hyperopia). Well-designed, high-quality intervention studies looking at the impact of spectacle wear on academic performance remain scarce, despite a large body of evidence suggesting an association between visual factors and academic performance in children.

There have been a number of high-quality intervention studies related to amblyopia treatment, which have reported improvements in visual acuity and stereoacuity (but not in academic performance) following spectacle intervention.[58–60] In addition, spectacle intervention has been demonstrated to reduce the incidence of accommodative esotropia and amblyopia in asymptomatic infants.[61] However, improvements in the visual function of school-age children (no longer at risk of developing accommodative esotropia or amblyopia) following spectacle intervention have been less well studied, particularly in asymptomatic children. This remains a prescribing 'grey area' for clinicians, with many prescribing decisions based on clinical intuition, rather than published evidence. Consideration of near visual function plays a role in prescribing philosophies, including accommodation measurements, given their association with subjective symptoms in school children.[62] Indeed, accommodation, binocular vision function and other visual parameters may all play a role in a child's visual performance, and subsequent ability to access and effectively engage with visual information in the classroom. However, these factors are outside the scope of the current review.

The remainder of this review examines, in detail, those studies that have investigated the relationship between visual acuity, refractive error, and educational-related outcome measures in children, with discussion of methodological limitations common in this body of research.

Visual acuity

There are diverse findings regarding the role of visual acuity on reading or academic performance. While many studies have reported that habitual distance visual acuity is unrelated to academic ability,[34,38,63] a number of studies have demonstrated a link

Study	Academic test	Classification of reduced academic performance
Bruce et al. (UK)[33]	Woodcock Reading Mastery Tests-Revised subtest: letter identification (standardised)	N/A
Chen et al. (Malaysia)[25]	Standardised school examination results: Malay and mathematics	Low achievement = failure in both language and mathematics (examination score of < 50%)
Dirani et al. (Singapore)[34]	Standard nationwide end of Grade 4 examination: English language, mother tongue competency and mathematics as well as number of books read per week (through parent-administered questionnaire)	N/A
Dusek et al. (Austria)[35]	Salzberg Reading Test: reading speed	N/A
Fulk and Goss (USA)[36]	Teacher evaluations of school performance: upper 25%, middle 50% and lower 25%	Lower 25% of children based on teacher evaluation
Goldstand et al. (Israel)[37]	Altalef Reading Screening Test, Tikva Reading Test and an academic performance questionnaire completed by classroom teachers: reading, spelling, mathematics, composition and general academic success	N/A
Grisham et al. (USA)[38]	Poor reading performance determined by the school (teacher report) and defined as reading two grade levels or more below grade level	Two grade levels or more below grade level
Hopkins et al. (Australia)[31]	Neale Test of reading ability: reading accuracy and reading comprehension	N/A
Krumholtz (USA)[27]	New York City Wide Reading Test administered by the Board of Education	Two groups: better (top 25% of class) and poorer (bottom 25% of class) achieving students
Kulp (USA)[26]	Classroom teachers' ratings (kindergarten to Grade 3): reading, mathematics, writing and spelling (Grades 2–3 only); Stanford diagnostic reading test, 4th edition: Grade 1; Otis-Lennon School Ability Test (OLSAT): Grade 2	OLSAT: below average, average and above average
Kulp and Schmidt (USA)[39]	Classroom teachers' ratings (kindergarten to Grade 3): reading, mathematics, writing and spelling (Grades 2–3 only) Stanford Diagnostic Reading Test, 4th edition: Grade 1; Otis-Lennon School Ability Test: Grade 2	N/A
Kulp et al. (USA)[40]	Test of Preschool Early Literacy (TOPEL): print knowledge, definitional vocabulary and phonological awareness subtests	N/A
Morad et al. (Israel)[41]	SHEMA Test for reading comprehension, used by Israel Ministry of Education	N/A
Narayanasamy et al. (Australia)[42–44]	Neale Test of reading ability: reading accuracy, reading comprehension and reading rate	N/A
Quaid et al. (Canada)[45]	Students with Individual Education Plans (IEPs) for reading: students with a reading IEP are typically two grade levels behind their grade level in reading ability	Students with a reading IEP and controls (non-IEP students in the same age group)

Table 1. Description of the academic tests and performance criteria (where available) which have been used in a selection of studies evaluating visual function and academic performance

Study	Academic test	Classification of reduced academic performance
Rosner and Rosner (USA)[28,46]	Iowa Test of Basic Skills (ITBS)	1994: percentile ranks: < 40, 40–60, > 60 1997: low scorers: < 25th percentile
Shankar et al. (Canada)[47]	Wide Range Achievement Test (WRAT-III): standardised test of letter and word recognition and naming; Peabody Picture Vocabulary Test-III (PPVT): standardised test of receptive vocabulary	N/A
Shin et al. (South Korea)[29]	School-administered achievement tests: reading, mathematics, social science and science	N/A
Solan et al. (USA)[48]	Gates-MacGinitie Reading Test: comprehension subtest	Reading disability = scores 0.5–1.0 SD below national means
van Rijn et al. (Netherlands)[49]	One-minute Test (standard list of regular words) and the Klepel (list of non-words)	N/A
White et al. (Australia)[9]	NAPLAN: standardised tests of reading, writing, language conventions and numeracy referenced against the national minimum standard	N/A
Williams et al. (UK)[30]	Standardised Assessment Tests (SATS): English, mathematics and science and National Foundation for Educational Research Progress in English tests: reading and writing skills	N/A
Wood et al. (Australia)[50]	NAPLAN: standardised tests of reading, writing, language conventions and numeracy referenced against the national minimum standard	N/A

Table 1. Continued

between habitual visual acuity and reading or school performance.[25,33,64] Direct comparisons between studies can be difficult due to inconsistencies in terminology, with some authors considering uncorrected vision to be a measure of visual acuity.[65] Protocols or analyses also vary with respect to measures of monocular or binocular visual acuity, where some studies utilise data from the better eye only.[34]

Reduced habitual distance visual acuity (worse than 0.10 logMAR) was reported to be significantly associated with lower reading performance (Edwards Diagnostic Reading test) in Grade 2 children.[64] In another study of Grade 2 children, significantly more students whose academic performance was rated as low (scoring less than 50 per cent on school-based examinations), failed a distance visual acuity test (worse than 0.20 logMAR) compared to children who passed; 12 per cent and four per cent respectively failed the visual acuity criteria.[25] A recent study of a large UK cohort of children aged 4–5 years also found that reduced visual acuity at school entry was linked with reduced school literacy (Woodcock Reading Mastery Tests-Revised [WRMT-R] subtest: letter identification).[33] This latter finding is particularly relevant given that early literacy has been shown to be a key indicator of future reading and educational ability.[66] In a prospective longitudinal study of Chinese middle school children (Grades 7 to 9), Jan et al.[65] observed a significant association between poorer habitual acuity of the better eye at the initial eye examination in Grade 7, and lower scores on a standardised academic test in Grade 9. In the latter study, presenting visual acuity included measures of unaided vision.

Conversely, other studies have failed to find an association between visual acuity and reading or other forms of academic performance. Helveston et al.[63] reported that reduced distance visual acuity (worse than 0.3 logMAR) was not associated with reading ability in children from Grades 1 to 3. However, in this study, individual teachers' perceptions were used to categorise children's reading abilities, rather than a standardised method. In addition, the vast majority of children examined (more than 90 per cent) had 'normal' (6/9 or better) visual acuity. Similarly, Dirani et al.[34] failed to find a relationship between academic performance, as measured by the nationwide Grade 4 examinations of language and mathematics proficiency, and habitual distance visual acuity in Grade 3 and 4 Singaporean children. Again, this negative result may be attributed to the lack of variation in visual acuity within the sample, with the mean visual acuity (± SD) being 0.10 ± 0.17 logMAR and 0.08 ± 0.17 logMAR in Grades 3 and 4, respectively.

Collectively these studies demonstrate substantial discrepancies in the evidence linking visual acuity and academic performance. This may result from the large proportion of children in these studies who had relatively good visual acuity, as well as non-standardised methods used to measure academic performance, as is often the case in this area of research. Differences also exist between studies regarding the cut-off criteria adopted to define 'poor' or 'reduced' visual acuity.

Near visual acuity has not been considered in the majority of these studies, even though near tasks constitute a major component of classroom activities.[6] Indeed, the few studies that have investigated the association between habitual near visual acuity and reading performance have failed to find a significant relationship; importantly, most of these studies did not consider near acuity reserve.[63,64,67] The Vision in Pre-schoolers - Hyperopia in Pre-schoolers (VIP-HIP) study group reported that near visual acuity was associated with reduced early literacy scores (Test of Preschool Early Literacy, TOPEL) in hyperopic children, with lower TOPEL scores for hyperopic children with binocular near visual acuity of 6/12 or worse compared with hyperopic children with near visual acuity better than 6/12 and with emmetropic children. However, the association between near acuity and TOPEL scores was only evaluated in children with hyperopia of at least 3.00 D and when other factors such as stereoacuity and accommodative lag were included in the model, near visual acuity was no longer significant.[40]

Typically, studies investigating the influence of reduced visual acuity on academic performance do not take into account the underlying causes of impaired vision (for example, ocular pathology, amblyopia or uncorrected refractive error). However, the studies described in the following sections have attempted to refine their parameters of interest in order to determine the influence of specific refractive errors (either corrected or uncorrected) on reading and academic ability.

Hyperopia

Hyperopia is common in children, with prevalence data ranging between 0.8–34 per cent, depending on the definition of hyperopia, assessment technique, age and ethnic background of the various study populations.[68–78] Numerous studies have reported that uncorrected hyperopia is associated with poorer performance on academic-related outcome measures such as reading ability, educational or academic achievement test outcomes and literacy scores.[27,28,30,36,40,45,47] It has been suggested that the impact of uncorrected hyperopia on these outcomes may be because the accommodative-vergence demand required to sustain clear focus during near tasks results in symptoms such as asthenopia, headaches, and intermittent blurring of print.[13] The effort involved in functioning with moderate to higher levels of uncorrected hyperopia is likely to be responsible for these symptoms and can additionally result in fatigue and disengagement with learning activities. This in turn has the potential to make it difficult for affected individuals to perform efficiently in the classroom and may reduce their academic performance.

Rosner and Rosner[51] reported that the prevalence of uncorrected hyperopia (≥ 1.00 D, based on a retrospective review of record cards) in a sample of children aged six to 12 years old was higher in those with learning and reading difficulties than in a control group (54 per cent and 16 per cent respectively). However, school-based examinations, a non-standardised measure, were used to categorise the children into the different learning difficulty groups. A decade later, the same authors reported that children with uncorrected hyperopia of > 1.25 D, measured using non-cycloplegic retinoscopy, had significantly lower academic test scores (Iowa Test of Basic Skills) compared to emmetropic or uncorrected myopic children.[28] However, the participants were not screened for any other visual function disorders (for example, binocular vision anomalies) which may have confounded the results.

Williams et al.[30] showed that Grade 3 children who failed a hyperopia screening examination – the plus lens test (PLT) – scored significantly lower on Standardised Achievement Tests (SATs) than those children who passed. In the same study, the lowest scores on the National Foundation for Educational Research (NFER) Progress in English test were observed in the most hyperopic group; however, this outcome did not reach statistical significance. A limitation of the study was the use of only the PLT to screen for hyperopia, and the fact that optometric assessment was only undertaken on those children who failed the PLT. The PLT can elicit false negative results when children with uncorrected hyperopia do not relax their accommodation when viewing through the plus lens.[79] Importantly, the study did not determine the rate of false negatives of the PLT for the detection of hyperopia, meaning that it was possible that some children with latent hyperopia may have been inappropriately allocated into the control group.

In a more recent study, four- and five-year-old children with uncorrected hyperopia between 3.00 and 6.00 D scored significantly lower on a standardised measure of early literacy (TOPEL) than children with emmetropia, after adjusting for age, race/ethnicity and parent/caregiver's education.[40] This association remained significant, when hyperopia was re-defined as ≥ 4.00 D. Indeed, the definitions used for hyperopia vary considerably between studies, making collation of data to identify overall trends and patterns challenging. Table 2 lists the different classifications for hyperopia that have been adopted in this area of research.

There have been attempts to empirically determine the minimum level of uncorrected hyperopia that results in functional problems, with these investigations typically involving adult participants. Walton et al.[80] examined the impact of increasing levels of simulated hyperopia in young optometry students (22 to 31 years) on the Otis-Lennon Mental Ability test. Test performance decreased significantly with 2.00 D of induced hyperopia, with a non-significant test score reduction for 1.50 D. The authors concluded from these findings that uncorrected hyperopia of 1.50 D should be considered as the referral point for vision screening, while 2.00 D was regarded as the threshold for the correction of hyperopia. However, participants were not screened prior to inclusion in the study and thus other co-existing vision problems, such as binocular vision anomalies, that may have influenced performance were not accounted for. Garzia et al.[81] reported that 2.00 D of simulated bilateral hyperopia significantly increased reading time by 11 per cent, but did not impact on accuracy, in visually normal university students (6/6 corrected acuity and normal amplitudes of accommodation). The authors suggested that the extra time required by the participants to complete the test was a consequence of the simulated hyperopia, making accurate reading of the text more challenging. However, neither of these two simulation studies considered the potential impact of prolonged near work in the presence of

Study	Hyperopia definition
Fulk and Goss (USA)[36]	Mean hyperopic spherical equivalent of 0.75 D or more in either eye (non-cycloplegic autorefraction)
Krumholtz (USA)[27]	Fail plus lens test (+2.00 D)
Kulp et al. (USA)[40]	≥ 3.00 D in the more hyperopic meridian of at least one eye (cycloplegic autorefraction)
Rosner and Rosner (USA)[28]	10 different refractive error classifications
Quaid et al. (Canada)[45]	No classification for hyperopia. Mean cycloplegic autorefraction and subjective refraction compared between reading groups
Shankar et al. (Canada)[47]	More hyperopic meridian ≥ 2.00 D for both eyes (cycloplegic autorefraction and retinoscopy)
Williams et al. (UK)[30]	Failure on the plus lens test (+4.00 D), and then either hyperopia of > 3.00 D combined or > 1.25 D in best eye, based on optometric assessment (spectacle prescription)

Table 2. Definitions used for hyperopia in studies reporting a positive association between academic performance and hyperopic refractive error

imposed hyperopia; this is an important issue given that prolonged near work has recently been shown to be an integral component of children's activities in contemporary classrooms.[6]

In order to address these limitations, Narayanasamy et al.[42] employed a repeated measures design to investigate the impact of simulated hyperopia on academic-related performance in children aged 10–12 years without habitual refractive error, amblyopia or binocular vision anomalies. Outcome measures included reading rate, accuracy and comprehension using the Neale Test. The effect of simulated refractive error, in combination with sustained near work, was also examined, since prolonged near tasks greater than 20 minutes in duration are typical in modern classrooms.[6] Simulated bilateral hyperopia of 2.50 D alone resulted in a two to five per cent decrease in reading rate, accuracy and comprehension performance; however, when combined with a 20-minute near task, it resulted in performance deficits of nine to 21 per cent across the three outcome measures (all $p < 0.01$) (Figure 2). These findings suggest that a relatively low level of uncorrected bilateral hyperopia during childhood may impair reading performance and have a detrimental effect upon learning and academic performance. However, a limitation of studies that simulate hyperopia is the inability to account for the role of accommodation as a compensatory mechanism. Asymptomatic hyperopes tend to rely more on their accommodative and vergence function in order to sustain clear and comfortable vision at near; the accommodative demand for visually normal emmetropes (subjects in simulation studies) would be less. It is possible that this difference in accommodative function between groups may explain differences in reading performance following simulation. It is therefore critical that accommodative and near visual function are investigated in detail when prescribing for hyperopia (with the primary purpose of reducing near visual stress), including accommodative posture, amplitude and range, as well as near visual acuities.

In summary, while many studies have demonstrated a positive association between uncorrected hyperopia and academic performance, there is no consensus regarding the minimum level of uncorrected hyperopia that negatively affects reading ability or general academic performance in children. Cotter[82] suggested that hyperopia greater than 1.25 D might be corrected in children with no other visual problems to benefit reading and close work, particularly if there are concerns around the child's ability to sustain consistent and comfortable accommodation at near. This is similar to Leat's[83] recommendation that optometrists should consider prescribing the full hyperopic (non-cycloplegic) refraction for occasional or full-time wear, when it is 1.50 D or more in asymptomatic children during their school years. Importantly, these recommendations are largely based on experience and clinical intuition, rather than evidence derived from well-designed studies that have examined the causative effect of different levels of uncorrected refractive errors on educational outcomes. Additionally, there is little clear evidence regarding the benefits of correcting hyperopia in school children.[83] One recent study demonstrating the positive effects of full hyperopic prescription, even for levels as low as 0.50 D, on reading speed (an increase of 13 per cent was found), provides some useful evidence.[49] However, the limitations that exist in this latter study (including small sample size and recruitment strategy for hyperopes) mean that carefully designed studies in this area are still required in order to inform evidence-based prescribing guidelines for hyperopia.

Myopia

In contrast to uncorrected hyperopia, both corrected and uncorrected myopia have been reported to be associated with higher intelligence scores and improvements in reading ability and other academic-related outcome measures.[84–86] One explanation for this could be that less accommodative effort is required by those with uncorrected myopia; therefore these children are better suited for sustained near activities than those with uncorrected hyperopia.[87] Correction of myopia would eliminate this advantage, unless a near addition is prescribed (or spectacles are worn for distance viewing only). An additional factor to consider when prescribing for myopia is the risk of myopia progression. Full myopic correction should be prescribed, as bilateral under-correction may result in an increase in myopia progression.[88] In cases of accompanying accommodative lag, near esophoria and where short working distances are habitually adopted, a near addition has been shown to slow myopia progression.[89]

Another possible explanation for the higher intelligence scores and reading ability is that uncorrected myopic children are less likely to participate in activities that require clear distance vision and spend more time engaged in near activities such as reading. This, in turn, may result more generally in the acquisition of better reading skills and academic abilities.[87] However, while there is evidence of an association between myopia and near work activity,[90] many hypotheses concerning myopia and academic performance in children are not supported by evidence from well-designed studies.

Grosvenor[86] reported that IQ scores were nine per cent higher in a sample of 11–13-year-old children with myopia, compared to children with hyperopia. However, the difference was only evident for a 'verbal' IQ test (Otis Self-Administered Test) and not

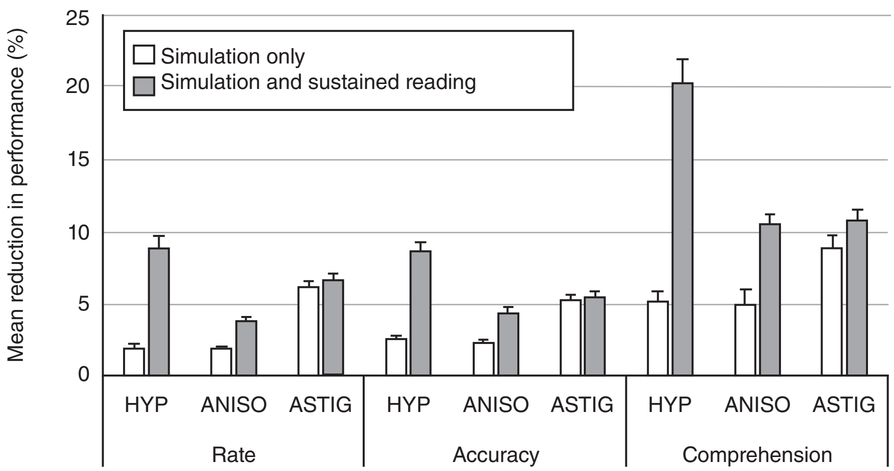

Figure 2. The group mean reduction in reading performance in children (reading rate, accuracy, and comprehension from the Neale Analysis of Reading Ability Test) relative to optimal refractive correction, due to refractive error simulation (2.50 D bilateral hyperopia, 0.75 D monocular hyperopic anisometropia, and 1.50 D bilateral astigmatism) (white bars) and refractive error simulation combined with a 20-minute reading task (grey bars). Compiled from Narayanasamy et al.[42–44] Error bars represent one standard error of the mean.

for 'non-verbal' testing (Raven Matrix Test) and it has been suggested that differences in reading and language skills that impact on IQ scores may underlie these differences. The Avon Longitudinal Study of Parents and Children (ALSPAC) in the UK also showed an association between verbal IQ (measured using the Wechsler Intelligence Scale for Children [WISC III] test) and myopia in 11-year-old children, with those children ranking in the highest quartile for the verbal IQ test being twice as likely to be myopic; again, this trend was only observed for the verbal IQ scores.[91] In a large scale study, the Singapore Cohort Study of the Risk Factors for Myopia (SCORM), an association between non-verbal IQ (Raven Matrix Test) and myopia was also observed. Children in the highest quartile for non-verbal IQ scores had the highest prevalence of myopia; however, it was not reported whether the participants had corrected or uncorrected myopia, which is a significant limitation of the study.[92] An important issue highlighted by the above studies is that IQ could be a potential confounding factor when interpreting the association between visual factors and learning ability; however, this issue is typically not addressed in most studies.[23]

Astigmatism

Astigmatism is another common refractive error in primary school children, with one Australian study suggesting that 24 per cent of correctable visual impairment in a sample of six-year-old children was attributable to 1.00 DC or more of astigmatism alone, and 47 per cent when occurring in conjunction with spherical refractive error.[93] Although a number of published prescribing guidelines include specific recommendations for refractive correction of childhood astigmatism, threshold levels for correction are primarily selected to ensure prevention of meridional amblyopia, particularly for oblique astigmatism, or for improving visual acuity.[94–96] Importantly, the effects of astigmatic blur on visual function are different from those of spherical blur. For example in adults, the impact of astigmatic blur on visual acuity varies according to the orientation of the cylinder axis[97] and the reduction in visual acuity with simulated astigmatic blur is twice that of the equivalent level of spherical defocus.[98] Furthermore, unlike spherical blur which is most problematic at near or far (hyperopic and myopic blur respectively), astigmatism can result in blurred vision across a range of distances.[99]

However, there is limited evidence to define the minimum level of astigmatism that should be corrected to ensure optimal visual performance, including improvements in visual acuity, stereoacuity and contrast sensitivity, all of which have been shown to be impaired in astigmatism.[100] Up until approximately school age, childhood astigmatism can potentially affect normal visual development and is associated with amblyopia, abnormal binocular vision and myopia development.[101] Some authors recommend that astigmatism as low as 0.50 D should be corrected, particularly if associated with oblique or against-the-rule (ATR) axes, or if asthenopic symptoms are present[102,103] aligning with findings from a recent study that reported a trend of better grating acuity (and visually evoked potential amplitude) in children without astigmatism, compared to those with astigmatism as low as 0.50 DC (who were corrected).[104] Other authors suggest that astigmatism of 0.75 D or more should always be corrected in school children, irrespective of symptoms.[83,105] Published guidelines also suggest that the correction of astigmatism between 1.00 to 1.50 D may benefit school-aged children.[106] Importantly, the prescribing guidelines outlined above are largely based on practitioner clinical experience, rather than empirical evidence, which is limited and where it does exist, is derived from a range of different study designs and approaches.[83,102,103,105,106]

In studies from populations known to have a high prevalence of astigmatism, lower reading scores in children with uncorrected astigmatism (both ≥ 1.00 D and ≥ 2.00 D) have been compared to non-astigmatic children from the same population.[53,107] Interestingly, spectacle correction improved oral reading rates only in those with astigmatism of at least 3.00 D, with the beneficial effects becoming greater with increasing grade level (which is likely to be associated with the corresponding decrease in text size that occurs with increasing grade levels).[107]

There have been a number of studies that have used repeated measures designs that simulate astigmatism to determine the minimum levels that significantly degrade visual or functional performance; however, they have largely been undertaken in adult populations. In a study of older adults (50–69 years), Wolffsohn et al.[108] reported that simulated astigmatism as low as 1.00 D significantly reduced high and low contrast acuity and impaired functional performance, including reading speed and reading texts on mobile phones or computer screens. In younger adults (18–33 years), Wills et al.[109] demonstrated that simulated astigmatism as low as 1.00 D significantly reduced reading speed (Discrete Reading Rate test) by up to 24 per cent for smaller text sizes. In a more recent study, Casagrande et al.[110]

showed that simulated astigmatism as low as 0.75 D reduced reading performance by approximately 18 per cent (Salzburg Reading Desk) in young adults, but did not control for the change in spherical equivalent power associated with the imposed astigmatic defocus.

The majority of evidence regarding the impact of uncorrected astigmatism on functional measures has been limited to adults. One exception is a recent study which investigated the impact of simulated bilateral astigmatism (1.50 D) and sustained near work upon academic-related outcome measures in children, using a repeated measures simulation design while controlling for spherical defocus.[44] Simulated astigmatism of 1.50 D (both with-the-rule [WTR] and ATR) resulted in a five to 12 per cent reduction in reading, visual information processing and reading-related eye movements, which did not alter appreciably following 20 minutes of sustained near activity (Figure 2).[44] This suggests the possibility of short-term adaptation to imposed astigmatic blur in children, consistent with previous reports in adult studies.[111,112]

In addition to the power of the astigmatic error, the orientation of the axis has been shown to differentially affect vision and functional performance;[108–110,113] however, the majority of these studies have focused on adults and have reported conflicting results. Some studies have reported that ATR astigmatism results in a greater reduction in performance for both visual acuity and reading outcomes,[108,109] while others suggest that WTR is more detrimental to performance than ATR,[110,114] and yet others report equivalent performance deficits for WTR and ATR astigmatic simulations.[44,97,113,115] In addition, some studies have demonstrated that oblique astigmatism (the least common type of astigmatism found in children) has the most detrimental effect on vision and functional performance in adults compared to WTR and ATR astigmatism.[113] A recent study showed that the effects of astigmatic axis are also dependent on the typography of the alphabetic language used.[116] These inconsistencies between studies are likely to be a result of differences in the methodologies employed, including factors such as the method of astigmatic simulation (cylindrical lenses with or without spherical equivalent compensation), functional outcome measures (visual acuity, reading or other specific task-related performances), the age of participants (young or older adults), pupil size (natural or artificial) and the method of accommodative control (with or without cycloplegia).

Non-amblyopic anisometropia

There is limited evidence regarding the impact of uncorrected anisometropia on children's performances in school. Although some studies have investigated the visual deficits associated with amblyopic anisometropia,[117,118] few have explored functional deficits associated with non-amblyopic anisometropia, which can potentially disrupt binocular co-ordination due to interocular differences in accommodative demand,[119] or retinal image size.[120] This may result in visual symptoms such as headaches and eyestrain,[121] which can contribute to a reduction in functional performance.[115] However, the mechanisms underlying this association have not been fully established.

Eames[52] reported a significantly higher prevalence of anisometropia (> 1.00 D interocular difference) in a cohort of 'reading disabled' children (13 per cent) compared to an age- and IQ-matched control group (six per cent) ($p < 0.01$). Similarly, Drasdo[122] observed that the prevalence of anisometropia in a group of 'poor readers' and a control group was 26 per cent and eight per cent respectively, although the difference did not reach statistical significance. However, both of these less recent studies failed to explain the criteria used to classify children as 'reading disabled' or 'poor readers'. Eames[123] also reported that a significantly higher proportion of children with uncorrected hyperopic anisometropia were below their chronological reading age (using the Gates Silent Reading Test) when compared to a control group (56 per cent and 24 per cent respectively, $p < 0.01$). An improvement in the median reading level (Gates Silent Reading Age) of the anisometropic cohort following six months of full-time refractive correction was demonstrated; however, the educational or statistical significance of this reading improvement was not specified. Furthermore, children with amblyopia were not excluded from the anisometropia group, limiting the significance of the findings with respect to the correction of non-amblyopic refractive error alone. While Eames[123] suggested that the correction of anisometropia resulted in improved reading performance across the cohort, the observed improvement may be a result of improved binocular and spatial vision (visual acuity and contrast sensitivity) in the children with amblyopic anisometropia, rather than an outcome of refractive correction in children with lower levels of non-amblyopic anisometropia. Importantly, the level of refractive difference between the eyes used to define anisometropia was also not reported.

Other studies have sought to determine the minimum level of anisometropia that is of functional importance through the simulation of uncorrected anisometropia in adults. Simulation of both myopic and hyperopic anisometropia (spherical and astigmatic) as low as 1.00 D degrades binocular vision, as observed by a reduction in stereopsis using the Titmus stereotest and the presence of foveal suppression using the Worth-four-dot test.[124–126] Spherical anisometropia has a greater impact on binocularity than astigmatic anisometropia, due to the global blur induced by spherical defocus compared to the meridional blur associated with simulated astigmatism.[126] However, these studies confirmed that gross fusion under more natural conditions (using Bagolini lenses) was still intact in the presence of up to 3.00 D of simulated anisometropia.

While the correction of moderate levels of childhood anisometropia (> 1.00 D) is recommended to minimise the risk of developing monocular refractive amblyopia and sensory deprivation-induced strabismus, the evidence concerning the correction of lower levels of non-amblyogenic hyperopic anisometropia is less clear.[127,128] In order to assess the impact of a low level of uncorrected hyperopic anisometropia (0.75 D) upon academic-related performance in children, Narayanasamy et al.[43] employed a repeated measures design. Simulated hyperopic anisometropia of 0.75 D resulted in a two to five per cent decrease in reading rate, accuracy and comprehension which decreased further to four to 11 per cent following 20 minutes of near work activity (all $p < 0.001$) (Figure 2), despite the maintenance of high levels of stereoacuity, and irrespective of which eye experienced the defocus (dominant or non-dominant). This study suggests that the correction of non-amblyogenic levels of hyperopic anisometropia during childhood may be of benefit in relation to reading performance and potentially, overall academic performance.

In summary, while numerous studies have suggested that uncorrected refractive errors (hyperopia, hyperopic anisometropia and astigmatism) have a detrimental effect upon functional performance in children, with the potential to influence academic outcomes, a variety of study designs and experimental techniques have been used which limit the validity of the conclusions. Further research is required to determine the minimum threshold of refractive error at which optical correction would be of functional benefit for each of these conditions.

Conclusions

Although good vision has been proposed to be important for optimal school performance,[13,129] the available evidence regarding the visual demands of modern primary school classrooms and the link between various visual characteristics and academic-related performance remains limited. Poor research methodology weakens the strength of the findings of much of the research in this field. Inappropriate study designs, inconsistencies in defining and quantifying reading or academic performance, the use of non-standardised outcome measures to assess academic performance and experimental bias all contribute to sub-optimal research methods. In addition, there is limited evidence on the effect of refractive correction on classroom performance.

These gaps in existing knowledge regarding visual characteristics and academic-related performance are particularly important to address, given that the few published professional guidelines available for clinicians that address this issue are not evidence-based. Current paediatric management decisions are often based on clinical intuition and the experience of individual practitioners, leading to inconsistencies in management approaches and a wide range of minimum prescribing levels used to manage these conditions. Understanding the visual demands in the modern classroom, as well as the impact of common visual anomalies on children's performances in academic-related tasks, is critical to inform clinical decision-making.

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