Visual Function in New Zealand Children: from Preschool to Primary School

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Optometry, the University of Auckland, 2021.

Abstract

Vision screening plays a key role in detecting childhood vision conditions. Uncorrected refractive error is the leading cause of visual impairment in children and has been associated with reduced academic performance. This thesis investigated the role of the current preschool vision screening programme in detecting vision conditions, as well as the associations of vision conditions with reading parameters, in New Zealand children.

Retrospective record reviews, analysis of population level data and comparison with international gold standard vision screening protocols were used to assess the efficacy of the current preschool vision screening programme. Additionally, standard optometric clinical techniques were used to complete comprehensive eye examinations, along with assessment of reading ability and eye movement.

The current preschool vision screening programme achieved high overall coverage and testability. However, a lower proportion of Māori and Pacific children and those living in high deprivation communities received vision screening and follow-up care compared with their peers. Refractive error, most commonly astigmatism (65-80% of cases), was present in up to one third of children. Up to 84% of New Zealand children with ametropia did not have appropriate correction. While the current vision screening programme was effective for detecting children with amblyopia risk factors, the addition of autorefraction significantly improved its sensitivity for detecting significant refractive error ($P = 0.01$). Children referred from preschool vision screening also achieved lower scores on a test of early literacy compared with children who passed vision screening ($P = 0.01$). Poorer near VA and stereoacuity were associated with reduced reading scores and eye movement patterns that were similar to those seen in younger and less proficient readers.

Equity-based improvements are required to ensure detection and treatment of vision conditions in New Zealand children through more appropriate screening targets and protocols, and improved access to screening and follow-up eye care. In particular, children with vision conditions that may affect near visual function and reading outcomes require referral for follow-up eye care. Improving screening and access to eye care will improve equity by ensuring that all children have appropriate correction to improve their health and educational outcomes.

Acknowledgements

I would like to express my sincere gratitude to my supervisors Dr Joanna Black, Professor Nicola Anstice and Dr Carol Chelimo for all of your ongoing support, guidance and encouragement. You have taught me so much, encouraged me when the tasks seemed insurmountable and reigned me in from overthinking. A special thank you also to Professor Cameron Grant for his invaluable feedback on all aspects of this thesis.

I would like to thank the University of Auckland for providing financial support through a Senior Health Research Scholarship and the New Zealand Association of Optometrists for a Postgraduate Scholarship. Without this support this thesis would not have been possible. Thanks also to the SJ Taylor Fund, the Health Research Council and the Maurice and Phyllis Paykel Trust for project funding.

I would like to express a special thank you to Dr Lucy Goodman who acted as a research assistant but more importantly as a friend and supporter. This genuinely could not have been done without you.

I would also like to thank Dr Alison Leversha and Alison Burge for sharing the Welcome to School project with me. What you do is truly amazing. I am also deeply grateful to all of the schools, caregivers and in particular, the children who participated in each of the projects. It was such a pleasure to work with all of you.

Finally, I would like to thank all of my friends and family for supporting me every step of the way. To my Mum and Dad for your encouragement and support. To Colin for always being there and for providing in house technical support. And to Claire and Fleur for being my greatest supporters, for piloting methods, acting as models and generally being amazing.

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Glossary of abbreviations

AC/A ratios	Accommodative convergence to accommodation ratio
AIC	Akaike Information Criterion
ANOVA	Analysis of variance
aOR	Adjusted odds ratio
arcsec	Seconds of arc (unit of threshold for stereopsis)
ATS	Amblyopia Treatment Study
AUC	Area under the curve
B4SC	B4 School Check
Beery VMI	Beery-Buktenica Developmental Test of Visual-Motor Integration
CI	Confidence interval
CISS	Convergence insufficiency symptom score
D	Dioptres
DC	Dioptres cylinder
DHB	District Health Board
DIBELS	Dynamic Indicators of Basic Early Literacy
ETDRS	Early Treatment Diabetic Retinopathy Study
EVA	Electronic visual acuity (testing system)
Hd	Distance heterophoria
Hn	Near heterophoria
IDI	Integrated data infrastructure
IPD	Interpupillary distance
IQR	Interquartile range
logMAR	Logarithm of the minimum angle of resolution (base 10)
m	Metres
MC	Motor Coordination
MELAA	Middle Eastern/Latin American/African
mm	Millimetres
ms	Milliseconds
NFD	Near fixation distance
NZ	Aotearoa/New Zealand
NZDep	New Zealand Index of Deprivation
OR	Odds ratio
RAF	Royal Air Force
RAPD	Relative afferent pupillary defect

ROC	Receiver operating curve
s	Seconds
SD	Standard deviation
SE	Standard error
VA	Visual Acuity
VMI	Visual-motor integration
VP	Visual perception
WTS study	Welcome to School study
Δ	Prism dioptres

Glossary of terms

Accommodation	Process by which the eye changes focus to clearly view a near object
Amblyopia	"Lazy eye" reduction in best corrected visual acuity in the absence of pathology, associated with presence of an amblyopia risk factor
Anisocoria	Difference in pupil size between the two eyes
Anisometropia	Difference in refractive error between the two eyes
Asthenopia	Eyestrain symptoms including headache, eyestrain, ocular discomfort
Astigmatism	Irregular curvature of the cornea or lens resulting in blurred or distorted vision
Convergence	The ability to turn the eyes inwards to look at a close object
Cycloplegia	Paralysis of the accommodation of the eye caused by pharmacologic action on the ciliary muscle of the eye
Diplopia	Double vision
Divergence	The ability to turn the eyes outwards to look at a distant object
Dyslexia	Specific learning difficulty characterised by difficulty reading, writing and spelling
Emmetropia	No significant focusing error
Emmetropisation	Process by which eye growth is regulated resulting in refractive errors near to emmetropia
Esophoria	Tendency of the eyes to turn inwards when there is no adequate fixation stimulus
Esotropia	Inward turning eye
Exophoria	Tendency of the eyes to turn outwards when there is no adequate fixation stimulus
Exotropia	Outward turning eye
Heterophoria	Tendency of the eyes to be misaligned when there is no adequate fixation stimulus (latent deviation)
Heterotropia	Abnormal alignment of the eyes, also referred to as strabismus
Hyperopia	Long sightedness - focusing error requiring excess ocular accommodation to obtain clear vision
Incomitance	Manifest or latent deviation differs according to which eye is fixating or which direction the eyes are looking
Iwi	Tribal group
Keratometry	Measurement of corneal curvature
Lag of accommodation	Difference between required and actual accommodation where

	accommodation is less than required
Lead of accommodation	Difference between required and actual accommodation where accommodation is more than required
Myopia	Short sightedness - focusing error resulting in blurred distance vision
Ptosis	A drooping eyelid
Refractive error	Focusing error of the eye
Saccade	Eye movement of short duration and high velocity
Significant refractive error	Focusing error requiring optical correction
Spherical equivalent	Measurement of refractive error, calculated by sphere power in dioptres plus half negative cylinder power in dioptres
Stereoacuity	Threshold measurement of stereopsis
Stereopsis	Perception of depth
Strabismus	Abnormal alignment of the eyes, also referred to as heterotropia
Vergence	Simultaneous movement of the eyes towards or away from each other to enable single binocular vision
Visual impairment	Reduction in visual acuity
Visual motor integration	Degree to which visual perception and hand movements are coordinated
Visual perception	Process of organising a processing visual information
Whānau	Family or extended family

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Chapter 4 The effect of induced blur on the Beery-Buktenica test of visual-motor integration and its supplemental tests

Article reference: Findlay, R., Black, J., van der Werf, B., Chelimo, C., Grant, C. C., Anstice, N. (2020). The effect of induced blur on the Beery-Buktenica developmental test of visual-motor integration and its supplemental tests. *PLoS One.* doi:10.1371/journal.pone.0237807

Publisher: PLOS

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Chapter 5 Vision screening in New Zealand preschool children: is it equitable?

Article reference: Findlay, R., Hamm, L., Anstice, N., Chelimo, C., Grant, CC., Bowden, N., Kokaua, J., Black, J. (2021). Vision screening in New Zealand preschool children: is it equitable? *Journal of Paediatrics and Child Health.* doi:10.1111/jpc.15548

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Chapter 7 Diagnostic accuracy of the Parr vision test, single crowded Lea symbols and Spot vision screener for vision screening of preschool children aged 4-5 years in Aotearoa/New Zealand.

Article reference: Findlay, R., Black, J., Goodman, L., Chelimo, C., Grant, C. C., & Anstice, N. (2021). Diagnostic accuracy of the Parr vision test, single crowded Lea symbols and Spot vision screener for vision screening of preschool children aged 4-5 years in Aotearoa/New Zealand. *Ophthalmic and Physiological Optics*. doi:10.1111/opo.12816

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Chapter 8 Visual function in children aged 6-7 years living in an area of known socioeconomic disadvantage

Article reference: Findlay, R., Black, J., Anstice, N., Burge, A., & Leversha, A. (2020). The prevalence of refractive error and visual impairment among New Zealand children in a community with significant socioeconomic disadvantage: is current preschool vision screening effective? *The New Zealand Medical Journal, 133*(1513), 33-41.

Publisher: New Zealand Medical Association

Approval: Approval provided by the publisher 5 July 2021

Chapter 1: Introduction

Amblyopia and uncorrected refractive error are two of the leading causes of visual impairment in children (He et al., 2004; Varma, Tarczy-Hornoch, & Jiang, 2017). The World Health Organization estimates that 2.2 billion people worldwide have visual impairment and almost half of these could have been prevented or are yet to be addressed (World Health Organization, 2019). Globally in 2004, 12.8 million children aged 5-15 years were visually impaired due to uncorrected or inadequately corrected refractive errors (Resnikoff, Pascolini, Mariotti, & Pokharel, 2008).

Uncorrected significant refractive error (need for glasses) in preschool-aged children may result in development of amblyopia (commonly referred to as 'lazy eye') (Holmes & Clarke, 2006) or strabismus (a turned eye) (Tang et al., 2016). Additionally, children with uncorrected refractive error or binocular vision anomalies may have blurred distance and/or near vision and asthenopic symptoms such as tiredness, discomfort when reading, headaches, blurred vision and intermittent diplopia (Abdi & Rydberg, 2005). Among school-aged children, up to 15% may have reduced unaided visual acuity (VA) (Ma et al., 2016) with uncorrected refractive error as the cause in up to 96% of these children (He et al., 2004).

Learning in a classroom environment requires adequate distance and near VA as well as accurate accommodation (change in focus to clearly view a near object) and binocular function to maintain clear, comfortable vision at all distances. Uncorrected refractive error, reduced VA and binocular vision anomalies are associated with reduced early literacy and academic outcomes (Bruce, Fairley, Chambers, Wright, & Sheldon, 2016; Hopkins, Narayanasamy, Vincent, Sampson, & Wood, 2019; Kulp et al., 2016; Maples, 2003). Additionally, visual perception (the process of organising and processing visual information) and visual motor integration (the degree to which visual perception and hand movements are coordinated) are associated with academic performance (Hopkins, Black, White, & Wood, 2019) and are detrimentally affected by uncorrected refractive error (Harvey, Twelker, et al., 2017; Kulp et al., 2017; Roch-Levecq, Brody, Thomas, & Brown, 2008). Thus, children with undetected vision conditions may be academically disadvantaged compared to those with normal vision. In Aotearoa/New Zealand (NZ), this is of particular importance for children of Māori and Pacific ethnicities and those from areas of socioeconomic disadvantage for whom this is likely to be a preventable contributor to poorer educational outcomes than their peers (Hunter et al., 2016; OECD, 2018; Song, Perry, & McConney, 2014).

Vision screening plays an important role in the early detection and timely treatment of childhood vision conditions. Vision screening is particularly important in disadvantaged populations for whom barriers

may otherwise prevent identification, referral, and treatment. Visual impairment is correlated with socioeconomic status (Robaei et al., 2005) and children living in areas of socioeconomic disadvantage are less likely to see an eye care practitioner than those living in more advantaged areas (Majeed, Williams, Northstone, & Ben-Shlomo, 2008; Stein, Andrews, Musch, Green, & Lee, 2016). Children with vision conditions frequently do not report visual symptoms (Irving et al., 2016), and early vision screening and treatment results in improved visual outcomes and reduces the prevalence of amblyopia (Mathers, Keyes, & Wright, 2010). The most appropriate screening strategy for a population depends on the vision conditions targeted by screening, the age of the children being screened, and the prevalence of vision conditions in the population. However, currently no large-scale population data exists regarding the visual status or the refractive error profile of NZ children. Therefore, determining the prevalence of vision conditions and establishing which conditions detrimentally affect academic performance is important to enable development of effective vision screening protocols for NZ children.

1.1 Thesis overview

This thesis consists of eleven chapters and reports the results of six studies examining vision screening, the prevalence of vision conditions in NZ children and the effect of uncorrected vision anomalies on reading parameters. The remainder of *Chapter 1* provides an overview of the peer-reviewed literature regarding visual function in children and the effect of uncorrected refractive error and visual impairment on educational outcomes and vision screening in children.

Chapter 2 provides a summary of eye care in the NZ healthcare system and current vision screening protocols. *Chapter 3* describes the methods used for the comprehensive eye examinations for the studies reported in Chapters 7 to 10 and presents the definitions for vision conditions used throughout this thesis. *Chapter 4* reports the results of a preliminary study investigating the effect of optically induced near blur on performance on the Beery VMI.

Chapters 5 and 6 present the results of two studies that reviewed data from the current B4 School Check (B4SC) preschool vision screening programme. *Chapter 5* reviews coverage and testability data relating to the current preschool vision screening programme and investigates differences across population groups defined by ethnicity, area-level socioeconomic deprivation and geographical region.

Chapter 6 examines the visual outcomes of children enrolled in *Growing Up in New Zealand*, a birth cohort study, who failed the B4SC vision screening and were referred for follow-up. These children were referred to the Ophthalmology Department of Counties Manukau District Health Board (DHB), which serves the South Auckland region and is the primary referral point for preschool children in this area with suspected vision anomalies. The study reported in this chapter describes compliance with

follow-up from screening and associations between vision screening outcome and cognitive measures at age 4 years.

Chapter 7 reports the results of a diagnostic accuracy study investigating the efficacy of three screening methods in detecting amblyopia risk factors and significant refractive error in preschool-aged children. The single crowded Lea symbols and the use of an automated measurement of refractive error (non-cycloplegic autorefraction) were evaluated with as alternatives to the current B4SC vision screening protocol in NZ (VA screening with the Parr vision test).

Chapters 8 to 10 present the results of two studies examining vision conditions in school aged children in Auckland, NZ. *Chapter 8* reports the results of a study investigating refractive error, visual impairment, and the efficacy of preschool vision screening in children aged 6-7 years living in a socioeconomically disadvantaged region. Chapters 9 and 10 describe the findings of a study of vision conditions in children aged 7-10 years and recruited in schools with a wider range of socioeconomic backgrounds. *Chapter 9* describes the vision conditions and B4SC vision screening results for these children and *Chapter 10* examines the associations between uncorrected vision conditions and measures of reading ability

Chapter 11 provides an overall discussion of the findings of this thesis in the context of international research and systems. This is a thesis with publications and as such, there is some minor repetition of literature review and methods within Chapters 4 to 10.

1.2 Visual acuity and amblyopia

1.2.1 Visual acuity

Uncorrected refractive errors and amblyopia are common causes of reduced VA in children (Robaei et al., 2005). Children with visual impairment due to uncorrected refractive error have been reported to experience loss of self-confidence, loss of self-worth, reduced community participation, humiliation, and discrimination (Chan, Singer, & Naidoo, 2020).

The Refractive Error Study in Children Multi-Country Survey was established to provide standard protocols for measuring refractive error and visual impairment in children, allowing direct comparison between studies in different locations (Negrel, Maul, Pokharel, Zhao, & Ellwein, 2000). The definitions for visual impairment employed in these studies have been used throughout this thesis to enable comparisons with these studies (see Chapter 3 for definitions).

Population studies have shown the prevalence of unaided visual impairment in school-aged children to range from 2.9% in Nepal to more than 30% in China and some South East Asian countries,

corresponding with higher levels of myopia in these countries (Table 1-1). Up to 98% of this visual impairment is the result of uncorrected refractive error. Studies from Australia and the United Kingdom have found an association between the prevalence of visual impairment and socioeconomic status (Majeed et al., 2008; Robaei et al., 2005). Visual impairment is also associated with ethnicity. Children of Chinese ethnicity have high prevalence of myopia and correctible visual impairment (Goh, Abqariyah, Pokharel, & Ellwein, 2005; Robaei, Huynh, Kifley, & Mitchell, 2006). Furthermore, studies of children in Ireland and the United Kingdom have found a lower proportion of Caucasian children with visual impairment compared with those of other ethnicities (Bruce, Santorelli, et al., 2018; Harrington, Stack, Saunders, & O'Dwyer, 2019). There are, however, currently no published data regarding correctable visual impairment and its causes in NZ children.

1.2.2 Amblyopia

Amblyopia is a neurodevelopmental condition in which there is a reduction in best corrected VA due to degradation of the retinal image by an amblyopia risk factor during the critical period of visual development (Holmes & Clarke, 2006). Amblyopia risk factors include a physical obstruction of the visual pathway (such as by cataract or ptosis), strabismus, anisometropia (a difference in refraction between the two eyes), or bilateral high refractive error. Because amblyopia is neurological, the VA reduction persists after the amblyopia risk factor is treated (such as removal of a cataract, strabismus surgery or spectacle wear). The levels of refractive error considered to cause amblyopia as agreed by the American Academy of Ophthalmology are used throughout this thesis (see Chapter 3 for definitions).

Bilateral amblyopia can result in permanent visual disability. Unilateral amblyopia is associated with reduced stereoacuity (threshold measure of depth perception) (Wallace et al., 2011) and deficits in fine motor skills (Webber, Wood, Gole, & Brown, 2008), as well as an increased lifetime risk of bilateral visual impairment due to injury or disease to the non-amblyopic eye (Rahi, Logan, Timms, Russell-Eggitt, & Taylor, 2002; van Leeuwen et al., 2007).

Population-based studies have found that unilateral amblyopia does not significantly impact educational, health or social outcomes (Rahi, Cumberland, & Peckham, 2006; Wilson & Welch, 2013). However, unilateral amblyopia is important at an individual level as unilateral reduced visual acuity may prevent individuals from qualifying for a commercial driver's licence and precludes them from certain occupations (Webber, 2018). Unilateral amblyopia is associated with doubling of the lifetime risk of bilateral vision loss due to trauma or pathology of the sound eye (Rahi et al., 2002). Unilateral amblyopia also results in altered binocular vision perception leading to degraded sensory fusion and poor or absent stereopsis. Children with amblyopia read more slowly than children without amblyopia and those who are no longer amblyopic following strabismus treatment (Kelly, Jost, De La Cruz, &

Birch, 2015). Children with amblyopia also have worse motor skills than those with normal vision (Webber, Wood, & Thompson, 2016). Amblyopia can be successfully treated by removal of the amblyopia risk factor through surgery or spectacle correction, followed by occlusion or atropine penalisation of the non-amblyopic eye (Holmes et al., 2011; Jonas et al., 2017; Pediatric Eye Disease Investigator Group, 2006). Amblyopia treatment may lead to social distress and bullying, however earlier treatment may reduce these adverse effects (Hrisos, Clarke, & Wright, 2004; Jonas et al., 2017).

Although the prevalence of amblyopia is reasonably low (0.5-8.1%; worldwide pooled prevalence 1.8% (Hashemi, Pakzad, et al., 2018)), amblyopia accounts for up to 15% of unaided visual impairment in children (Table 1-1). Unilateral amblyopia accounts for approximately 75% of all amblyopia (Vision in Preschoolers Study Group, 2004a). One NZ study of children born in Dunedin in the 1970s found the prevalence of amblyopia to be 1.8%-3.5% (Wilson & Welch, 2013). However, the current prevalence of amblyopia in NZ is unknown.

As amblyopia can be successfully treated in children (Holmes & Clarke, 2006), amblyopia prevalence in a country or region is largely dependent on the vision screening protocols and access to eye care in that area. Amblyopia management comprises removal of the amblyopia risk factor and treatment of any residual unilateral VA deficit (Holmes & Clarke, 2006). Spectacle correction is an effective first line treatment for strabismic and refractive amblyopia and results in resolution of amblyopia in up to one third of unilateral and three quarters of bilateral cases (Pediatric Eye Disease Investigator Group, 2006; Wallace et al., 2007). Residual unilateral amblyopia is treated using occlusion or atropine penalisation of the non-amblyopic eye to improve VA in the amblyopic eye (Pediatric Eye Disease Investigator Group, 2008). Amblyopia treatment is most effective if initiated before seven years of age (Holmes et al., 2011).

Table 1-1: Prevalence and causes of visual impairment in children by country

Region and Country	Number of participants	Age (years)	Prevalence of uncorrected visual impairment (%)	Cause of visual impairment			Population type
				Refractive error (%)	Amblyopia (%)	Pathology (%)	Unexplained (%)	
Africa								
Somalia (Abdi Ahmed, Alrasheed, & Alghamdi, 2020)	1204	6-15	13.6	76.8	22.0	1.2		Random cluster school sample
South Africa (Magakwe, Xulu-Kasaba, & Hansraj, 2020)	326	6-18	12.3	80.0	10.0	10.0		Random cluster school sample
South Africa (Naidoo et al., 2003)	4890	5-15	2.7	66.4	9.4	22.6	14.8	Population
Uganda (Kawuma & Mayeku, 2002)	623	6-9	12.0	97.3		0.5		School
Americas								
Brazil (Moraes Ibrahim et al., 2013)	1590	10-15	4.5	89.0	5.5	5.5		Population
Chile (Maul, Barroso, Munoz, Sperduto, & Ellwein, 2000)	5303	5-15	15.8	62.1	9.0	4.8	34.9	Population
Europe								
Turkey (Caca et al., 2013)	21062	6-14	17.5	79.6	2.6	11.0	16.6	Random cluster school sample

Region and Country	Number of participants	Age (years)	Prevalence of uncorrected visual impairment (%)	Cause of visual impairment			Population type
				Refractive error (%)	Amblyopia (%)	Pathology (%)	Unexplained (%)	
Eastern Mediterranean								
Iran (Rezvan et al., 2012)	1551	6-17	2.2	91.1	8.9			Random cluster school sample
Iran (Fotouhi, Hashemi, Khabazkhoob, & Mohammad, 2007)	5544	7-15	7.1	87.3	13.2	4.1	2.0	Random cluster school sample
South East Asia								
Kingdom of Bhutan (Sharma et al., 2020)	4985	10-15	14.5	94.2	5.1	2.6	1.1	Population
India (Dandona et al., 2002)	4074	7-15	5.0	53.0	15.5	18.0	13.5	Population
India (Murthy et al., 2002)	6447	5-15	9.8	80.9	6.4	9.2	7.1	Population
Nepal (Pokharel, Negrel, Munoz, & Ellwein, 2000)	5067	5-15	2.9	55.1	12.3	19.6	15.9	Population
Pakistan (Gull, 2014)	45122	5-16	3.4	98.3	2.8	1.3		Random cluster school sample
Thailand (Yingyong, 2010)	2340	6-12	39.7	97.6	0.5	0.8	1.1	Random cluster school sample

Region and Country	Number of participants	Age (years)	Prevalence of uncorrected visual impairment (%)	Cause of visual impairment				Population type
				Refractive error (%)	Amblyopia (%)	Pathology (%)	Unexplained (%)	
Western Pacific								
Australia (Robaei et al., 2005)	1738	6	4.1	69.0	22.5	2.8	5.6	Population
Australia (Robaei, Huynh, et al., 2006)	2352	12	7.4	89.2	5.2	2.6	3.0	Population
China (Zhao et al., 2000)	3007	5-15	12.8	87.8	7.2	2.0	4.9	Population
China (He et al., 2004)	4364	5-15	31.3	95.6	2.8	0.5	3.5	Population
China (Wu et al., 2013)	6026	4-18	34.1	96.6	2.2	0.3	1.1	Random cluster school sample
China (Ma et al., 2016)	8398	3-10	19.8	93.2	0.9	0.01		Random cluster school sample
Malaysia (Goh et al., 2005)	4634	7-15	22.6	89.5	2.9	0.9	12.7	Population

Visual impairment: visual acuity worse than 0.3 logMAR in one or both eyes

1.3 Refractive error

Uncorrected refractive error is the most common cause of visual impairment and blindness in children (Dandona & Dandona, 2001; Resnikoff et al., 2008). High refractive error present from a young age may result in amblyopia development (Holmes & Clarke, 2006). Non-amblyogenic refractive errors result in correctable reduced VA at distance and/or near (American Academy of Ophthalmology Preferred Practice Patterns Committee, 2017). Measurement of refractive error using cycloplegia is the gold standard for epidemiological studies as non-cycloplegic measurements underestimate hyperopia prevalence and overestimate myopia prevalence (Fotedar et al., 2007; Fotouhi, Morgan, Iribarren, Khabazkhoob, & Hashemi, 2012; Zhu et al., 2016). The definitions for refractive error described by the Refractive Error Study in Children Multi-Country Survey Studies using cycloplegic methods are used to define refractive error throughout this thesis (see Chapter 3 for definitions) (Negrel et al., 2000).

1.3.1 Refractive error development

Both genetic and environmental factors influence the development of refractive errors (Baird, Schäche, & Dirani, 2010) and early development of refractive error may also be influenced by the presence of systemic conditions (Marr, Halliwell-Ewen, Fisher, Soler, & Ainsworth, 2001; Marr, Harvey, & Ainsworth, 2003). The distribution of refraction in new-borns is wider than in older children and adults (Gwiazda, Thorn, Bauer, & Held, 1993). Refractive error distribution changes during infancy and throughout the preschool years by a process called emmetropisation, which actively regulates eye growth resulting in refractive errors at or near emmetropia (Flitcroft, 2014). The rate of emmetropisation depends on the initial refractive error, with a greater rate of change in children with larger early refractive errors (Mutti et al., 2005). However, children with very high refractive errors in infancy are less likely to emmetropise than those with lower refractive errors (Mutti et al., 2009). In humans, emmetropisation is considered to be complete by six years of age (Flitcroft, 2014).

Myopia (short-sightedness) frequently develops during the school years in children who were previously emmetropic (Flitcroft, 2014) and myopia prevalence and magnitude increase with age (French, Morgan, Burlutsky, Mitchell, & Rose, 2013; Li et al., 2013; Zhao et al., 2002). In contrast, hyperopia (long-sightedness) and astigmatism (irregular curvature of the cornea or lens causing blurred or distorted vision at distance and near) usually develop during the preschool years. Hyperopia in school-aged children results from infantile hyperopia that does not emmetropise (Flitcroft, 2014). Hyperopia prevalence and magnitude decreases with age (French et al., 2013; Zhao et al., 2002). Similarly, while the prevalence of astigmatism reduces significantly during infancy, most reduction occurs in the first 18 months of life and astigmatism may remain present in preschool-aged and school-

aged children (Atkinson, Braddick, & French, 1980; Mayer, Hansen, Moore, Kim, & Fulton, 2001). On average, astigmatism remains stable in school-aged children, however, changes are seen on an individual level and development of new cases is not uncommon (O'Donoghue et al., 2011; Tong et al., 2004; Zhao et al., 2002).

1.3.2 Refractive error prevalence

Refractive error prevalence varies with geographic location, with populations in East Asia having a high prevalence of myopia and astigmatism (Table 10-2) and particular populations, such as Native Americans, having a high prevalence of significant astigmatism (Harvey et al., 2010). The prevalence of myopia has been increasing worldwide, and it is estimated that by 2050, half of the world's population will have myopia (Holden et al., 2016).

Studies of school-aged children in Australia have shown overall refractive error prevalence of 12-14% (French et al., 2013). In comparison with East Asian countries and countries with primarily European Caucasian populations, Australia has a lower prevalence of myopia (French et al., 2013). Indigenous children in Australia have lower prevalence of refractive error than non-indigenous children (Hopkins, Sampson, Hendicott, & Wood, 2016) and children living in areas of socioeconomic deprivation have significantly lower prevalence of myopia compared with children from other areas (Fu, Watt, Junghans, Delaveris, & Stapleton, 2020).

There are, however, no contemporary refractive error prevalence data for NZ children, and it is unknown whether ethnic differences exist within the NZ population, particularly for children of Māori (the indigenous population of NZ) and Pacific ethnicities. While studies of the Australian population are likely to provide data most similar to the NZ population, NZ has a significantly different demographic profile (Australian Bureau of Statistics, 2017; Statistics New Zealand, 2020). Limited population data of refractive error in Pacific nations have shown a low prevalence of refractive error (Barnes et al., 2011; Lindquist, Cama, & Keeffe, 2011), however it is unknown if this is different for Pacific children living in NZ. Similarly, NZ has a growing Asian population, and it is unknown whether Asian children resident in NZ have refractive error prevalence similar to that seen in East Asian countries.

Table 10-2: Refractive error prevalence in school-aged children by region and country

Global region and country	Number of participants	Age (years)	Refractive error prevalence (%)			Population type
			Hyperopia	Astigmatism	Myopia	
Africa						
Equatorial Guinea (Soler, Anera, Castro, Jiménez, & Jiménez, 2015)	425	6-16	3.1	32.5	10.4	School
Morocco (Anera, Soler, De La Cruz Cardona, Salas, & Ortiz, 2009)	545	6-16	18.3	23.5	6.1	School
Somalia (Abdi Ahmed et al., 2020)	1204	6-15	2.7	3.9	9.1	Random cluster school sample
South Africa (Magakwe et al., 2020)	326	6-18	2.8	7.4	10.4	Random cluster school sample
South Africa (Naidoo et al., 2003)	4890	5-15	2.9	9.2	1.8	Population
Americas						
Brazil (Moraes Ibrahim et al., 2013)	1590	10-15	1.0	3.1	3.1	Population
Chile (Maul et al., 2000)	5303	5-15	14.5	27.2	5.8	Population
Mexico (Signes-Soler, Pinero, Murillo, & Tablada, 2019)	2647	5-14	0.6	5.3	4.6	Random cluster school sample

Global region and country	Number of participants	Age (years)	Refractive error prevalence (%)			Population type
			Hyperopia	Astigmatism	Myopia	
Eastern Mediterranean						
Iran (Rezvan et al., 2012)	1551	6-17	5.4	11.5	4.3	Random cluster school sample
Iran (Hashemi et al., 2016)	4106	7	6.2	17.4	3.0	Random cluster school sample
Iran (Rajavi et al., 2015)	2410	7-12	3.5	22.6	4.9	Random cluster school sample
Iran (Fotouhi et al., 2007)	5544	7-15	16.6	18.7	3.4	Random cluster school sample
Europe						
Republic of Ireland (Harrington, Stack, et al., 2019)	1626	6-7	25.0	19.2	3.3	Random cluster school sample
		12-13	8.9	15.9	19.9	
Poland (Czepita, Mojsa, Ustianowska, Czepita, & Lachowicz, 2007)	5724	6-18	38.0 (≥ 1.00 D)	4.0	13.0	School
Sweden (Grönlund, Andersson, Aring, Hård, & Hellström, 2006)	143	4-15	9.1	22.4	6.3	School
Turkey (Gursoy, Basmak, Yaz, & Colak, 2013)	709	7-8		11.0	22.6	Random cluster school sample
Turkey (Caca et al., 2013)	21062	6-14	5.9	14.3 (≥ 0.50 D)	3.2	Random cluster school sample

Global region and country	Number of participants	Age (years)	Refractive error prevalence (%)			Population type
			Hyperopia	Astigmatism	Myopia	
South East Asia						
Kingdom of Bhutan (Sharma et al., 2020)	4985	10-15	2.2	9.8	6.6	Random cluster school sample
India (Dandona et al., 2002)	4074	7-15	0.8	3.8	4.1	Population
India (Murthy et al., 2002)	6447	5-15	7.7	10.2	7.4	Population
Nepal (Pokharel et al., 2000)	5067	5-15	1.4	2.3	1.2	Population
Thailand (Yingyong, 2010)	2340	6-12	1.3	0.2	7.5	Random cluster school sample
Western Pacific						
Australia (French et al., 2013; Huynh et al., 2006)	1765	6	9.4	10.3	1.4	Random cluster school sample
Australia (Huynh, Kifley, Rose, Morgan, & Mitchell, 2007; Ip, Huynh, et al., 2008)	2353	12	3.5	13.6	11.9	Random cluster school sample
Australia (Indigenous) (Hopkins et al., 2016)	181	5-13	5.1	3.4 (≥ 1.00 D)	1.7	School
Australia (Non-indigenous) (Hopkins et al., 2016)	414	5-13	8.1	1.9 (≥ 1.00 D)	4.0	School
China (Zhao et al., 2000)	5884	5-15	2.6	13.5	14.9	Population
China (He et al., 2004)	4364	5-15	5.8	33.6	35.1	Population
China (Wu et al., 2013)	6026	4-18	5.8	36.3	36.9	Random cluster school sample

Global region and country	Number of participants	Age (years)	Refractive error prevalence (%)			Population type
			Hyperopia	Astigmatism	Myopia	
Western Pacific						
Laos (Casson et al., 2012)	2899	6-11	2.8	9.0	0.8	Random cluster school sample
Malaysia (Goh et al., 2005)	4634	7-15	1.3	15.7	19.3	Population
New Zealand (Williams, Sanderson, Share, & Silva, 1988)	537	11	4.8 (> +2.25 D)		4.3	Birth cohort
Vanuatu (Garner et al., 1988)	827	6-19	0.0	0.7 (> 1.00 D)	4.7	School

Myopia ≤ -0.50 D, Hyperopia ≥ +2.00 D, Astigmatism ≥ 0.75 D except where stated otherwise

D = dioptres

* Non-cycloplegic

1.3.3 Ocular associations of refractive error

Significant refractive errors are associated with reductions in VA and stereoacuity, as well as development of strabismus and amblyopia (Colburn et al., 2010; Kulp et al., 2014; Tang et al., 2016).

Uncorrected hyperopia is associated with strabismus, most commonly esotropia, with increased risk with increasing hyperopia (Colburn et al., 2010; Ip, Robaei, et al., 2008; Tang et al., 2016). Additionally, children with hyperopia have increased risk of amblyopia (Klimek, Cruz, Scott, & Davitt, 2004; Pascual et al., 2014). Children with hyperopia also exhibit deficits in accommodation, convergence, stereoacuity and attention (Ciner, Orlansky, & Ying, 2016; Ip, Robaei, et al., 2008; Kulp et al., 2017). Hyperopia of more than +3.25 dioptres is also associated with a higher prevalence of astigmatism and anisometropia (Kulp et al., 2014).

Uncorrected astigmatism is associated with both esotropia and exotropia (Maconachie, Gottlob, & McLean, 2013), deficits in VA, contrast sensitivity and stereoacuity, and can result in amblyopia development (Harvey, Dobson, Miller, & Clifford-Donaldson, 2008). Astigmatism present in infancy (Gwiazda, Grice, Held, McLellan, & Thorn, 2000) and in children aged 3-6 years (Fan et al., 2004) has been associated with myopia development later in childhood. Astigmatism may also be an early sign of keratoconus, a bilateral progressive localised thinning of the corneal stroma resulting in protrusion of the affected cornea (Romero-Jiménez, Santodomingo-Rubido, & Wolffsohn, 2010). Keratoconus is the leading indication for corneal transplantation in NZ (Crawford, McKelvie, Craig, McGhee, & Patel, 2017) and has greater prevalence and severity in individuals of Māori and Pacific ethnicities (Crawford et al., 2017; Owens & Gamble, 2003; Papali'i-Curtin et al., 2019). Early detection and treatment of keratoconus can reduce visual loss (McGhee, Kim, & Wilson, 2015).

Myopia causes visual impairment and is associated with strabismus, primarily exotropia (Tang et al., 2016), and with amblyopia and anisometropia (Fitzgerald, Chung, & Krumholtz, 2005). Additionally, myopia is associated with increased risk of ocular pathology in adulthood, including cataract, glaucoma, and retinal conditions, which can lead to permanent visual loss (Wong, Ferreira, Hughes, Carter, & Mitchell, 2014). This risk increases with increasing magnitude of myopic refractive error.

1.3.4 Refractive error correction

Refractive error correction can improve VA, resolve asthenopic symptoms (Abdi & Rydberg, 2005) and is the first line of treatment in strabismic, anisometropic and bilateral refractive amblyopia (Asper, Watt, & Khuu, 2018; Wallace et al., 2007). The level of refractive error requiring correction differs depending on age. Optometric prescribing guidelines for preschool-aged children (3-5 years) are largely evidence-based (American Academy of Ophthalmology Preferred Practice Patterns Committee, 2017; Leat, 2011).

Refractive error correction in preschool-aged children is aimed at the prevention and treatment of amblyopia and strabismus, while allowing for emmetropisation (Holmes & Clarke, 2006; Leat, 2011). There is frequently lack of agreement between practitioners regarding the levels of refractive error requiring correction in school-aged children (Cotter, 2007; Donahue, 2007; Sharma & Gaur, 2018). (American Academy of Ophthalmology Preferred Practice Patterns Committee, 2017).

Correction of hyperopia in preschool-aged children is aimed at prevention of amblyopia in children with high hyperopia and correction of any associated esotropia (Cotter, 2007; Leat, 2011). In school-aged children, however, there is a lack of evidence regarding the effect of mild to moderate amounts of hyperopia and prescribing for these refractive errors tends to be based on clinical experience (Hopkins, Narayanasamy, et al., 2019).

Similarly, current guidelines for correction of astigmatism tend to be directed at the prevention of meridional amblyopia or improvement of VA (Harvey, Miller, Dobson, & Clifford, 2005; Leat, 2011) and do not address the minimum levels of astigmatism that should be corrected to provide optimal visual performance and academic ability (Hopkins, Narayanasamy, et al., 2019). Further research is required to determine the minimum levels of hyperopia and astigmatism that require correction to optimise visual function and academic outcomes.

Full correction of myopic refractive error in school-aged children is important, as bilateral under-correction can result in increased myopia progression (Chung, Mohidin, & O'Leary, 2002). There is, however, currently a lack of consensus regarding the level of myopia that should be corrected in preschool-aged children (Wolffsohn et al., 2020).

1.4 Binocular Function

Binocular vision anomalies are the second most common eye condition in children following refractive errors (Scheiman et al., 1996). Binocular vision anomalies include strabismus, as well as non-strabismic anomalies of convergence (the ability to turn the eyes inwards to look at a close object) or divergence (the ability to turn the eyes outwards to look at a distant object) and accommodation. These conditions are associated with asthenopic symptoms such as tiredness, discomfort when reading, headaches, blurred vision, diplopia, sleepiness, difficulty concentrating, movement of print, and loss of comprehension after short periods of reading or performing close activities (Abdi & Rydberg, 2005; Borsting, Rouse, Deland, et al., 2003). When the eyes accommodate to bring a near object into focus, they also converge to keep the image single and thus accommodation and convergence problems frequently occur together (Marran, De Land, & Nguyen, 2006). Accommodative and convergence problems are often related to uncorrected refractive error and correction of refractive error can resolve symptoms and signs (Dwyer & Wick, 1995).

1.4.1 Strabismus

Strabismus is a misalignment of the eyes, and in this thesis refers to any manifest deviation. Strabismus is a risk factor for the development of amblyopia (Holmes & Clarke, 2006) and also affects the development of stereopsis (perception of depth) and consequently fine motor skills (Hrisos, Clarke, Kelly, Henderson, & Wright, 2006; Webber et al., 2008). Children with strabismus have a higher prevalence of symptoms of anxiety and depression compared with children without strabismus (Chai et al., 2009). Globally, strabismus prevalence has been estimated to be 1.9% (Hashemi et al., 2019), with significant differences between different populations (Table 1-3). Accommodative esotropia resulting from uncorrected hyperopia can resolve with spectacle correction of hyperopia (Mulvihill, MacCann, Flitcroft, & O'Keefe, 2000), while other strabismus may require surgical correction of the misalignment.

1.4.2 Non-strabismic binocular vision anomalies

The prevalence of non-strabismic binocular vision anomalies has been less rigorously studied than refractive error and visual impairment. Non-strabismic binocular vision anomalies are characterised by latent deviations of eye alignment. There is a paucity of population-based studies and a lack of consistency in diagnostic criteria for binocular vision anomalies, resulting in considerable variation in the estimated prevalence of these conditions (Cacho-Martínez, García-Muñoz, & Ruiz-Cantero, 2010). The most common classification for non-strabismic binocular vision anomalies refers to convergence insufficiency, convergence excess, divergence insufficiency and divergence excess (Scheiman, 2014). This classification system takes an integrative approach and considers the results of several diagnostic tests of vergence and accommodation. A binocular vision anomaly is diagnosed when a participant scores below expected values on more than one parameter (Scheiman, 2014). This system has been used to define non-strabismic binocular vision anomalies in this thesis (see Chapter 3 for definitions).

Non-strabismic binocular vision anomalies are associated with symptoms including asthenopia, blurred vision, diplopia, fatigue, loss of concentration, sleepiness and symptoms that are worse at the end of the day (Scheiman, 2014). Children with convergence insufficiency, convergence excess and accommodative insufficiency have symptoms associated with near tasks, while those with divergence excess and divergence insufficiency have symptoms associated with distance tasks. Children with basic esophoria or exophoria have symptoms associated with both distance and near tasks.

Convergence insufficiency is the most common binocular vision (Table 1-3) and thus it has been the most widely studied. The Convergence Insufficiency Symptom Survey is a validated tool for measuring symptoms in patients with convergence insufficiency; symptomatic convergence insufficiency is defined by a score of 16 or more (Borsting, Rouse, Mitchell, et al., 2003; Convergence

Insufficiency Treatment Trial Investigator Group, 2009). In a study of Australian schoolchildren, non-strabismic convergence insufficiency was twice as common in indigenous than in non-indigenous children (Hopkins et al., 2016). Convergence insufficiency can be successfully treated with home and office based therapy regimens (Convergence Insufficiency Treatment Trial Study Group, 2008) and improvements in symptoms and signs are maintained for at least one year after discontinuing treatment (Convergence Insufficiency Treatment Trial Study Group, 2009).

There are currently no population-based estimates for normative values of vergence, stereoacuity and accommodative parameters in NZ children. Similarly, the prevalence of strabismus, non-strabismic binocular vision and accommodative anomalies are also unknown.

1.4.3 Stereoacuity

Stereopsis is the discrimination of depth based on horizontal retinal image disparity between the two eyes (Ciner et al., 2014). Stereoacuity is the threshold measurement of stereopsis. Stereoacuity improves with age during childhood (Birch et al., 2008). Reduced stereoacuity is associated with strabismus, amblyopia, significant refractive error, anisometropia and reduced VA (Ciner et al., 2014; Guo et al., 2016; Robaei, Huynh, Kifley, Gole, & Mitchell, 2007). Improvements in stereoacuity are seen following amblyopia treatment (Stewart et al., 2013), strabismus surgery (Adams et al., 2008; Birch, Fawcett, & Stager, 2000) or refractive correction (Richardson, Wright, Hrisos, Buck, & Clarke, 2005).

Table 1-3: Prevalence of strabismus and non-strabismic binocular vision anomalies

Condition and Country	Number of participants	Age (years)	Prevalence (%)	Population type
Strabismus				
Australia (Ip, Robaei, Rochtchina, & Mitchell, 2006)	1462	6	2.6	Population
Australia (Junghans, Kiely, Crewther, & Crewther, 2002)	2697	3-12	0.3	School
USA (Vision in Preschoolers Study Group, 2004a)	2588	3-5	2.6	School
China (Chen et al., 2020)	2018	3-5	2.5	Population
United Kingdom (Bruce & Santorelli, 2016)	17018	4-5	2.4	Population
Iran (Hashemi et al., 2015)	3675	7	1.7	Population
India (Sharma, Maitreya, Semwal, & Bahadur, 2017)	5918	5-16	0.4	Population
Convergence insufficiency				
Australia (Indigenous) (Hopkins et al., 2016)	181	5-13	10.3	School
Australia (Non-indigenous) (Hopkins et al., 2016)	414	5-13	5.2	School
Australia (Dwyer, 1992)	144	7-18	33.0	Clinic
USA (Scheiman et al., 1996)	1650	6-18	5.3	Clinic
USA (Rouse et al., 1999)	684	9-13	13.0	School
USA (Borsting, Rouse, Deland, et al., 2003)	392	7-13	17.3	School
USA (Rouse, Hyman, Hussein, & Solan, 1998)	620	8-12	17.6	Clinic
India (Hussaindeen et al., 2017)	920	7-17	17.0	Population
Sweden (Abdi & Rydberg, 2005)	120	6-16	18.3	School
South Korea (Jang & Park, 2015)	589	8-13	10.3	School
Convergence excess				
Australia (Indigenous) (Hopkins et al., 2016)	181	5-13	5.4	School
Australia (Non-indigenous) (Hopkins et al., 2016)	414	5-13	5.4	School
Australia (Dwyer, 1992)	144	7-18	15.0	Clinic
USA (Scheiman et al., 1996)	1650	6-18	8.2	Clinic
India (Hussaindeen et al., 2017)	920	7-17	1.7	Population
South Korea (Jang & Park, 2015)	589	8-13	1.9	School

Condition and Country	Number of participants	Age (years)	Prevalence (%)	Population type
Divergence insufficiency				
Australia (Indigenous) (Hopkins et al., 2016)	181	5-13	1.7	School
Australia (Non-indigenous) (Hopkins et al., 2016)	414	5-13	4.7	School
Australia (Dwyer, 1992)	144	7-18	0.7	Clinic
USA (Scheiman et al., 1996)	1650	6-18	0.2	Clinic
India (Hussaindeen et al., 2017)	920	7-17	0.1	Population
Divergence excess				
Australia (Indigenous) (Hopkins et al., 2016)	181	5-13	4.8	School
Australia (Non-indigenous) (Hopkins et al., 2016)	414	5-13	8.8	School
USA (Scheiman et al., 1996)	1650	6-18	0.7	Clinic
India (Hussaindeen et al., 2017)	920	7-17	0.2	Population
Basic exophoria				
Australia (Indigenous) (Hopkins et al., 2016)	181	5-13	2.1	School
Australia (Non-indigenous) (Hopkins et al., 2016)	414	5-13	4.1	School
USA (Scheiman et al., 1996)	1650	6-18	0.7	Clinic
India (Hussaindeen et al., 2017)	920	7-17	0.0	Population
South Korea (Jang & Park, 2015)	589	8-13	1.0	School
Basic esophoria				
Australia (Indigenous) (Hopkins et al., 2016)	181	5-13	0.7	School
Australia (Non-indigenous) (Hopkins et al., 2016)	414	5-13	4.1	School
USA (Scheiman et al., 1996)	1650	6-18	0.3	Clinic

USA = United States of America

1.5 Visual function and academic achievement

More than two-thirds of school classroom time is spent doing academic tasks requiring visual input including distance viewing, near reading and writing, screen-based tasks, and distance to near work (Narayanasamy, Vincent, Sampson, & Wood, 2016). These require adequate VA to see clearly at all distances as well as accurate accommodation and binocular function to maintain clear and comfortable vision. Despite the high level of visual input in classroom learning, there is a lack of consensus regarding the levels of refractive error and reduction in VA that may negatively impact academic performance (Hopkins, Narayanasamy, et al., 2019). Studies investigating the association between

vision and academic achievement have been performed with differing study designs, populations, and outcome measures. Study populations are frequently categorised into those with 'learning disability', 'dyslexia' or 'poor readers' without standard definitions and using non-standardised educational measures such as teacher judgment or school-based tests (Collins, Mudie, Inns, & Repka, 2017; Hopkins, Narayanasamy, et al., 2019).

Physical aspects of the classroom environment influence visual requirements; classroom size affects distance VA requirements, while illumination levels affect the contrast of learning materials (Langford & Hug, 2010; Narayanasamy et al., 2016). Studies of classroom ergonomics have found that minimum distance VA requirements range from 0.06 to 0.64 logMAR (6/7.5 to 6/24) (Narayanasamy et al., 2016; Negiloni, Ramani, & Sudhir, 2017). Unsurprisingly, distance VA demand is greater for children located in the back of the classroom compared with those in the front of the classroom (Langford & Hug, 2010; Negiloni et al., 2017). There is also a move towards 'innovative learning environments', large flexible spaces in which two or more teachers work collaboratively (Cardno, Tolmie, & Howse, 2017). This type of learning environment may result in greater distance VA demands compared with the traditional classrooms evaluated in the current literature. Almost two thirds of time spent on academic-related tasks involves near or computer-based work (Narayanasamy et al., 2016). Near VA demand varies from 0.08 to 0.47 logMAR (6/7.5 to 6/19), including a VA reserve to enable sustained reading (Narayanasamy et al., 2016). As grade level and difficulty increase, there is a reduction in text size with an associated increase in near VA demand (Langford & Hug, 2010; Negiloni et al., 2017).

Limited evidence shows that spectacle wear by children improves academic performance. Studies of children aged 9-12 years in China (Glewwe, Park, & Zhao, 2016; Ma et al., 2014) and the United States (Glewwe, West, & Lee, 2018; Slavin et al., 2018) have shown provision of glasses to children with refractive error results in improved academic scores. Additionally, a study of children aged 5-7 years in the United Kingdom found children with refractive error who were compliant with spectacle wear had better VA and early literacy scores compared with those who were non-compliant with wearing their refractive correction (Bruce, Kelly, et al., 2018). A study in China also showed that children aged 9-12 years with significant refractive error who wore glasses performed better on standardised tests of mathematics and literacy, and the odds of failing a class were reduced by 35% compared with matched controls without glasses (Hannum & Zhang, 2012). Furthermore, in a qualitative analysis of the effect of prescription glasses, teachers, students, and parents reported improvements in school function (Dudovitz, Izadpanah, Chung, & Slusser, 2016).

1.5.1 Reading development

Reading can be defined as the process of extracting meaning from written text (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Inability to read is a significant obstacle to learning and may have long

term educational, social and economic consequences (Handler & Fierson, 2011). In addition, academic achievement is associated with self-esteem in children (Booth & Gerard, 2011). Early identification of reading difficulties and intervention are essential to improve reading ability. Children with a reading disability that is identified in the first two years of school have a 90% chance of improving to an age-appropriate level, whereas children who are identified after four years at school have a 74% likelihood of continuing to struggle in high school (Handler & Fierson, 2017). Reading requires sufficient VA to see print, accurate accommodation and convergence, and accurate performance of a series of eye movements and fixations (Handler & Fierson, 2017). The print size of reading materials should be double the just-readable print size (near VA) for comfortable reading (Chung, Jarvis, & Cheung, 2007).

Reading development is based on phonology and requires adequate oral language development and fluent word identification (Handler & Fierson, 2017; Vellutino et al., 2004). Early language skills predict cognitive and language skills in older children (Marchman & Fernald, 2008) and visual impairment is associated with delayed early language development (McConachie & Moore, 1994). Therefore, early detection of refractive error resulting in reduced VA is important for oral language and later reading development.

Reading ability can be assessed by measures of reading speed (time taken to read a passage of text), fluency (a measure of speed, accuracy and expression when reading aloud) and comprehension (the process of generating meaning from text) (Collins et al., 2017; Handler & Fierson, 2017). In the early school grades, where children are "learning to read", reading instruction is focused on decoding individual words with less emphasis on comprehension (Borsting & Rouse, 1994). As children move to the higher grades, children are "reading to learn", text becomes smaller, and a greater emphasis is placed on comprehension.

1.5.2 Eye movements

Reading English language text requires focusing on words selectively from left to right using saccades (eye movements of short duration and high velocity) to sequentially fixate text (Birch & Kelly, 2017; Rayner, 1985; Vinuela-Navarro, Erichsen, Williams, & Woodhouse, 2017). Saccade length is dependent on ability to recognise letters, the length of the word before the saccade and reading comprehension (Handler & Fierson, 2017). Regressive saccades are used to recheck words and comprehension (Handler & Fierson, 2017). When a reader moves fixation to a new word, the preferred landing position is the centre of the new word; other landing positions make it more likely the word will be re-fixated with an additional corrective saccade (Birch & Kelly, 2017). As reading skills improve, reading speed increases with reduced numbers of refixations (Vorstius, Radach, & Lonigan, 2014).

Skilled readers perform saccades on average every quarter of a second with an average saccade length of two degrees of visual angle (6-8 characters of standard sized text) and average fixation duration of 200-250 milliseconds (ms) (Rayner, 1985). Skilled readers use 85% forward saccades and 15% regressive saccades (Rayner, 1985). Less skilled and beginner readers have shorter forward saccades, an increased number of regressive saccades (25%) and longer fixation times (Handler & Fierson, 2017; Rayner, 1985; Soh, 2016). Eye movements develop during the primary school years with reductions in the number of fixations and regressions (Scheiman & Rouse, 2006).

Eye tracking methods allow direct observation and recording of eye movements and have been used to study eye movements during reading in research for more than 40 years (Rayner, 1978, 1998). However, traditional eye tracking systems have not been suitable for use in paediatric clinical practice due to high cost and invasive techniques including head restraint or attachment of the device directly to the eyes (Eizenman, Frecker, & Hallett, 1984; Robinson, 1963). Optometrists have therefore relied on direct observation and tests that indirectly assess eye movements. The Developmental Eye Movement (DEM) test has been widely used for the assessment of saccadic eye movements during reading (Garzia, Richman, Nicholson, & Gaines, 1990; Kulp & Schmidt, 1997; Powers, Grisham, & Riles, 2008). However, comparison with eye tracking measures has shown that while test performance is related to aspects of reading performance, it does not directly correlate with eye movement parameters (Ayton, Abel, Fricke, & McBrien, 2009). Recent advances in technology, including systems that use optical sensors to detect eye position, and reductions in cost have made eye tracking systems suitable for use in clinical situations (Thomson, 2017).

1.5.3 Visual acuity and academic outcomes

1.5.3.1 Visual acuity

Reduced distance and near VA affects the ability of children to access learning materials, particularly as classroom size and grade level increase, due to increasing VA demands (Langford & Hug, 2010). Studies examining associations between VA and academic ability, however, have produced equivocal results. Some studies have found an association between habitual distance VA and academic performance (Bruce et al., 2016; Chen, Bleything, & Lim, 2011; Jan et al., 2019), while other studies have found no association (Dirani et al., 2010; Grisham, Powers, & Riles, 2007; Helveston et al., 1985). In preschool children in the United Kingdom, literacy scores were significantly associated with presenting distance VA, independent of cognitive ability, as well as demographic and socioeconomic factors (Bruce et al., 2016). Similarly, distance and near VA were correlated with academic scores in a study of American children aged 6-12 years (Maples, 2003). In contrast, other studies have found no association between reduced distance VA and measures of reading ability. In a study of schoolchildren in Singapore aged 9-10 years, presenting distance VA was not related to academic school performance

(Dirani et al., 2010). The children in this study were older than in the study by Bruce et al. and it is unknown whether this age difference may have affected the outcomes. Similarly, a study of children with and without delayed reading skills found no significant difference in VA between children in the two groups (Vinuela-Navarro et al., 2017). Proposed reasons for disparities in study results include differences in criteria for abnormal VA and large numbers of children with normal VA within study populations (Hopkins, Narayanasamy, et al., 2019). Additionally, studies frequently do not analyse these results according to type of refractive error; children with low to moderate levels of myopia frequently have normal VA at near whereas children with high myopia, hyperopia and astigmatism typically have reduced near VA.

Despite the fact that near activities contribute to a significant proportion of classroom learning, studies examining associations of near VA with academic performance are limited (Hopkins, Narayanasamy, et al., 2019). The Vision in Preschoolers study found that children with hyperopia and reduced near visual function had reduced scores on preschool tests of early literacy (Kulp et al., 2016). Further research is required to fully understand the impact of reduced near VA on academic outcomes.

1.5.3.2 Amblyopia

Studies of amblyopia and reading ability have provided mixed results (Webber, 2018). Population studies have found no association between amblyopia and reading ability (Rahi et al., 2006; Wilson & Welch, 2013). However, experimental studies have found that children with amblyopia read more slowly and exhibit different eye movement patterns than non-amblyopic controls. Children with anisometropic (Kelly et al., 2015), strabismic (Kanonidou, Proudlock, & Gottlob, 2010) and micro-strabismic amblyopia (Stifter, Burggasser, Hirmann, Thaler, & Radner, 2005) exhibit reduced reading speeds compared with non-amblyopic children. Likewise, children with amblyopia have below average oral reading performance (Kugathasan, Partanen, Chu, Lyons, & Giaschi, 2019) compared with their non-amblyopic counterparts. Compared with children without amblyopia, those with anisometropic amblyopia exhibit fixation instability and an increased number of forward saccades with slower initiation and more variable saccade amplitudes (Kelly et al., 2017). Additionally, children with strabismic amblyopia perform more regressive saccades and have longer fixation durations than those without amblyopia (Kanonidou et al., 2010). These results suggest that amblyopia may have a more significant impact on reading ability for some children.

1.5.4 Refractive error and academic outcomes

Studies of associations between refractive error and measures of academic ability have provided conflicting results (Table 1-4) potentially due to differences in refractive error definitions and academic characteristics used to define study populations which also make comparisons between studies problematic (Hopkins, Narayanasamy, et al., 2019).

Some studies have found associations between refractive error prevalence and academic scores in children considered to be 'learning disabled'. A study comparing proficient and non-proficient readers found that children who were not proficient readers were more likely to fail a vision screening than proficient readers (Goldstand, Koslowe, & Parush, 2005). In contrast, other studies have found no association between refractive error and academic performance. Several studies that have compared children with average and delayed reading skills have found no differences in refractive error between the groups (Creavin, Lingam, Steer, & Williams, 2015; Dusek, Pierscionek, & McClelland, 2010; Helveston et al., 1985; Vellutino et al., 2004; Vinuela-Navarro et al., 2017).

Simulated refractive error is commonly used to investigate the effect of refractive error on visual and academic parameters. Studies in adults have shown reductions in distance and near VA and reading speed under simulated spherical (Chung et al., 2007) and astigmatic (Wolffsohn, Bhogal, & Shah, 2011) blur conditions. Similarly, in children, reading speed, accuracy and comprehension are all reduced with simulated hyperopia (Narayanasamy, Vincent, Sampson, & Wood, 2015a), hyperopic astigmatism (Narayanasamy, Vincent, Sampson, & Wood, 2015b) and hyperopic anisometropia (Narayanasamy, Vincent, Sampson, & Wood, 2014). However, participants in these studies generally have normal baseline VA and may perform differently to those with uncorrected refractive error who have adapted to their visual impairment.

Table 1-4: Summary of studies investigating associations between refractive error and academic ability

Refractive error and country	Age (years)	Refractive error definition (Dioptres)	Academic measure	Findings
Hyperopia				
Australia (Hopkins, Sampson, Hendicott, & Wood, 2017)	6-13	≥ +1.50	Neale Analysis of Reading Ability	No difference between children with and without hyperopia.
Canada (Shankar, Evans, & Bobier, 2007)	4-7	≥ +2.00	Wide Range Achievement Test Peabody Picture Vocabulary Test Rosner Test of Auditory Analysis Emergent Orthography Test	Reduced performance on letter and word recognition, receptive vocabulary, emergent orthography.
Canada (Quaid & Simpson, 2013)	6-16		Children with an Individual Education Plan	Children with an Individual Education Plan had significantly higher hyperopia than controls.
Netherlands (van Rijn et al., 2014)	9-10	≥ +0.75	One-Minute Test Klepel	Significantly lower scores for children with hyperopia compared with those with myopia on the One-Minute Test but not the Klepel. Correction of hyperopia resulted in improved scores on the One-Minute Test but not the Klepel.
New Zealand (Williams, Sanderson, et al., 1988)	7-11	> +2.25	WISC-R IQ test Burt Word Reading Test	Children with hyperopia significantly lower IQ scores. No significant differences Burt Word Reading Test.

Refractive error and country	Age (years)	Refractive error definition (Dioptres)	Academic measure	Findings
Hyperopia				
USA (Fulk & Goss, 2001)	4-15		Teacher evaluations	Children with hyperopia more frequently in lower achievement category than those with myopia or emmetropia.
USA (Krumholtz, 2000)		Hyperopia assessment screening	Citywide achievement test scores	Hyperopia assessment screening predictive of children in the lowest 25% of achievement test scores.
USA (Kulp et al., 2016)	4-5	≥ +3.00	Test of Preschool Early Literacy	Significantly lower scores for children with hyperopia ≥ +4.00 D or ≥ +3.00 D to ≤ +6.00 D with reduced near VA or stereopsis.
USA (Rosner & Rosner, 1987)	6-12	≥ +1.00	Learning difficulties as assessed by schools/parents	Hyperopia more prevalent in children with learning difficulties.
USA (Rosner, 1997)	6-11	> +1.25	Iowa Test of Basic Skills	Significantly lower scores for children with hyperopia.

Refractive error and country	Age (years)	Refractive error definition (Dioptres)	Academic measure	Findings
Astigmatism				
USA (Garber, 1981)	5-12	≥ 2.00	Stanford Achievement Test Classroom reading grades	Reduced scores on classroom reading grades but not Stanford Achievement Test.
USA (Harvey, Miller, Twelker, & Davis, 2016)	8-14	≥ 1.00	Dynamic Indicators of Basic Early Literacy Skills	Uncorrected astigmatism associated with poorer oral reading fluency scores.
USA (Harvey et al., 2018)	1-3	> 2.00	Bayley Scales of Infant and Toddler Development	Uncorrected astigmatism associated with poorer performance on cognitive, language and fine motor tasks but not gross motor tasks.
USA (Orlansky et al., 2015)	3-5	> 0.25	Work Sampling System Ages and Stages Questionnaire	Astigmatism associated with reduced test scores.

Refractive error and country	Age (years)	Refractive error definition (Dioptres)	Academic measure	Findings
Myopia				
Netherlands (van Rijn et al., 2014)	9-10	Clinically significant	One-Minute Test Klepel	Significantly higher scores for children with myopia compared with those with hyperopia in the One-Minute Test but not the Klepel.
New Zealand (Williams, Sanderson, et al., 1988)	7-11	≤ -0.50	WISC-R IQ test Burt Word Reading Test	Children with myopia significantly higher IQ scores but no significant differences in Burt Word Reading Test results.
Singapore (Saw et al., 2007)	10-12	≤ -0.50	Standard nationwide examination results	Children with examination scores in the highest quartile more likely to be myopic than those with scores in the lowest quartile.
UK (Stewart-Brown, Haslum, & Butler, 1985)	10	Poor distance VA without reduced near VA	British Ability Scales Edinburgh Reading Test	Children with reduced distance vision and perfect near VA scored significantly higher on tests of intelligence and reading than those with no defects.
UK (Williams, Miller, Gazzard, & Saw, 2008)	7-10	≤ -1.50 (non-cycloplegic)	Standardised Assessment Tests Weschler Objective Reading Dimension Test WISC	Reading assessments, verbal IQ and maths results associated with myopia at 7 years.
USA (Mutti, Mitchell, Moeschberger, Jones, & Zadnik, 2002)	13-14	≤ -0.75	Iowa Test of Basic Skills	Children with myopia scored higher than those with emmetropia in reading and total language.

D = dioptres

WISC = Weschler Intelligence Scales for Children

1.5.4.1 Hyperopia

Children with hyperopia often have reduced VA at distance and near but may achieve clear vision by using accommodative effort (American Optometric Association, 2010). However, this may result in symptoms such as asthenopia, headaches and intermittent blurring of print as well as fatigue and disengagement with learning activities (Hopkins, Narayanasamy, et al., 2019). Studies of simulated spherical refractive error have shown significant reductions in distance and near VA and reading speed in adults (Chung et al., 2007). Likewise simulated hyperopia (+2.50 dioptres) resulted in lower scores for reading rate, accuracy and comprehension in children aged 10-12 years with further reductions observed following sustained near work (Narayanasamy et al., 2015a).

In some studies, hyperopia has been associated with reduced scores on tests of reading, early literacy and other academic measures in preschool and school-aged children (Fulk & Goss, 2001; Krumholtz, 2000; Kulp et al., 2016; Quaid & Simpson, 2013; Rosner, 1997; Shankar et al., 2007; Simons & Gassler, 1988; Williams, Latif, Hannington, & Watkins, 2005). In a large scale study, the Vision in Preschoolers study group found that preschool children aged 4-5 years with uncorrected hyperopia (between +3.00 dioptres and +6.00 dioptres) and reduced near visual function (reduced near VA or reduced near stereoacuity) scored significantly lower in a test of preschool early literacy than preschool children of the same age without refractive error (Kulp et al., 2016). Similarly, a study of preschool children aged 3-7 years showed children with hyperopia (+2.00 dioptres or more) had significantly reduced performance on tests used to indicate emergent literacy skills compared with children without refractive error (Shankar et al., 2007). There were no significant differences in VA between the two groups, indicating the difference in performance was not due to inability to see the text but may be related to difficulties with sustained focus. Rosner (Rosner & Rosner, 1987) found that hyperopia was more prevalent among children who were considered ‘learning disabled’ than those without learning disability and, in a further study, found lower achievement test scores in children with more than +1.25 dioptres of hyperopia (Rosner, 1997). In an additional study comparing children with learning difficulties to controls, children with learning difficulties had greater prevalence of hyperopia (Quaid & Simpson, 2013). In children aged 7-8 years, those with hyperopia (more than +3.00 dioptres) scored lowest on tests of educational achievement, although in this study a plus lens test was used to screen for hyperopia which may have resulted in some children with hyperopia being incorrectly classified as controls (Williams et al., 2005).

In a study of correction of hyperopia in children aged 9-10 years, children who received full correction of their refractive error showed a significant increase in reading speed compared with those who were uncorrected or a placebo correction (van Rijn et al., 2014). In contrast, in a study of Australian schoolchildren, Hopkins et al. (Hopkins et al., 2017), found no difference in reading accuracy and reading comprehension between children with and without uncorrected hyperopia (+1.50 dioptres or

more). The authors suggested that other factors affecting educational factors may have coexisted in this population and may have masked the impact of hyperopia in these children.

1.5.4.2 Astigmatism

Children with uncorrected astigmatism have reduced VA, stereoacuity and contrast sensitivity (Harvey, Dobson, Miller, & Clifford-Donaldson, 2007). Reduced VA in astigmatism differs from other refractive errors in that the blur varies dependent on orientation. Studies of simulated astigmatism have shown significant reductions in distance and near VA and reading speed in adults (Casagrande et al., 2014; Wills et al., 2012; Wolffsohn et al., 2011) and children (Narayanasamy et al., 2015b).

A study of children from a population with a high prevalence of astigmatism found that uncorrected astigmatism resulted in a decrease in classroom performance based on non-standardised teacher assessments but there was no difference in standard achievement test scores (Garber, 1981). More recent studies in preschool-aged children have shown uncorrected astigmatism results in poorer performance on cognitive, language and fine motor tasks (Harvey et al., 2018) and detrimentally affects academic readiness (Orlansky et al., 2015). Additionally, a study of school-aged children found children with uncorrected astigmatism (greater than 1.00 D) had reduced oral reading fluency scores compared with those with low or no astigmatism (Harvey et al., 2016). Reading fluency improved with spectacle correction, with greater improvement in children with higher magnitudes of astigmatism.

1.5.4.3 Myopia

Uncorrected myopia causes reduced distance VA (Robaei et al., 2005). Children with mild to moderate myopia have normal near VA, whereas high myopia results in reduced near VA. Myopia has been associated with average or above average reading and intelligence test scores (Mutti et al., 2002; Simons & Gassler, 1988; Stewart-Brown et al., 1985; Williams, Sanderson, et al., 1988) and children with myopia have increased reading speeds compared with children with hyperopia (van Rijn et al., 2014). In children aged 10-12 years in Singapore, myopia was associated with higher academic achievement, with higher examination scores associated with higher levels of myopia (Saw et al., 2007). However, correction of moderate myopia has been shown to improve self-reported visual functioning in children (Esteso et al., 2007). Furthermore, provision of glasses to children aged 9-12 years in China, of whom 95% of children with refractive error had myopia, resulted in improvement in academic test scores when compared to controls who did not receive glasses (Ma et al., 2014).

1.5.5 Binocular function and academic outcomes

Binocular vision anomalies, including disorders of convergence and accommodation, can cause blurred vision and discomfort when performing near tasks (Handler & Fierson, 2017) however the effect of binocular vision anomalies on academic outcomes is unknown.

1.5.5.1 Strabismus

Studies of the effect of strabismus on academic outcomes are limited but the available evidence suggests that strabismus is detrimental to reading outcomes and improvements are seen following strabismus surgery (Kugathasan et al., 2019; Ridha, Sarac, & Erzurum, 2014). Children with strabismus have more self- and parent-reported academic difficulties than those without strabismus (Menon, Saha, Tandon, Mehta, & Khokhar, 2002; Reed, Kraft, & Buncic, 2004). A study of French children aged 11-15 years found differences in eye movements while reading between children with strabismus and controls (Perrin Fievez, Lions, & Bucci, 2018). Children with strabismus read more slowly than age-matched controls and had improvements in reading speed and numbers of regressive saccades following strabismus surgery. Additionally, in a study of American children aged 5-14 years, correction of strabismus resulted in improvement reading measures six weeks after surgery compared to their pre-surgical performance (Ridha et al., 2014).

1.5.5.2 Non-strabismic binocular vision anomalies

The relationship between non-strabismic binocular vision anomalies and academic outcomes is unclear. Heterophorias (latent deviations of eye alignment) have been associated with poorer reading ability with a meta-analysis finding that distance exophoria and esophoria were associated with average or above average reading skills and near exophoria and vertical heterophoria were associated with below average reading skills (Simons & Gassler, 1988). Another study found that Howell card heterophorias correlated with scores on the Iowa Test of Basic Skills (Maples, 2003). These results suggest that binocular vision anomalies may be associated with reduced reading outcomes, however, further research is required.

Some studies have found associations between vergence facility and reading speed (Quaid & Simpson, 2013) and near point of convergence and reading ability (Evans, Drasdo, & Richards, 1992). Additionally, near point of convergence was found to be correlated with scores of academic ability (Maples, 2003). In a study of children aged 10-14 years in Sudan, convergence insufficiency and weak positive fusional reserves were more common in children with poor academic performance (Alrasheed, 2020). In contrast, the results of a meta-analysis found that near point of convergence was not associated with reading skill (Simons & Gassler, 1988). Similarly, a study of Australian schoolchildren aged 6-13 years found no difference in reading accuracy and reading comprehension between children with and without convergence insufficiency (Hopkins et al., 2017). In an additional study comparing children with learning difficulties to controls, children with learning difficulties had a higher prevalence of convergence insufficiency and reduced vergence reserves (Quaid & Simpson, 2013). Successful treatment of convergence insufficiency is associated with reduction in adverse academic behaviours observed by parents (Borsting et al., 2012), however, treatment of convergence

insufficiency does not result in improvements in reading performance (Convergence Insufficiency Treatment Trial-Attention and Reading Trial Investigator Group, 2019).

Accommodative insufficiency has been associated with poorer academic outcomes. In a study of children referred for suspected reading disability, amplitude of accommodation was significantly correlated with reading ability (Evans et al., 1992). In a study of Spanish children aged 8-13 years, children classified as poor readers had reduced monocular amplitude of accommodation compared with controls (Palomo-Alvarez & Puell, 2008). Similarly, children with accommodative dysfunction and those with combined accommodative and vergence problems had lower academic achievement than children with normal binocular vision (Shin, Park, & Park, 2009). A further study showed that amplitude of accommodation, accommodative lag and accommodative facility were all correlated with scores of academic ability (Maples, 2003).

1.5.5.3 Stereoacuity

Two studies of children aged 5-8 years in the United States found that stereoacuity was correlated with scores on standardised tests of reading ability (Kulp & Schmidt, 1996b, 2002). In a study of Australian children aged 6-8 years, stereoacuity was also associated with reduced reading and mathematics test scores (Hopkins, Black, et al., 2019). A study of American school children aged 6-12 years found that stereoacuity was correlated with scores on the Iowa Test of Basic Skills (Maples, 2003). In contrast, a study of Australian children aged 8-9 years found no association between stereoacuity and academic outcomes. Deficits in stereoacuity have been associated with reduced reading speed (Kelly et al., 2015) and fixation instability (Birch, Subramanian, & Weakley, 2013) in experimental studies.

1.5.6 Visual perception

Visual perception is the process of organising and processing visual information (Kulp, 1999) and visual-motor integration (VMI) is the degree to which visual perception and finger-hand movements are coordinated (Beery & Beery, 2010). Visual perceptual and visual-motor integration skills have been found to be significantly related to achievement in reading (Helveston et al., 1985; Kavale, 1982) and written mathematics (Solan, 1987). Performance on tests of visual perception have been shown to be affected by refractive error. Children with hyperopia are more likely to fail tests of visual perceptual skills than children with myopia and those without refractive error (Rosner & Gruber, 1985).

The Beery-Buktenica Test of Visual-Motor Integration (Beery VMI) is a standardized test of VMI that is frequently used by occupational therapists and neuropsychologists (Rabin, Barr, & Burton, 2005; Rodger, Brown, & Brown, 2005). Reduced performance on the Beery VMI occurs in pre-school aged children with uncorrected hyperopia and astigmatism (Roch-Levecq et al., 2008), and those with uncorrected hyperopia and reduced near function (Kulp et al., 2017), as well as school-aged children

with astigmatism (Harvey, Twelker, et al., 2017). In contrast, a study of children aged 4-7 years found no significant differences in VMI performance between children with hyperopia and those without refractive error (Shankar et al., 2007). These differences may be the result of differing refractive error definitions and varying effects of refractive error on VA.

Several studies have shown performance of children on the Beery VMI is related to academic achievement (Lowther, Rainey, Kidd, Horner, & Connell, 2000; Santi, Francis, Currie, & Wang, 2015; Sortor & Kulp, 2003) and VMI has been found to be a strong predictor of academic success (Fowler & Cross, 1986; Klein, 1978; Maples, 2003). VMI results have been found to be significantly related to reading, mathematics, writing and spelling ability (Barnhardt, Borsting, Deland, Pham, & Vu, 2005; di Tore et al., 2016; Hopkins, Black, et al., 2019; Kulp, 1999; Pienaar, Barhorst, & Twisk, 2014). Impaired visual perceptual skills have also been found to be significantly more prevalent in children with learning difficulties than those without learning difficulties (Rosner & Rosner, 1987). In a cohort of 8-year-old children in Malaysia, children with average or above average academic achievement on standardised examinations achieved better scores on tests of visual perception than those with below average achievement (Chen et al., 2011). Similarly, a study of children aged 6-9 years in the United States found significant differences in scores achieved on the VMI and its subtests between children in the upper and lower quartiles for maths and reading achievement (Sortor & Kulp, 2003). Furthermore a study of children aged 10-12 years in Italy, found strong relationships between reading speed and VMI scores and reading accuracy and VMI scores (di Tore et al., 2016). A major limitation of many of the studies investigating associations between VMI and academic outcomes is that the children did not receive comprehensive vision examinations, so the effect of uncorrected refractive error and reduced VA is unknown. Therefore, further research is required to determine the relationship between uncorrected vision conditions, VMI and academic outcomes.

1.6 Summary

While uncorrected refractive error has been identified as the leading cause of vision impairment in children worldwide, the impact on children in NZ remains unknown. There are currently a lack of population-based prevalence measures of visual impairment, refractive error, and binocular vision anomalies for NZ children.

Despite differences in methodology and definitions, the currently available evidence indicates that uncorrected vision problems in children result in reduced academic outcomes. In many studies, reduced distance VA has not been associated with reduced academic outcomes and similarly myopia has been associated with better academic outcomes than emmetropia or hyperopia. However, correction of myopia has also been associated with improvements in academic outcomes. Despite the more likely association of reduced near VA with academic outcomes, there have been few studies that

have evaluated near VA and academic outcomes. Preschool-aged children with hyperopia and reduced near VA have reduced scores of on tests of early literacy. Similarly, school-aged children with hyperopia and astigmatism have reduced performance on measures of reading ability and other academic outcomes. However, some studies have found no association between uncorrected hyperopia and astigmatism and reading ability. Further research is required to determine minimum levels of refractive error requiring correction to maximise educational outcomes. Similarly, there is limited evidence that strabismus and non-strabismic binocular vision anomalies are associated with reduced academic outcomes. The advent of new eye tracking technologies that are less invasive and more affordable provides the opportunity to examine the visual behaviours of children while reading and undertaking other near tasks.

Furthermore, academic achievement is associated with ethnicity and socioeconomic status. Children of Māori and Pacific ethnicity and those from socioeconomically disadvantaged communities are more likely to have poorer academic outcomes and to leave school without a qualification than their peers. Therefore, timely identification and treatment of abnormalities of visual function in these children is essential to ensuring that they are not further disadvantaged in the educational setting. Additionally, in view of the potentially blinding sequelae of myopia and keratoconus, it is important that these conditions are detected at an early stage of the disease. Understanding the prevalence of visual conditions in the NZ paediatric population and the impact of these conditions on reading and academic performance will identify which conditions need to be detected and treated to reduce inequities and improve visual function in NZ children.

Chapter 2: Access to eye care and vision screening in Aotearoa/New Zealand

Māori and Pacific people in NZ are more likely to have poorer health and educational outcomes compared with those for people from other ethnic groups (Marriott & Sim, 2015). Additionally, children whose families have lower socioeconomic status are more likely to have reduced access to health care services and poorer educational outcomes compared with children whose families are more socioeconomically advantaged (Brabyn & Barnett, 2004; OECD, 2018). Robust vision screening protocols are required to ensure that vision conditions in these children are detected and treated, thereby preventing permanent visual loss and further educational disadvantage. Additionally, it is imperative that systems are in place to ensure that children receive appropriate follow-up care if they fail vision screening. This chapter provides an overview of eye care services and vision screening within the NZ health system and issues surrounding equity and access to these services.

2.1 The New Zealand population

NZ is a multicultural society which includes multiple ethnic groups (Table 2-1). The demographic profile of NZ is changing; compared with the 2013 census, in 2018 there were increases in the proportion of the population who identified as Māori (14.9% to 16.5%), Pacific (7.4% to 8.1%) and Asian (11.8% to 15.1%). There is also significant population mobility. Among those who participated in the 2018 census, 17.1% did not live in the same residence and 2.7% had newly entered NZ, compared to one year beforehand (Statistics New Zealand, 2020).

Table 2-1: New Zealand population by ethnicity at 2018 Census (Statistics New Zealand, 2020)

Ethnicity	n (%)
European	3 297 864 (70.2)
Māori	775 836 (16.5)
Pacific Peoples	381 642 (8.1)
Asian	707 598 (15.1)
Middle Eastern/Latin American/African	70 332 (1.5)
Other	58 053 (1.2)
Total	4 699 755 (100.0)*

*People who responded in more than one ethnic group are counted in multiple groups

2.1.1 Measures of socioeconomic status

The New Zealand Index of Deprivation and school decile ratings are two commonly used measures of socioeconomic status in NZ.

2.1.1.1 New Zealand Index of Deprivation

The New Zealand Index of Deprivation (NZDep) combines variables from the NZ census data to assign a deprivation score to each geographic meshblock (small area containing a median of approximately 80 people) in NZ (Atkinson, Salmond, & Crampton, 2014). Deprivation variables include those describing internet access, income, unemployment, educational qualifications, home ownership, single parent families, household crowding and household access to a vehicle. NZDep scores are grouped into deciles on a scale of 1 to 10 with each decile including one tenth of the NZ population. For the NZDep, a decile of 1 identifies households in the least deprived 10% of meshblocks and decile 10 households in the most deprived decile of meshblocks.

2.1.1.2 School decile ratings

NZ school decile ratings are a measure of the socioeconomic status of the community in which a school's students reside. School deciles are used to allocate funding to state (public) and state-integrated schools for general operations and other key resources. School deciles are determined by assigning the residential addresses of the students to NZ Census meshblocks (Ministry of Education, 2020). Meshblocks are then categorised using data collected at the national census which allows for measurement of five equally weighted socioeconomic indicators: the percentage of households with income in the lowest 20% for the country, the percentage of parents employed in the lowest skill level occupational groups, household crowding, the percentage of parents with no educational qualifications and the percentage of parents receiving income support benefits. In contrast to NZDep deciles, Decile 1 schools are the 10% of schools with the highest proportion of students from low socioeconomic communities while Decile 10 schools have the lowest proportion of these students.

2.2 The New Zealand Healthcare system

NZ has a centralised government and provision of health services is overseen by the Ministry of Health. The country is geographically divided into twenty District Health Boards (DHBs) that are responsible for providing or funding services within their region (Ministry of Health, 2017). Eligible NZ residents receive public hospital treatment at no charge, but with significant waiting lists for non-urgent health care issues (Siciliani, Moran, & Borowitz, 2014). There is also a private healthcare practitioner and hospital system which charges a fee for service for more rapid access to non-urgent care.

Eye care services in NZ are mainly provided by optometrists and ophthalmologists in a hospital or community setting. Hospital ophthalmology and optometry services are publicly funded with no direct

cost to patients or their whānau (family or extended family), but do not normally include routine assessment and treatment of refractive error, except in children less than five years of age. Children five years of age and older receive eye-care services primarily provided by community-based optometrists who are not government funded, requiring payment to be made by the patient's whānau.

2.2.1 Health equity

The Treaty of Waitangi is the founding document of NZ, an agreement between Māori chiefs and representatives of the British Crown, signed in 1840, which guaranteed Māori the same rights and privileges as British subjects (Orange, 2015). Despite the Treaty, colonisation resulted in loss of land, cultural identity and other resources by Māori. Consequently, higher proportions of Māori live in areas with higher NZDep scores and are less advantaged in a range of socioeconomic indicators compared with non-Māori (Ministry of Health, 2019b). Under Article Three of the Treaty, Māori have the right to equal health outcomes, and thus the NZ Government has responsibilities to improve health outcomes and reduce inequities for Māori (Reid et al., 2017). The Ministry of Health has therefore developed He Korowai Oranga, a Māori Health Strategy designed to reduce inequities and achieve the best health outcomes for Māori (Ministry of Health, 2014a).

Poorer health outcomes, reduced life expectancy and lower self-rated health have been reported among people living in more, compared to less, deprived areas, as well as in those of Māori or Pacific ethnicity compared with those of NZ European ethnicity (Hill, 2008; Ministry of Social Development, 2016). Families of Māori and Pacific ethnicity and those living in socioeconomic deprivation have reduced access to healthcare services due to financial, geographic and cultural barriers (Brabyn & Barnett, 2004; Health Quality and Safety Commission New Zealand, 2018; Paine, Harris, Stanley, & Cormack, 2018). Families of Māori and Pacific ethnicity more frequently live in areas of high deprivation than those of European/Other ethnicity (Paine et al., 2018). Furthermore, the proportion of people living in material hardship is higher for individuals of Māori and Pacific ethnicity and those living in areas of socioeconomic deprivation compared with those of other ethnicities or living in less deprived areas (Ministry of Social Development, 2016).

Cost is a significant barrier to accessing primary health care services in NZ for Māori, younger and more deprived populations (Health Quality and Safety Commission New Zealand, 2018). In addition, a lack of eligibility for publicly funded services and inability to confirm eligibility are barriers to receiving hospital care. Although general practitioner visits are free for most children under five years of age, costs of after-hours appointments, lack of transport and lack of parental availability to accompany children have been identified as barriers preventing children receiving primary health care (Morton et al., 2017). Financial issues are likely to also affect access of NZ children to both hospital and community-based eye care services.

There is also increasing evidence that cultural factors including personal and institutional racism and lack of trust in healthcare systems influence access and utilisation by Māori and Pacific whānau (Paine et al., 2018). People of Māori, Asian and Pacific ethnicities are more likely to report experiencing racial discrimination or unfair treatment based on ethnicity than those of European/other ethnicities (Harris et al., 2006; Ministry of Health, 2019b). Similarly, people with low or middle incomes are more likely to report being discriminated against than those with higher incomes (Ministry of Social Development, 2016). Previous experiences of discrimination make adults less likely to seek healthcare for their children and as a result, children of caregivers who have experienced racism are more like to have unmet healthcare needs (Paine et al., 2018).

Health literacy refers to the ability to obtain, process and understand basic health information and services to make informed and appropriate health decisions (Ministry of Health, 2010). Poor health literacy is associated with poor health status and may be a strong contributor to health inequalities. On average, NZ adults have poor health literacy skills, with average scores less than the minimum required for individuals to meet the complex demands of daily life and work (Ministry of Health, 2010). In particular, Māori adults have lower health literacy scores than non-Māori (Ministry of Health, 2010) and Pacific adults have lower general literacy skills than European and Māori adults (Ministry of Social Development, 2016). Additionally, low health literacy is associated with low socioeconomic status (Stormacq, Van den Broucke, & Wosinski, 2019). People with poor health literacy are less likely to use preventative services such as screening programmes, have less knowledge of their illness and treatment, and poorer ability to interpret labels and health messages (Berkman, Sheridan, Donahue, Halpern, & Crotty, 2011).

The Ministry of Health's definition of equity recognises that differing strategies are required for groups with different levels of advantage to achieve equitable health outcomes (Ministry of Health, 2019a). As such, the New Zealand Ministry of Health has identified reducing inequity and improving health outcomes for Māori and Pacific peoples as health priorities (Minister of Health, 2016).

2.3 Unmet eye care need in children

Utilisation of eye care services is influenced by the availability, accessibility, affordability and acceptability of services, and barriers such as socioeconomic status and perceived cost of eyecare can prevent patients from accessing services (World Health Organization, 2019). Poor health literacy has been associated with suboptimal adherence to eye examination guidelines and poorer eye health outcomes (World Health Organization, 2019). In a study of attitudes towards eye health in NZ, almost half of parents reported that their child had not, or they were unsure if their child had, received a comprehensive eye examination (Ahn, Frederikson, Borman, & Bednarek, 2011). A study from the United Kingdom found that 38% of respondents identified at least one barrier to seeking eye care for

their child, most commonly not knowing how or where to access eye health services (Donaldson, Subramanian, & Conway, 2018). Furthermore, studies from the United Kingdom and the United States have shown that children from families with low socioeconomic status are less likely to have seen an eye care specialist than those from more advantaged backgrounds (Majeed et al., 2008; Stein et al., 2016).

Children with significant refractive error frequently do not have appropriate correction (Resnikoff et al., 2008). Studies of school children aged 9-12 years in China have shown less than one in five children have appropriate glasses (Glewwe et al., 2016; Ma et al., 2014) and among secondary school aged children in China, over 60% who needed glasses were not wearing appropriate correction (Congdon et al., 2008). A further study of children aged 13-16 years in China showed that less than 10% of children with a vision problem wore glasses with a socioeconomic gradient associated with access to vision correction (Hannum & Zhang, 2012). However, the refractive error profile of children in China may be different from NZ, due to the high prevalence of myopia in East Asian countries (Hashemi, Fotouhi, et al., 2018). Similarly, a study of children in the United States showed that 86% of children aged 5-16 years with high astigmatism were not wearing glasses (Harvey, Dobson, & Miller, 2006). There are currently no similar data regarding uncorrected refractive error and vision correction in NZ children.

Reasons for children not having glasses include non-participation in screening, lack of follow-up of screening recommendations, and loss or breakage of previously provided glasses. Additional factors that prevent children from wearing prescribed glasses include teasing and/or bullying, not liking spectacles, forgetting to wear them, parent disapproval, and misconceptions that wearing glasses will make vision worse (Morjaria, McCormick, & Gilbert, 2019).

2.4 Vision screening

Preschool vision screening plays a crucial role in the detection of strabismus, amblyopia, and significant refractive error in children. Although vision screening is generally perceived to be beneficial, no randomised controlled trials have been conducted to establish the effectiveness of, or the optimal age for, vision screening in children (Jonas et al., 2017; Powell, Wedner, & Hatt, 2004). However, populations who have not received vision screening have a higher prevalence of amblyopia than seen in screened populations (Høeg et al., 2015; Polling, Loudon, & Klaver, 2012; Thorisdottir, Faxen, Blohme, Sheikh, & Malmsjo, 2019). Vision screening of preschool children allows detection of amblyopia risk factors at an age when treatment is most effective (Holmes et al., 2011). Failure to detect and treat vision problems during childhood may result in permanent vision loss. Additionally, vision screening allows detection and correction of non-amblyogenic refractive errors that may be associated with reduced early literacy and academic outcomes (Hopkins, Narayanasamy, et al., 2019).

2.4.1 Vision screening tests

A variety of tests are available for vision screening in children and the most appropriate test depends on the age and ability of the child and the target condition(s) of the screening. If detection of refractive error is a target of vision screening, it is important to know the refractive error profile of the population to optimise screening strategies.

Assessment of distance VA is commonly used to screen children for reduced vision using age-appropriate tests (Cotter, Cyert, Miller, & Quinn, 2015; Jonas et al., 2017; Powell et al., 2004). Distance VA screening is effective in detecting myopia but is poor at detecting significant hyperopia and/or astigmatism (Jin et al., 2015; Leone, Mitchell, Morgan, Kifley, & Rose, 2010; O'Donoghue, Rudnicka, McClelland, Logan, & Saunders, 2012). Children with hyperopia may pass a distance VA screening using accommodation (Quaid & Simpson, 2013) and children with uncorrected astigmatism frequently achieve sufficient VA to allow them to meet the minimum pass criterion (Garber, 1981). In particular, VA measurements using current preschool vision charts are ineffective in detecting levels of astigmatism that may be amblyogenic (Little, Molloy, & Saunders, 2012). Furthermore, binocular vision anomalies infrequently affect distance VA and thus will often remain undetected following vision screening comprising only measurement of distance VA. Strabismus is not directly screened for using VA screening. Large angle strabismus will frequently be observed by family members or health care practitioners, while functionally significant smaller angle unilateral strabismus will be identified through reduced VA (Hull et al., 2017). However, alternating or intermittent strabismus may remain undetected.

Using instrument-based screening (photorefraction or autorefraction) to detect refractive error can reduce screening times and increase testability, particularly for younger children (Modest et al., 2017). Additionally, some instruments allow direct detection of strabismus and media opacities (Cotter et al., 2015). A recent meta-analysis of vision screening using the Spot and Plusoptix photoscreeners found high sensitivity and moderate specificity of both instruments in screening for amblyopia risk factors, particularly in Asian populations where the prevalence of myopia is high (Zhang, Wang, Li, & Jiang, 2019). In a population of preschool-aged Native American children with a high prevalence of astigmatism, non-cycloplegic autorefraction and autokeratometry had a higher testability and were more accurate than VA screening (Miller, Dobson, Harvey, & Sherrill, 2001).

The large-scale Vision in Preschoolers study assessed the efficacy of vision screening tests for the detection of amblyopia in pre-school aged children in the United States compared with comprehensive eye examinations (Vision in Preschoolers Study Group, 2004a). The study found high testability for all tests investigated when delivered by eye-care professionals, nurses and lay screeners (Kulp & Vision in Preschoolers Study Group, 2009). For tests performed by eye-care professionals, non-cycloplegic

retinoscopy, autorefraction, and Lea symbols VA testing had the highest sensitivity, with similar sensitivity achieved by nurses and lay screeners using autorefraction (Kulp & Vision in Preschoolers Study Group, 2009). Sensitivity of VA testing by lay screeners was increased when the test distance was reduced from 3 m to 1.5 m (Vision in Preschoolers Study Group, 2005). Furthermore, detection of strabismus was improved with the addition of the cover test (eye care professionals) and the Stereo Smile stereoacuity test (nurses and lay screeners) to VA testing or autorefraction (Kulp & Vision in Preschoolers Study Group, 2009). Thus, the appropriate method for vision screening depends on the target condition(s), the refractive error profile of the population, and the personnel responsible for screening.

2.4.2 Vision screening programmes

Vision screening programmes vary widely internationally. Within the European Union, 97% of countries for which data was available had vision screening programmes (Sloot et al., 2015). VA measurement was used in all countries, with the age of first measurement between three and seven years. Coverage of the targeted population varied from programmes that had recently been initiated to greater than 95% of the population. For example, the Netherlands has a well-established and extensive vision screening programme consisting of up to seven visits before seven years of age with more than 99% children receiving at least one vision screening (De Koning et al., 2013). In contrast, some countries such as Australia and the United States do not have universal vision screening programmes; vision screening requirements are determined on a local or state level (Hopkins, Sampson, Hendicott, & Wood, 2013).

2.4.3 Follow-up from vision screening

Effective screening programmes reliably detect the target condition and ensure that treatment is available, affordable and utilised. Studies examining compliance with follow-up of failed vision screening have found that families with lower incomes are less likely to obtain follow up eye care than those with higher incomes (Kemper, Uren, & Clark, 2006; Mark & Mark, 1999; Tjiam et al., 2011). Financial barriers include inability to pay for eye care services, lack of awareness or language barriers preventing access to schemes providing eye exams or glasses, and the perception that the glasses provided by these schemes are of inferior quality (Holzhauser, Herring, & Montgomery, 2002; Kimel, 2006). Additionally, logistical issues resulting in lack of follow-up include problems with scheduling appointments, forgetting appointments, available appointments conflicting with caregivers' work schedules, a shortage of paediatric eye care providers and appointments not being available within a reasonable time frame (Holzhauser et al., 2002; Kemper et al., 2006; Kimel, 2006; Yawn, Kurland, Butterfield, & Johnson, 1998). Social and perceptual barriers also prevent follow-up of screening recommendations. These include unpredictable family schedules and worries about basic needs that

prevent thinking about the future, not considering glasses or eye care a priority, not believing the child needed a professional exam, and not being aware of screening failure (Kemper et al., 2006; Kimel, 2006; Mark & Mark, 1999; Su et al., 2013; Tjiam et al., 2011; Williams et al., 2013; Yawn et al., 1998).

2.4.4 B4 School Check

In NZ, children receive a universal, free, health and developmental check, the B4 School Check (B4SC), at four years of age. The overarching objectives of the B4SC are to promote health and wellbeing in preschool aged children and identify any behavioural, developmental or other health concerns that may adversely affect a child's ability to learn in the school environment (Ministry of Health, 2014b). The B4SC is administered independently by each DHB and locations and personnel for testing vary between regions.

As part of the B4SC, distance VA screening is performed by vision-hearing technicians (trained lay screeners) using the Parr vision chart (Figure 2-1) (Parr, 1981) with the specific aim of detecting amblyopia. Vision screening primarily takes place in preschools, with children who do not attend preschool being invited to attend a clinic or offered a home visit. Written consent is obtained from a caregiver either by the preschool prior to the screening or by the vision-hearing technician at the screening. Referral pathways differ between DHBs and follow-up of screening referrals is carried out by each DHB (Ministry of Health, 2014b). However, there are currently no formal systems in place to ascertain whether referred children attend further tests, receive a prescription or purchase glasses, and communication of results between DHBs is limited. Records of B4SC vision screening are maintained by DHBs and results reported to the Ministry of Health. This data is also held in the Integrated Data Infrastructure, a large NZ research database that holds de-identified microdata about individuals and households.

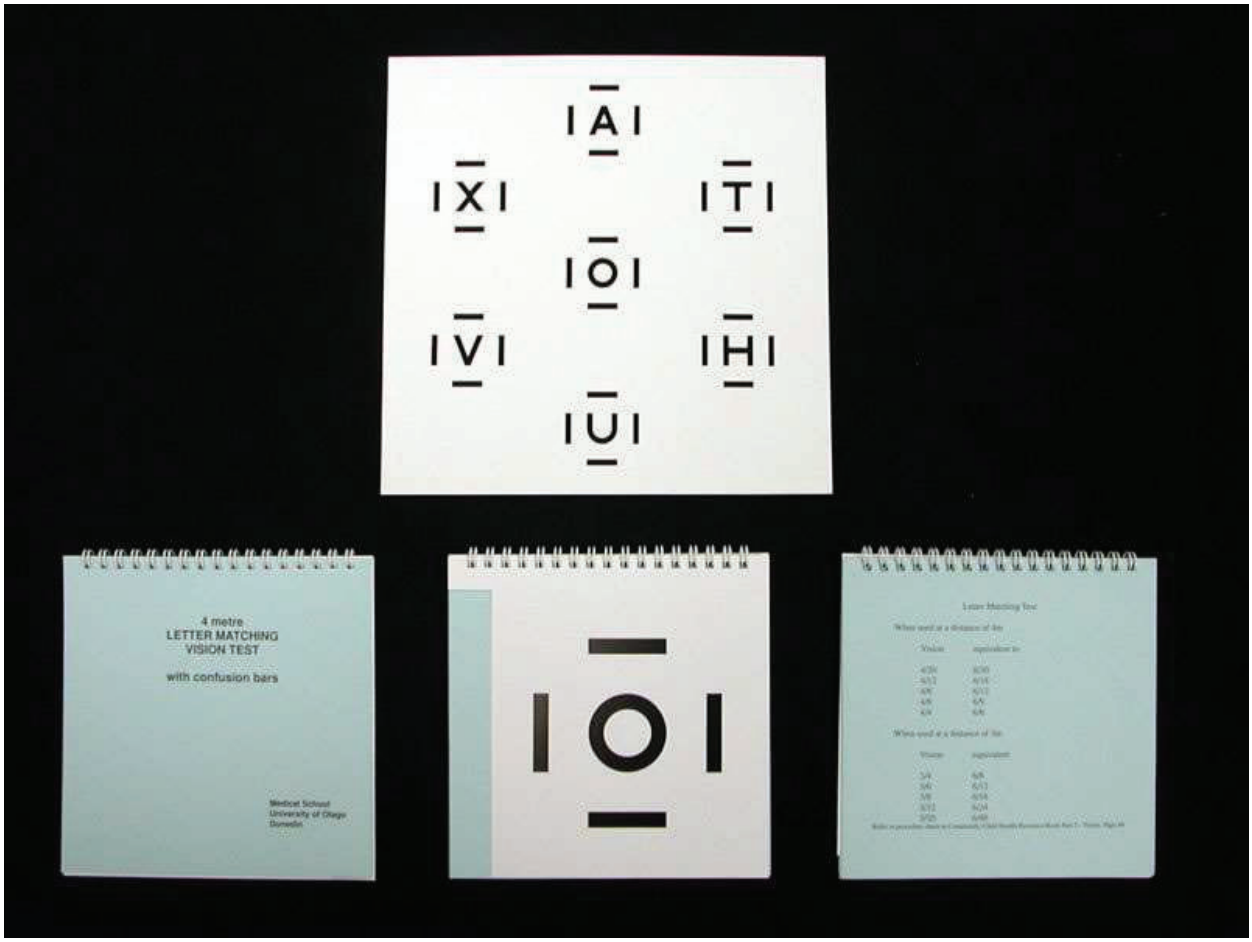

Figure 2-1: Parr vision test and matching card

2.4.4.1 B4 School Check outcomes

Retrospective reviews of B4SC vision screening referrals have found that the B4SC has significant numbers of false positive referrals, with more than 50% of children failing vision screening not having a diagnosed eye condition (Anstice, Spink, & Abdul-Rahman, 2012; Langeslag-Smith, Vandal, Briane, Thompson, & Anstice, 2015; Muller, Mitchell, & Wilson, 2019). Additionally, studies of vision screening outcomes in South Auckland found poor agreement between unaided VA at screening and measurement of threshold VA by the hospital eye department (Anstice et al., 2012; Langeslag-Smith et al., 2015). Each of these studies was limited to children who had been referred from their B4SC vision screening. There is currently no published data on the outcome of children who passed or did not receive B4SC vision screening.

2.4.4.2 B4 School Check coverage

Coverage of the B4SC vision screening is high. A review of B4SC data collated for the period from July 2011-June 2015 showed 86-91% of eligible children received vision and hearing checks (Gibb, Milne, Shackleton, Taylor, & Audas, 2019). In studies of the vision screening component of the B4SC, completion rates were 89.2% of eligible children in the Counties-Manukau DHB region (Langeslag-

Smith et al., 2015), 92.1% in the Southern DHB region and 98.4% in the Tairāwhiti DHB region (Muller et al., 2019), indicating differences in B4SC vision screening coverage between different regions.

Ethnic and socioeconomic inequities are seen in both overall B4SC participation and completion of vision screening (Gibb et al., 2019). Children of Māori or Pacific ethnicities are less likely to complete the complete B4SC (Gibb et al., 2019) as well as the vision screening component, than those of European or Asian ethnicity (Gibb et al., 2019; Langeslag-Smith et al., 2015). Similarly, children from areas of greater socioeconomic deprivation are less likely to complete the check than those from more advantaged areas (Gibb et al., 2019; Langeslag-Smith et al., 2015). Focus groups conducted with low income Māori and Pacific parents found the majority of participants had limited or no awareness of the B4SC and this was associated with a lack of perceived benefit of the checks (Premium Research Limited, 2014). This study also identified concerns with strangers carrying out the checks and potential blame or judgement of parents and their children (Premium Research Limited, 2014). Additionally, lower participation in formal early childhood education by Māori and Pacific children compared with other ethnic groups (Ministry of Social Development, 2016) may provide a barrier to B4SC vision screening completion.

While B4SC vision screening coverage is high, non-NZ residence at four years of age, and movement between DHB regions may result in some children not receiving vision screening before attending school. As an example of household mobility in NZ, between birth and two years of age, 45% of the *Growing Up in New Zealand* birth cohort had moved at least once, resulting in significant numbers moving to different DHB regions (Morton et al., 2014). Additionally, in the 2018 census, 4.7% of children aged 0-15 years were living outside NZ, and 30% were living in a different location, at the previous census, five years prior (Statistics New Zealand, 2020).

2.4.4.3 Follow-up

In a study of B4SC outcomes, 80% of children referred in Counties-Manukau DHB, were seen at the hospital eye department (Langeslag-Smith et al., 2015). Conversely, in Tairāwhiti and Southern DHBs, follow-up with the hospital eye department or a community optometrist was only identified for half of children referred (Muller et al., 2019). These differences may be explained by different referral pathways between DHBs. In the Counties Manukau DHB region, all patients are referred to the hospital eye department which has no direct cost to the whānau, however, significant barriers to treatment still exist. Transport issues such as not owning a car, cost of car ownership and affordability of public transport can prevent families from attending appointments (Lee & North, 2013). Further barriers include language and communication difficulties, inability to attend appointments on specific days and lack of childcare for other children (Lee & North, 2013; Ludeke et al., 2012). In many DHBs,

children who fail to meet a VA threshold are recommended to see their local optometrist (with payment made by the caregivers at the time of the appointment). Similarly, studies in China and the United States have found higher attendance at follow-up in groups that received a specific appointment, compared with those who received a recommendation for follow-up (Rodriguez, Srivastava, & Landau, 2018; Zeng et al., 2020). Children who require spectacles or other treatment may require additional appointments for dispensing of glasses and follow-up of treatment, placing an additional burden on families.

In NZ, a subsidy is available to children from families who hold a community services card (issued to individuals with a low income to reduce healthcare costs) or a high use health card (provided to frequent users of primary care services), to help cover the cost of eye examinations and spectacles. However, the family must present to the community optometrist with the appropriate documentation to access this funding, and this process can be challenging to navigate. Additionally, many people who are entitled to a community services card do not realise they are eligible and eligible people frequently do not have a card (Gribben, 1996; Sopoaga, Parkin, & Gray, 2012). It has also been identified that the cut-off for eligibility for a community services card creates a "poverty trap" for those at the low-end of the non-eligible population (Crampton & Gibson, 1998). This may result in whānau who are not eligible for a community services card, and consequently the spectacle subsidy, being unable to afford eye-care services. Furthermore, the subsidy has a limited value per year and if glasses are lost or broken, no additional funding is available for replacement.

2.4.5 Vision screening in school-aged children

New Zealand children receive a further universal vision screening at 11-12 years of age which comprises a distance VA measurement using a Snellen chart (Ministry of Health, 2021). This screening is aimed at detecting newly developed conditions, particularly myopia, and any previously undetected conditions. While amblyopia treatment is most effective before seven years of age, VA improvements with treatment are still seen in older children, making vision screening beneficial in children who may not have previously received screening. Prompt detection of myopia is also important to identify children with low to moderate myopia to reduce progression and reduce prevalence of associated ocular complications through myopia control interventions (Saw, Matsumura, & Hoang, 2019).

2.5 Summary

Vision screening is of particular importance for children of Māori and Pacific ethnicity and those from areas of socioeconomic disadvantage who may have poorer educational outcomes than their peers (Hunter et al., 2016; OECD, 2018; Song et al., 2014). These children also face significant barriers to

accessing culturally safe health care and are less likely to present independently to an eye care practitioner (Majeed et al., 2008; Stein et al., 2016). Therefore, they have the potential to gain the most benefit from vision screening programmes targeted to detect eye conditions likely to be detrimental to academic progress. Evaluation of current screening programmes and protocols, and determination of refractive error profiles of NZ children will allow targeting of vision screening programmes to meet the needs of NZ children and improve equity in health and educational outcomes.

2.6 Thesis aims

The aims of this thesis, therefore, were to investigate the role and efficacy of preschool vision screening, the effect of uncorrected vision problems and mild-moderate visual impairment on reading parameters, and to better understand the impact of these factors on health equity for NZ children.

Specifically, the aims of this thesis are to:

1. Evaluate the coverage and follow-up of the current B4SC preschool vision screening programme.
2. Investigate the efficacy of the current preschool vision screening test compared with internationally recognised gold-standard protocols.
3. Systematically evaluate the effect of reduced near vision (via induced optical blur) on VMI, visual perception and motor coordination as potential indicators for poorer academic outcomes.
4. Investigate the prevalence of visual impairment, refractive error, and other vision conditions in NZ children.
5. Assess the effect of vision conditions in NZ children on VMI, reading ability and eye movements while reading.

Chapter 3: Methods

This chapter details the methodology for the comprehensive eye examinations completed for the studies described in Chapters 7-10. Additionally, the definitions for visual conditions and visual impairment used throughout this thesis are described. All visual assessments were completed by the thesis author with the assistance of a trained research assistant.

3.1 Venue for examinations

Ocular examinations were primarily carried out in a quiet room such as an empty classroom or meeting room in the children's schools. A small number of children were examined in the Optometry Clinic at the University of Auckland Grafton Campus.

3.2 Demographic information

Ethnicity was defined by caregivers for their children and categorised as per NZ Statistics Level 1 (Statistics New Zealand, 2005). Where participants identified with more than one ethnic group, priority was assigned in the following order: Māori, Pacific, Asian and European/Others.

Socioeconomic deprivation level was determined by using each participant's home address to determine their NZDep score (Atkinson et al., 2014). NZDep2013 scores were categorised as low (deciles 1-3), moderate (deciles 4-7) or high (deciles 8-10) deprivation. For the NZDep index, a decile of 1 identifies households in the least deprived 10% of meshblocks and decile 10 households in the most deprived decile of meshblocks.

School decile ratings, which are a measure of the socioeconomic status of the community in which the school's students reside (Ministry of Education, 2020), were categorised as low (deciles 1-3), medium (deciles 4-7) or high (deciles 8-10). Decile 1 schools are the 10% of schools in NZ with the highest proportion of students from low socioeconomic communities, while decile 10 schools have the lowest proportion of these students. Thus, school decile ratings (where decile 1 represents schools with the largest proportion of students residing in low socioeconomic communities) are ordered the opposite to the NZDep Index (where decile 1 represents the least deprived socioeconomic communities).

3.3 Visual acuity assessment

3.3.1 Distance visual acuity

Unaided and habitually corrected distance VA were measured right eye, left eye and then binocularly at 3 m using an Electronic Visual Acuity (EVA) testing system (Jaeb Center for Health Research, U.S.A.). This test presented single Sloan letter optotypes surrounded by crowding bars using an adaptive staircase technique to determine threshold VA. Letter presentation was randomised to prevent the child memorising the presentation order. A matching card was given to children unable to accurately name letters and they were asked to indicate the matching letter on the card.

The Amblyopia Treatment Study (ATS) protocol (Moke et al., 2001) was used for presenting the letters on the EVA system for the studies presented in Chapter 7 (children aged 4-5 years) and Chapter 8 (children living in an area with socioeconomic disadvantage). The HOTV test has excellent testability and test-retest reliability in children aged 5-7 years (Holmes et al., 2001). Up to four letters were presented at each logMAR level and a logMAR level was considered successfully completed if the child named three out of three or three out of four letters correctly. VA was scored as the smallest acuity level that was successfully completed.

For the study presented in Chapters 9 and 10 (children aged 7-10 years), letters were presented on the EVA system according to the Early Treatment for Diabetic Retinopathy Study (ETDRS) protocol (Beck et al., 2003). VA measurements using the ETDRS chart have high testability (Rice, Leske, & Holmes, 2004) and test-retest reliability similar to adults (Manny, Hussein, Gwiazda, Marsh-Tootle, & Group, 2003) in children aged 7-12 years. Five letters were presented at each acuity level and VA was scored for each letter correctly identified.

3.3.2 Near visual acuity

Unaided and habitually corrected near VA were measured monocularly and then binocularly using the Sloan Letter near logMAR acuity chart (Good-Lite Co., U.S.A.) at 40 cm. This chart presents proportionally spaced lines in ETDRS format with 5 letters on each line. The child was asked to name the first letter on each line. When the child named the first letter of a line incorrectly, they were asked to read all the letters on the previous line (one line larger). If at least three letters on this larger line were correctly identified, the child was asked to proceed to the following line. VA was scored in logMAR as the smallest line at which the child identified at least three letters correctly, with 0.02 added for each letter incorrectly identified and 0.02 deducted for each additional letter correctly identified. After VA was measured for the right eye, the opposite side of the card was used for the left eye and the original side for binocular measurement to reduce learning effects. A matching chart was used for

children unable to accurately name letters and Lea Symbols and number optotype near charts were available for children who were unable to match letters.

3.3.3 Spectacle corrected visual acuity

For the study presented in Chapters 9 and 10, VA was assessed following subjective refraction (see section 3.4.3) at distance using an ETDRS chart viewed at 3 m and at near using the Lighthouse near logMAR acuity chart presented at 40 cm. The procedure and scoring were the same as for measurement of unaided and habitually corrected near VA.

3.4 Refractive error assessment

Refractive error was recorded in negative cylinder form as:

Spherical power in dioptres (D) / Cylindrical power in dioptres (DC) x Axis of astigmatism.

For classification of myopia and hyperopia, the spherical equivalent was calculated as the spherical power plus half the cylindrical power. Astigmatism was classified using the cylindrical power.

3.4.1 Retinoscopy

Cycloplegic retinoscopy was performed a minimum of 40 minutes after instillation of Cyclopentolate 1% (Bausch & Lomb, NZ) into each eye (Hopkins, Sampson, Hendicott, Lacherez, & Wood, 2012; Yazdani, Sadeghi, Momeni-Moghaddam, Zarifmahmoudi, & Ehsaei, 2018). Cycloplegia was considered to be complete when the pupils had a minimum diameter of 6 mm and were unreactive to light (Negrel et al., 2000). With the patient wearing a trial frame and viewing a letter target at 3 m, retinoscopy was performed along both principal meridians using loose lenses.

For the study reported in Chapters 9 and 10, retinoscopy was also performed prior to cycloplegia with the child viewing a letter target at 3 m with plus fogging lenses in place in a trial frame.

3.4.2 Autorefraction

Non-cycloplegic autorefraction was completed using the Spot vision screener VS100 (Software version 3.0.04.02, Welch Allyn, U.S.A.) and the Nidek ARK-30 Type R (Nidek Co, Japan) (Chapter 8) or the Nidek HandyRef-K (Nidek Co, Japan) (Chapters 9 and 10) to allow assessment of automated measurements of refractive error as vision screening tools. Autorefraction measurements were also repeated following cycloplegia for children in the studies reported in Chapters 8, 9 and 10.

3.4.3 Subjective refraction

Using the non-cycloplegic retinoscopy results as a baseline, subjective refraction was performed to determine the spectacle prescription that gave best VA. With the non-cycloplegic retinoscopy results in the trial frame and the participant viewing a letter at threshold acuity, spherical trial lenses were presented to determine the least minus sphere lens giving the best VA. The Jackson Cross Cylinder (JCC) technique and a round target were used to determine the cylindrical component of the prescription.

3.5 Binocular vision assessment

Measures of binocular function were completed with the child's habitual correction in place; either unaided or with the child's usual spectacles. The range of binocular vision tests were chosen for each study based on the age and cognitive ability of the participating children. For the study presented in Chapter 7, only the cover test, near stereopsis and ocular motility were assessed. The study presented in Chapter 8 used the same tests of binocular function as Chapter 7 and additionally included measures of binocular motor fusion and NPC. All the procedures in this section were used in the study described in Chapters 9 and 10.

3.5.1 Cover test

The cover-uncover test and alternating cover test were performed to determine the presence of heterotropia (manifest deviation) or heterophoria (latent deviation) in primary position (Scheiman, 2014). The prism cover test was performed to measure the magnitude of any deviation in prism dioptres (Δ). Cover testing was performed with the child viewing a letter target at 6 m and repeated with a viewing distance of 40 cm.

The accommodative convergence to accommodation (AC/A) ratio was calculated using the formula:

$$AC/A = IPD\ (cm) + NFD\ (m)\ (Hn - Hd)$$

where IPD is the interpupillary distance in centimetres, NFD is the near fixation distance in metres, Hn is the near heterophoria (esophoria is plus and exophoria is minus) and Hd is the distance heterophoria (esophoria is plus and exophoria is minus) (Scheiman, 2014).

3.5.2 Ocular motility

Ocular motility was assessed using the Double H test (Evans, 2009). Nystagmus and changes in lid position in different positions of gaze were also screened for during ocular motility assessment. Restrictions, relative over- or under-actions, A or V patterns, incomitancy and other abnormalities were recorded.

3.5.3 Stereoacuity

Distance and near stereotests were both completed with the children wearing polarising glasses. Prior to testing, the children were asked to identify black and white pictures of the geometric test shapes. If they were unable to name or match the shapes, they were considered unable to complete the test.

Near stereoacuity was measured using the Randot Preschool Stereotest (2012, Stereo Optical Company Inc) at 40 cm (Birch et al., 2008). The test consists of a book with plates with sets of four shapes (one is blank, the other three contain shapes) at six disparities (800, 400, 200, 100, 60 and 40 arcsec). Stereoacuity was recorded as the smallest disparity level at which the child could correctly identify two (out of four) or more of the shapes.

Distance stereoacuity was measured using the Distance Randot Stereotest (Chapters 9 and 10) (Stereo Optical Company Inc) (Wang et al., 2010). The test comprises eight test plates, with two shapes at each of four disparities (400, 200, 100 and 60 arcsec). Stereoacuity was recorded as the smallest disparity level at which the child could identify both shapes correctly.

3.5.4 Binocular motor fusion

Binocular motor fusion was assessed using the 20 Δ base out test (Kaban, Smith, Beldavs, Cadera, & Orton, 1995). With the child fixating on a small target at 40 cm, a 20 Δ base out prism was placed in front of the right eye. This was then repeated for the left eye. A fixational movement indicated the presence of binocular motor fusion.

3.5.5 Near point of convergence

The near point of convergence was measured using the Royal Air Force (RAF) rule (Good-Lite Co., U.S.A.) (Neely, 1956; Scheiman, 2014). While viewing binocularly, the near point of convergence was measured as the distance in centimetres where the child reported diplopia of a vertical line target or when the examiner observed one eye ceased fixating on the target.

3.5.6 Near point of accommodation

Near point of accommodation was measured with the push-up test using the RAF rule (Scheiman, 2014). With the fellow eye occluded, a small letter target was moved close until the child reported the target had blurred. This was repeated three times for each eye, then three times binocularly. The dioptric distance at which the target blurred was recorded for each measurement.

3.5.7 Fusional vergence reserves

Positive and negative fusional reserves were measured at 6 m and 40 cm using horizontal prism bars (step vergence reserves) to determine the blur, break and recovery points for both base in and base out prism (Scheiman, 2014). The child was asked to fixate on the distance letter target and to inform the examiner as soon as the letter became blurred and could no longer be cleared (blur point), the moment it became double and could not be made single again (break point) and when the target became single again (recovery point).

3.5.8 Accuracy of accommodation

Dynamic retinoscopy was performed for assessment of lag or lead of accommodation using the Monocular Estimation Method (Rouse et al., 1982). The lens required to neutralise the movement of the retinoscopy reflex while the child was viewing a near target at 40 cm was recorded as the lag (plus lens) or lead (minus lens) of accommodation.

3.6 Ocular health examination

3.6.1 Pupillary reactions

Pupil size was observed in bright and dim light conditions to assess for anisocoria (unequal pupil size). Direct and consensual light reflexes were assessed by shining a direct ophthalmoscope into each eye and observing the pupil reactions. The near reflex was assessed by bringing a small target close to the child. The swinging flashlight test was used to determine if a relative afferent pupillary defect (RAPD) was present (Stanley & Baise, 1968).

3.6.2 Visual fields

Visual fields were screened using the confrontation method (Elliott, North, & Flanagan, 1997). With their left eye occluded, the child was asked to fixate on the examiner's nose. A small target was introduced from outside the peripheral visual field and the child was asked to indicate when they first saw the target. This was repeated for all four quadrants in the right and left eyes separately. The presence of full fields was noted, or any restrictions described.

3.6.3 Anterior segment examination

Using a portable hand-held slit lamp, the anterior segment was examined to assess the health of the anterior eye and to assess whether the anterior chamber angle was adequate for dilation.

3.6.4 Fundus examination

Binocular indirect ophthalmoscopic examination was performed on participants with dilated pupils to evaluate the health of the internal structures of the eye. The posterior pole and mid-peripheral retina were examined in all positions of gaze for each eye.

3.7 Visual-motor integration

The Beery VMI (sixth edition) was used to assess visual-motor integration (Beery et al., 2010). This test involves copying a developmental series of geometric forms in the test booklet using paper and pencil. Following completion of the VMI, the supplemental tests of visual perception and then motor coordination were administered. All three components were administered and scored according to the instructions in the manual. Raw scores were converted to standard scores (mean of 100 and standard deviation of 15) using the tables in the manual to allow comparison of results for participants of different ages.

3.8 Reading ability

The Neale Analysis of Reading Ability was used to assess reading ability (Neale, 1999). The Australian form of this test was used due to its relevance to NZ children and to allow comparison with recent studies (Hopkins, Narayanasamy, et al., 2019; Narayanasamy et al., 2014; Narayanasamy et al., 2015a, 2015b). Form 1 of this test was administered according to the instructions in the manual with participants wearing their habitual correction. The test involves reading aloud passages of text with increasing difficulty and answering a series of comprehension questions regarding the text. Accuracy (range 1-94), comprehension (range 1-40) and rate (range 6-122) scores were calculated according to the criteria in the manual.

3.9 Eye movement assessment

The Clinical Eye Tracker (Thomson Software Solutions) was used to assess eye movements during reading. The system comprised a monitor with an attached eye tracking bar that used infrared cameras to detect eye position to within less than one degree and recorded eye position at approximately 60 measurements per second (Thomson, 2017). The Clinical Eye Tracker is a clinically available system that allows direct observation and recording of simultaneous binocular eye movements without the need for a head restraint.

3.10 Referral for follow-up

Children with uncorrected or under-corrected refractive error or with binocular vision anomalies were referred to an optometrist for further evaluation. Children with ocular health abnormalities were referred to an ophthalmologist.

3.11 Summary of studies

A summary of the methods used for comprehensive eye examinations is given in Table 3-1.

Table 3-1: Summary of methods used for comprehensive eye examinations

	Improving B4 School Check Efficacy (Chapter 7)	**Welcome to School (Chapter 8)**	**Visual function and reading (Chapters 9 and 10)**
Distance visual acuity (electronic visual acuity testing system)	Amblyopia treatment study protocol	Amblyopia treatment study protocol	Early treatment for diabetic retinopathy study protocol
Near visual acuity	Not assessed	Lighthouse near logMAR chart	Lighthouse near logMAR chart
Binocular vision assessment	Cover test Ocular motility assessment Randot near stereotest	Cover test Ocular motility assessment Randot near stereotest Binocular motor fusion Near point of convergence and accommodation	Cover test Ocular motility assessment Randot distance and near stereotest Binocular motor fusion Near point of convergence and accommodation Fusional vergence reserves Lag of accommodation
Refractive error assessment	Retinoscopy†	Retinoscopy‡	Retinoscopy‡ Subjective refraction
Autorefraction	Spot vision screener VS100*	Spot vision screener VS100† Nidek ARK-30 Type R†	Spot vision screener VS100† Nidek HandyRef-K†
Ocular health assessment	Pupillary light reflex Binocular indirect ophthalmoscopy	Pupillary light reflex Binocular indirect ophthalmoscopy Anterior segment examination Confrontation visual fields	Pupillary light reflex Binocular indirect ophthalmoscopy Anterior segment examination Confrontation visual fields

* Performed prior to cycloplegia

† Performed after cycloplegia

‡ Performed both prior to and after cycloplegia

3.12 Definitions

3.12.1 Significant refractive error

The definitions for significant refractive error used by the Refractive Error Studies in Children study group have been used throughout this thesis to enable comparisons between the thesis chapters and with other studies that have used the same definitions (Table 3-2). A child was considered to have significant refractive error if they met the criteria for myopia, hyperopia and/or astigmatism in either eye following cycloplegic refraction.

Table 3-2: Definitions for significant refractive error (Negrel et al., 2000)

Refractive error	Definition
Myopia*	≤ -0.50 D
Hyperopia*	≥ +2.00 D
Astigmatism	≥ 0.75 D

*Spherical equivalent

D = dioptres

3.12.2 Visual impairment

The Refractive Error Studies in Children classified VA into five categories, which are used to define visual impairment in this thesis (Negrel et al., 2000) (Table 3-3). To explore the effects of mildly reduced visual acuity, for the study described in Chapters 9 and 10, reduced VA was defined as VA in the better eye of 0.1 to 0.2 logMAR. Where single letter scoring was using in VA measurement, the child was considered to have successfully achieved a logMAR level if they correctly named four of the five letters for that level.

Table 3-3 Definitions for visual impairment

Visual impairment category	**Visual acuity**
Reduced visual acuity	0.1 logMAR (6/7.5) to 0.2 logMAR (6/9.5) in the better eye
Visual impairment	
No visual impairment either eye	0.2 logMAR (6/9.5) or better each eye
Visual impairment one eye	Worse than 0.2 logMAR (6/9.5) one eye only
Mild visual impairment	0.3 logMAR (6/12) to 0.5 (6/19) in the better eye
Moderate visual impairment	0.6 logMAR (6/24) to 0.9 (6/48) in the better eye
Severe visual impairment	Worse than 1.0 logMAR (6/60) in the better eye

3.12.3 Amblyopia risk factors

Amblyopia risk factors cause degradation of the retinal image which may result in amblyopia development (Holmes & Clarke, 2006). The levels of refractive errors considered to induce amblyopia that have been used in this thesis are those recommended by the American Academy of Ophthalmology as requiring correction to prevent the development of amblyopia (Table 3-4).

Table 3-4: Definitions for amblyopia risk factors (American Academy of Ophthalmology Preferred Practice Patterns Committee, 2017)

Risk Factor	Definition
Visual pathway obstruction	Visual pathway obstruction present
Strabismus	Any manifest deviation
Anisometropia	
Myopia*	≥ 2.50 D
Hyperopia*	≥ 1.50 D
Astigmatism	≥ 1.50 D in any meridian
Bilateral refractive error	
Myopia*	≤ -2.50 D
Hyperopia*	≥ 3.50 D
Astigmatism	≥ 1.50 D

* Spherical equivalent

D = dioptres

3.12.4 Binocular vision anomalies

Binocular vision anomalies are defined in Chapters 9 and 10 according to the integrative approach which considers the results of several different tests of vergence and accommodation, whereby the child is diagnosed with a binocular vision anomaly if they score below expected values on more than one test (Table 3-5) (Scheiman, 2014). The expected values used for classification in this thesis are those collated by Scheiman and Wick. Reduced stereoacuity is defined as near stereoacuity of worse than 60 arcsec measured using the Randot Preschool Stereotest (Birch et al., 2008).

Table 3-5: Definitions for binocular vision anomalies (Scheiman, 2014)

Binocular vision anomaly	Definition
Strabismus	Any manifest deviation
Convergence insufficiency	Near exophoria ≥ 4 Δ more exophoric than distance phoria And at least one of: Near point of convergence > 6 cm Failing Sheard's criterion* or positive fusional vergence ≤ 15 Δ at near
Convergence excess	Near esophoria (≥ 1 Δ) And at least one of: High AC/A (> 6 Δ/D) Reduced negative fusional vergence at near (< 7 Δ) Poor recovery from base in prism at near (< 3 Δ)
Divergence insufficiency	Distance esophoria > 1 Δ more esophoric than near heterophoria And two of: Low AC/A (< 2 Δ/D) Low negative fusional vergence at distance (< 4 Δ) Poor recovery to base in prism at distance (< 2 Δ)
Divergence excess	Distance exophoria ≥ 1 Δ more exophoric than near heterophoria And two of: High AC/A (> 6 Δ/D) Low positive fusional vergence at distance (< 4 Δ) Low negative fusional vergence at near (< 7 Δ) Poor recovery to base out prism at distance (< 5 Δ)
Accommodative insufficiency	Both of: Reduced amplitude of accommodation by 2 D or more from average for age† High monocular estimation method lag of accommodation (≥ +1.00 D)

AC/A = accommodative convergence to accommodation ratio, D = dioptres, Δ = prism dioptres

* Positive fusional reserves less than twice the magnitude of the exophoria at near (Sheard, 1930)

† 18-0.3xage in years (Hofstetter, 1950)

Chapter 4: The effect of induced blur on the Beery-Buktenica developmental test of visual-motor integration and its supplemental tests

The review of the literature presented in Chapter 1 highlighted that, despite many studies reporting associations between Beery VMI scores and scores on tests of academic ability, refractive error and VA were frequently not measured in these studies. This chapter presents a published paper reporting a pilot study that was developed to determine the effect of blur on performance on the Beery VMI and its supplemental tests. Lenses in a trial frame were used to simulate anisometropic, spherical and astigmatic near blur resulting in near visual impairment (near VA of 0.3 logMAR).

The authors of this paper are Rebecca Findlay, Joanna Black, Bert van der Werf, Carol Chelimo, Cameron C Grant and Nicola Anstice. The thesis author developed the clinical testing procedures, collected the data, and prepared the manuscript (including all figures and tables).

This manuscript was first submitted to PLoS One on 15 March 2020, the manuscript was accepted for publication on 3 August 2020 and appeared online on 21 August 2020. The details of the reference to the article and the copyright licence from the publisher can be found on page xxxii.

4.1 Introduction

The Beery VMI is a commonly used, standardized test of VMI. However, its administration can be problematic in children with undiagnosed vision disorders because the effect of reduced near VA on test results has not been systematically explored. The Beery VMI involves copying a series of geometric forms of increasing difficulty (Beery & Beery, 2010). It is commonly used by neuropsychologists and occupational therapists (Rabin et al., 2005; Rodger et al., 2005) as it has been standardised multiple times on more than 13,000 children and 1,000 adults for both individual and group administration (Beery & Beery, 2010). It has high reliability and intra-scorer and inter-scorer agreement in adults and children (Beery & Beery, 2010; Brown, Chinner, & Stagnitti, 2010; Harvey, Leonard-Green, et al., 2017; Preda, 1997).

The Beery VMI includes supplemental tests of Visual Perception (VP) and Motor Coordination (MC). The VP supplemental test assesses visual analysis skills in a format which requires minimal motor input. A reference form is shown with several similar shapes below it; the subject must choose which shape is identical to the original form. The MC test minimises visual analysis by providing examples, starting dots, and paths as visual guides for the required motor tasks. For each item on the MC supplemental test, the participant is asked to draw within specific lines on the form. To limit the size and cost of the testing booklets, the size of the items on the VP and MC are different to those on the

VMI (Beery & Beery, 2010), and the size of test forms decreases with increasing difficulty in these supplemental tests. Although the accompanying instruction manual advises examiners to refer any patient suspected of having reduced VA for a vision examination, there is no specific information regarding the minimum required VA, illumination or testing distance.

Several studies have shown that the performance of children on the Beery VMI is related to academic achievement (Lowther et al., 2000; Santi et al., 2015; Sortor & Kulp, 2003) and VMI is a strong predictor of academic success in children at ages 5-8 years (Fowler & Cross, 1986; Klein, 1978; Maples, 2003). VP and VMI scores are significantly associated with reading achievement, handwriting skills and written mathematics ability in school-aged children (Cornhill & Case-Smith, 1996; Helveston et al., 1985; Hopkins, Black, et al., 2019; Kavale, 1982; Solan, Mozlin, & Rumpf, 1985). Likewise, visual perceptual dysfunction is significantly more prevalent in 6-12 year old children with learning difficulties than those without (Rosner & Rosner, 1987).

Uncorrected ametropia is associated with poorer performance on visuocognitive and visuomotor tests (Atkinson et al., 2005) and impaired visual perceptual skills (Rosner & Gruber, 1985), but data on the relationship between refractive error and VMI is limited. Some studies have found significantly lower VMI or VP supplemental test scores in children with uncorrected hyperopia associated with reduced binocular near VA or poor stereopsis (Kulp et al., 2017), bilateral uncorrected astigmatism (Harvey, Twelker, et al., 2017) and uncorrected hyperopia and astigmatism (Roch-Levecq et al., 2008). In contrast, other studies have shown no association between VMI scores and refractive error (Shankar et al., 2007). These differences may be the result of differing refractive error definitions and the variable effect of refractive error, particularly hyperopia and astigmatism, on VA. It is unclear from the current literature whether reduced performance on the VMI and its supplemental tests is due to reduced VA or to delayed development of visual perceptual skills in children with refractive error, or a combination of both of these factors.

Therefore, the purpose of this study was to determine the VA demand and the spacing of the test forms of the Beery VMI and its supplemental tests, in order to investigate the effect of reduced near VA (to a predetermined acuity level) caused by induced optical blur on the results of these tests in paediatric and adult participants.

4.2 Methods

Ethical approval was obtained from the University of Auckland Human Participants Ethics Committee (Reference number: 020592) and the research followed the tenets of the Declaration of Helsinki. Adult participants and parents of child participants provided written informed consent, with children providing written assent.

4.2.1 Test design

The overall size of each test form (test shape) along its longest dimension, critical detail size for each test form (smallest detail of form), and the distance between the centre of each form and an adjacent source of crowding were measured using Vernier callipers (Table 4-1). The VA demand was calculated based on the critical detail size and a viewing distance of 40 cm. The angular separation between each form and its adjacent crowding source was then calculated.

Table 4-1: Features considered to be critical details and crowding sources for the Visual Motor Integration, Visual Perception and Motor Coordination tests.

Test	Critical detail	Crowding source
Visual Motor Integration	Stroke width of test forms	Adjacent form
Visual Perception	Stroke width of reference forms	Box surrounding reference form
Motor Coordination		
Forms 4-21	Diameter of starting dots	Adjacent form
Forms 22-30	Width of border lines of test forms	Adjacent form

4.2.2 Participants

Two groups of participants, adults aged 18 years or older and children aged 7-12 years, were recruited via convenience sampling. Participants were excluded from the study if they had habitual near VA less than 0.1 logMAR in either eye, a difference in VA between their eyes of greater than 0.1 logMAR, or any self-reported pre-existing ocular health or neurological conditions. All participants were assessed (by the thesis author) at the University of Auckland, School of Optometry and Vision Science or in their own homes.

4.2.3 Test procedures

The participants' right, left and then binocular habitual near VA were measured with the Sloan Letter near VA chart (Good-Lite Company) viewed at 40 cm. With their habitual near prescription in a trial frame, participants were asked to view the 0.3 logMAR line on the near VA chart. With the left eye occluded, plus spherical lenses were added in front of the right eye until the 0.3 logMAR line was no longer visible. The last lens where the 0.3 logMAR line was visible was recorded. This procedure was repeated for the left eye then binocularly. To induce with-the-rule astigmatic blur, the assessor added negative cylinders with the axis vertical and a balancing plus spherical lens of half the cylindrical power to maintain a plano spherical equivalent.

Participants completed four sessions, in which they performed the Beery VMI and the VP and MC supplemental tests under the different blur conditions (habitual near correction, monocular spherical

blur (right eye), binocular spherical blur and binocular astigmatic blur) in a randomized order. The interval between sessions ranged between one and 27 weeks.

The Beery VMI was performed according to the test directions given in the manual (Beery & Beery, 2010), with the exception that participants were asked to perform the test at 40 cm, to ensure the level of blur and visual angle of the test forms remained constant. The VMI assessment was followed by the VP and MC supplementary tests for all participants at each session. Forms were scored by the lead author, while blinded to the blur condition, according to standardized criteria (Beery & Beery, 2010).

4.2.4 Statistical analysis

A sample size of 14 participants was estimated to be sufficient to detect a 15 point difference in the VMI standardized score (one standard deviation [SD] away from the mean), with a power of 80% and a two-sided significance of 5%, assuming a standard deviation of 13.7 (Roch-Levecq et al., 2008). This estimate was increased to 20 participants to allow for a predicted dropout of 30% for the four measurement visits combined.

Raw scores of the VMI and the VP and MC supplemental tests were converted to standard scores (mean of 100, standard deviation of 15) using the tables provided in the manual (Beery & Beery, 2010). Scores were fitted simultaneously using a full linear mixed model including all interactions between the independent variables blur condition, test type (VMI or VP or MC supplementary test), sex, age group (child or adult) and age (years). Previous experimental test condition and test order were included to account for the repeated measurements and possible learning effects. The model also included participant identifier and date of measurement as random factors. The best model was that with the minimum value for the Akaike Information Criterion (AIC) (Burnham & Anderson, 2002). All variables were included in the initial model and then those that decreased the AIC value were removed from the model; this was also done for the random terms. Data analysis was conducted using R (version 3.5.1) (R Core Team, 2018). The models were fitted with the lmer function from the lme4 package of R (Bates, Mächler, Bolker, & Walker, 2014).

4.3 Results

4.3.1 Test design

For the Beery VMI, stroke width, overall test stimulus size and box size remained constant for all forms throughout the test. For both the VP and MC supplemental tests, overall test stimulus size, box size and inter-stimulus distance reduced with increasing difficulty (Table 4-2 and Table 4-3).

Table 4-2: Measurements of form size, critical detail and visual acuity demand for the Visual Motor Integration, Visual Perception, Motor Coordination tests

Test	Form	Overall form size (mm)	Critical detail size (mm)	Visual acuity demand of critical detail at 40 cm (logMAR [MAR])
VMI	All Forms	50.6	1.3	1.04 (11')
VP	Forms 4-9	20.0	0.7	0.78 (6')
	Forms 10-16	17.5	0.5	0.60 (4')
	Forms 17-30	10.0	0.3	0.30 (2')
MC	Forms 7-11	51.4*	4.0	1.53 (34')
	Forms 12-16	44.8*	2.5	1.30 (20')
	Forms 17-21	46.0*	1.7	1.15 (14')
	Forms 22-27	39.4*	0.3	0.30 (2')
	Forms 28-30	27.0*	0.3	0.30 (2')

VMI = visual motor integration, VP = visual perception, MC = motor coordination

*Forms in these groups were not of uniform size, mean sizes reported

Table 4-3: Measurements of form size and distance between form size and crowding detail for the Visual Motor Integration, Visual Perception, Motor Coordination tests

Test	Form	Overall form size (mm)	Centre to centre separation of forms and crowding detail (mm)	Angular separation of forms and crowding detail at 40 cm (degrees)
VMI	All Forms	50.6	84.2	12.0
VP	Forms 4-9	20.0	15.5	2.2
	Forms 10-16	17.5	12.5	1.8
	Forms 17-30	10.0	6.0	0.9
MC	Forms 7-11	51.4*	56.7†	8.1
	Forms 12-16	44.8*	55.7†	7.9
	Forms 17-21	46.0*	55.3†	7.9
	Forms 22-27	39.4*	45.2†	6.4
	Forms 28-30	27.0*	48.8†	7.0

VMI = visual motor integration, VP = visual perception, MC = motor coordination

* Forms in these groups were not of uniform size, mean sizes reported

† Centre to centre form separations in these groups were not uniform, mean separations reported

4.3.2 Experimental Results

Twenty children (mean [SD] age of 9.8 [1.9] years, 60% female) and nineteen adults (mean [SD] age of 37.3 [6.4] years, 63% female) participated in this study. Mean (SD) of binocular near VA was -0.07 (0.10) logMAR for children and -0.09 (0.08) logMAR for adults. Mean levels of optical blur required to give VA of 0.3 logMAR are shown in Table 4-4. All participants were able to complete the VMI and both supplemental tests under all conditions of defocus. Mean standard scores (SD), with and without induced optical blur, are shown in Figure 4-1and Figure 4-2.

Table 4-4: Mean optical blur required to reduce near visual acuity to 0.3 logMAR

Group	Monocular Spherical Blur (D) Mean ± SD	Binocular Spherical Blur (D) Mean ± SD	Binocular Astigmatic Blur (DC) Mean ± SD
Children (n=20)	2.89 ± 0.54	3.00 ± 0.69	2.10 ± 0.77
Adults (n=19)	2.45 ± 0.69	2.58 ± 0.56	2.00 ± 0.58

D = dioptres, DC = dioptres cylinder, SD = standard deviation

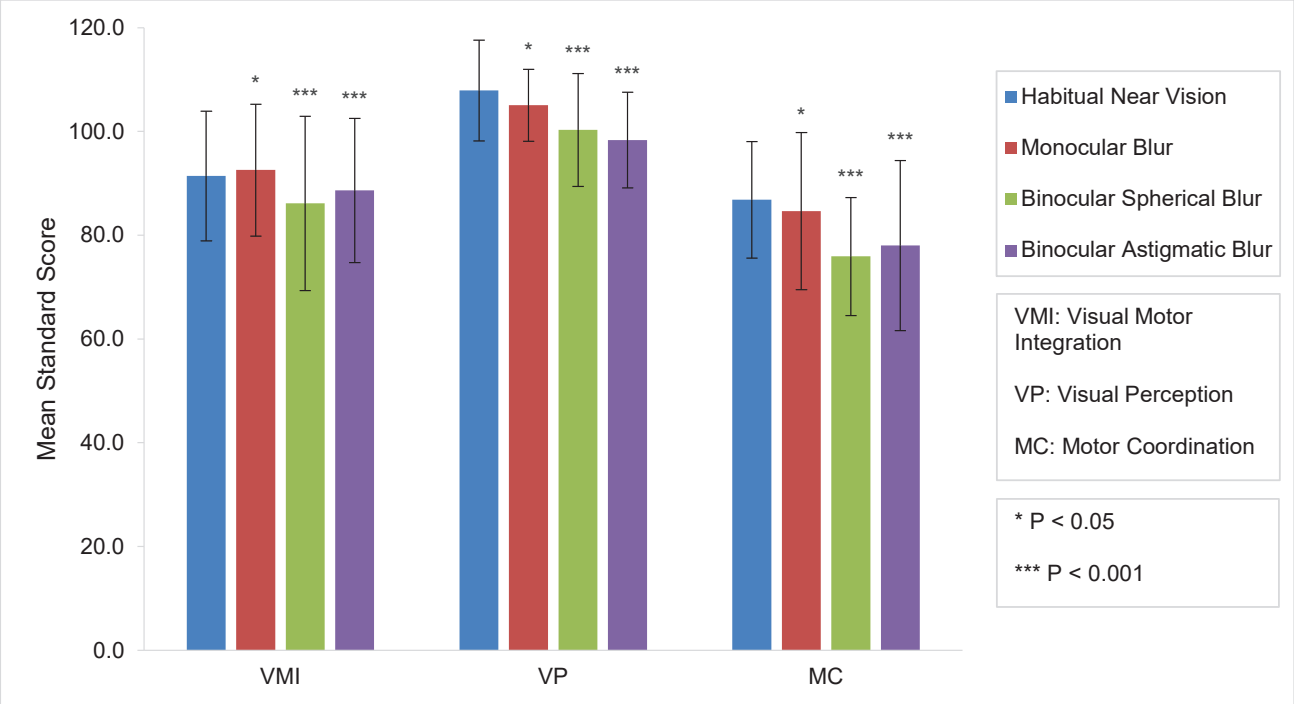

Figure 4-1: Mean (± standard deviation) standardised scores for Visual Motor Integration and supplemental tests for each blur condition in children (n=20)

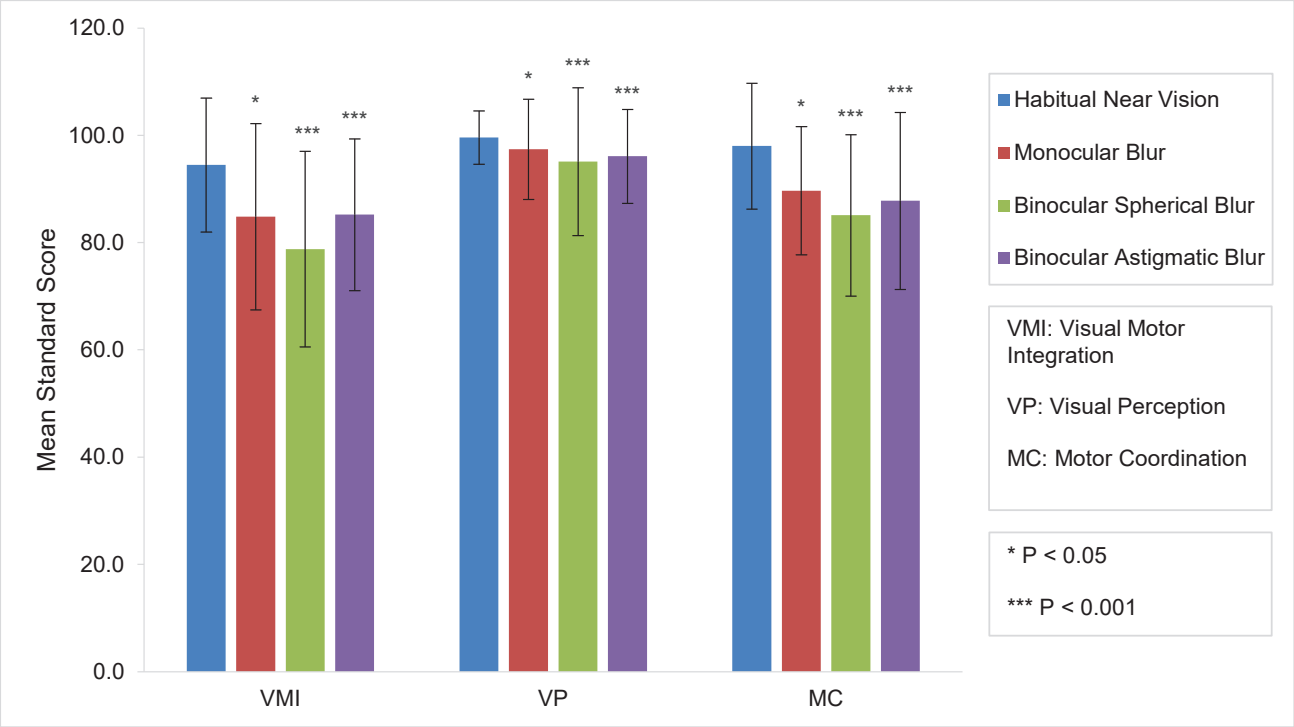

Figure 4-2: Mean (± standard deviation) standardised scores for Visual Motor Integration and supplemental tests for each blur condition in adults (n=19)

4.3.3 Analysis

Baseline VMI, VP and MC mean scores were within the age-appropriate standardized normal range for both adults and children. Linear mixed model analysis showed that reduced near VA from each of the simulated refractive blur conditions was associated with reduced mean scores for each of the VMI, VP and MC tests compared with habitual near vision. For each of the tests, the greatest decrease in mean score was due to binocular spherical blur (-9.63 points, $t = -5.94$, $P < 0.001$), followed by binocular astigmatic blur (-6.91 points, $t = -4.15$, $P < 0.001$) and then monocular spherical blur (-3.68 points, $t = -2.29$, $P = 0.022$). Age, previous experimental test condition and test order were removed from the maximal model as their inclusion resulted in higher AIC values. While standard scores were significantly reduced for children compared with adults (-7.79 points, $t = -4.19$, $P < 0.001$) and males compared with females (-3.96 points, $t = -2.65$, $P = 0.008$), the effect of induced blur was the same for all groups. While monocular blur reduced the standard score for VMI in the mixed model for both children and adults, there were outliers among the children who performed significantly better under the monocular blur condition resulting in a higher mean value.

4.4 Discussion

Reduced near VA from induced optical blur was associated with poorer performance on the Beery VMI and its VP and MC supplemental tests for both children and adults. Our findings suggest that in

individuals with uncorrected spherical or astigmatic ametropia, particularly if it is binocular, reduced scores on the Beery VMI and its supplemental tests may be the result of reduced near VA and not reflect reduced visual-motor abilities.

The findings from this study support previous studies which have shown a reduction in VMI scores in children with hyperopia and reduced near visual function (Kulp et al., 2017), children with bilateral uncorrected astigmatism (Harvey, Twelker, et al., 2017) and those with hyperopia and astigmatism (Roch-Levecq et al., 2008). The participants in this study required an average of 3.00 D of spherical blur and 2.00 D of astigmatic blur to achieve near VA of 0.3 logMAR. Harvey *et al.* (Harvey, Twelker, et al., 2017) found that both astigmatism (≥ 1.00 DC) and reduced near VA were significantly associated with performance on the VMI and the VP supplemental test. Similarly, Kulp *et al.* (Kulp et al., 2017) found reduced VMI and VP scores in children with hyperopia (≥ 3 D and ≤ 6 D) and reduced near VA but no difference between emmetropic children and children with hyperopia overall; their findings suggest that deficits in near VA associated with optical blur were likely the cause of the reduction in performance rather than the presence of refractive error alone. In contrast, Roch-Levecq *et al*. (Roch-Levecq et al., 2008) found reduced test scores in children with ametropia but did not find any correlation between VMI scores and either distance or near VA.

Uncorrected refractive error, in particular uncorrected hyperopia and astigmatism, may result in reduced near VA (Jin et al., 2015; Narayanasamy et al., 2015a, 2015b). Studies of near VA in typically developing children are limited. However, up to 5% of children may have near VA of 0.3 logMAR or worse and children who are born preterm may have poorer near VA than children born full-term (Larsson, Rydberg, & Holmström, 2005; Myers, Gidlewski, Quinn, Miller, & Dobson, 1999). Additionally, adults with presbyopia will have reduced near VA unless appropriately corrected for their near working distance. An acuity reserve, whereby the print size of reading materials is double the just-readable print size (near VA), is recommended for comfortable reading (Chung et al., 2007).

For the VP and MC supplemental tests, overall form size reduces with increasing form difficulty. Likewise, there is a reduction in the critical detail size and consequently the visual angle, increasing VA demand as patients progress through the test. In the present study, forms 17-30 of the VP supplemental test and 22-30 of the MC supplemental test were at the limit of the participants' near VA under induced blur conditions. Therefore, the absence of an acuity reserve may have affected performance on these tasks. Compared to the VMI test, an individual with inadequate near VA may perform more poorly on the VP and MC supplemental tests due to insufficient VA to resolve the critical detail of the test forms rather than an actual deficiency in visual perception or motor coordination.

The VA demand remains constant throughout the test for the Beery VMI due to standard form and critical detail size which remain unchanged throughout the test. Even considering an acuity reserve, this test should be accessible to individuals with near VA of 1.34 logMAR or better; however, VMI performance in our study was decreased with induced optical blur sufficient to reduce near VA to only 0.3 logMAR. This is in agreement with studies of children with uncorrected astigmatism and hyperopia with reduced near visual function which also found reduced performance on the VMI despite the supra-threshold size of the test forms (Harvey, Twelker, et al., 2017; Kulp et al., 2017). Our findings suggest that the induced blur affects not only VA but also visual-motor integration. Because optical blur was introduced for only short time periods in emmetropic children and children with corrected ametropia, our results suggest that the reduction in VMI scores seen with optical defocus in this study were due to a direct effect of the induced blur rather than deficient visual-motor development.

Visual perceptual skills have been associated with academic ability (Helveston et al., 1985; Kavale, 1982; Solan et al., 1985) and are often investigated in children with academic delays. Additionally, deficient visual perceptual skills have been shown to improve with therapy (Case-Smith, 2002; Dankert, Davies, & Gavin, 2003; Tzuriel & Eiboshitz, 1992). Recommending a vision examination for individuals who "display behavior that causes an examiner to suspect a visual acuity problem" (Beery & Beery, 2010), as suggested in the manual, appears to be insufficient to rule out reduced VA associated with optical blur, given that decreased performance on the VMI and its supplemental tests may be the only sign of reduced VA for an examiner. Therefore, children should receive a comprehensive eye examination and correction of refractive errors that reduce near VA prior to VMI testing. Where VMI testing is used for screening in a group setting, children with reduced VMI scores should be referred for a comprehensive eye examination prior to the diagnosis of a deficit in VMI and initiation of therapy.

Participants were asked to perform the test at 40 cm to maintain consistent blur and visual angle of the test stimuli. These instructions differ from those in the manual which does not specify a test distance (Beery & Beery, 2010), allowing the individual to perform the test at a self-determined near distance allowing for stature and comfortable viewing distance. This can reduce the VA demand, particularly in children who may have shorter working distances; however, our results suggest that near blur affects performance even where the test form is well above the VA threshold.

Crowding refers to the detrimental influence of an object's surroundings on visual discrimination (Levi, 2008). Crowding is important in individuals with macular degeneration, amblyopia and dyslexia and is commonly measured by considering the distance between the centres of adjacent targets (Levi, 2008). In addition to the reduction in the form size for the VP and MC supplementary tests, there is

also a reduction in the distance between the centre of forms and their crowding detail as form difficulty increases, particularly for the VP supplementary test. Participants in this study were excluded if they had any self-reported eye disease or neurological condition, or a difference in VA between the eyes, thus, crowding is unlikely to have had an effect in this study. However, in individuals with amblyopia, macular degeneration or dyslexia, crowding may result in impaired performance on the VP supplemental test due to reduced spacing of forms in this test (Levi, 2008).

This study has several potential limitations. Participants wore their habitual near correction and did not receive a full subjective refraction before VMI testing. Thus, participants may not have been optimally corrected, and this may have affected their performance. However, participants still performed significantly better with their habitual correction than with induced blur. Participants repeated VMI testing on multiple occasions, at different inter-test intervals. Repeat testing may have been subject to learning effects and the impact of differing inter-test intervals on the results is unknown, however, test order was randomised to minimise the influence of these factors on the results. Additionally, although induced blur is a method commonly used in research (Narayanasamy et al., 2015a, 2015b; Wills et al., 2012), it differs from uncorrected refractive error and participants with induced blur may perform differently to those with uncorrected refractive error to which they have adapted. In this study, we used different levels of optical blur for different participants to achieve a standard near VA level, rather than a constant level of optical blur. Inducing blur to give a pre-determined VA level allowed us to examine the effect of reduced VA on VMI results rather than merely refractive error as previous studies have shown conflicting results. However, this meant each participant experienced different levels of optical blur for a given test condition, and our study design does not allow us to provide details of minimum blur thresholds for performing the VMI test.

Testing in this study was undertaken under daylight luminance conditions. VA is detrimentally affected by low luminance and contrast conditions and larger critical detail size is required to give the same VA in these conditions. While in-office administration of the Beery VMI is likely to be performed in high luminance conditions, group administration of the test may be conducted in classroom settings where illumination levels can be variable and may not meet minimum standards (Narayanasamy et al., 2016). The Beery VMI manual does not provide guidelines for illumination and further study is required to determine the effect of luminance conditions on performance on the Beery VMI and its supplemental tests, and the minimum luminance requirements for effective administration.

In summary, our findings highlight the importance of excluding reduced near VA due to optical defocus as the cause of reduced performance on the Beery VMI and its supplemental tests before diagnosing impairment and initiating treatment strategies. While test forms on the VP and MC supplemental tests were at the limits of near VA with induced blur in our study, performance on the

Beery VMI was also reduced despite forms being within the VA threshold. A comprehensive vision examination and correction of any refractive error that reduces near VA should be completed before VMI assessment, and children who have reduced scores following assessment of VMI should receive a vision examination prior to diagnosis and treatment.

Chapter 5: Vision screening in New Zealand preschool children: is it equitable?

The literature review in Chapter 2 identified that while coverage of the B4SC vision screening had been evaluated in individual DHB regions, no national evaluation of B4SC vision screening data had been published. This chapter presents a published paper describing the results of a study utilising population-level data to evaluate coverage and testability of the B4SC vision screening programme.

The authors of this paper are Rebecca Findlay, Lisa Hamm, Nicola Anstice, Carol Chelimo, Cameron C Grant, Nicholas Bowden, Jesse Kokaua and Joanna Black. The thesis author analysed the data and prepared the manuscript (including all figures and tables).

This manuscript was first submitted to the Journal of Paediatrics and Child Health on 10 September 2020, the manuscript was accepted for publication on 19 April 2021 and was published online on 10 May 2021. Minor changes have been made to the paper to limit repetition and maintain consistency within this thesis. The details of the reference to the article and the copyright licence from the publisher can be found on page xxxii.

5.1 Introduction

Uncorrected refractive error and amblyopia ('lazy eye') are the most common causes of visual impairment in children (He et al., 2004; Varma et al., 2017). Amblyopia, if untreated, may result in permanent vision loss and therapy is most effective in children less than seven years of age (Holmes et al., 2011). Additionally, refractive error and reduced VA are associated with reduced early literacy and educational outcomes (Hopkins, Narayanasamy, et al., 2019). Thus, it is important to detect and treat refractive error and amblyopia risk factors in children.

Vision screening has an important role in detection of childhood vision problems, as children often do not report symptoms (Irving et al., 2016). Vision screening is particularly important for children from families living in lower socioeconomic areas as they are less likely to present to an eye-care professional for a comprehensive eye examination than those living in more socioeconomically advantaged areas (Majeed et al., 2008). Families of Māori and Pacific ethnicity more frequently reside in areas of socioeconomic disadvantage than families of other ethnicities (Ministry of Social Development, 2016). Furthermore, children of Māori and Pacific ethnicities and those living in areas of socioeconomic disadvantage have poorer health and educational outcomes compared with children of other ethnicities or children living in more advantaged areas respectively (Ministry of Social

Development, 2016). Thus, it is important to identify vision problems in children from these groups to prevent further disadvantage.

Preschool children in NZ are offered a universal, free, well-child check, the B4SC, at four years of age (Ministry of Health, 2014b). The check includes measures of hearing and vision as well as general health and development, growth measurements, and social and emotional wellbeing. The B4SC programme is administered independently by twenty DHBs who provide or fund services in their geographic region. However, delivery models and referral pathways differ between DHBs. B4SC data is collated by each DHB and reported to the Ministry of Health. Families may decline screening or children may not be screened due to difficulties in contacting caregivers or scheduling screening. Children of Māori or Pacific ethnicity and those living in areas of higher socioeconomic deprivation are less likely to participate in the B4SC programme (Gibb et al., 2019).

Vision and hearing screening are usually completed separately from the health and developmental assessments completed in the B4SC (Gibb et al., 2019). Vision screening is completed using the Parr vision test (Figure 2-1) (Parr, 1981), a letter matching test calibrated for use at 4 m. Coverage of the B4SC vision screening and outcome of referrals have previously been investigated in individual DHBs (Langeslag-Smith et al., 2015; Muller et al., 2019). However, there are currently no published population data regarding coverage or testability of children for the universal B4SC vision screening programme, and it is unknown whether it reaches Māori and Pacific children and children from families living in high deprivation communities at the same rate as other groups. The aims of this study, therefore, were to determine nationwide coverage and testability for the vision screening component of the B4SC by ethnicity, socioeconomic deprivation and DHB region.

5.2 Methods

Aggregated data from 1 July 2011 to 30 June 2015 were sourced from the Statistics New Zealand Integrated Data Infrastructure (IDI) (Milne et al., 2019), a large research database that holds de-identified microdata from government and non-government organisations about people in New Zealand. Ethical approval was obtained from the University of Otago Human Research Ethics Committee.

5.2.1 Eligible population

The eligible population were determined using methods developed previously (Gibb, Bycroft, & Matheson-Dunning, 2016; Zhao, Gibb, Jackson, Mehta, & Exeter, 2018). Children were included in the study population if they had a health or birth record in NZ, were included in the IDI spine (which

includes all individuals with a NZ birth, tax or immigration record) and were alive and resident in NZ at the end of the year in which they had their fourth birthday.

5.2.2 Ethnicity

Ethnicity was determined using the source ranked ethnicity table in the IDI and defined as per New Zealand Statistics Level 1 (Statistics New Zealand, 2005). Where individuals identified with more than one ethnic group, priority was assigned in the following order: Māori, Pacific, Asian, Middle Eastern/Latin American/African (MELAA), and European/Others.

5.2.3 Socioeconomic deprivation

Socioeconomic deprivation was measured using the NZDep2013, an area-based measure of socioeconomic deprivation (Atkinson et al., 2014), based on the location of the child's usual residence at the time of their fourth birthday or the first residence recorded within the 12 months following their fourth birthday. Each residence was assigned to a small geographic area to which a summary score of socioeconomic deprivation was assigned, based upon nine variables collected at the 2013 national census which measure eight dimensions of household deprivation (Atkinson et al., 2014). Scores were then collapsed into quintiles (1 representing the least deprived to 5 representing the most deprived quintile).

5.2.4 District Health Board region

DHB region was defined as the region in which the child resided at the time of their fourth birthday, or the first residence recorded within the 12 months following their fourth birthday.

5.2.5 Vision screening

Vision-hearing technicians (lay screeners) measure monocular unaided VA using the Parr vision test, a letter-matching test, in a community setting. Children who attend screening have three possible outcomes: Pass (VA 6/9 or better both eyes), Rescreen (VA 6/6 one eye and 6/9 other eye, or not cooperative with screening) or Refer (VA 6/12 or worse in either eye on initial screen; or on rescreening 6/9 or worse in either or both eyes, or unable to complete VA measurement). Rescreening should take place within three to six months. Children who are referred are advised to see a community optometrist or referred to the regional hospital ophthalmology department, depending on the local DHB referral pathways.

5.2.6 Coverage

Children with a B4SC vision screening outcome (Pass, Refer or Rescreen) were considered to have attended vision screening. B4SC vision screening coverage was calculated as the number of children who attended vision screen as a percentage of eligible children.

5.2.7 Testability

Testability was determined by comparing the number of children with a recorded VA measurement in each eye with the total number of children who attended screening. Children with a screening outcome of Refer or Rescreen for whom there was no VA measurement recorded were considered to have attended but were unable to complete screening and were therefore considered not testable.

5.2.8 Data analysis

Data extraction was carried out using SAS 7.1 within the IDI environment and analysis was conducted using SPSS Statistics (Version 26, IBM Corporation, USA). Descriptive statistics were used to summarise the data. Logistic regression was used to examine whether B4SC coverage and testability differed between ethnic groups, NZDep quintiles and DHB regions, with associations described using odds ratios and 95% confidence intervals. A two-tailed $P < .05$ was considered statistically significant.

5.3 Results

Vision screening coverage was high, with 89.5% of eligible children attending screening. Overall testability was high, with 97.7% of screened children having a VA measurement completed in each eye. Differences were observed in both coverage and testability by ethnicity (Table 5-1), socioeconomic status (Table 5-2) and DHB region (Table 5-3).

5.3.1 Ethnicity

Children identifying as Māori, Pacific, Asian or MELAA were significantly less likely to attend vision screenings than those of European/other ethnicities. Children of Māori and of Pacific ethnicity, but not children of Asian or MELAA ethnicities, had significantly lower testability than children of European ethnicity.

Table 5-1: B4 School Check vision screening coverage and testability by ethnicity

Vision screening coverage						
Ethnicity	**Attended screening**	**Not screened**	**Total**	**Coverage (%)**	**Odds Ratio (95% CI)**	**P-value**
European/Other	102 312	8352	110 667	92.5	Reference	Reference
Māori	68 889	11 256	80 145	86.0	0.50 (0.49-0.52)	<0.001
Pacific	23 532	3924	27 453	85.7	0.49 (0.47-0.51)	<0.001
Asian	24 378	2208	26 586	91.7	0.90 (0.86-0.95)	<0.001
MELAA	6603	822	7425	88.9	0.66 (0.61-0.71)	<0.001
Vision screening testability						
Ethnicity	**Visual acuity recorded**	**No visual acuity**	**Total**	**Testable (%)**	**Odds Ratio (95% CI)**	**P-value**
European/Other	100 707	1605	102 312	98.4	Reference	Reference
Māori	66 417	2472	68 889	96.4	0.43 (0.40-0.46)	<0.001
Pacific	22 848	504	23 532	97.1	0.72 (0.65-0.80)	<0.001
Asian	23 982	396	24 378	98.4	0.97 (0.86-1.08)	0.53
MELAA	6492	111	6603	98.3	0.93 (0.77-1.13)	0.48

CI = confidence interval, MELAA = Middle Eastern/Latin American/African

5.3.2 Socioeconomic status

Children living in households in the fifth (most deprived) to second quintile were significantly less likely to attend vision screenings than those from households in the first (least deprived) quintile. Testability also varied significantly and was highest and lowest for children living in the least deprived quintile (98.7%) and the most deprived quintile (96.3%) of area-level deprivation, respectively.

Table 5-2: B4 School Check vision screening coverage and testability by socioeconomic status

Vision screening coverage						
NZDep quintile†	**Attended screening**	**Not screened**	**Total**	**Coverage (%)**	**Odds Ratio (95% CI)**	**P-value**
1 (least deprived)	41 565	3396	44 961	92.5	Reference	Reference
2	40 854	3864	44 718	91.4	0.86 (0.82-0.90)	<0.001
3	41 727	4458	46 185	90.4	0.76 (0.73-0.80)	<0.001
4	44 064	5187	49 251	89.5	0.69 (0.66-0.73)	<0.001
5 (most deprived)	56 541	8886	65 427	86.4	0.52 (0.50-0.54)	<0.001
Vision screening testability						
NZDep quintile†	**Visual acuity recorded**	**No visual acuity**	**Total**	**Testable (%)**	**Odds Ratio (95% CI)**	**P-value**
1 (least deprived)	41 043	522	41 565	98.7	Reference	Reference
2	40 287	567	40 854	98.6	0.90 (0.80-1.02)	0.10
3	40 908	819	41 727	98.0	0.64 (0.57-0.71)	<0.001
4	43 002	1062	44 064	97.6	0.52 (0.46-0.57)	<0.001
5 (most deprived)	54 462	2079	56 541	96.3	0.33 (0.30-0.37)	<0.001

CI = confidence interval

† A small area level measure of household deprivation based upon nine variables collected at the 2013 national census which measure eight dimensions of household deprivation (Atkinson et al., 2014)

5.3.3 DHB region

There were statistically significant differences in vision screening coverage (Table 5-3) and testability (Table 5-4) across the twenty DHB regions throughout New Zealand. South Canterbury DHB had the highest coverage with 96.4% of children screened compared with 80.4% in Capital and Coast DHB. Testability was highest in Southern DHB (99.3%) and lowest in Whanganui DHB (93.2%).

Table 5-3: B4 School Check vision screening coverage by District Health Board region

Vision screening coverage						
DHB Region	**Attended screening**	**Not screened**	**Total**	**Coverage (%)**	**Odds Ratio (95% CI)**	**P-value**
Auckland	20 664	2799	23 463	88.1	Reference	Reference
Bay of Plenty	11 364	879	12 243	92.8	1.75 (1.62-1.90)	<0.001
Canterbury	23 586	1926	25 512	92.5	1.66 (1.56-1.76)	<0.001
Capital and Coast	12 126	2961	15 087	80.4	0.55 (0.52-0.59)	<0.001
Counties Manukau	30 585	3375	33 390	90.1	1.23 (1.16-1.29)	<0.001
Hawke's Bay	8739	687	9426	92.7	1.72 (1.58-1.88)	<0.001
Hutt Valley	7317	1254	8571	85.4	0.79 (0.74-0.85)	<0.001
Lakes	6279	417	6696	93.8	2.04 (1.83-2.27)	<0.001
MidCentral	8325	1149	9474	87.9	0.98 (0.91-1.06)	0.62
Nelson Marlborough	6504	630	7134	91.2	1.40 (1.28-1.53)	<0.001
Northland	7869	1863	9732	80.9	0.57 (0.54-0.61)	<0.001
South Canterbury	2679	99	2778	96.4	3.67 (2.99-4.50)	<0.001
Southern	14 040	1128	15 168	92.6	1.69 (1.57-1.81)	<0.001
Tairāwhiti	2883	324	3207	89.9	1.20 (1.07-1.36)	0.003
Taranaki	5949	879	6828	87.1	0.92 (0.85-0.99)	0.04
Waikato	21 285	1383	22 668	93.9	2.09 (1.95-2.23)	<0.001
Wairarapa	2019	234	2253	89.6	1.17 (1.02-1.35)	0.03
Waitematā	28 122	3120	31242	90.0	1.22 (1.16-1.29)	<0.001
West Coast	1461	252	1713	85.3	0.79 (0.68-0.90)	<0.001
Whanganui	3048	459	3507	86.9	0.90 (0.81-1.00)	0.05

CI = confidence interval, DHB = District Health Board

Table 5-4: B4 School Check vision screening testability by District Health Board region

DHB Region	Visual acuity recorded	No visual acuity	Total	Testable (%)	Odds Ratio (95% CI)	P-value
Auckland	20 445	219	20 664	98.9	Reference	Reference
Bay of Plenty	11 103	261	11 364	97.7	0.45 (0.38-0.55)	<0.001
Canterbury	22 962	624	23 586	97.4	0.39 (0.34-0.46)	<0.001
Capital and Coast	11 721	405	12 126	96.7	0.31 (0.26-0.37)	<0.001
Counties Manukau	30 012	573	30 585	98.1	0.56 (0.48-0.66)	<0.001
Hawke's Bay	8283	456	8739	94.8	0.19 (0.17-0.23)	<0.001
Hutt Valley	7140	177	7317	97.6	0.43 (0.35-0.53)	<0.001
Lakes	6006	273	6279	95.7	0.24 (0.20-0.28)	<0.001
MidCentral	8151	174	8325	97.9	0.50 (0.41-0.61)	<0.001
Nelson Marlborough	6420	84	6504	98.7	0.82 (0.64-1.05)	0.12
Northland	7506	363	7869	95.4	0.22 (0.19-0.26)	<0.001
South Canterbury	2637	42	2679	98.4	0.67 (0.48-0.94)	0.02
Southern	13 941	99	14 040	99.3	1.51 (1.19-1.91)	<0.001
Tairāwhiti	2811	72	2883	97.5	0.42 (0.32-0.55)	<0.001
Taranaki	5847	102	5949	98.3	0.62 (0.49-0.78)	<0.001
Waikato	20 736	549	21 285	97.4	0.41 (0.35-0.47)	<0.001
Wairarapa	1968	51	2019	97.5	0.41 (0.30-0.56)	<0.001
Waitematā	27 846	276	28 122	99.0	1.08 (0.90-1.29)	0.39
West Coast	1407	54	1461	96.3	0.28 (0.21-0.38)	<0.001
Whanganui	2841	207	3048	93.2	0.14 (0.12-0.18)	<0.001

CI = confidence interval, DHB = District Health Board

5.4 Discussion

This national level study of preschool vision screening in children aged 4-5 years shows that significant disparities exist in vision screening coverage and testability in NZ. While the B4SC vision screening has good overall coverage and testability, disparities were observed by ethnicity, socioeconomic deprivation and region. Vision screening was less likely to be attended by non-European children, but Māori and Pacific families also had lower rates of testability if screening was attended compared with children of European ethnicity. Similarly, children living in high deprivation areas had reduced B4SC vision screening coverage and testability compared to children living in more socioeconomically advantaged areas. Interventions are required to ensure that these children at risk of poorer health and educational outcomes have vision problems detected and treated.

Overall coverage of the B4SC vision screening is high (89.5%) and comparable with countries within the European Union with established vision screening programmes (Sloot et al., 2015). However, coverage was lower for children of Māori (86.0%) and Pacific (85.7%) ethnicities and those living in households in lower socioeconomic areas (most deprived quintile 86.4%), resulting in a larger proportion of children from these ethnic and socioeconomic groups not receiving vision screening. Although it has been shown that children from lower socioeconomic groups are less likely to receive a comprehensive vision assessment (Majeed et al., 2008), there is a paucity of data on vision screening coverage in these populations. Likewise, there is little data regarding vision screening and comprehensive eye examinations in indigenous paediatric populations. The results of this study are, however, in agreement with previous studies of the overall B4SC programme (Gibb et al., 2019), and of B4SC vision screening in a single DHB (Langeslag-Smith et al., 2015), that showed lower screening coverage amongst children of Māori or Pacific ethnicities and those living in areas of greater socioeconomic disadvantage.

Focus groups conducted with Māori and Pacific parents from more socioeconomically deprived households have identified their lack of awareness of the B4SC programme and concerns with potential blame or judgement as barriers to participation (Premium Research Limited, 2014). Furthermore, as consent to vision screening is frequently obtained through the early childcare provider, this may provide a barrier to participation. These barriers need addressing to improve coverage to ensure that all NZ children receive vision screening. Differing strategies are required to reach children from more socioeconomically deprived areas and to enable Māori and Pacific families to feel comfortable about engaging with the B4SC programme and hence improve equity in vision screening coverage (Ministry of Health, 2019a). Potential strategies include increasing community engagement, Iwi (tribal) partnerships and collaboration with early childhood centres and schools. For a screening programme to be effective, the screening test used must be completed successfully by the target population. Although

overall testability in this population was high (97.7%), it was lower in children from Māori (96.4%) or Pacific (97.1%) ethnic groups, and those living in areas of higher socioeconomic deprivation (most deprived quintile 96.3%). These results are comparable to those seen in the Sydney Paediatric Eye Disease Study which reported testability of 95% in children aged 48 to <54 months, increasing to 98% in children aged 54 to <60 months, but lower testability in both age groups for children of 'other' ethnicity compared with children of European Caucasian ethnicity (Leone et al., 2012).

In some NZ DHB regions, more than half of children with a Rescreen or Refer outcome did not complete the VA measurement. As children unable to complete the screening test are referred for comprehensive eye evaluation, this may result in referral of children without a vision problem. This is consistent with previous studies examining B4SC vision screening outcomes which have shown significant rates of false positive referrals (Langeslag-Smith et al., 2015; Muller et al., 2019). Improving testability may therefore help to reduce the number of false positive referrals, which in turn would reduce unnecessary parental concern, and personal financial costs including travel and time off work for caregivers. This is particularly important for families of Māori and Pacific ethnicity and those from areas of socioeconomic disadvantage who face significant barriers when accessing healthcare (Morton et al., 2017).

Testability could be improved by employing alternative testing protocols. The Parr vision test was developed in NZ but includes letters that are not found in the Māori and Pacific alphabets. Although a Māori language version is available, it does not have crowding bars (which improve detection of amblyopia) and therefore it is not routinely used for B4SC vision screening. Furthermore, the test is calibrated for use at 4 m, while best practice guidelines recommend screening at a distance of 1.5 m. A shorter testing distance may improve children's attention and allow testing in smaller spaces, preventing distractions (Cotter et al., 2015). Testability in the B4SC vision screening programme may be improved by using a test that includes appropriate letter choices or symbols, and reducing the testing distance. Instrument-based screening, for example with automated measures of refractive error, is not currently utilised for preschool vision screening in NZ. One possible method for improving the current B4SC vision screening protocol, would be utilising instrument-based screening for retesting of children who are unable to complete the VA task which may improve overall testability as instrument-based screening is quick to administer and requires minimal cooperation by the child (Cotter et al., 2015).

This study shows that further investment and research is needed to improve equity in B4SC vision screening in NZ by increasing coverage and testability for children of Māori or Pacific ethnicities and children living in households in areas of greater socioeconomic disadvantage. This service delivery should be developed under a *responsiveness to Māori* framework to improve equity and healthcare outcomes for Māori (Reid et al., 2017). Additionally, research is required to determine whether

regional differences in coverage and testability are due to differences in demographic profile, geographic distribution or service delivery. More detailed evaluation of the B4SC vision screening programme in different DHBs will highlight processes that work well. Implementation of these processes across all DHBs could reduce DHB level variability in vision screening coverage and testability, and thus improve coverage and testability at a national level.

A strength of this study is the use of a large, linked dataset enabling assessment of coverage and testability specifically of the B4SC vision screening across the population. Limitations of this study include the bivariate nature of the analysis; children of Māori and Pacific ethnicity are over-represented within areas of greater socioeconomic deprivation and there is likely an interaction between ethnicity and area-level deprivation in contributing to a reduced likelihood of attendance at or successfully completion of vision screening. However, this interaction could not be examined in this study because of the use of aggregated data. Furthermore, performing multivariable analysis would have restricted the eligible population due to incomplete data, therefore reducing the generalisability of the results. Additionally, determining testability by identifying children for whom no VA was recorded does not differentiate between visual, behavioural or cognitive reasons for not completing the assessment.

In summary, despite high overall coverage and testability of the B4SC vision screening programme, inequities are evident. Policy changes and equity-focused initiatives, specifically targeting children from Māori and Pacific families, and those living in high deprivation communities, are needed to ensure that all children receive and complete vision screening. This is essential to ensure that these children who have known disparities in educational and health outcomes are not further disadvantaged by uncorrected vision problems.

Chapter 6: Eye care following preschool vision screening: Data from the *Growing Up in New Zealand* study

The literature review presented in Chapter 2 and the study in Chapter 5 identified disparities in B4SC vision screening coverage, with smaller proportions of Māori and Pacific children, and those living in areas of socioeconomic deprivation, receiving vision screening than their peers. This chapter utilises data collected in the *Growing Up in New Zealand* cohort study to examine outcomes of children following referral from the B4SC vision screening programme. Utilising data from the *Growing Up in New Zealand* cohort study allowed evaluation of vision screening results alongside cognitive measures assessed at the same age.

6.1 Introduction

Failure to detect and treat vision problems during childhood may result in permanent visual loss (Holmes & Clarke, 2006). Therefore, vision screening in children is important in the detection of vision problems as children frequently do not report symptoms (Irving et al., 2016). Children living in areas with greater socioeconomic disadvantage are less likely to see an eye care professional than those from more advantaged areas (Majeed et al., 2008), and socioeconomic disadvantage is associated with increased amblyopia prevalence (Harrington, Breslin, O'Dwyer, & Saunders, 2019). In NZ, children of Māori and Pacific ethnicity more frequently live in areas of socioeconomic disadvantage than children from other ethnic groups (Paine et al., 2018).

As part of the B4SC nationwide well child check, preschool children in NZ receive a vision screening at 4-5 years of age (Ministry of Health, 2014b). However, the availability and utilisation of follow-up health care services are essential to the success of any screening programme (Wilson & Jungner, 1968). The B4SC and subsequent referral processes are administered independently in each of the country's twenty DHBs. The B4SC vision screening is usually completed at the child's early childhood education centre, or the child is invited to attend screening at a clinic (Ministry of Health, 2014b). In the Counties Manukau DHB catchment area, all children who fail the B4SC vision screening are referred to the hospital eye department for publicly funded eye care services. In other DHBs, some children who are referred from vision screening receive a recommendation to see their local optometrist. There are currently no data investigating the influence of ethnic and socioeconomic factors on compliance with follow-up from vision screening in NZ.

This thesis chapter addresses this gap in knowledge with a study that aims to:

1. Determine the visual outcomes of children enrolled in the Growing Up in New Zealand cohort study and residing in the Counties Manukau DHB area following B4SC vision screening;
2. Examine compliance with recommended follow-up after vision screening; and
3. Assess the associations of referral from the B4SC vision screening check with measures of school readiness and early literacy at four years of age.

Determining vision screening outcomes provides a unique opportunity to examine these screening results in the context of social and cognitive measures that were assessed at the same age.

6.2 Methods

6.2.1 Data source and study sample

The research followed the tenets of the Declaration of Helsinki. Ethical approval was obtained from the Northern Y Health and Disability Ethics Committee of the New Zealand Ministry of Health (Reference number: NTY/08/06/055). Approval for this research was also obtained from the Counties Manukau Health Research Office. The *Growing Up in New Zealand* study's Data Access Committee also approved access to data sets used in this project.

Growing Up in New Zealand is a large multidisciplinary prospective study investigating health, education and social outcomes in a cohort of 6853 NZ children (Morton et al., 2012). The children in the study were born in 2009 and 2010 and were therefore scheduled to receive their B4SC between 2013 and 2015. Consent was obtained for participation on enrolment into the study and separate consent was obtained for access to data held by the Ministry of Health during the 54 month data collection wave.

A retrospective records review of the B4SC vision screening results was undertaken for children from the *Growing Up in New Zealand* study whose parents had provided consent for data linkage. The retrospective review was restricted to participants who were living in the Counties Manukau DHB catchment area at the time of screening (n = 1879). Children who had been categorised as 'Under care' (n = 41) in the B4SC data or whose date of birth was not valid for a *Growing Up in New Zealand* participant (n < 10) were excluded from data analysis. This resulted in a study sample of 1847 children (Figure 6-1).

6.2.2 Measures

Data obtained from the *Growing Up in New Zealand* B4SC dataset included ethnicity (classified as per NZ Statistics level 1 (Statistics New Zealand, 2005)), date of vision screening, B4SC vision screening

outcome, right eye and left eye unaided VA measured at screening, and date of referral for children who failed the vision screening.

B4SC vision screening was carried out using the Parr vision test (Figure 2-1) (Parr, 1981), a single, crowded, letter matching task, (similar to the Sheridan Gardiner chart), at a distance of 4 m. For the right eye, then the left eye (with the opposite eye occluded), the test booklet was shown to the child who was asked to identify the corresponding letter on a matching card. VA was recorded as the smallest letter size that the child identified two out of three letters correctly. Possible B4SC vision screening outcomes were: 'Pass', 'Rescreen', 'Refer', 'Decline [to participate in B4SC vision screening]' or 'Under care [of an eye care professional]'. A 'Rescreen' outcome indicated that the child attended screening and either achieved VA measurements of 6/6 in one eye and 6/9 in the fellow eye, or was unable to complete screening on that occasion due to behavioural or other reasons. As this outcome is indicative of an incomplete screening, children with a 'Rescreen' outcome were excluded from all analyses apart from comparisons between those who declined and consented to screening.

For those children who were referred from the vision screening, hospital eye department records were used to collate information on unaided VA at presentation, cycloplegic refraction, visual diagnosis, best-corrected VA at discharge, and number of attended and non-attended or rescheduled follow-up visits.

Cognitive measures used by *Growing Up in New Zealand* in the 54 month data collection wave included a Name and Numbers task derived from the 'Who Am I?' developmental assessment (De Lemos & Doig, 1999) and the Letter Naming Fluency task from the Dynamic Indicators of Basic Early Literacy (DIBELS) Tools (Good III & Kaminski, 2011).

The Name and Numbers task comprised four parts. Two tasks, name and number writing, were adopted from the 'Who Am I?' developmental assessment, a measure of school readiness (De Lemos, 2002). Children were given a worksheet and asked to write their name on the first page and some numbers on the following page. Additionally, children were asked to count aloud from one to ten and then backwards from ten to one. Responses for the writing tasks were scored according to the standard scoring manual (Rothman, 2005). The counting tasks were scored as the number of correct digits in the longest sequence given by the child. A total score (ranging from 0 to 28) was calculated by summing the individual scores for each task.

Letter naming fluency is predictive of later reading achievement (Adams, 1990) and the DIBELS letter naming fluency tool has been validated in NZ children (Schaughency & Suggate, 2008). For the DIBELS letter naming fluency task, children were presented with a page of randomly ordered uppercase and lowercase letters and using standardised directions, asked to name the letters (Good III

& Kaminski, 2011). The task was scored according to the instructions in the manual, with the total score (ranging from 0 to 110) being the number of letters correctly named in one minute.

Data obtained from the *Growing Up in New Zealand* 54-month follow-up included the NZDep2013 Index of Deprivation (an area-based measure of socioeconomic deprivation) (Atkinson et al., 2014), name and numbers task scores, and DIBELS letter naming fluency scores. NZDep2013 scores were categorised as low (deciles 1-3), moderate (deciles 4-7) or high (deciles 8-10) deprivation.

6.2.3 Definitions for visual outcomes

Visual conditions were classified using the same definitions used throughout this thesis, as described in Chapter 3. Refractive error was classified using the cycloplegic retinoscopy results from the hospital eye department records. Clinically significant refractive error (Table 3-2) and visual impairment (Table 3-3) were defined according to the Refractive Error Studies in Children group, (Negrel et al., 2000) and amblyopia risk factors (Table 3-4) were defined according to the American Academy of Ophthalmology (Holmes & Clarke, 2006).

6.2.4 Data analysis

Data analysis was conducted using IBM SPSS Statistics (Version 26, IBM Corporation, USA). A two-tailed $P < .05$ was considered statistically significant. Descriptive statistics were used to summarise the data using counts and percentages (for categorical variables) or medians and interquartile ranges (IQR; for non-parametric variables). Owing to study ethical requirements, "<10" denotes categories with fewer than 10 participants.

The chi-squared test was used to assess whether there were differences by ethnicity and socioeconomic deprivation in the proportion of children who: 1) declined vision screening versus consented to screening; and 2) were referred after screening versus passed vision screening. Among children who were referred (n = 176), the chi-squared test was used to assess ethnic and socioeconomic differences in the proportion of children who attended a referral appointment versus those who did not and, of those who attended a referral appointment (n = 138), children who failed to attend follow-up appointments versus those who had no unattended appointments. Children of "European" and "Other" ethnicities were classified in a single group in to ensure that categories with fewer than 10 participants are suppressed.

The Mann-Whitney U test was used to examine whether the distribution of Name and Numbers total test scores and DIBELS letter naming fluency scores (non-parametric variables) differed between children who were referred and those who passed vision screening.

Using median-splits of for Name and Numbers total test scores and DIBELS letter naming fluency scores as dependent variables (dichotomous), separate logistic regression models (for non-parametric outcome variables) examined whether children who were referred (compared to those who passed vision screening) were less likely to achieve scores above the median value. These models adjusted for the following potential confounding variables: child's birthweight, sex, ethnicity, and area-level socioeconomic deprivation. The results were summarised using adjusted odds ratios (aOR) and their 95% confidence intervals (CI).

6.3 Results

6.3.1 Study sample

The characteristics of the study population are shown in Table 6-1. The 1847 participants (961 [51%] male, 812 [43%] European ethnicity) had a median (IQR) age of 4.24 (4.13-4.44) years.

Table 6-1: Characteristics of participants from the *Growing Up in New Zealand* study living in the Counties Manukau region at four years of age

Characteristic	**n (%) (n=1847)**
Age (median [IQR])	4.24 (4.13-4.44)
Sex	
Female	900 (48.7)
Male	947 (51.3)
Child ethnicity	
Māori	301 (16.3)
Pacific	460 (24.9)
European	795 (43.0)
Other	291 (15.8)
Socioeconomic deprivation*	
Deciles 1 to 3 (low)	502 (27.2)
Deciles 4 to 7 (moderate)	510 (27.6)
Deciles 8 to 10 (high)	830 (44.9)
Unknown	<10 (0.3)

IQR = interquartile range

* Deciles based on NZDep2013 scores. Decile 1 households are located in the least deprived 10% of meshblocks and decile 10 households are located in the most deprived 10% of meshblocks.

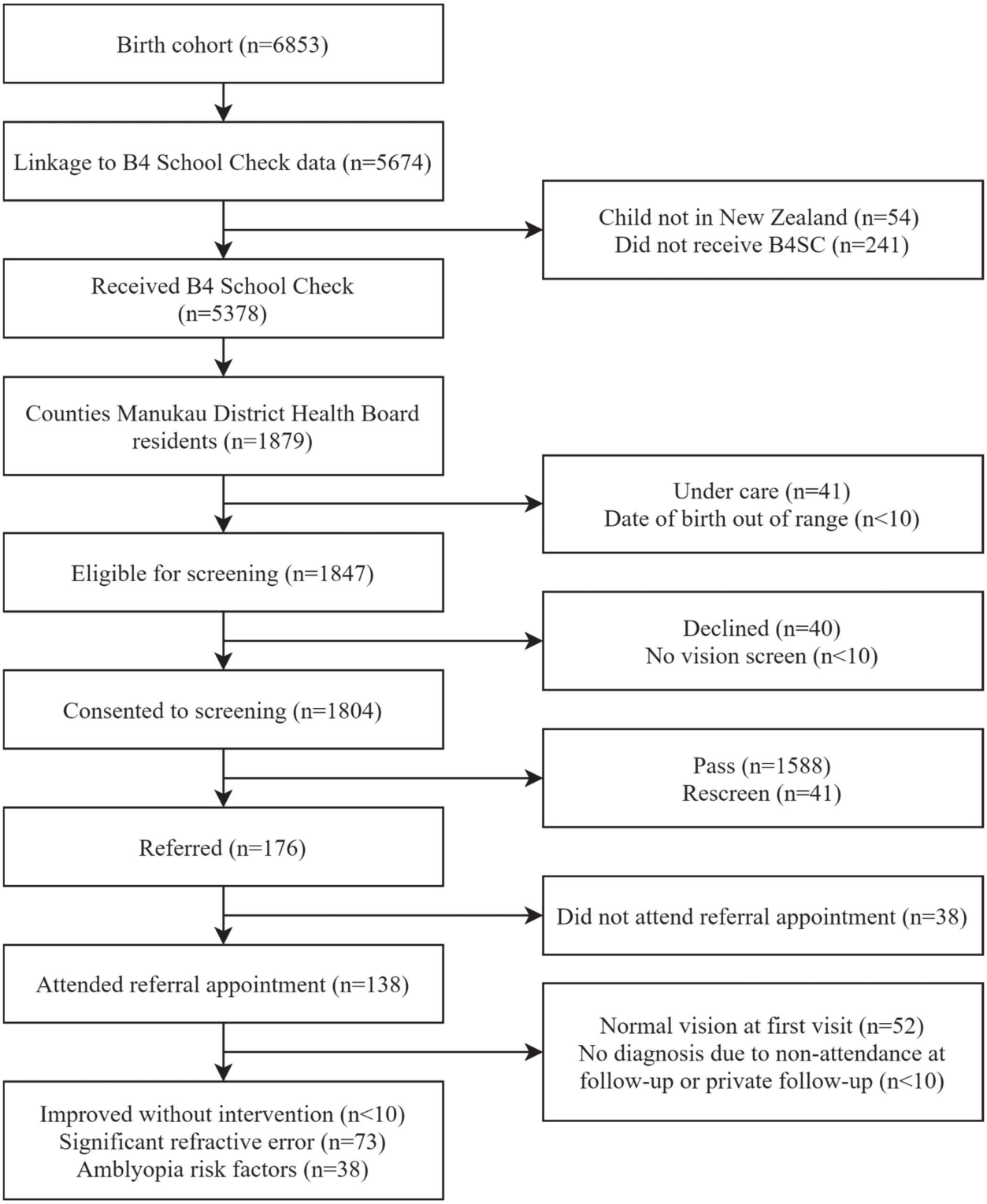

Figure 6-1: Flow diagram of vision screening eligibility, consent, referral and outcome for children enrolled in the *Growing Up in New Zealand* study and residing in the Counties Manukau District Health Board region

6.3.2 Consent for and referral from vision screening

Children received vision screening between May 2013 and April 2015. Forty children declined vision screening (Figure 6-1).

There were no significant differences by ethnic group in the proportion of children whose parents consented for vision screening versus those that declined vision screening (Figure 6-2). In contrast, there was a significant difference by socioeconomic deprivation in the proportion of children whose parents consented for vision screening versus declined vision screening (Figure 6-3). Compared to children whose parents consented for vision screening, a larger proportion of the children whose parents declined vision screening lived in households in one of the three most socioeconomically deprived area deciles (deciles 8-10) (65% vs 45%, P = 0.03).

There was no significant difference by ethnic group (Figure 6-2) or socioeconomic status (Figure 6-3) in the proportion of children who passed vision screening versus those who were referred on from vision screening.

6.3.3 Attendance at referral appointments and follow-up appointments

Thirty-eight children (21.6%) were referred from the B4SC vision screening but did not attend a referral appointment at the hospital eye department (Figure 6-1). The most frequently recorded reason for non-attendance at a referral appointment was no reply from the child's family (22/38, 57.9%). Other reasons included: appointment was scheduled but not attended, no referral in the system, seen by a private provider, referral declined by provider, and appointment declined by parents.

Among those referred for comprehensive eye examinations there were significant differences between ethnic groups in attendance at referral appointments and follow-up appointments (Figure 6-2). Compared with children who attended referral appointments, a larger proportion of those who did not attend referral appointments were of Māori or Pacific ethnicities (P = 0.04). Furthermore, compared to children who attended all follow-up appointments, a larger proportion of those who did not attend at least one follow-up appointment were of Māori or Pacific ethnicities (P = 0.001). In contrast, there were no significant differences in attendance at referral or follow-up appointments by area-level socioeconomic deprivation (Figure 6-3).

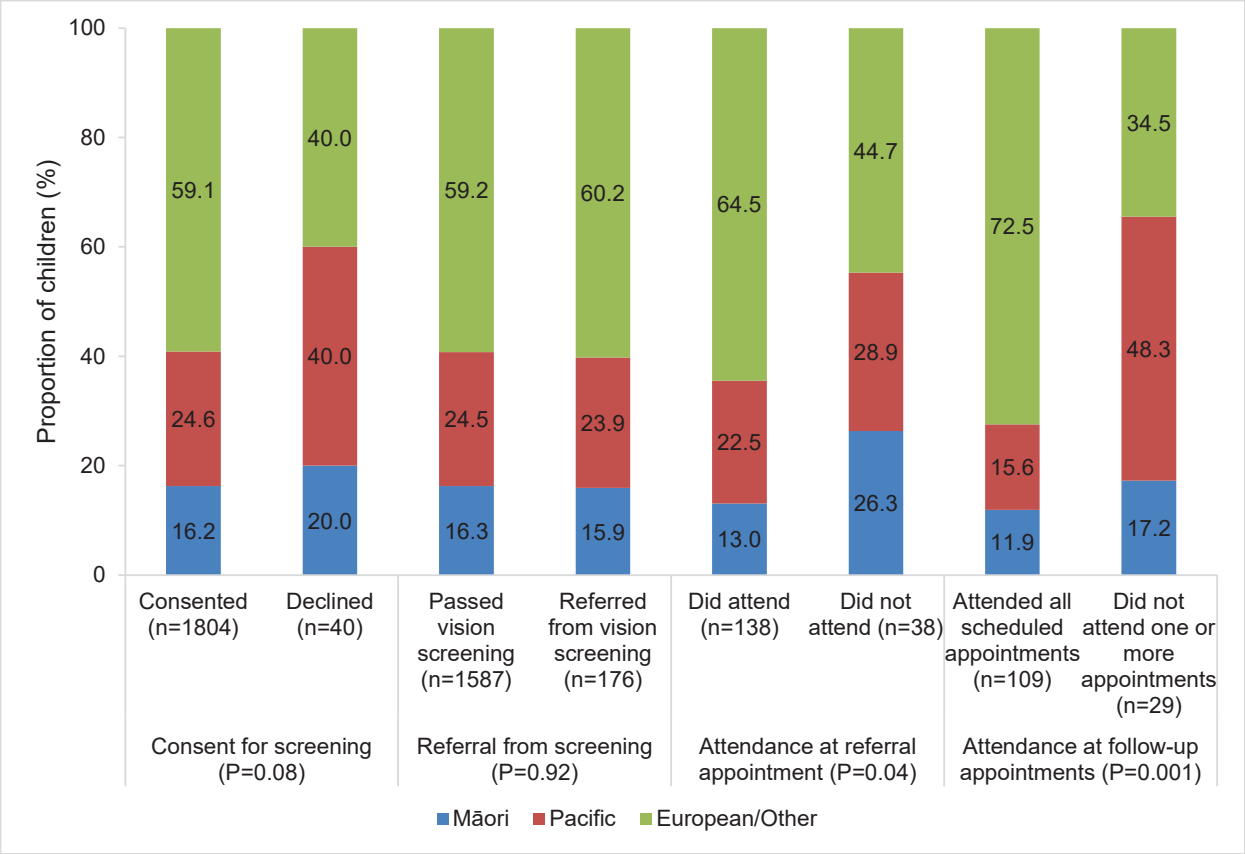

Figure 6-2: Consent for screening, referral from screening, and attendance at referral appointments and follow-up appointments by child ethnicity

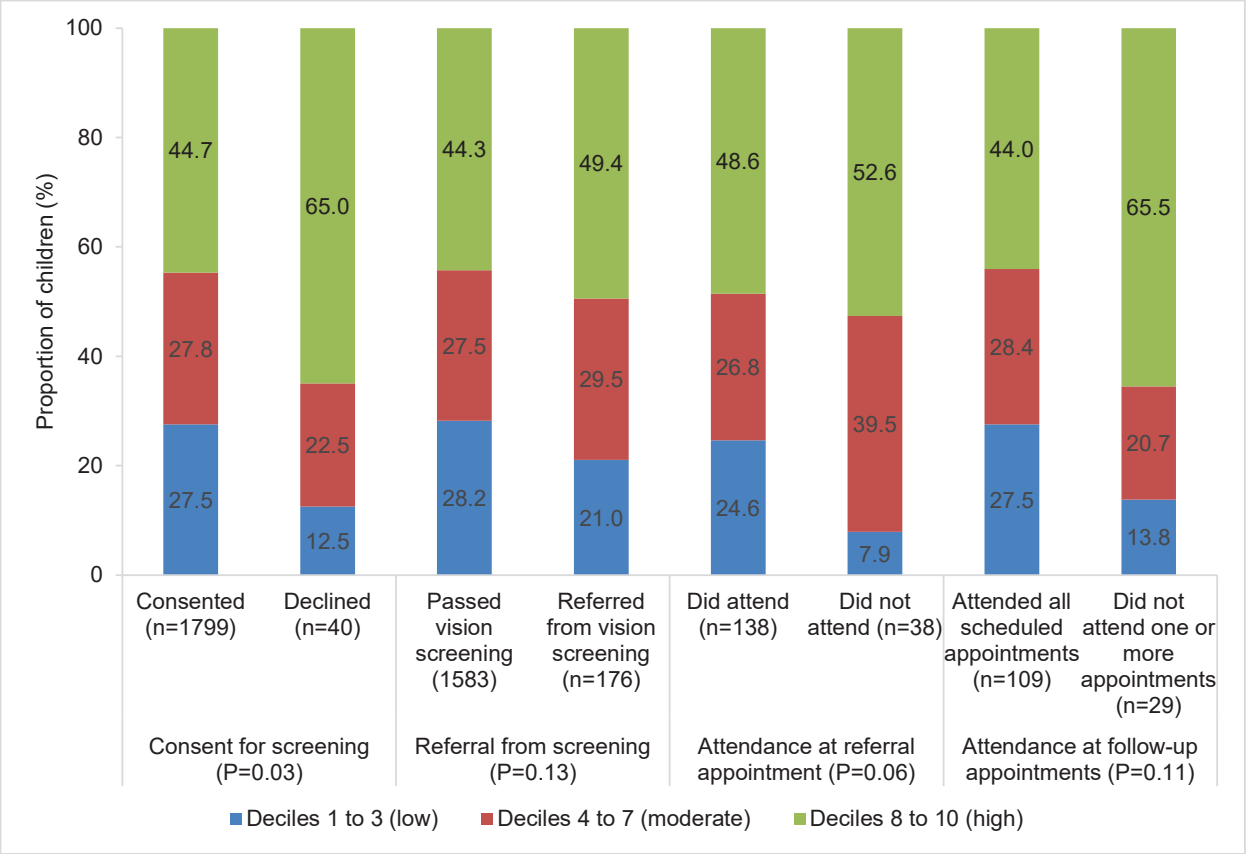

Figure 6-3: Consent for screening, referral from screening, and attendance at referral appointments and follow-up appointments by area-level socioeconomic deprivation of household where child lives

6.3.4 Visual outcomes

Among the 138 children who attended the hospital for a referral appointment, 74 children had visual impairment detected at their initial appointment (Table 6-2). Of these, 63 had a diagnosed visual condition. A small number of children (n < 10) did not attend follow-up visits or elected to be seen by a private provider following an initial consultation which precluded a final diagnosis of the cause of their reduced vision being established. Of the 64 children without visual impairment, 51 were discharged with no visual abnormality, while 13 had a diagnosed visual condition (i.e. significant refractive error or strabismus in the presence of normal unaided distance vision). A small number of children (n < 10) without a diagnosed visual condition had reduced VA at their initial hospital appointment but achieved normal VA at a subsequent visit without any intervention.

Table 6-2: Visual outcomes of children who attended a referral appointment

Visual outcome	n (%) (n=138)
Visual acuity	
Visual impairment (n=74)	
Visual impairment with subsequent improvement*	<10 (5.1)
Visual impairment with diagnosed ocular condition	63 (45.6)
Visual impairment with no diagnosis made†	<10 (2.9)
Normal visual acuity (n=64)	
Normal visual acuity with no ocular condition	51 (37.0)
Normal visual acuity with ocular condition	13 (7.2)
Visual conditions (n=76)	
Refractive error (n=73) ‡	
Myopia	16 (11.6)
Hyperopia	36 (26.1)
Astigmatism	49 (35.5)
Amblyopia risk factors§	38 (27.5)

* Unexplained reduced visual acuity at initial visit that improved without treatment

† No diagnosis made due to follow-up with private provider or non-attendance at follow-up appointment

‡ 14 children had both myopia and astigmatism and 14 had both hyperopia and astigmatism

§ 35 children had both refractive error and amblyopia risk factors

6.3.5 Cognitive outcomes

The Name and Numbers and DIBELS letter naming fluency tasks were completed by 1808/1879 (96.3%) and 1,733/1,879 (92.3%) children, respectively. For both tasks, the median values of the participants' total scores were significantly lower for children who were referred from the B4SC vision screening compared with those who passed the B4SC vision screening (Table 6-3). In the logistic regression analysis (adjusted for birthweight, sex, ethnic group, and area-level socioeconomic deprivation), B4SC vision screening outcome was significantly associated with DIBELS letter naming fluency scores (P = 0.01) but not Name and Numbers total test scores (P = 0.05) (Table 6-4). The adjusted analysis showed that compared to children who passed vision screening, those who were referred from screening were less likely to achieve scores above the median value on the DIBELS letter naming fluency task (aOR = 0.61; 95% CI = 0.43-0.88).

Table 6-3: Name and numbers and DIBELS letter naming fluency scores by B4SC outcome

	Name and numbers scores			DIBELS letter naming fluency scores		
	n (%) (n=1708)	Median (IQR)	P-value	n (%) (n=1633)	Median (IQR)	P-value
B4SC vision screening outcome						
Passed	1535 (89.9)	17 (13-23)	0.001	1473 (90.2)	4 (1.0-12.0)	0.02
Referred	173 (10.1)	15 (9-20)		160 (9.8)	2 (0.0-7.8)	

B4SC = B4 School Check, IQR = interquartile range

Table 6-4: Logistic regression analysis of measures of school readiness and early literacy at four years of age in relation to the B4 School Check vision screening outcome

	Name and numbers total scores				DIBELS letter naming fluency total scores			
	≤ median (≤ 17) n (%)	> median (> 17) n (%)	Adjusted* OR† (95% CI)	P-value	≤ median (≤ 3) n (%)	> median (> 3) n (%)	Adjusted* OR† (95% CI)	P-value
B4SC vision screening outcome								
Passed	845 (88.4)	690 (91.8)	Reference		732 (88.4)	741 (92.0)	Reference	
Referred	111 (11.6)	62 (8.2)	0.71 (0.51-1.00)	0.05	96 (11.6)	64 (8.0)	0.61 (0.43-0.88)	0.01

B4SC = B4 School Check, CI = confidence interval, OR = odds ratio

* Adjusted for child's birthweight, sex, ethnicity and area-level socioeconomic deprivation.

† Logistic regression analysis modeling the probability that total scores (separate models) are above the median value.

6.4 Discussion

The results of this chapter highlight that the B4SC vision screening programme in NZ identifies children at risk of refractive error, strabismus, and amblyopia. However, one in five children failed to benefit from this screening check due to not receiving follow-up care. Our findings also show that children who are referred from preschool vision screening achieve lower scores on letter naming fluency, a key predictor of reading ability in later childhood (Adams, 1990), than those who pass vision screening. This underlines the importance of screening follow-up.

In the present study, preschool vision screening was most likely the first indication of a vision condition in 76 children who were not previously under the care of an eye care practitioner. Half of these children had amblyopia risk factors and were therefore at risk of long-term visual impairment without detection and treatment of the underlying vision disorder (Holmes & Clarke, 2006). However, one in five children in this study who were referred for further eye care did not attend a referral appointment. Furthermore, among children who did attend a referral appointment, one in five then failed to attend one or more follow-up appointments. Non-attendance at both referral and follow-up appointments was seen more frequently in Māori and Pacific children compared with children from other ethnic groups.

Previous studies of follow-up from vision screening referrals in NZ have shown contrasting results. Similar to the results of the present study, a previous study of children seen at Counties Manukau DHB found that 80% of children referred from B4SC vision screening were seen at the hospital eye department (Langeslag-Smith et al., 2015). In contrast, a study of B4SC vision screening outcomes in Tairāwhiti and Southland DHBs was only able to obtain follow-up results for half of the children referred following vision screening (Muller et al., 2019). The contrast in findings in the study by Muller *et al.* could be because it relied on voluntary participation by community optometrists and thus may have underestimated the follow-up care received, and/or may reflect differences in referral pathways between DHBs. Referral pathways differ between regions depending on the local availability of eye care resources (Ministry of Health, 2014b). In some regions, all children are referred into the public health system where an appointment is facilitated by the DHB with no direct appointment cost to the child's family/whānau. In other regions, the family receives a recommendation to seek follow-up with a local optometrist. These children do not receive a specific referral appointment. Families may also be required to pay a fee for service if they are not eligible to receive government subsidies to cover the cost of the eye examination. These factors are likely to contribute to further inequities in regions where eye care is provided in the community rather than through the local DHB.

Although examination and follow-up within the public health system is at no direct cost to the whānau, barriers to accessing care remain. Inability to get an appointment at a suitable time, lack of transport,

and parents not having time to take their child to the doctor were identified as barriers to accessing primary care within the *Growing Up in New Zealand* cohort (Morton et al., 2017) and are likely to also affect the ability of parents to access eye care services for their children. In NZ, children's glasses are available at no direct cost to holders of a community services card, issued to low income earners to assist with the cost of healthcare. However, families who are eligible for a community services card are often unaware of their eligibility and thus do not hold a card (Gribben, 1996; Sopoaga et al., 2012).

Poor health literacy is associated with reduced adherence with attendance at eye examinations and recommended treatment (Muir et al., 2006; Schillinger et al., 2002). Health literacy is poor in NZ adults (Ministry of Health, 2010) which may contribute to families declining screening and affect the parents' ability to access eye care for their children following a referral from screening. Furthermore, cultural factors including institutional and personal racism, and language barriers may influence access to healthcare services (Ludeke et al., 2012; Paine et al., 2018). Further research is required to determine the barriers to attendance at both referral and follow-up appointments, and to develop strategies for improving access to eye care services for these families. Such research should be developed with a *Kaupapa Māori* approach to ensure improvement in Māori health and elimination of health inequities (Reid et al., 2017).

Specific interventions to reduce non-attendance rates for eye appointments following referral from screening for Māori and Pacific children are required to improve visual outcomes and reduce the burden of missed appointments on limited public health resources. Possible strategies to overcome problems with follow-up include co-location of services, so that assessment and provision of glasses take place at the location of screening, collaboration with other services that are currently providing health care to children, and enhanced parental education and communication of results (Burnett et al., 2018; Mehravaran, Quan, Hendler, Yu, & Coleman, 2018). Studies in Tanzania (Wedner et al., 2008) and China (Ma et al., 2014) have shown that providing children with free glasses that are dispensed to them in schools results in higher uptake of glasses than providing a prescription and/or voucher for glasses. Furthermore, a study in the United States showed that educating adults with written material and videos during a vision screening session increased follow-up rates compared with those who did not receive the educational intervention (Mehravaran et al., 2018).

In the present study, children who were referred from vision screening achieved poorer results on the DIBELS letter naming fluency task, compared with those who passed the B4SC vision screen. These findings suggest that children who are referred from preschool vision screening in NZ are at risk of poor literacy development. Previous studies have found that preschool-aged children with reduced VA (Bruce et al., 2016), uncorrected hyperopia (Kulp et al., 2016), or astigmatism (Orlansky et al., 2015) have reduced scores on tests of early literacy compared with children with normal VA and no refractive

error. Similarly, in a study of Australian children aged 8-9 years, children who failed vision screening performed more poorly on standardised tests of literacy and numeracy than those who passed vision screening (White, Wood, Black, & Hopkins, 2017). Children in NZ from areas of socioeconomic deprivation, and those of Māori and Pacific ethnicities, are more likely to have poorer academic outcomes than their peers (Marriott & Sim, 2015; OECD, 2018). Thus, detection and correction of any vision problems that may affect academic performance is particularly important for these children to prevent further disadvantage.

While the present study showed that children who were referred from vision screening also had lower median scores on the Name and Numbers task, compared with those who passed the screening, this was not statistically significant in the adjusted logistic regression model. This may be due to differences in the format of the Name and Numbers test compared with the DIBELS letter naming fluency task. While the DIBELS task involved recognition of written letters, the Name and Numbers task required written and verbal responses to verbal instructions from the assessor. Additionally, while the Name and Numbers test included tasks derived from the 'Who Am I?' standardised test that has been used in other longitudinal studies (De Lemos, 2002), the complete test was not administered in the *Growing Up in New Zealand* study. It is unclear how these modifications to the 'Who Am I' test affect the ability of the test to discriminate between children with age-appropriate and delayed school readiness skills.

Limitations of the present study include its retrospective nature, and only including the referral results of those children who were referred from the screening and received follow-up care in Counties Manukau DHB. Due to differences in referral pathways and demographics between DHBs, the generalisability of the results to the remainder of NZ may be limited. As all children in the Counties Manukau DHB are referred to the public hospital eye department and live in a mainly urban area, it is likely that access to eye care following the B4SC vision screening in this region is better compared with other areas of NZ. The study design also did not allow for assessment of access for eye care from community and private providers; however, recorded reasons for non-attendance suggest that less than 10% of children who did not attend a referral appointment received eye care elsewhere.

The retrospective nature of the study also means that the cause of reduced cognitive scores in children who were referred from vision screening cannot be determined. They may be the result of uncorrected vision problems or cognitive issues that may have resulted in the vision screening failure. Additionally, research in this thesis has shown that children with significant refractive errors may pass vision screening (Chapter 8). Further research is required to investigate the association between referral from vision screening and reduced scores on cognitive tests.

The *Growing Up in New Zealand study* was powered based on overall developmental outcomes, however the present study used only a subset of the data collected, therefore it is possible that the

sample size was insufficient to detect significant differences. Post-hoc power calculations show that at the 0.05 significance level the analyses had 62% power to detect a significant difference for the Name and Numbers task and 67% power to detect a significant difference for the DIBELS letter naming fluency task. Therefore, studies with larger samples are required to confirm these results.

In summary, preschool vision screening in NZ identifies children with reduced VA from uncorrected refractive error and with amblyopia risk factors, resulting in diagnosis and treatment for these children. However, non-attendance at referral and follow-up appointments limits the efficacy of the screening programme, particularly for children of Māori and Pacific ethnicity. Children who are referred from vision screening achieve lower scores on letter naming fluency, which may have implications in terms of school readiness and acquisition of early literacy skills. These children require further assessment and treatment of vision and other conditions that may limit their ability to learn in the classroom environment. Equity-based improvements are required to ensure that all children receive vision screening and appropriate follow-up eye care.

Chapter 7: Diagnostic accuracy of the Parr vision test, single crowded Lea symbols and Spot vision screener for vision screening of preschool children in Aotearoa/New Zealand

The study presented in Chapter 5 identified disparities in testability of the current B4SC vision screening protocol. Additionally, literature reviewed in Chapter 2 and the study presented in Chapter 6 identified some children are referred from the B4SC vision screening with no diagnosed vision condition. Therefore, this chapter presents a published paper comparing the diagnostic accuracy of the current B4SC vision screening test to alternative vision screening tools.

The authors of this paper are Rebecca Findlay, Joanna Black, Lucy Goodman, Carol Chelimo, Cameron C Grant, and Nicola Anstice. The thesis author performed the comprehensive eye examinations, performed the analysis and prepared the manuscript (including all figures and tables). This manuscript was first submitted to Ophthalmic and Physiological Optics on 27 September 2020, the manuscript was accepted for publication on 5 March 2021 and was published online on 3 April 2021. Minor changes have been made to the paper to limit repetition and maintain consistency within this thesis. The details of the reference to the article and the copyright licence from the publisher can be found on page xxxiii.

7.1 Introduction

In NZ, four year old children participate in a nationwide well-child programme (known as the 'B4 School Check') which aims to identify any health or developmental issues that may limit a child's performance at school (Ministry of Health, 2014b). As part of this programme, children receive vision screening, administered by lay screeners in a community setting with the specific aim of detecting amblyopia. Vision screening comprises only the assessment of unaided VA using the Parr vision test (Figure 2-1) (Parr, 1981), a letter recognition test similar to the Sheridan Gardner chart (Sheridan & Gardiner, 1970).

As eye conditions in children are frequently asymptomatic (Irving et al., 2016), vision screening plays an important role in detecting vision disorders, particularly for children from lower socioeconomic areas who are less likely to receive a comprehensive eye examination than those from more socioeconomically advantaged areas (Majeed et al., 2008). Early detection of childhood vision problems can reduce the incidence and severity of visual impairment and amblyopia (Jonas et al., 2017), as amblyopia treatment is most effective in children less than seven years of age (Holmes et al., 2011). Additionally, uncorrected refractive error in children, in particular hyperopia and astigmatism,

is associated with reduced scores on tests of early literacy, reading ability and academic achievement (Harvey et al., 2016; Hopkins, Narayanasamy, et al., 2019; Kulp et al., 2016). VA screening, while being effective in detecting myopia, is not reliable for detection of hyperopia or astigmatism (Leone et al., 2010).

Distance VA is not considered to be a significant predictor of school performance (Dirani et al., 2010). A study of children aged 6-7 years from a socioeconomically disadvantaged area of Auckland, NZ, found that 26% of children who had passed their preschool vision screening had undetected significant refractive error (Chapter 8) (Findlay, Black, Anstice, Burge, & Leversha, 2020). Thus, improvements to the vision screening protocol, including detection of significant refractive error as a screening target, may be required.

Guidelines developed by the National Expert Panel to the National Center for Children's Vision and Eye Health in the United States recommend either autorefraction or VA testing, using either single optotype HOTV or Lea symbols surrounded by crowding bars, as best practice vision screening methods in preschool aged children (Cotter et al., 2015). As the HOTV includes letters that are not in the Māori and many of the Pacific alphabets, use of the Lea symbols may be more appropriate in NZ.

The Spot vision screener is an autorefractor that has good sensitivity and specificity (Gaiser, Moore, Srinivasan, Solaka, & He, 2020), with the additional benefit of screening for ocular misalignment (Peterseim et al., 2015). Automated measures of refractive error are relatively easy to administer in preschool aged children and achieve similar results to recognition VA tasks (Vision in Preschoolers Study Group, 2005), but are not currently used for vision screening in NZ.

The current preschool vision screening test used in NZ, the Parr vision test, comprises seven letters (A, T, H, U, V, X and O) surrounded by confusion bars. There is no published validation of the Parr vision test against other commonly used paediatric screening tools. Additionally, this acuity chart does not meet international VA chart guidelines due to the letters being of unequal legibility, and the chart progressing through the letter sizes in a non-logarithmic manner (Anstice & Thompson, 2014). In contrast, Lea symbols were developed specifically for VA testing in young children and consist of four age-appropriate familiar picture optotypes that blur equally at threshold (Hyvarinen, Nasanen, & Laurinen, 1980). The Lea symbols achieve high sensitivity and specificity for detecting visual conditions in preschool-aged children (Vision in Preschoolers Study Group, 2010). Lea symbols have high similarity compared with letter optotypes (Candy, Mishoulam, Nosofsky, & Dobson, 2011), and thus are less likely to be correctly identified by factors other than the critical detail of the optotype such as overall optotype shape.

The referral criteria from the current NZ preschool vision screening programme are conservative in comparison to those recommended internationally. International guidelines recommend a referral threshold of 0.3 logMAR (equivalent to 6/12) or worse in either eye for children aged 48 to less than 72 months old (Cotter et al., 2015). While current preschool vision screening adheres to this 0.3 logMAR threshold, children with suprathreshold vision who have a two line difference in VA that persists on rescreening performed 3-6 months later are also referred for further assessment (Ministry of Health, 2014b).

The aim of this cross-sectional diagnostic accuracy study (Mallett, Halligan, Thompson, Collins, & Altman, 2012) was to compare the efficacy of the current NZ vision screening test (the Parr vision test) with two alternative tests (the Lea symbols and the Spot vision screener) for detecting amblyopia risk factors and significant refractive error, as determined by a comprehensive eye examination including cycloplegic retinoscopy. Additionally, this study aimed to evaluate the effect of different referral criteria on the sensitivity and specificity of each test; and explore the test-retest variability of the vision screening measures to quantify the reliability of these tests in a NZ population.

7.2 Methods

The research followed the tenets of the Declaration of Helsinki. Ethical approval was granted by the University of Auckland Human Ethics Committee (Reference Number 010584). For each participating child, written parental consent and child assent were obtained.

7.2.1 Recruitment of participants

Children aged 4-5 years were recruited via convenience sampling (Etikan, Musa, & Alkassim, 2016) from the University of Auckland Optometry Clinic and from primary schools in Auckland, NZ. To ensure that a sufficient number of children with a positive screening result were included in the sample, the study specifically recruited children with vision disorders and those at increased risk of uncorrected vision problems: children of Māori and/or Pacific ethnicity and those attending schools in areas with higher socioeconomic deprivation, identified by a lower school decile rating (decile 1 schools are the 10% of schools in NZ with the highest proportion of students from households in low socioeconomic neighbourhoods, decile 10 schools have the lowest proportion of students from households in low socioeconomic neighbourhoods). Vision testing took place at each respective recruitment location.

Ethnicity was self-identified and then categorised as per Statistics New Zealand Level 1 criteria which classifies the population into seven ethnic groups (Statistics New Zealand, 2005). Where individuals recorded more than one ethnic group, priority was assigned in the following order to categorise

individuals into a single ethnic group: Māori, Pacific, Asian, and a combined group of European and Others (Ministry of Health, 2004).

7.2.2 Screening tests

All participants received vision screening administered by a lay screener. Two lay screeners worked consecutively. Both lay screeners received training on administration of the tests. The second lay screener observed and performed screening under supervision to ensure consistency.

VA testing was completed with the Parr vision test (University of Otago) (Parr, 1981) and the single optotype crowded version of the Lea symbols test (Good-Lite Company) (Hyvarinen et al., 1980). Binocular pre-testing was performed at 50 cm for both VA tests to ensure the participant was able to complete the task prior to VA measurement. The VA tests were administered in their standard forms at their calibrated distances of 4 m (Parr vision test) and 3 m (Lea symbols). For both tests, VA was measured in the right eye followed by the left eye. VA was recorded using the whole line scoring method. VA was recorded as the smallest size at which the participant correctly identified (by naming or matching) 3 out of 4 possible symbols for the Lea symbols, and 2 out of 3 possible letters for the Parr vision test. To limit participant fatigue or learning effects, the Parr vision test and the Lea symbols were administered in a pre-determined randomised order.

Non-cycloplegic autorefraction was measured after VA was recorded using the Spot vision screener VS100 (Software version 3.0.04.02, Welch Allyn Inc.) held approximately 1 m from the participant while the child was asked to fixate the coloured lights.

7.2.3 Comprehensive eye examinations

Comprehensive eye examinations were completed by a trained paediatric optometrist. These comprised measurement of VA, distance and near cover test, measurement of stereoacuity, cycloplegic retinoscopy and ocular fundus examination (Vision in Preschoolers Study Group, 2004a). VA was measured using the electronic amblyopia treatment study (e-ATS) protocol (Moke et al., 2001) presented on an EVA testing system and using a letter matching card. Near stereoacuity was measured using the Randot Preschool Stereotest at 40cm (2012, Stereo Optical Company Inc) (Birch et al., 2008).

The screening tests and the comprehensive eye examinations were performed independently on the same day and the lay screener and the optometrist were masked to each other's results.

7.2.4 Test-retest variability

The screening tests were performed on a subgroup of children (n=30) on two occasions to assess the test-retest variability of the VA and autorefraction measures.

7.2.5 Testability

For the VA tests, children were considered testable if they could successfully complete the binocular pre-test. For the Spot vision screener, children were considered testable if a refractive error measurement could be achieved for each eye.

7.2.6 Classification of participants

Children with an ocular condition were identified from the comprehensive eye examination based on the presence of ocular pathology, significant refractive error (Table 3-2) or amblyopia risk factors (Table 3-4). Children who met the criteria for more than one ocular condition were included in the counts for each condition present.

7.2.7 Screening test failure

Children were classified as failing a screening test if they met the predetermined failure criteria in one or both eyes (Table 7-1). The failure criteria for the Parr vision test were the same criteria currently used in the NZ preschool vision screening programme, and the equivalent criteria were used for the Lea symbols. The failure criteria for the Spot vision screener were set as the pre-programmed referral thresholds for the instrument. Children who were untestable were considered screening failures as they are more likely to have an ocular condition (Maguire & Vision in Preschoolers Study, 2007) and would be referred for further testing in the current NZ preschool vision screening programme (Ministry of Health, 2014b). When combining results of two screening tests, children were considered to have failed when failure criteria for at least one of the screening tests were met. When one of the screening tests was incomplete and the other test was a pass, the child was considered to have passed screening.

Table 7-1: Predetermined failure criteria for index screening tests

Index screening test	Failure criteria
Parr vision test	VA ≥ 0.3 logMAR or a 2-line difference in VA
Lea symbols	VA ≥ 0.3 logMAR or a 2-line difference in VA
Spot vision screener	Myopia ≤ -1.25 D
	Hyperopia ≥ +2.50 D
	Astigmatism ≥ -1.75 D
	Anisometropia ≥ 1.00 D
	Ocular misalignment
	Anisocoria ≥ 1 mm

D = dioptres, VA = visual acuity

7.2.8 Sample size calculation

Sample size calculations were performed using MedCalc (MedCalc® Statistical Software version 19.2, MedCalc Software Ltd, Ostend, Belgium; https://www.medcalc.org; 2020) based on an expected area under the Receiver Operator Characteristic (ROC) curve of 0.75, and a ratio of negative to positive groups of 9:1 (which assumes 10% of the sample would have a vision disorder) (Langeslag-Smith et al., 2015). A sample of 165 children was estimated as sufficient to provide 90% power at a significance level of 0.05. The target sample size was increased to 200 children to allow for those who might be unable to complete any screening tests or the comprehensive eye examination.

7.2.9 Data analysis

Calculation of sensitivity and specificity and ROC curve analysis were performed using MedCalc. McNemar chi-square testing was performed using IBM SPSS Statistics (Version 26, IBM Corporation, US). The Bland-Altman plots were constructed in Microsoft Excel for Office 365 (Microsoft Corporation, US).

The sensitivity and specificity were calculated for each screening test by comparing the screening outcome (pass/fail) to the results of the comprehensive eye examination. Sensitivity and specificity were calculated for any ocular condition (presence of any of ocular pathology, refractive error, or amblyopia risk factors), as well as independently for detecting amblyopia risk factors. Pairwise comparisons of sensitivity and specificity between screening tests were made using the McNemar chi-square test for correlated data. A two-tailed $P < .05$ was considered statistically significant. Diagnostic accuracy measures for the Parr vision test and the Lea symbols were calculated for both the referral criteria recommended by international guidelines (0.3 logMAR or worse) and the current NZ national referral criteria (0.3 logMAR or worse or a 2-line difference in VA). Children who did not complete the comprehensive eye examination were excluded from the sensitivity and specificity analyses.

ROC curves were plotted for the three different screening tests for detecting any ocular condition and for amblyopia risk factors. The Spot vision screener measurements were plotted using the most positive sphere component and the cylinder component separately. The sensitivity and specificity for different referral criteria were determined, as well as the failure criteria to detect children with reduced vision. The area under the curve (AUC) for the different screening instruments for detecting any ocular condition and for detecting amblyopia risk factors were compared.

Bland-Altman plots (Bland & Altman, 1986) were performed to explore test-retest variability in the results. The mean of the repeated measurements was plotted against the difference in measurements and the 95% limits of agreement calculated.

7.3 Results

7.3.1 Participants

Parental consent was obtained for 219 participants. Three participants were excluded as they were older than five years, and fourteen children were not tested as they were not present at school during testing sessions or did not assent to testing (Figure 7-1). Participant characteristics are shown in Table 7-2.

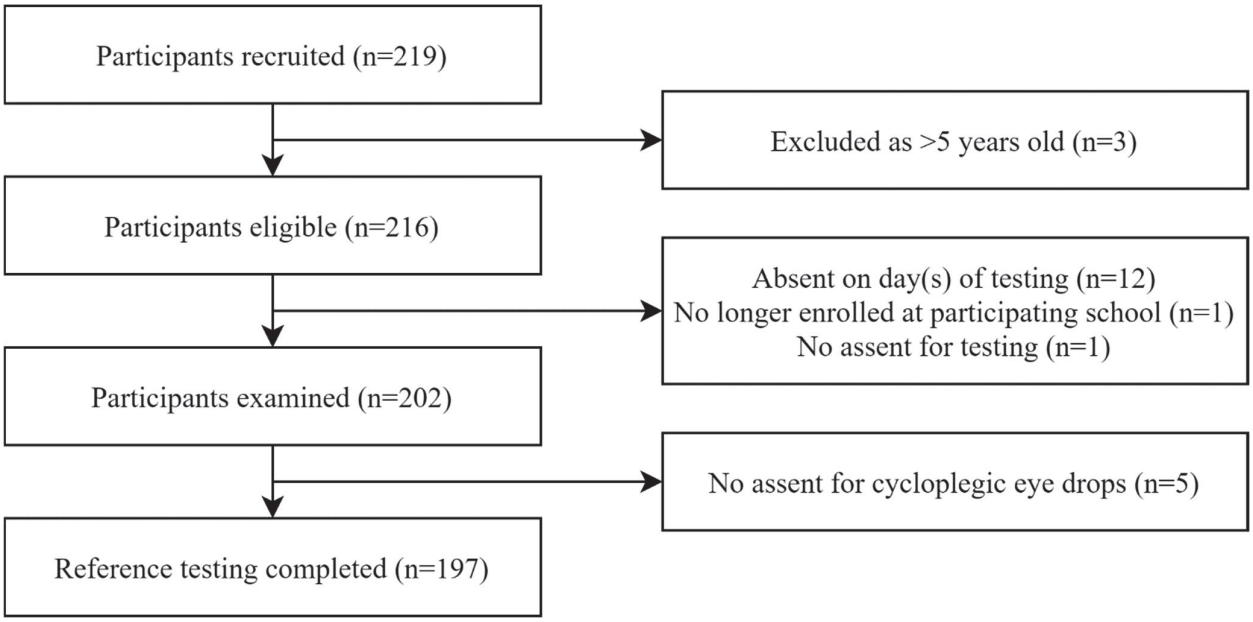

Figure 7-1: Recruitment flow for participants in the study

Table 7-2: Participant characteristics

	n (%) (n=202)
Sex	
Female	104 (51.5)
Male	98 (48.5)
Ethnicity	
European/Other ethnicities	29 (15.8)
Māori	29 (15.8)
Pacific	42 (20.8)
Asian	51 (25.2)
Not stated	48 (23.8)
School decile rating*	
Low (deciles 1 to 3)	136 (67.3)
Medium (deciles 4 to 7)	15 (7.4)
High (deciles 8 to 10)	28 (13.9)
Not stated/not at school	23 (11.4)

* Decile 1 schools are the 10% of schools in NZ with the highest proportion of students from low socioeconomic neighbourhoods, decile 10 schools have the lowest proportion of students from these neighbourhoods.

7.3.2 Testability

Testability was high for all three index tests: the Parr vision test was completed by 196/197 (99.5%), the Lea symbols by 194/197 (98.5%), and the Spot vision screener by 186/189 (98.4%) participants. The Spot vision screener was unavailable and therefore not attempted for eight participants.

7.3.3 Ocular conditions

Comprehensive eye examination testing, including cycloplegic refraction, was completed for 197 children (Figure 7-1). Ocular conditions were detected in 46 children (23.4%) (Table 7-3); ocular pathology was detected in 2 children (1.0%), refractive error in 43 children (21.8%) and amblyopia risk factors in 14 children (7.1%).

Table 7-3: Prevalence of ocular conditions in study children identified by the comprehensive eye examination

Condition	n (%) (n=197)
Ocular pathology*	
Total	2 (1.0)
Significant refractive error†	
Hyperopia	18 (9.1)
Myopia	5 (2.5)
Astigmatism	31 (15.7)
Any refractive error	43 (21.8)
Amblyopia risk factors	
Strabismus‡	4 (2.0)
Anisometropia	4 (2.0)
Bilateral refractive error	9 (4.6)
Any amblyopia risk factor	14 (7.1)
Any ocular condition	
Total	46 (23.4)
Normal ocular examination	
Total	151 (76.6)

Children with more than one condition were included in multiple categories

* The two children with ocular pathology (one prior retinal laser treatment and one heavily myelinated optic nerve head) also had significant refractive error

† Four children had astigmatism and myopia, four children had astigmatism and hyperopia

‡ The four children with strabismus also had significant refractive error

7.3.4 Diagnostic accuracy

Table 7-4 presents sensitivity and specificity for the three screening tests administered separately and in combination for detecting any ocular condition, and for detecting amblyopia risk factors, along with the P-values associated with pairwise comparisons with the Parr vision test. The sensitivity of the Lea symbols and the Spot vision screener tests did not differ significantly from the Parr vision test (P = 0.63

and P = 0.82, respectively for any ocular condition and P = 0.38 and P = 0.63 for amblyopia risk factors). In contrast, the Lea symbols and Spot vision screener had significantly higher specificity (P < 0.001) than the Parr vision test for detecting both any ocular condition and amblyopia risk factors. Addition of the Spot vision screener to the Parr vision test increased screening sensitivity for detecting any ocular condition, but not for amblyopia risk factors. Addition of the Spot vision screener to the Lea symbols did not increase sensitivity but increased the specificity of screening for any ocular condition and for amblyopia risk factors.

Table 7-4: Diagnostic accuracy results and P-values for comparisons of screening tests with Parr vision test for detecting any ocular condition and amblyopia risk factors

	Screening test				
	Parr	**Lea**	**Spot**	**Parr and Spot**	**Lea and Spot**
Any ocular condition					
Sensitivity	0.50	0.44	0.43	0.68	0.53
P-value		0.63	0.82	0.01	0.82
Specificity	0.81	0.93	0.98	0.81	0.94
P-value		<0.001	<0.001	1.00	0.001
Amblyopia risk factor(s)					
Sensitivity	0.64	0.86	0.73	0.82	0.82
P-value		0.38	0.63	0.25	0.38
Specificity	0.77	0.90	0.93	0.74	0.88
P-value		<0.001	<0.001	0.03	0.01

Lea = single crowded Lea symbols, Parr = Parr vision test, Spot = Spot vision screener

7.3.5 Referral criteria

The sensitivity and specificity for different referral criteria for each screening instrument calculated from ROC curves are shown in Table 7-5 and Table 7-6. For the Parr vision test and the Lea symbols, the optimal referral cut-off was lower (i.e. a better level of VA) than the current referral criterion (0.3 logMAR or worse). Changing to this lower referral threshold resulted in an increased sensitivity and decreased specificity for detecting any ocular condition and amblyopia risk factors.

Similarly, for the most positive sphere measurement found on the Spot vision screener, the optimal cut-off was lower (i.e. less hyperopia) than the Spot vision screener referral criteria, thus improving sensitivity for detecting any ocular condition and amblyopia risk factors while maintaining good (90%) specificity. For detecting any ocular condition, the optimal cylinder cut-off for the Spot vision screener was lower (i.e. less astigmatism) than the Spot vision screener referral criteria, whereas a higher cut-off gave optimal sensitivity and specificity for detecting amblyopia risk factors.

Comparison of the AUC for each of the screening tests showed no significant differences for detecting any ocular condition. For detecting amblyopia risk factors, the spherical component of the Spot vision screener produced significantly less AUC than the Parr vision test (P = 0.01), Lea symbols (P = 0.001) and Spot vision screener cylinder (P = 0.002).

Table 7-5: Sensitivity and specificity for different referral criteria for each screening instrument for detecting any ocular condition

Test	Refer if equal to or worse than*	Sensitivity	Specificity	Area under curve
Parr vision test	**0.2**	**0.71**	**0.72**	0.742
	0.3	*0.24*	*0.98*	
	0.4	0.11	1.00	
Single crowded Lea symbols	0.1	0.89	0.40	0.784
	0.2	**0.62**	**0.83**	
	0.3	*0.36*	*0.99*	
	0.4	0.22	0.99	
Spot vision screener Sphere	**1.25**	**0.41**	**0.90**	0.679
	1.50	0.31	0.95	
	1.75	0.23	0.98	
	2.00	0.15	0.99	
	2.25	0.13	1.00	
	2.50	*0.10*	*1.00*	
Spot vision screener Cylinder	**1.00**	**0.67**	**0.80**	0.773
	1.25	0.46	0.92	
	1.50	0.44	0.97	
	1.75	*0.31*	*0.99*	

* Referral criteria logMAR acuity level for the Parr vision test and the single crowded Lea symbols and refractive error in dioptres for the Spot vision screener

Values in bold represent optimal referral criteria maximising sensitivity and specificity

Values in italics represent current referral criteria (Parr vision test and single crowded Lea symbols) and pre-programmed referral criteria (Spot vision screener)

Table 7-6: Sensitivity and specificity for different referral criteria for each screening instrument for detecting amblyopia risk factors

Test	Refer if equal to or worse than*	Sensitivity	Specificity	Area under curve
Parr vision test	**0.2**	**1.00**	**0.66**	0.931
	0.3	*0.64*	*0.97*	
	0.4	0.36	1.00	
Single crowded Lea symbols	0.1	1.00	0.36	0.962
	0.2	**1.00**	**0.78**	
	0.3	*0.79*	*0.97*	
	0.4	0.50	0.98	
Spot vision screener Sphere	1.25	0.30	0.84	0.595
	1.50	**0.30**	**0.90**	
	1.75	0.20	0.94	
	2.00	0.10	0.97	
	2.25	0.10	0.98	
	2.50	*0.0*	*0.99*	
Spot vision screener Cylinder	1.50	0.70	0.92	0.925
	1.75	*0.70*	*0.97*	
	2.00	0.70	0.98	
	2.25	**0.70**	**1.00**	

* Referral criteria logMAR acuity level for the Parr vision test and the single crowded Lea symbols and refractive error in dioptres for the Spot vision screener

Values in bold represent optimal referral criteria maximising sensitivity and specificity

Values in italics represent current referral criteria (Parr vision test and single crowded Lea symbols) and pre-programmed referral criteria (Spot vision screener)

Table 7-7 compares the referral criteria for unaided VA of 0.3 logMAR or worse (as per international guidelines) and the same criteria with addition of a two line difference in VA (as per NZ's current referral criteria). The additional two line interocular difference criteria increased the sensitivity of the Parr vision test (both alone and in combination with the Spot vision screener) for detecting any ocular condition, but not for detecting amblyopia risk factors. Conversely, addition of a two line interocular difference criteria did not change sensitivity for the Lea symbols (both alone and in combination with the Spot vision screener). However, adding the two line interocular difference criterion reduced specificity for the Parr vision test and the Lea symbols, both alone and in combination with the Spot vision screener.

Table 7-7: Diagnostic accuracy for the Parr vision test (cut-off ≥ 0.3 logMAR) and single crowded Lea symbols (cut-off ≥ 0.3 logMAR) alone or with a 2 line interocular difference and in combination with the Spot vision screener as screening tests for ocular conditions

Visual acuity test						
	Parr	**Parr with IOD**	**P-value**	**Lea**	**Lea with IOD**	**P-value**
Any ocular condition						
Sensitivity	0.26	0.50	0.001	0.37	0.44	0.25
Specificity	0.98	0.81	<0.001	0.98	0.93	0.02
Amblyopia risk factors						
Sensitivity	0.64	0.64	1.00	0.79	0.82	1.00
Specificity	0.97	0.77	<0.001	0.95	0.88	<0.001
Visual acuity test in combination with Spot vision screener						
	Parr and Spot	**Parr with IOD and Spot**	**P-value**	**Lea and Spot**	**Lea with IOD and Spot**	**P-value**
Any ocular condition						
Sensitivity	0.48	0.68	0.008	0.48	0.53	0.50
Specificity	0.98	0.81	<0.001	0.98	0.94	0.02
Amblyopia risk factors						
Sensitivity	0.82	0.82	1.00	0.82	0.86	1.00
Specificity	0.93	0.74	<0.001	0.93	0.90	0.004

IOD = 2-line interocular difference in VA, Lea = single crowded Lea symbols, Parr = Parr vision test, Spot = Spot vision screener

7.3.6 Test duration

Time taken to complete VA measurement for both the Parr vision test and the Lea symbols was assessed for 191 participants. Median (IQR) test duration was significantly longer for the Lea symbols than for the Parr vision test (204 [168-257] seconds vs 146 [117-189] seconds, p<0.001).

7.3.7 Test-retest variability

Bland-Altman plots (Figure 7-2) showed no significant differences between the repeated measurements for the right eyes of participants who received screening on two occasions, and the 95% limits of agreement were similar for the two VA tests.

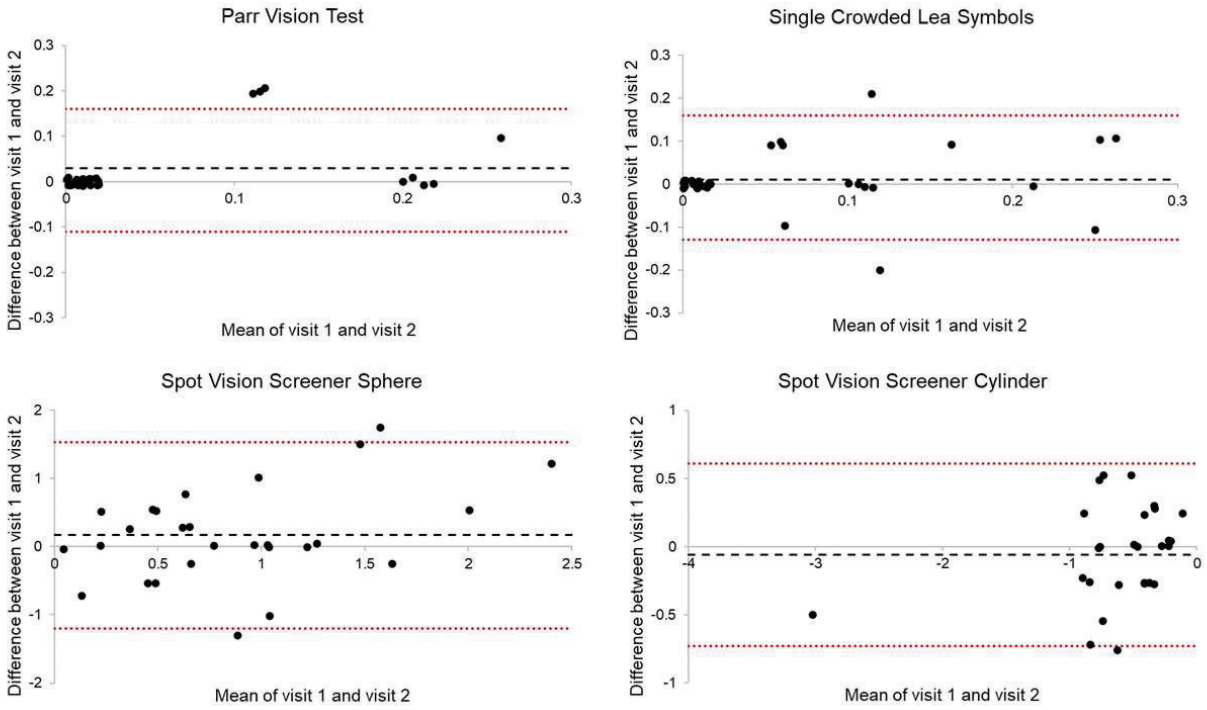

Figure 7-2: Bland-Altman plots for repeated measurements for the three screening tests for the right eye of participants (n = 30) that were screened on two occasions.
The central broken black line shows the mean difference and the upper and lower dotted red lines show the 95% limits of agreement.

7.4 Discussion

The current preschool vision screening test used in NZ, the Parr vision test, provides sensitivity for detecting ocular conditions in children that is not significantly different to the two alternative tests investigated: the Spot vision screener and the Lea symbols. However, for detecting amblyopia risk factors, use of the Spot vision screener or the Lea symbols may reduce the burden of false positive referrals from the vision screening programme. Furthermore, addition of the Spot vision screener to the current preschool vision screening protocol may increase the number of children with refractive error correctly identified which could improve academic outcomes for these children (Glewwe et al., 2018). This would ensure that preschool vision screening aligns better with the purpose of the well-child programme, which is to detect conditions that may affect a child's ability to learn in the classroom environment.

For detecting amblyopia risk factors, greatest sensitivity (86%) and specificity (90%) were achieved with use of the Lea symbols, compared with the Parr vision test and the Spot vision screener. Additionally, application of the two line difference criteria currently employed in the preschool vision screening resulted in no significant change in sensitivity but a reduction in specificity for both the Parr vision test and the Lea symbols. Therefore, for detecting amblyopia risk factors only, a change in the

screening instrument from the Parr vision test to the Lea symbols or the Spot vision screener and removal of the two line difference criteria will increase specificity, thus reducing the number of false positive referrals, without affecting sensitivity. While the stated target of preschool vision screening in NZ is amblyopia, screening directly for amblyopia is not possible as diagnosis requires correction of any risk factors and re-measurement of VA. In this study all tests had high testability, however, previous studies, have shown reduced testability for the ETDRS, compared with HOTV and Lea symbols (Anstice et al., 2017). ETDRS has a larger letter set similar to the Parr vision test. The similar sensitivity of the Lea symbols and the Spot vision screener suggest that they are suitable alternatives for children who are unable to complete the Parr vision test.

Vision screening is of particular importance in detecting vision problems in children of families in lower socioeconomic groups (Majeed et al., 2008). In NZ, children of Māori and Pacific ethnicities are over-represented in lower socioeconomic groups (Ministry of Social Development, 2016). Hence, targeting conditions prevalent in these children will ensure that screening is more robust. While the presence of amblyopia risk factors puts children at risk of permanent vision loss (Holmes & Clarke, 2006), these risk factors are relatively uncommon. In this study, 7.1% of children had amblyopia risk factors. In contrast, 21.8% of children had significant refractive error, 97.8% of which was hyperopia and/or astigmatism. These results are similar to those of a recent study of 6-7 year old NZ children living in an area of known socioeconomic deprivation in which 6.1% of children had amblyopia risk factors and 31.6% had significant refractive error (97.2% was hyperopia and/or astigmatism) (Chapter 8) (Findlay et al., 2020).

Although autorefraction has been found to be more effective than VA screening in detecting hyperopia and astigmatism (Fotouhi, KhabazKhoob, Hashemi, Yekta, & Mohammad, 2011; Miller et al., 2001), few preschool vision screening programmes include the use of autorefraction or photorefraction in their protocols (Hopkins et al., 2013; Sloot et al., 2015). For detecting any ocular condition, the combination of the Parr vision test and the Spot vision screener gave the highest sensitivity (68%) with moderate specificity (81%). Similarly, the United States Preventative Services Task Force 2017 guidelines recommend the use of multiple screening tests to identify preschool children at higher risk of vision problems (Jonas et al., 2017). In a Canadian study comparing five screening tests in a population of 4-5 year old children with a relatively high prevalence of astigmatism, the combination of a VA test with a photoscreener achieved higher sensitivity than use of a VA test alone (Nishimura, Wong, Cohen, Thorpe, & Maurer, 2019). Automated measures of refractive error are also quick to administer and require minimal cooperation from the child (Cotter et al., 2015). Targeting screening to detect significant refractive error by employing appropriate tests will ensure detection of amblyogenic factors, but also enable detection of smaller magnitude refractive errors that may reduce performance of academic tasks (Cotter et al., 2015; Hopkins, Narayanasamy, et al., 2019).

ROC curve analysis identifies the optimal referral criteria for each of the screening tests used individually, as well as sensitivity and specificity values for different referral criteria. Comparison of the AUC for the different screening tests showed no significant difference between the tests for detecting any ocular condition or amblyopia risk factors. Altering the cut-off values for referral for the Spot vision screener, particularly for the sphere measurement by decreasing it to +1.25 D, could increase the sensitivity of the test. These results are similar to a previous study of the Spot vision screener in an American population of children aged 24-96 months with a similar refractive error profile (Gaiser et al., 2020). Furthermore, altering cut-off values for the VA tests to 0.2 logMAR or worse, would increase sensitivity by 25-45% but would also result in a reduction in specificity by 15-30% which will result in an increase in false positive referrals. The addition of the Spot vision screener to a VA test may be a more appropriate alternative to ensure that children with ocular conditions are referred, due to poor sensitivity of VA tests alone in detecting hyperopia and astigmatism (Fotouhi et al., 2011). Inclusion of the Spot vision screener increases the sensitivity of the Parr vision test for detecting any ocular condition without a corresponding reduction in specificity. The appropriate balance between sensitivity and specificity for a screening programme depends both on the local availability of eyecare resources and the severity/prognosis of the condition being screened for. Where eyecare resources are limited, increasing specificity may be appropriate to prevent unnecessary referrals. Conversely, improving sensitivity where eyecare resources are accessible will ensure that children with an eye condition are referred for diagnosis and treatment, thereby helping to reduce inequities for children living in low socioeconomic neighbourhoods. Adding the Spot vision screener to the current vision screening protocol will not significantly increase screening time but adds additional equipment cost. Policy makers need to consider the impact of the additional screening cost compared with the benefit of identifying more children with a visual condition.

The 95% limits of agreement for each of the three screening tests in the Bland-Altman plots showed good repeatability of the tests when administered by a lay screener. Both the Parr vision test and the Lea symbols had limits of agreement within 0.15 logMAR, similar to VA measurements of children and adults by eyecare practitioners (Manny et al., 2003; Shah, Laidlaw, Rashid, & Hysi, 2012). Likewise, the limits of agreement for the Spot vision screener cylinder measurements were -0.73 D to +0.61 D, similar to those in a study of repeatability of Spot vision screener measurements (Satou, Nogami, Takahashi, Ito, & Niida, 2019). However, the limits of agreement for the sphere measurements were wider. This may be due to the higher prevalence of hyperopia among study participants and variability caused by changes in accommodation.

To our knowledge, this is the first study to examine the efficacy of the Parr vision test, currently used throughout NZ, in comparison with other validated vision screening tools. This diagnostic accuracy study showed no significant difference in sensitivity between the three screening tests in this population

for detection of ocular conditions as determined by a comprehensive eye examination. While the two VA tests differ in optotype design, number of optotypes presented at each acuity level and test distance, this did not appear to result in a significant difference in sensitivity between the two tests.

Previous studies have shown that letter optotypes do not have equal legibility (Ferris, Freidlin, Kassoff, Green, & Milton, 1993). In contrast, the four Lea symbols blur equally at threshold (Hyvarinen et al., 1980) and have high similarity (Candy et al., 2011). These differences suggest the letter optotypes of the Parr vision test may be easier to identify by guessing. However, the larger letter set of the Parr vision test (seven letters compared with the four Lea symbols), the possible increased difficulty with identification of letters compared with pictures, and other behavioural or cognitive factors (Vision in Preschoolers Study Group, 2004b), may offset any increased likelihood of correctly guessing the optotype due to differences in legibility. In particular, children who identify letters by naming (rather than matching) may select letters that are not within the letter set, significantly reducing the probability of guessing (Carkeet, 2001).

Previous research has shown nearly equal VA reductions with induced spherical and cylindrical defocus for both letter optotypes and Lea symbols (Paudel et al., 2017). Furthermore, the lower specificity of the Parr vision test compared with the Lea symbols indicates a larger number of false positive results suggesting a lower number of correct guesses at threshold. The results of the current study indicate the Parr vision test provides an acceptable paediatric vision screening tool, with a shorter testing time than the Lea symbols. Additionally, the Spot vision screener or the Lea Symbols provide appropriate alternatives when a child is unable to complete screening with the Parr vision test.

This study has several potential limitations. The cross sectional design prevented us from determining true amblyopia prevalence, which would require reassessment following a period of spectacle wear, thus amblyopia risk factors were used as indicators of amblyopia. Lighting conditions were not controlled for in this study which may affect the VA measurements. However, the majority of testing in schools was conducted in classrooms and boardrooms which have a minimum illumination requirement of 240 lux (Standards Australia/Standards New Zealand, 2008) with each child completing the two VA measurements under the same lighting conditions. This is also a good representation of the actual screening environment encountered in community screening in NZ (Ministry of Health, 2014b). The VA tests were performed in their standard forms at their calibrated distances. The closer testing distance of the Lea symbols (3 m) may mean that it is less likely to detect low myopia. However, the prevalence of any amount of myopia was low in this population so this did not affect sensitivity. Additionally, cooperation and testability were likely higher in this sample than in the general population, as parents were unlikely to consent to participation for children with significant behavioural or cognitive challenges.

Generalisability may be limited due to the sampling of children only in urban Auckland schools. Children with ocular conditions and those from areas of socioeconomic disadvantage were purposefully oversampled. As a result, children of Pacific and Asian ethnicities were also over-represented; this may limit the generalisability to the entire population but ensures that vision screening is appropriate and meets the needs of the most vulnerable children. The NZ Ministry of Health have prioritised reducing inequities and improving health outcomes (Minister of Health, 2016); specifically the NZ government have responsibilities under the Treaty of Waitangi to improve health outcomes for Māori (Reid & Robson, 2007). Additionally, the positive predictive value of the Parr vision test using the same referral criteria as the preschool vision screening is similar in this study (0.44) to that reported in previous retrospective reviews of preschool vision screening outcomes (Langeslag-Smith et al., 2015; Muller et al., 2019). This suggests the results reported in this study are comparable to what would be achieved in the community setting.

Further research is required to determine the visual profile of NZ children and therefore the most appropriate screening protocols for detecting vision conditions. A longitudinal study including a broader cross section of NZ children could follow outcomes over time to determine the age-related prevalence of amblyopia and refractive error in the population and the efficacy and cost-effectiveness of different screening protocols (Schmucker et al., 2009). Further evaluation of the Parr vision test including more detailed modelling of the optical and psychophysical limits of optotype identification of this acuity test would allow for more accurate comparison of the Parr vision test with the Lea optotypes.

In summary, the Parr vision test provides similar sensitivity for detecting ocular conditions in NZ children as two previously validated and internationally recognised vision screening tests. Consideration should be given to including significant refractive error as a target condition of vision screening to ensure that all children with vision problems that may affect academic ability are identified. The addition of the Spot vision screener to VA testing should be considered to ensure that children with refractive error are identified.

Chapter 8: Visual function in children aged 6-7 years living in an area of known socioeconomic disadvantage

The literature review presented in Chapters 1 and 2 identified a lack of data regarding visual function in NZ children and disparities in health outcomes for children living in areas of socioeconomic disadvantage, compared to those in more advantaged areas. This chapter presents a published paper detailing the results of a study investigating visual function in children enrolled in the Welcome to School study which investigated health, educational and social outcomes of children living in a socioeconomically disadvantaged area. It also provided the opportunity to examine the visual outcomes of children who were not referred from B4SC and those who did not receive screening.

The authors of this paper are Rebecca Findlay, Joanna Black, Nicola Anstice, Alison Burge and Alison Leversha. The thesis author developed the clinical testing procedures, performed the comprehensive eye examinations, conducted the analysis and prepared the manuscript (including all figures and tables). This manuscript was first submitted to the New Zealand Medical Journal on 13 October 2019, the manuscript was accepted for publication on 17 February 2020 and was published on 24 April 2020. Minor changes have been made to the paper to limit repetition and maintain consistency within this thesis. The details of the reference to the article and the copyright licence from the publisher can be found on page xxxiii.

8.1 Introduction

On a typical day, around 70% of classroom time is spent performing academic tasks which require visual input (Narayanasamy et al., 2016). Uncorrected refractive errors account for up to 96% of visual impairment in school-aged children and are associated with the development of amblyopia and strabismus (Tang et al., 2016). Amblyopia or "lazy eye" is a reduction in best corrected VA in the presence of an amblyopia risk factor and in the absence of ocular pathology (Holmes & Clarke, 2006). Amblyopia risk factors include visual pathway obstruction, strabismus ("squint" or turned eye), anisometropia (difference in refractive error between the two eyes) and bilateral high refractive error (Holmes & Clarke, 2006). Amblyopia treatment is most effective before seven years of age, thus it is important to identify children with amblyopia risk factors at a young age (Holmes et al., 2011). Additionally, lesser amounts of uncorrected hyperopia and astigmatism (irregular curvature of the cornea or lens causing blurred vision) have been associated with reduced performance in tests of early literacy, reading ability and academic achievement (Harvey et al., 2016; Hopkins, Narayanasamy, et al., 2019; Kulp et al., 2016).

Studies of refractive error distribution have been conducted in many countries and the prevalence, particularly of myopia, varies considerably by geographic location (Hashemi, Fotouhi, et al., 2018). Population-based studies of children in Australia have shown overall refractive error prevalence of 12-14%, with higher prevalence of hyperopia and astigmatism in young school aged children, and increased myopia prevalence in older children (French et al., 2013; Hashemi, Fotouhi, et al., 2018). Unfortunately, similar contemporary refractive error data does not exist for NZ children, and it is not known whether ethnic differences exist, particularly for children of Māori and Pacific ethnicities. Distance VA screening is commonly used worldwide to detect reduced vision in children. It is effective in detecting myopia but poor at detecting significant hyperopia and astigmatism as children with these conditions often achieve sufficient distance VA to pass a screening (O'Donoghue et al., 2012). Therefore, understanding the refractive error profile of NZ children is essential to ensure screening strategies identify children who will benefit from refractive correction.

Preschool children in NZ receive a universal, free, well child check, the B4SC, at four years of age which aims to identify behavioural, developmental and other health concerns which could negatively impact on their ability to learn in the school environment (Ministry of Health, 2014b). The B4SC has excellent coverage, with 96.7% of eligible children, and 94.5% of children living in high deprivation communities in the Auckland region completing the check in 2017 (Robinson & Wignall, 2019). As part of the B4SC, vision-hearing technicians measure distance VA using the Parr vision chart (Figure 2-1) (Parr, 1981) with the specific aim of identifying children who may have amblyopia (Ministry of Health, 2014b). Recent studies of children assessed following referral from the B4SC vision screening show high numbers of false positive referrals and low positive predictive value (Langeslag-Smith et al., 2015; Muller et al., 2019), however, there are currently no data for children who passed the B4SC or did not receive screening.

The aims of this study were, therefore, to determine the prevalence of refractive error and visual impairment in a cohort of 6-7-year-old children in the multicultural community of Tāmaki, and to evaluate the efficacy of the B4SC vision screening programme in this community.

8.2 Methods

The research followed the tenets of the Declaration of Helsinki. Ethical approval was attained from the Central Health and Disability Ethics Committee of the New Zealand Ministry of Health with an amendment to the protocol (Reference number: 15/CEN/224/AM04). Parental consent for a comprehensive vision assessment was obtained for all participants and assent was obtained from the child.

8.2.1 Participants

Welcome-to-School (WTS) was a multidisciplinary collaborative study of children from schools in the Manaiakalani Community of Learning in Tāmaki: the Auckland suburbs of Glen Innes, Point England and Panmure Bridge. Children were recruited into the WTS project on school entry at five years of age. Children received a comprehensive health, developmental, educational and social assessment and appropriate referrals and linkages made. These same children and whānau were contacted by the WTS research nurse approximately a year later at 6-7 years of age. This project was discussed and informed consent for formal vision assessment obtained. All children for whom their parents gave consent for the vision examination in the follow-up study were assessed.

8.2.2 Data collection

Data were collated from a parental questionnaire, a health and developmental assessment, school entry educational assessment, oral health assessment and formal speech and language assessment. Demographic data included their address, NZDepIndex (an area based measure of socioeconomic deprivation) (Atkinson et al., 2014), and ethnicity, defined as per NZ statistics Level 1 (Statistics New Zealand, 2005). B4SC results were obtained from the Well Child Manager within Planning and Funding at Auckland DHB.

8.2.3 Vision assessment

Two authors (RF and JB) conducted comprehensive eye examinations of the participating children in their schools. Vision assessment comprised measurement of distance VA using the e-ATS protocol presented on an EVA testing system (JAEB Centre for Health Research) (Moke et al., 2001) viewed at 3 m; and near VA using the Sloan Letter Near LogMAR acuity chart (Good-Lite Company) viewed at 40 cm.

Binocular vision assessment included the cover test at distance and near for detection and measurement of strabismus, near point of convergence using the Royal Air Force (RAF) rule (Good-Lite Company) (Neely, 1956), ocular motility assessment and measurement of near stereoacuity using the Randot Preschool Stereotest at 40cm (2012, Stereo Optical Company Inc) (Birch et al., 2008).

Non-cycloplegic autorefraction was measured with the Spot Vision Screener VS100 (Software version 3.0.04.02, Welch Allyn Inc) and the Nidek ARK-30 Type R (Nidek Co Ltd). Following cycloplegia (a minimum of 40 minutes after instillation of one drop of Cyclopentolate 1% and when pupils were no longer reactive), autorefraction was repeated and cycloplegic retinoscopy was performed.

Ocular health was evaluated by assessment of pupillary reactions, slit lamp evaluation of the anterior segment and binocular indirect ophthalmoscopy.

8.2.4 Definitions

Significant refractive error (Table 3-2), visual impairment (Table 3-3) and amblyopia risk factors (Table 3-4) were defined as described in Chapter 3. Convergence insufficiency was defined as exophoria greater at near than distance and receded near point of convergence (Borsting, Rouse, Deland, et al., 2003).

8.2.5 Analysis

Each participant was assessed for significant refractive error, amblyopia risk factors and ocular pathology. The results were compared with their B4SC vision screening results. Data analysis was conducted using IBM SPSS Statistics (Version 25, IBM Corporation, USA). Descriptive statistics were used to summarise the data using counts and percentages (for categorical variables). The chi-squared test was used to compare the proportions of children with significant refractive error between different ethnic groups.

8.3 Results

8.3.1 Study population

Of the 120 children enrolled in WTS, consent for vision assessment was obtained for 115 children: full consent for 113 children and consent for examination without cycloplegia for two children. Vision testing was completed for 114 children: one child left their school before vision assessment was completed.

8.3.2 Demographic characteristics

All children lived in a community with significant socioeconomic disadvantage; NZDepIndex quintile 5 (deciles 9 and 10). The mean age at testing was 6.72 years (range 6.14-7.24 years). There were more boys than girls in the cohort and the majority were of Māori or Pacific ethnicities (Table 8-1).

Table 8-1: Demographic characteristics of study participants

	n (%) (n=114)
Gender	
Female	51 (44.7)
Male	63 (55.3)
Ethnicity	
Māori	25 (21.9)
Pacific (Tongan, Samoan, CI Māori, Other)	66 (57.9)
Other (NZ European, Asian, European)	23 (20.2)

8.3.3 Refractive error

Thirty-six participants (31.6%) had significant refractive error, most commonly astigmatism (29 participants, 80.6% of refractive errors, all "with-the-rule" with the steepest meridian vertically). Seven participants (6.1%) had amblyopia risk factors: two anisometropia, four bilateral astigmatism and one bilateral hyperopia. Two of these participants also had strabismus. Compared with children without refractive error, there was no difference in the proportion of children with myopia, hyperopia and astigmatism between ethnic groups (Table 8-2; myopia P = 0.22, hyperopia P = 0.22, astigmatism P = 0.68).

Table 8-2: Prevalence of refractive error and amblyopia risk factors

Ethnicity	Myopia (n=4) n (%)	Hyperopia (n=7) n (%)	Astigmatism* (n=29) n (%)	Any refractive error (n=36) n (%)	Amblyopia risk factors (n=7) n (%)
Māori	0 (0.0)	3 (42.9)	8 (27.6)	11 (30.6)	2 (28.6)
Pacific	4 (100.0)	4 (57.1)	16 (55.2)	20 (55.5)	5 (71.4)
Other	0 (0.0)	0 (0.0)	5 (17.2)	5 (13.9)	0 (0.0)

*Three participants had myopia and astigmatism and one participant had hyperopia and astigmatism

Visual impairment

No participant had binocular distance visual impairment; all participants had unaided distance VA of 0.2 logMAR or better in at least one eye and 97.4% of participants had unaided distance VA of 0.2 logMAR or better in both eyes (Table 8-3). Causes of distance visual impairment were astigmatism (1, 0.9%), myopia (1, 0.9%) and anisometropia (1, 0.9%). Binocular near visual impairment was identified in 14 participants and a further 11 participants had monocular near visual impairment.

Table 8-3: Prevalence of unaided distance and near visual impairment

	Unaided Distance VA n (%)	Unaided Near VA n (%)
No visual impairment either eye	110 (97.4)	88 (77.9)
Visual impairment one eye	3 (2.6)	11 (9.7)
Mild visual impairment	0 (0)	13 (11.4)
Moderate visual impairment	0 (0)	1 (0.9)
Severe visual impairment	0 (0)	0 (0)

VA = visual acuity

8.3.4 Binocular function

Three participants (2.6%) had binocular vision anomalies. Two (1.8%) had strabismus for which they were under care: one was referred following the B4SC and the other did not receive a B4SC and was referred following the WTS assessment. A third participant had convergence insufficiency.

8.3.5 Ocular health evaluation

No anterior or posterior segment pathology was detected.

8.3.6 Efficacy of the B4SC vision screening

A significant number of children (13/114, 11.4%) did not receive a B4SC vision screening; one (0.9%) declined screening while twelve (10.5%) were unable to be contacted or scheduled (Table 8-4). A similar number (12/114, 10.5%) were identified for rescreening (borderline or inconclusive result), which had not been completed. No child with amblyopia risk factors passed the B4SC vision screening, however, two did not receive screening and one was identified for rescreening but did not receive follow-up. These children, therefore, remained undiagnosed at the time of WTS data collection. Eight children (7.0%) were referred from B4SC vision screening; six of these had significant refractive error and four also had amblyopia risk factors.

Table 8-4: B4SC vision screening outcomes, significant refractive error and amblyopia risk factors

B4SC Outcome	Cohort (n=114) n (%)	Significant Refractive Error (n=36) n (%)	Amblyopia Risk Factors (n=7) n (%)
Pass Bilaterally	80 (70.2)	21 (58.3)	0 (0)
Rescreen	13 (11.4)	4 (11.1)	1 (14.3)
Referred	8 (7.0)	6 (16.7)	4 (57.1)
Declined	1 (0.9)	0 (0)	0 (0)
Not screened	12 (10.5)	5 (13.9)	2 (28.6)

8.3.7 Vision correction

Only five of the 36 participants with significant refractive error (13.9%) and four of the seven participants with amblyopia risk factors (57.1%) were wearing glasses at the time of our assessment. More than half of the participants with significant refractive error (21/36, 58.3%) passed their B4SC vision screening and none of these had glasses our assessment.

8.4 Discussion

Almost one third of children aged 6-7 years in Tāmaki had significant refractive errors likely to affect reading development and academic achievement (Harvey et al., 2016; Hopkins, Narayanasamy, et al., 2019; Kulp et al., 2016), most of which were previously undetected. Over 80% of children with refractive error had astigmatism, a prevalence similar to that seen in studies of specific populations of school-aged children in the Americas but lower than countries in the Western Pacific region (Hashemi, Fotouhi, et al., 2018). The prevalence of myopia (3.5%) and hyperopia (6.1%) were low, similar that seen in six year old children in Australia (French et al., 2013) and much lower than myopia prevalence reported in East Asian countries (Hashemi, Fotouhi, et al., 2018).

The prevalence of unaided distance visual impairment in this cohort was low. All participants had VA of 0.2 logMAR or better in at least one eye and only three participants (2.6%) had monocular visual impairment, a level similar to that reported in six year old Australian children (Ip, Robaei, et al., 2008). Children with higher levels of astigmatism (more than 1.50 D) can frequently achieve unaided distance VA of 0.2 logMAR or better (O'Donoghue et al., 2012) which was the source of the disparity between refractive error prevalence and visual impairment in this cohort. Correction of astigmatism of 0.75 D or more is, however, recommended in published guidelines, even in children without symptoms (Leat, 2011).

Although most children in NZ receive a B4SC vision screening, inequities are evident and a significant number of children in this cohort failed to benefit from this health initiative. While the screening was

effective in detecting amblyopia, it was ineffective in detecting refractive error in this population with predominantly astigmatism. Consequently, many children in this cohort started school with uncorrected refractive errors potentially impacting their academic performance (Harvey et al., 2016; Hopkins, Narayanasamy, et al., 2019; Kulp et al., 2016). Therefore, for these children, the current B4SC vision screening did not meet the overall aim of the B4SC to detect conditions that may adversely affect a child's ability to learn in the school environment. Additionally, 10.5% of children in this cohort were not screened and a further 11.4% were recommended for rescreening which was not performed before school entry. Many of these children with uncompleted screenings had amblyopia risk factors and significant refractive error. In 2017, in the Auckland and Waitemata District Health Board catchment areas, 5.3% of children from high deprivation households did not receive a B4SC vision screening and 7.5% were recommended for rescreening whereas in the most advantaged areas 4.9% were not screened and 4.3% were recommended for rescreening (Robinson & Wignall, 2019). Differing models are required to ensure all children receive screening and appropriate eyecare prior to school entry, irrespective of ethnicity and the community they live in (Ministry of Health, 2019a).

For this cohort living in socioeconomic deprivation, accessing eyecare services appears to have been problematic. Six children with significant refractive error were referred from the B4SC vision screening, but only four were wearing glasses. Moreover, nearly 60% of children with significant refractive error passed the screening and none of these children were wearing glasses at our assessment, suggesting no access to eyecare following screening. This is consistent with a UK study that found seven year old children from lower socioeconomic groups were less likely to have seen an eyecare specialist than those from more advantaged groups (Majeed et al., 2008). Previous studies have noted financial, logistical, social and perceptual issues prevent families from obtaining a vision assessment following a failed screening (Kimel, 2006). Additionally, there is increasing evidence that cultural factors including racism and lack of trust in healthcare systems influence access and utilisation by Māori and Pacific whānau (Paine et al., 2018). Optometry services in New Zealand are not government funded, and while limited subsidies are available for prescription glasses, the process can be difficult to navigate. Cost should not be a barrier for good care for children and funding for eyecare services should be available for all children. Culturally appropriate coordination is necessary to ensure children who are referred or identified for rescreening receive follow up and to assist whānau in accessing services.

The false positive referral rate from the B4SC vision screening in this cohort was low, with 75% of those referred having significant refractive error. This is contrary to previous retrospective reviews of B4SC vision screening referrals in NZ which found only 30-50% of children referred from vision screening had diagnosed vision conditions (Langeslag-Smith et al., 2015; Muller et al., 2019). The reasons for this disparity are unclear: screening and referral processes appear to differ between District

Health Boards and higher prevalence of the condition in the target population improves the positive predictive value of the test, which may explain the differences between the studies.

Three children in this cohort presented with binocular vision anomalies. Children with co-existing significant refractive error had been identified and referred for treatment. VA screening, however, is unlikely to identify children with intermittent or alternating strabismus without significant refractive error. Convergence insufficiency is also unlikely to be detected by VA screening and is associated with symptoms such as discomfort, loss of concentration, slow reading and need to re-read when completing near tasks (Borsting, Rouse, Deland, et al., 2003).

Limitations of this study include the small sample size which reduces the power to detect statistically important differences, particularly for comparing differences between ethnic groups. The children in this study received their B4SC vision screening at 4-5 years of age while formal vision assessment was conducted at 6-7 years of age, so the magnitude of refractive error may have changed between the two assessments. Previous studies, however, suggest that astigmatism remains stable or reduces across this age range (Zhao et al., 2002). Although this was a prospective cohort study, there was no control group and it is unclear whether the effects are a result of socioeconomic status, ethnicity or other factors.

Further investigation is necessary to determine the refractive error profile across a broader cross-section of NZ children and to establish methods of vision screening most effective for this population. A previous study found autorefraction superior to VA screening for detection of astigmatism (Miller et al., 2001), and the prevalence of near visual impairment was greater than distance visual impairment in this cohort, suggesting alternative screening strategies may be more appropriate to detect refractive error in the NZ population. The current Well Child Tamariki Ora review provides an opportunity to re-examine the rationale for the preschool vision screening and follow-up protocol. Additionally, research addressing attitudes and beliefs towards the B4SC vision screening and vision correction in children is required.

In conclusion, almost one third of children in this ethnically diverse cohort with known socioeconomic disadvantage had significant refractive error. The current B4SC vision screening was effective in detecting amblyopia but poor at detecting significant refractive error. As the goal of the B4SC is to detect and intervene on issues which could adversely impact educational outcomes, this research highlights a mismatch between the current vision screening protocol and the intent of the B4SC programme, particularly for socioeconomically disadvantaged Māori and Pacific children. This mismatch, in combination with the differential reach of the B4SC, is likely to be increasing inequities. This study suggests that urgent attention is required to review the B4SC vision screening protocol to ensure it is appropriate and equitable, so all children receive high quality vision screening and eyecare to improve their health, educational and social outcomes.

Chapter 9: Vision conditions and vision screening in children aged 7-10 years

The literature review presented in Chapters 1 and 2 identified a lack of data regarding visual function in NZ children. The study presented in Chapter 8 provided data regarding vision conditions in children of mainly Māori and Pacific ethnicities living in an area of socioeconomic disadvantage. Therefore, Chapters 9 and 10 present the results of a study completed with Auckland school children aged 7-10 years from across a wide range of socioeconomic and ethnic backgrounds. Chapter 9 describes the eye conditions and levels of visual impairment detected in this group of children. Chapter 10 explores the associations between vision conditions and reading parameters for the same children.

9.1 Introduction

Uncorrected refractive error, visual impairment and visual perceptual dysfunction are associated with reduced academic outcomes (Hopkins, Narayanasamy, et al., 2019; Sortor & Kulp, 2003). However, the prevalence of refractive error, binocular vision anomalies and impaired visual perceptual skills in NZ children is currently unknown. In particular, the visual profile of Māori children is undetermined. While limited studies have shown a low prevalence of refractive error in Pacific children (Barnes et al., 2011; Lindquist et al., 2011), it is not known whether this is the same for Pacific children living in NZ. Similarly, while multiple studies have shown high and increasing prevalence of myopia in East Asian children, it is not known whether this is also true of children from these ethnic groups who live in NZ.

Vision screening plays an important role in detecting vision conditions in children (Jonas et al., 2017). Current NZ vision screening protocols consist of unilateral VA screening (measurement of monocular vision at 4 m with the Parr vision test) (Figure 2-1) at 4-5 years of age, as part of the B4 School Check (B4SC) well child programme, and a further VA screening (using a Snellen chart at 6 m) at 11-12 years of age (Ministry of Health, 2014b). VA screening, while being effective in detecting children with myopia, does not accurately detect those children with low to moderate levels of hyperopia or astigmatism (Leone et al., 2010; O'Donoghue et al., 2012). Children with hyperopia and astigmatism frequently achieve VA that allows them to pass a screening (Garber, 1981), but still have reduced VA compared with their emmetropic peers and their own best corrected VA. Furthermore, VA screening is unlikely to detect children with binocular vision anomalies or those with impaired visual perceptual skills.

For screening to be effective, it is important to understand the visual profile of NZ children so that vision screening and intervention programmes can be targeted towards conditions that are prevalent in

the NZ paediatric population. The WTS study presented in Chapter 8 provided contemporary data regarding the vision conditions in children of predominantly Māori and Pacific ethnicity, living in an area of socioeconomic disadvantage. Based on the results of the WTS study, we hypothesised that NZ children have significant rates of uncorrected refractive error that is not detected by the current vision screening programme. The aim of the study presented in this chapter was to determine the visual profile of NZ children from across a wider range of socioeconomic and ethnic backgrounds.

Therefore, in children aged 7-10 years living in Auckland, NZ we aimed to:

1. Determine the proportion of children with corrected and uncorrected vision conditions (refractive error, binocular vision anomalies, amblyopia risk factors and poor visual-motor integration) and visual impairment.
2. Examine previous participation in, and outcomes of, the B4SC vision screening programme.

9.2 Methods

The research followed the tenets of the Declaration of Helsinki. Ethical approval was obtained from the University of Auckland Human Ethics Committee (Reference number: 020926). Consent was obtained from each participating child's parent or caregiver and assent was obtained from the child.

9.2.1 Participants

Children aged 7-10 years and their caregivers were recruited by convenience sampling in six primary schools in South Auckland, NZ. All children received a comprehensive eye examination that was completed at their school. Caregivers were invited to complete a questionnaire either online via an anonymous link or on a paper form (Appendix A). The questionnaire included questions about the child's ocular history, general health and caregiver concerns about any vision problems. This questionnaire was based on clinical paediatric optometric history taking and piloted with parents to ensure the questionnaire could be understood and answered by a lay person. Children also completed a separate questionnaire at the time of examination that included the Convergence Insufficiency Symptom Survey (CISS) (Borsting, Rouse, Mitchell, et al., 2003). Results of each child's B4SC vision screening was obtained from the Counties Manukau DHB B4SC Team.

Ethnicity was self-defined by each child's caregiver and categorised as per NZ Statistics Level 1 (Statistics New Zealand, 2005). Where participants identified with more than one ethnic group, priority used to assign a single ethnic group was in the following order: Māori, Pacific, Asian and European/Others. School decile ratings, which are a measure of the socioeconomic status of the community in which the school's students reside (Ministry of Education, 2020), were categorised as low (deciles 1-3), medium (deciles 4-7) or high (deciles 8-10). Decile 1 schools are the 10% of schools

in NZ with the highest proportion of students from low socioeconomic communities, while decile 10 schools have the lowest proportion of these students. Children and their caregivers were purposely recruited from schools classified as low, medium and high deciles to ensure that the study sample included children from a range of socioeconomic areas.

Children were considered to have attended a previous eye examination if it was stated in the caregiver questionnaire, if they were wearing glasses at the time of assessment, or if previous eye care provider details were provided on the consent form. Children were considered not to have attended a previous eye examination if this was stated in the caregiver questionnaire, or if it was indicated on the consent form. Children whose caregiver indicated in the questionnaire that they did not know if their child had previously attended an eye examination, or did not complete the questionnaire and the child was not wearing glasses at the time of the examination, and there was no clear indication on the consent form of previous examination status, were classified as unknown previous eye examination status.

9.2.2 Comprehensive eye examinations

Children were examined using the methods described in detail in Chapter 3 and summarised below.

Visual acuity

VA was measured unaided and using the participant's habitual correction, where available, at both distance and near. Distance VA was measured using the e-ETDRS protocol presented on an EVA testing system (JAEB Centre for Health Research) (Beck et al., 2003) at 3 m. Near VA was measured using the Sloan letter near logMAR acuity chart (Good-Lite Company) at 40 cm. A matching card was used for children unable to accurately name letters and alternative optotype charts (numbers or Lea symbols) were available for children who were unable to match letters. Best corrected VA was measured following subjective refraction.

Refractive error assessment

Retinoscopy without cycloplegia was performed in a trial frame with the participant viewing a target at 6 m through fogging lenses (+1.50 DS). Using the retinoscopy results as a baseline, subjective refraction using standard clinical techniques was performed to determine the most positive spectacle prescription giving the best VA. Non-cycloplegic autorefraction was performed using the Spot Vision Screener VS100 (Software version 3.0.04.02, Welch Allyn) and the Nidek Handheld Ref/Keratometer HandyRef-K (Nidek Co. Ltd, Japan). Refractive error assessment was repeated a minimum of 40 minutes after instillation of one drop of Cyclopentolate 1% to each eye using retinoscopy and autorefraction.

9.2.3 Binocular vision assessment

The cover-uncover test and alternating cover test were performed at 6 m and 40 cm to determine the presence of heterotropia or heterophoria in primary gaze. The prism cover test was performed to measure the magnitude of deviations. Positive and negative fusional reserves were measured at 6 m and 40 cm using a horizontal prism bar in free space to determine the blur, break and recovery values for both base in and base out prism.

Near point of convergence and near point of accommodation (monocular and binocular) were measured using the Royal Air Force (RAF) rule (Good-Lite Company) (Neely, 1956). Dynamic retinoscopy was performed for assessment of lag of accommodation using the Monocular Estimation Method (Rouse, London, & Allen, 1982). Near stereoacuity was measured using the Randot Preschool stereotest at 40 cm (2012, Stereo Optical Company Inc) and recorded as the smallest disparity at which the participant correctly identified two or more of the shapes (Birch et al., 2008). Distance stereoacuity was measured using the Distance Randot stereotest and recorded as the smallest disparity at which the participant correctly identified both shapes (Wang et al., 2010). Visual fields were screened using the simulated arc perimetry confrontation method.

9.2.4 Ocular health evaluation

Slit-lamp examination of the anterior segment was performed to assess the health of the anterior eye and to assess whether the anterior chamber was sufficiently open for safe pupillary dilation. Pupil reactions were assessed using a direct ophthalmoscope to assess direct and consensual light reflexes and to assess for the presence of anisocoria. The near light reflex was assessed by bringing a small target close to the participant. The swinging flashlight test was used to determine if a relative afferent pupillary defect was present. Binocular indirect ophthalmoscopic examination was performed on participants with dilated pupils to evaluate the health of the posterior segment of the eye.

9.2.5 Visual-motor integration

The Beery VMI (sixth edition) was used to assess visual-motor integration (VMI), visual perception (VP) and motor coordination (MC) (Beery & Beery, 2010). The tests were administered according to the standard protocol (Beery & Beery, 2010) and raw scores were converted to standard scores. Children completed the tests unaided or with their habitual correction, if available. Results for children whose raw scores fell outside of the standardised range, and therefore no standard score was available, were excluded from the data analysis.

9.2.6 Definitions for vision conditions

Vision conditions were classified using the same definitions used throughout this thesis, as described in Chapter 3. Refractive error was classified using the cycloplegic retinoscopy results. Clinically significant refractive error (Table 3-2) and visual impairment (Table 3-3) were defined according to the Refractive Error Studies in Children group (Negrel et al., 2000). Additionally, reduced VA was defined as VA in the better eye of 0.1 to 0.2 logMAR, to explore the effect of mildly reduced VA on visual function in these children. Where single letter scoring was used in VA measurement, the child was considered to have successfully achieved a logMAR level if they correctly named four of the five letters for that level. Amblyopia risk factors (Table 3-4) were defined according to the American Academy of Ophthalmology guidelines (Holmes & Clarke, 2006). Amblyopia was defined as visual impairment with an amblyopia risk factor in a child already wearing appropriate refractive correction.

Non-strabismic binocular vision anomalies were defined using the integrative analysis approach (Table 3-5) (Scheiman, 2014). Reduced stereoacuity was defined as near stereoacuity of greater than 60 arcsec measured using the Randot Preschool Stereotest (Birch et al., 2008). Children with a CISS of 16 or greater were classified as symptomatic and those with a score of less than 16 were classified as asymptomatic (Borsting, Rouse, Mitchell, et al., 2003). Children who had more than one vision condition were included in the counts for each condition they had.

9.2.7 Analysis

Data analysis was conducted using SPSS Statistics (Version 27, IBM Corporation, New York, USA). Descriptive statistics were used to summarise the data and presented as means and standard deviations (SD; for parametric data) and as medians and interquartile ranges (IQR; for non-parametric data).

The chi-squared test (or the Fisher's exact test if a cell count had less than five participants) was used to assess categorical variables. T-tests and the one-way ANOVA were used to compare means for parametric data, and the Mann-Whitney U test and the Kruskal Wallis test were used to compare medians for non-parametric data. A two-tailed $P < .05$ was considered statistically significant.

9.3 Results

9.3.1 Participants

Caregiver consent to participate in the study was obtained for 240 children. Two participants had left their schools prior to testing and one child did not assent to testing. Therefore, the final sample consisted of 237 children with a median (IQR) age of 9.3 (8.2-10.2) years. Demographic characteristics of the participants are shown in Table 9-1.

The caregiver questionnaire was completed by 65.0% (154/237) of caregivers. Completion of the caregiver questionnaire differed significantly by ethnicity and school decile (Table 9-1). Compared with caregivers who did not complete the questionnaire, a larger proportion of those who completed the questionnaire had children of European/other ethnicities or who attended schools in the three highest deciles (8-10).

Table 9-1: Demographic characteristics of child and parent participants

	Child participation	**Caregiver participation**		
		Questionnaire completed	**Not completed**	**P-value**
	n (%) (n=237)	**n (%) (n=154)**	**n (%) (n=83)**	
Age (median [IQR])	9.3 (8.2-10.2)			
Sex (n=237)				
Female	127 (53.6)	49 (59.0)	78 (50.6)	0.22
Male	110 (46.4)	34 (41.0)	76 (49.4)	
Child ethnicity (n=229)				
Māori	20 (8.4)	15 (9.7)	5 (6.7)	0.02
Pacific	46 (19.4)	26 (16.9)	20 (26.7)	
Asian	70 (29.5)	41 (26.6)	29 (38.7)	
European/others	93 (39.2)	72 (46.8)	21 (28.0)	
School decile (n=237)				
Low (deciles 1 to 3)	76 (32.1)	35 (22.7)	41 (49.4)	<0.001
Medium (deciles 4 to 7)	93 (39.2)	61 (39.6)	32 (38.6)	
High (deciles 8 to 10)	68 (28.7)	58 (37.7)	10 (12.0)	

IQR = interquartile range

There were significant differences in child ethnicity by school decile ($P < 0.001$), but not by sex or age group (Figure 9-1). Compared with children of European or other ethnic groups, a larger proportion of Pacific children attended schools with the lowest three decile ratings (1-3).

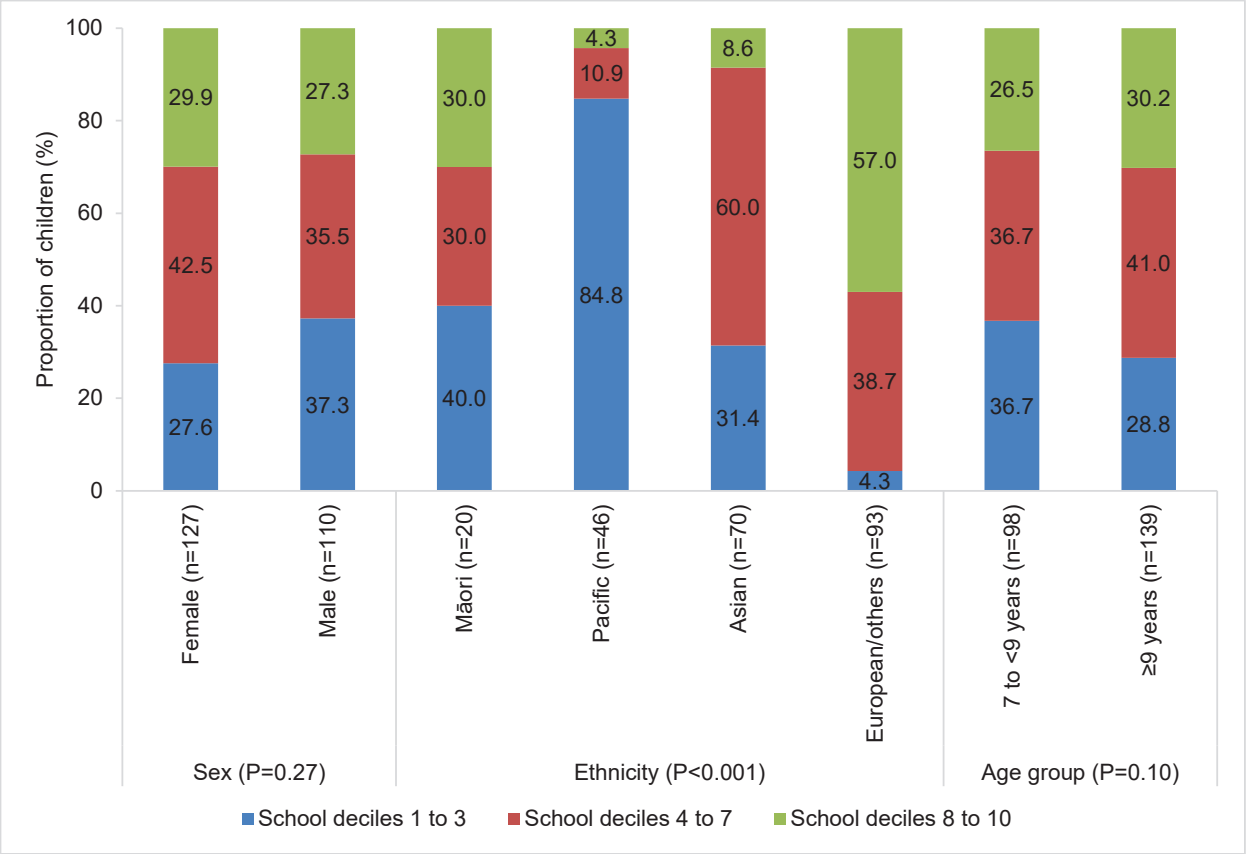

Figure 9-1: Comparison of sex, ethnicity and age group by school decile

9.3.2 Vision conditions

Refractive error

Cycloplegic refraction was completed for 220 children; 12 caregivers did not consent to use of cycloplegic eye drops and a further five children did not assent to instillation of drops on the day of examination.

Of children who completed cycloplegic refraction, 23.6% (52/220) had significant refractive error (Table 9-2). There were significant differences in the proportions of children with significant refractive error, compared with those without refractive error, by sex and ethnicity, but not age group (Table 9-3). Compared to children without refractive error, a larger proportion of children who were female or of Asian ethnicity had significant refractive error. There was a significant difference in the proportion of children with myopia compared to those without myopia by ethnicity, but not sex or age group (Table 9-4). Compared to children without myopia, a larger proportion of children with myopia were of Asian ethnicity. There were no significant differences in the proportions of children with and without hyperopia and astigmatism by sex, ethnicity or age group.

Of children with significant refractive error, only 44.2% (23/52) were wearing correction at the time of our assessment. There were significant differences in the proportion of children with refractive error currently wearing glasses compared with those who were uncorrected by age group, but not sex or ethnicity (Table 9-3). Compared to children with significant refractive error who were not wearing glasses, a larger proportion of children aged 9 years and older were wearing glasses.

Amblyopia risk factors

Amblyopia risk factors were detected in 20 children (Table 9-2). Of these, 85.0% (17/20) had significant refractive error. There was evidence of a previous eye examination for twelve of these children and their refractive error was corrected at the time of our assessment. Of the three children with amblyopia risk factors and no significant refractive error, two (66.7%) had evidence of a previous eye examination.

Binocular vision anomalies

Binocular vision anomalies were detected in 27 (11.5%) children (Table 9-2). The proportion of children with binocular vision anomalies did not differ by sex, ethnicity, or age group (Table 9-3).

Near stereoacuity testing was completed by all 237 children. Reduced stereoacuity was detected in 82 (34.6%) children (Table 9-2). There were no significant differences in the proportions of children with and without reduced stereoacuity by sex, ethnicity, or age group. There were significant differences in the proportions of children with versus without reduced stereoacuity among children with significant refractive error and binocular vision anomalies (Table 9-5). Compared to children without reduced stereoacuity, a larger proportion of those with reduced stereoacuity had significant refractive error ($P = 0.003$) or a binocular vision anomaly ($P = 0.004$).

Ocular pathology

Ocular pathology was not detected in any child in this study.

Table 9-2: Prevalence of vision conditions

Vision condition	n (%)
Refractive Error (either eye) (n=220)*	
Myopia	17 (7.7)
Hyperopia	17 (7.7)
Astigmatism	33 (15.0)
Any refractive error	52 (23.6)
Binocular vision anomalies (n=235)†	
Strabismus	6 (2.6)
Convergence insufficiency	7 (3.0)
Convergence excess	10 (4.3)
Divergence insufficiency	0 (0.0)
Divergence excess	1 (0.4)
Accommodative insufficiency	3 (1.3)
Any binocular vision anomaly	27 (11.5)
Amblyopia risk factors (n=220)†	
Strabismus	6 (2.6)
Anisometropia	7 (3.2)
Bilateral refractive error	12 (5.5)
Any amblyopia risk factor	20 (9.1)
Amblyopia	3 (1.4)
Ocular pathology	0 (0.0)
Any vision condition (n=220)‡	71 (30.0)

* 7 children had both myopia and astigmatism and 8 had both hyperopia and astigmatism.

† 1 child had both strabismus and anisometropia, 3 children had both strabismus and bilateral refractive error and 2 children had both anisometropia and bilateral refractive error.

‡ 8 children had both refractive error and a binocular vision anomaly, 17 had both refractive error and an amblyopia risk factor and 7 had both a binocular vision anomaly and an amblyopia risk factor.

Table 9-3: Presence of refractive error, refractive error correction and binocular vision anomalies by child's demographic characteristics

	Refractive error (n=220)			Refractive error correction (n=52)			Binocular vision anomalies (n=235)		
	Present	Not present	P-value	Corrected	Not corrected	P-value	Present	Not present	P-value
	n (%) (n=52)	n (%) (n=168)		n (%) (n=23)	n (%) (n=29)		n (%) (n=27)	n (%) (n=208)	
Sex									
Female	35 (67.3)	85 (50.6)	0.04	18 (78.3)	17 (58.6)	0.15	19 (70.4)	106 (51.0)	0.07
Male	17 (32.7)	83 (49.4)		5 (21.7)	12 (41.4)		8 (29.6)	102 (49.0)	
Child ethnicity									
Māori	2 (4.0)	17 (10.4)	0.04	1 (4.5)	1 (3.6)	0.23	1 (4.2)	19 (9.4)	0.10
Pacific	11 (22.0)	31 (18.9)		2 (9.1)	9 (32.1)		1 (4.2)	45 (22.2)	
Asian	22 (44.0)	42 (25.6)		11 (50.0)	11 (39.3)		9 (37.5)	60 (29.6)	
European/Other	15 (30.0)	74 (45.1)		8 (36.4)	7 (25.0)		13 (54.2)	79 (38.9)	
Age									
7 to < 9 years	17 (32.7)	79 (47.0)	0.07	4 (17.4)	13 (44.8)	0.04	7 (25.9)	93 (44.7)	0.06
≥ 9 years	35 (67.3)	89 (53.0)		19 (82.6)	16 (55.2)		20 (74.1)	115 (55.3)	

Table 9-4: Presence of myopia, hyperopia and astigmatism by child's demographic characteristics

	Myopia			Hyperopia			Astigmatism		
	Present n (%) (n=71)	**Not present n (%) (n=149)**	**P-value**	**Present n (%) (n=52)**	**Not present n (%) (n=168)**	**P-value**	**Present n (%) (n=27)**	**Not present n (%) (n=108)**	**P-value**
Sex (n=220)									
Female	13 (76.5)	107 (52.7)	0.06	11 (64.7)	109 (53.7)	0.45	23 (69.7)	97 (51.9)	0.06
Male	4 (23.5)	96 (47.3)		6 (35.3)	94 (46.3)		10 (30.3)	90 (48.1)	
Child ethnicity (n=214)									
Māori	1 (6.7)	18 (9.0)	0.01	1 (5.9)	18 (9.1)	0.81	1 (3.0)	18 (9.9)	0.08
Pacific	2 (13.3)	40 (20.1)		2 (11.8)	40 (20.3)		8 (24.2)	34 (18.8)	
Asian	10 (66.7)	54 (27.1)		5 (29.4)	59 (29.9)		15 (45.5)	49 (27.1)	
European/Other	2 (13.3)	87 (43.7)		9 (52.9)	80 (40.6)		9 (27.3)	80 (44.2)	
Age (n=220)									
7 to < 9 years	4 (23.5)	92 (45.3)	0.12	7 (41.2)	89 (43.8)	1.00	12 (36.4)	84 (44.9)	0.36
≥ 9 years	13 (76.5)	111 (54.7)		10 (58.8)	114 (56.2)		21 (63.6)	103 (55.1)	

Table 9-5: Reduced stereoacuity by child's demographic characteristics and presence of ocular conditions

	Reduced stereoacuity n (%) (n=82)	Not reduced n (%) (n=155)	P-value
Sex (n=237)			
Female	48 (58.5)	79 (51.0)	0.27
Male	34 (41.5)	76 (49.0)	
Ethnicity (n=229)			
Māori	7 (9.0)	13 (8.6)	0.97
Pacific	17 (21.8)	29 (19.2)	
Asian	23 (29.5)	47 (31.1)	
European/Other	31 (39.7)	62 (41.1)	
Age (n=237)			
7 to < 9 years	35 (42.7)	67 (43.2)	0.94
≥ 9 years	47 (57.3)	88 (56.8)	
Significant refractive error (n=220)			
Present	27 (35.5)	25 (17.4)	0.003
Not present	49 (64.5)	119 (82.6)	
Binocular vision anomalies (n=235)			
Present	16 (19.8)	11 (7.1)	0.004
Not present	65 (80.2)	143 (92.9)	

9.3.3 Visual acuity and visual impairment

The proportion of children with visual impairment was low; 94.9% (226/237) of children had presenting distance VA of 0.2 log MAR or better in one or both eyes and 95.8% (227/237) had presenting near VA of 0.2 log MAR or better in one or both eyes (Table 9-6). The most common cause of visual impairment was refractive error. Three children with visual impairment and amblyopia risk factors were wearing glasses at the time of our assessment and were considered to have amblyopia. Presenting visual impairment was detected in one child for distance VA and four children for near VA without any diagnosed ocular conditions.

Table 9-6: Prevalence and causes of distance and near visual impairment

	Distance			Near		
	Unaided vision	**Presenting vision**	**Spectacle corrected vision**	**Unaided vision**	**Presenting vision**	**Spectacle corrected vision**
	n (%) (n=236)	**n (%) (n=237)**	**n (%) (n=237)**	**n (%) (n=236)**	**n (%) (n=237)**	**n (%) (n=237)**
Visual impairment classification						
No visual impairment	207 (87.7)	217 (91.6)	224 (94.5)	199 (84.3)	213 (89.9)	220 (92.8)
Visual impairment one eye	12 (5.1)	9 (3.8)	9 (3.8)	19 (8.1)	14 (5.9)	9 (3.8)
Mild visual impairment	11 (4.7)	10 (4.2)	4 (1.7)	13 (5.5)	6 (2.5)	5 (2.1)
Moderate visual impairment	5 (2.1)	1 (0.4)	0 (0.0)	5 (2.1)	4 (1.7)	3 (1.3)
Severe visual impairment	1 (0.4)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Causes of visual impairment*						
Refractive error	9 (52.9)	4 (36.3)	1 (25.0)	10 (55.6)	6 (60.0)	2 (25.0)
Amblyopia	1 (5.8)	1 (14.3)	1 (25.0)	1 (5.6)	1 (10.0)	1 (12.5)
Binocular vision anomaly	3 (17.6)	2 (18.2)	1 (25.0)	7 (38.9)	7 (70.0)	1 (12.5)
Unexplained	4 (23.5)	4 (36.3)	1 (25.0)	5 (27.8)	5 (50.0)	4 (50.0)

* 5 children with unaided near visual impairment had a binocular vision anomaly and refractive error or amblyopia and 7 children with presenting near visual impairment had a binocular vision anomaly and refractive error or amblyopia.

In addition to those with visual impairment, presenting reduced VA of 0.1 to 0.2 logMAR in the better eye was measured in 8.9% (21/237) children at distance and 31.6% (75/237) children at near (Figure 9-2). There were significant differences in the proportions of children with visual impairment, reduced VA and not reduced VA at near versus distance for children with hyperopia, astigmatism and no refractive error but not myopia (Figure 9-2). Compared to children without these conditions, a larger proportion of children with hyperopia ($P < 0.001$), astigmatism ($P = 0.04$) and no refractive error ($P < 0.001$) had reduced VA at near versus distance.

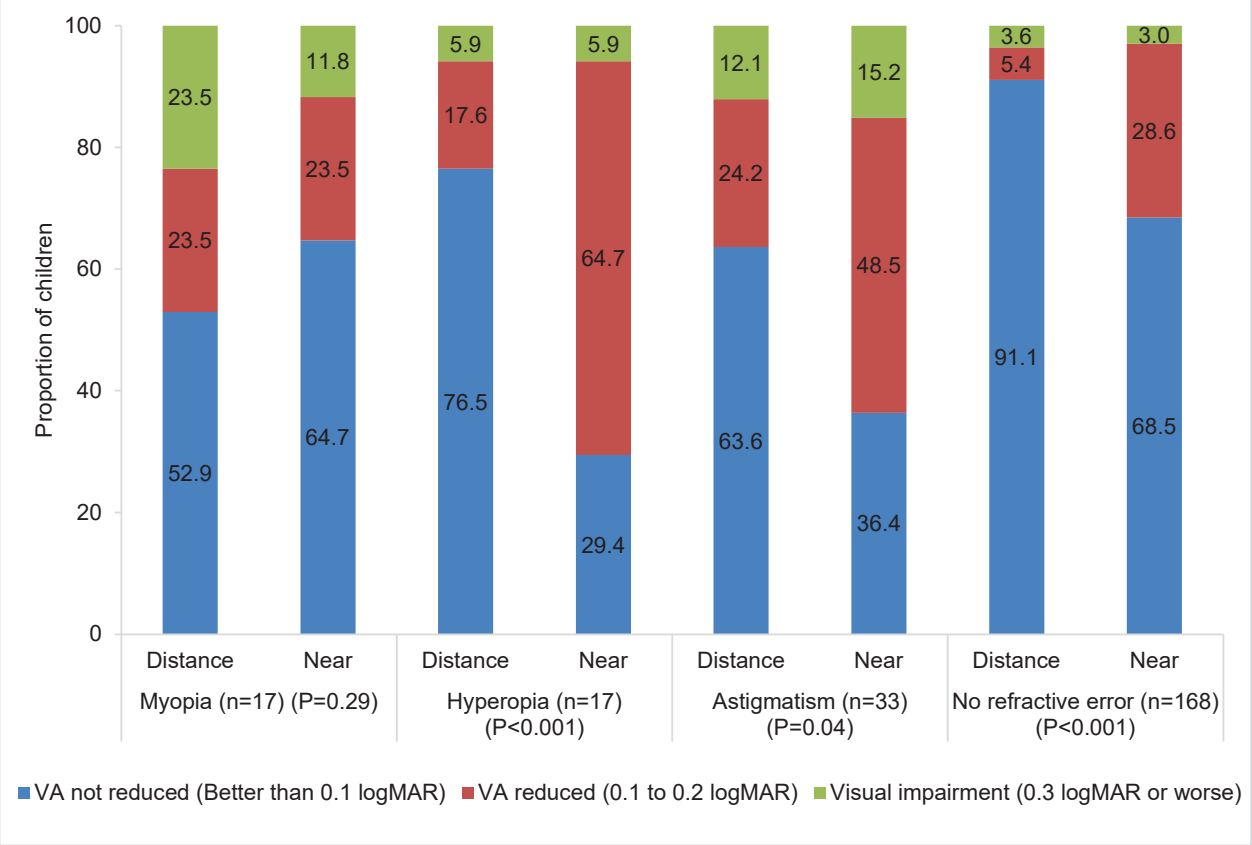

Figure 9-2: Distance and near presenting visual acuity categories by refractive error type

9.3.4 Previous eye examinations and ocular history

A total of 42.6% (101/237) of children had evidence of a previous eye examination. Of those caregivers who answered the questionnaire, 54.5% (84/154) reported that their child had previously attended an eye examination. Additionally, 12 children were wearing glasses and previous eye examination results were obtained for a further four children. Fifty-nine children (24.9%) had not attended a previous eye examination; this was reported by 46 caregivers on the questionnaire and indicated by 13 on the consent form. It was unclear whether the remaining 77 children had a

previously attended an examination, including 24 caregivers who were unsure of their child's previous eye examination status on the questionnaire.

The proportion of children who had evidence of a previous eye examination differed by ethnicity ($P < 0.001$), but not sex or age group (Figure 9-3). Compared with children of other ethnicities, a smaller proportion of children of Pacific ethnicity had evidence of a previous eye examination. The proportion of children who had evidence of a previous eye examination also differed by presence of significant refractive error ($P = 0.01$) and binocular vision anomalies ($P = 0.04$) (Figure 9-4). Compared to children without significant refractive error or binocular vision anomalies, a larger proportion of those with significant refractive error or binocular vision anomalies had evidence of a previous eye examination.

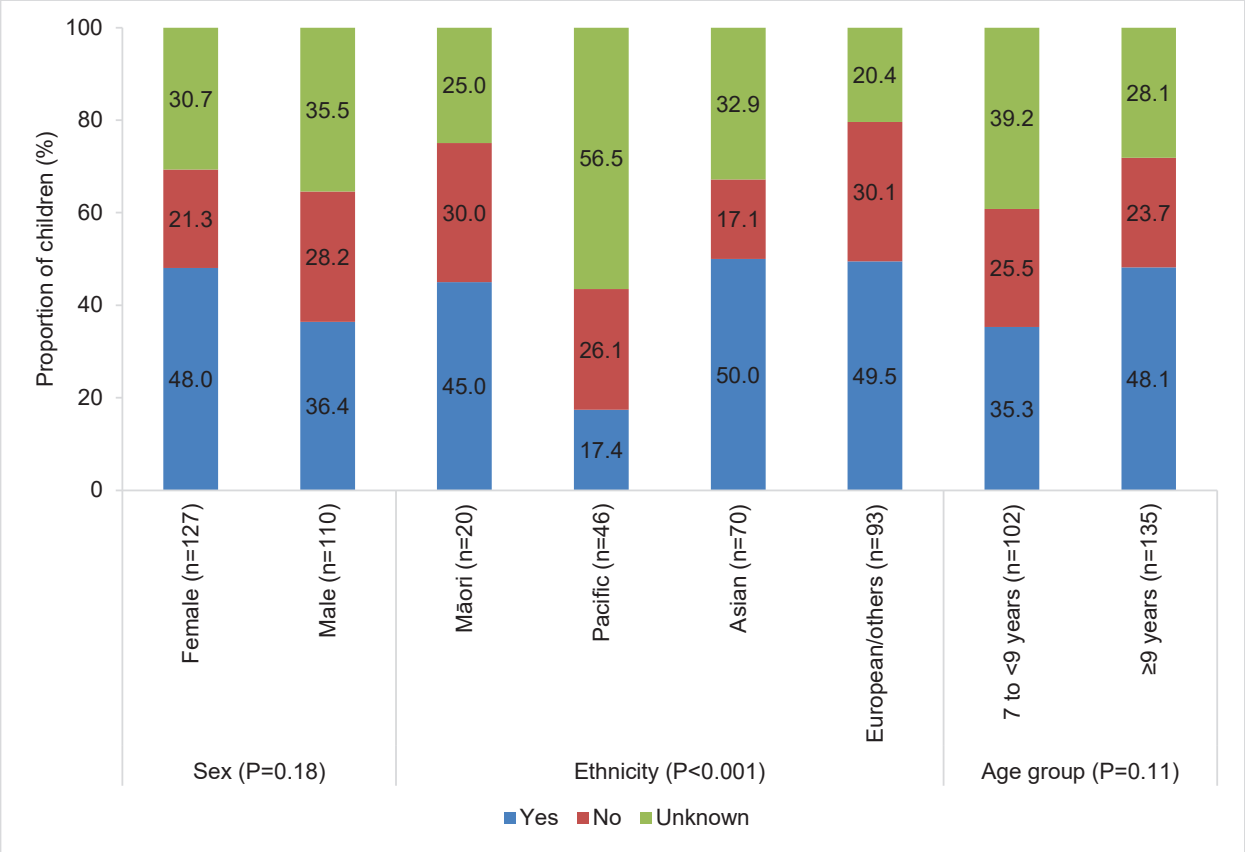

Figure 9-3: Evidence of previous eye examination by participant demographic characteristics

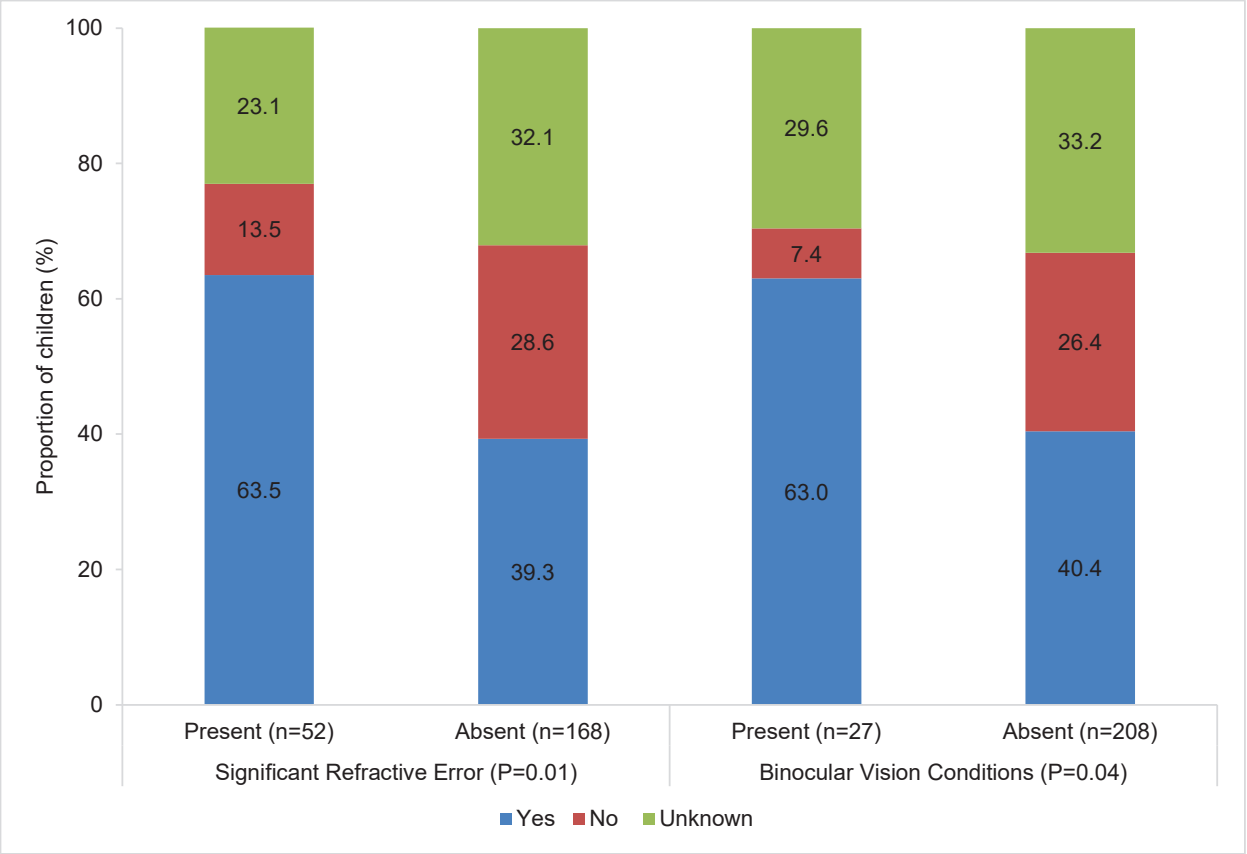

Figure 9-4: Evidence of previous eye examination by presence of significant refractive error and binocular vision anomalies

9.3.5 Symptoms

Of the 236 children who completed the CISS, 98 (41.4%) children had a total score of 16 or greater and were classified as symptomatic. There were no differences in the proportions of children classified as symptomatic or not symptomatic by demographic characteristics or by the presence of vision conditions (Table 9-7).

Of the 152 caregivers who answered the questionnaire, 67 (44.1%) reported one or more concerns with their child's vision. Of these, 67.2% (45/67) reported that their child had previously had an eye examination, 20.9% (14/67) had not, and 11.9% (8/67) were unsure. There were significant differences in the proportions of children with and without caregiver concerns by sex (P = 0.02) and presence of refractive error (P = 0.04) but not by ethnicity, age group, or presence of binocular vision anomalies (Table 9-7). Compared with caregivers who did not report concerns with their child's vision, a larger proportion of those who reported concerns with their child's vision were caregivers of children who were female or who had significant refractive error.

Table 9-7: Child symptoms and caregiver concerns by child demographic characteristics and presence of vision conditions

	Child CISS score (n=236)			Caregiver concern (n=152)		
	Symptomatic (≥ 16) n (%) (n=98)	Not symptomatic (< 16) n (%) (n=138)	P-value	One or more concerns n (%) (n=67)	No concerns n (%) (n=85)	P-value
Sex						
Female	49 (50.0)	78 (56.5)	0.32	41 (61.2)	36 (42.4)	0.02
Male	49 (50.0)	60 (43.5)		26 (38.8)	49 (57.6)	
Child ethnicity						
Māori	11 (11.7)	9 (6.7)	0.05	8 (11.9)	7 (8.2)	0.59
Pacific	25 (26.6)	21 (15.7)		9 (13.4)	16 (8.2)	
Asian	22 (23.4)	48 (35.8)		20 (29.5)	20 (23.5)	
European/Other	36 (38.3)	56 (41.8)		30 (44.8)	42 (49.4)	
Age group						
7 to < 9 years	40 (40.8)	61 (44.2)	0.60	24 (35.8)	35 (41.2)	0.50
≥ 9 years	58 (59.8)	77 (55.8)		43 (64.2)	50 (58.8)	
Significant refractive error						
Significant refractive error	19 (20.4)	33 (26.2)	0.32	21 (32.3)	10 (12.6)	0.04
No significant refractive error	74 (79.6)	93 (73.8)		44 (67.7)	69 (87.3)	
Binocular vision anomalies						
Binocular vision anomaly	15 (15.3)	12 (8.8)	0.13	10 (14.9)	6 (7.1)	0.12
No binocular vision anomaly	83 (84.7)	124 (91.2)		57 (85.1)	78 (92.9)	

CISS = Convergence Insufficiency Symptom Score

9.3.6 Visual-motor integration

The Beery VMI was completed by all 237 children. The raw scores were below the range for which standard scores are provided for nine children for the VP test and one participant for the MC test, therefore the results for these children were excluded from the analysis. Mean (SD) VMI and MC standard scores and median (IQR) VP standard scores are shown in Table 9-8. Mean VMI standard scores differed significantly by age group ($P < 0.001$), but not by sex or ethnicity. Children aged 7 to less than 9 years achieved significantly higher mean VMI standard scores than children aged 9 years and older. Median VP standard scores differed significantly by sex ($P = 0.04$), but not ethnicity or age group. Girls had significantly higher median VP standard scores compared with boys. There were also differences by sex ($P < 0.001$) and age group ($P = 0.02$) but not ethnicity in mean MC standard scores. Girls and children aged 7 to less than 9 years achieved higher mean MC standard scores than boys and children aged 9 years and older, respectively.

Table 9-8: Visual motor integration standard scores by demographic characteristics of child

	Visual motor integration			Visual perception			Motor coordination		
	n (%)	Mean (SD)	P-value	n (%)	Median (IQR)	P-value	n (%)	Mean (SD)	P-value
Total	237 (100.0)	88.1 (10.4)		228 (100.0)	99.0 (83.0-107.0)		236 (100.0)	88.0 (14.1)	
Sex									
Female	127 (53.6)	89.0 (10.8)	0.16	121 (53.1)	101.0 (86.5-109.0)	0.04	126 (53.4)	90.8 (13.9)	<0.001
Male	110 (46.4)	87.1 (10.0)		107 (46.9)	93.0 (81.0-106.0)		110 (46.6)	84.8 (13.6)	
Ethnicity									
NZ Māori	20 (8.7)	86.1 (12.5)	0.55	20 (9.0)	96.0 (81.0-105.5)	0.14	20 (8.8)	86.8 (16.3)	0.44
Pacific	46 (20.1)	90.0 (7.8)		45 (19.7)	91.0 (79.5-102.5)		46 (20.2)	91.0 (11.4)	
Asian	70 (30.6)	88.1 (10.7)		66 (28.9)	99.0 (82.0-108.3)		69 (30.2)	88.2 (15.1)	
European/Other	93 (40.6)	88.0 (11.1)		91 (39.9)	101.0 (89.0-108.0)		93 (40.8)	87.1 (13.9)	
Age									
7 to < 9 years	102 (43.0)	91.3 (9.5)	<0.001	96 (42.1)	99.0 (84.3-107.0)	0.90	101 (42.8)	91.3 (13.4)	0.02
≥ 9 years	135 (57.0)	85.7 (10.5)		132 (57.9)	98.5 (83.0-107.0)		135 (57.2)	85.6 (14.1)	

IQR = interquartile range, SD = standard deviation

9.3.7 B4 School Check vision screening

A B4SC vision screening outcome was recorded for 79.3% (188/237) children (Figure 9-5). Of these, 153 children passed screening, 24 were referred and 6 were identified for rescreening. No B4SC vision screening outcome was recorded 49 (20.6%) children and two (0.8%) caregivers declined vision screening for their child. Three children (1.3%) were under care of an eye care provider at the time of the B4SC vision screening.

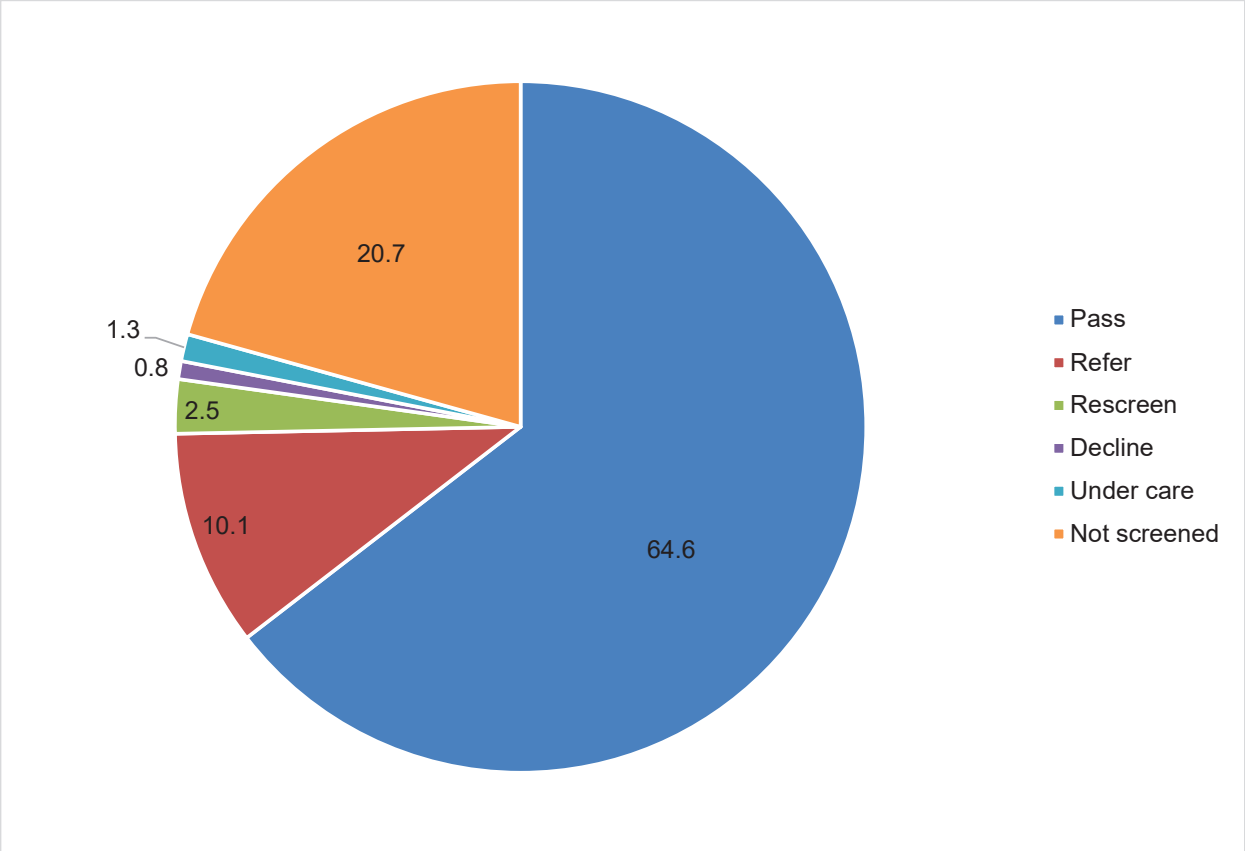

Figure 9-5: B4 School Check vision screening outcomes for study participants

Participation in the B4SC vision screening differed significantly by sex (P = 0.01) and age group (P = 0.01), but not ethnicity (Figure 9-6). A larger proportion of girls than boys, and a larger proportion of children aged 7 to less than 9 years compared with those 9 years and older, participated in the B4SC vision screening.

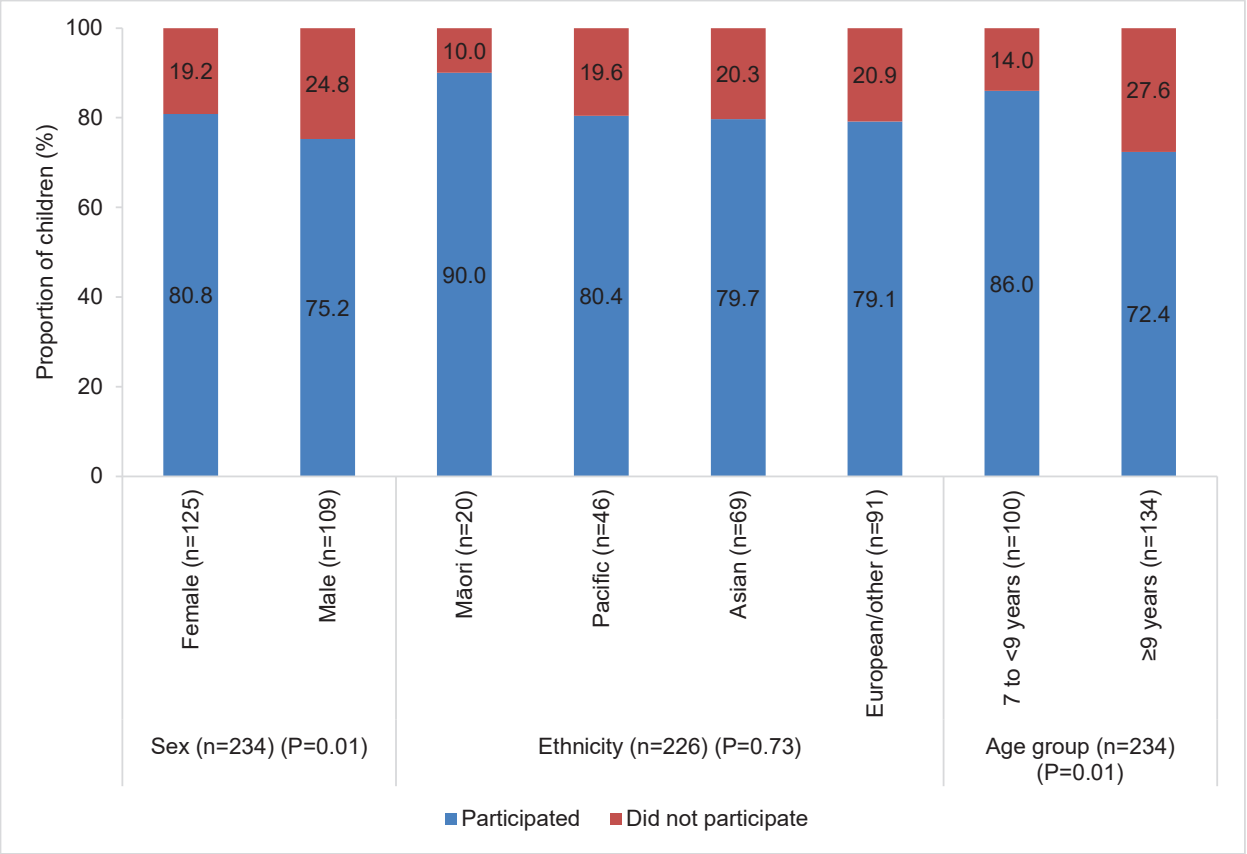

Figure 9-6: Participant demographic characteristics, previous examination and refractive error correction by B4 School Check participation

Among the 51 children who had not participated in B4SC vision screening, 20 (39.0%) children had evidence of having a previous eye examination. There was no significant difference in previous eye examination attendance or refractive error correction by B4SC participation (Figure 9-7). Of the children that did not participate in the B4SC vision screening, 23.5% (12/51) had significant refractive error at the time of our assessment including five (9.8%) with amblyopia risk factors; six children (50%) with significant refractive error had evidence of a previous examination and were wearing correction at the time of our assessment.

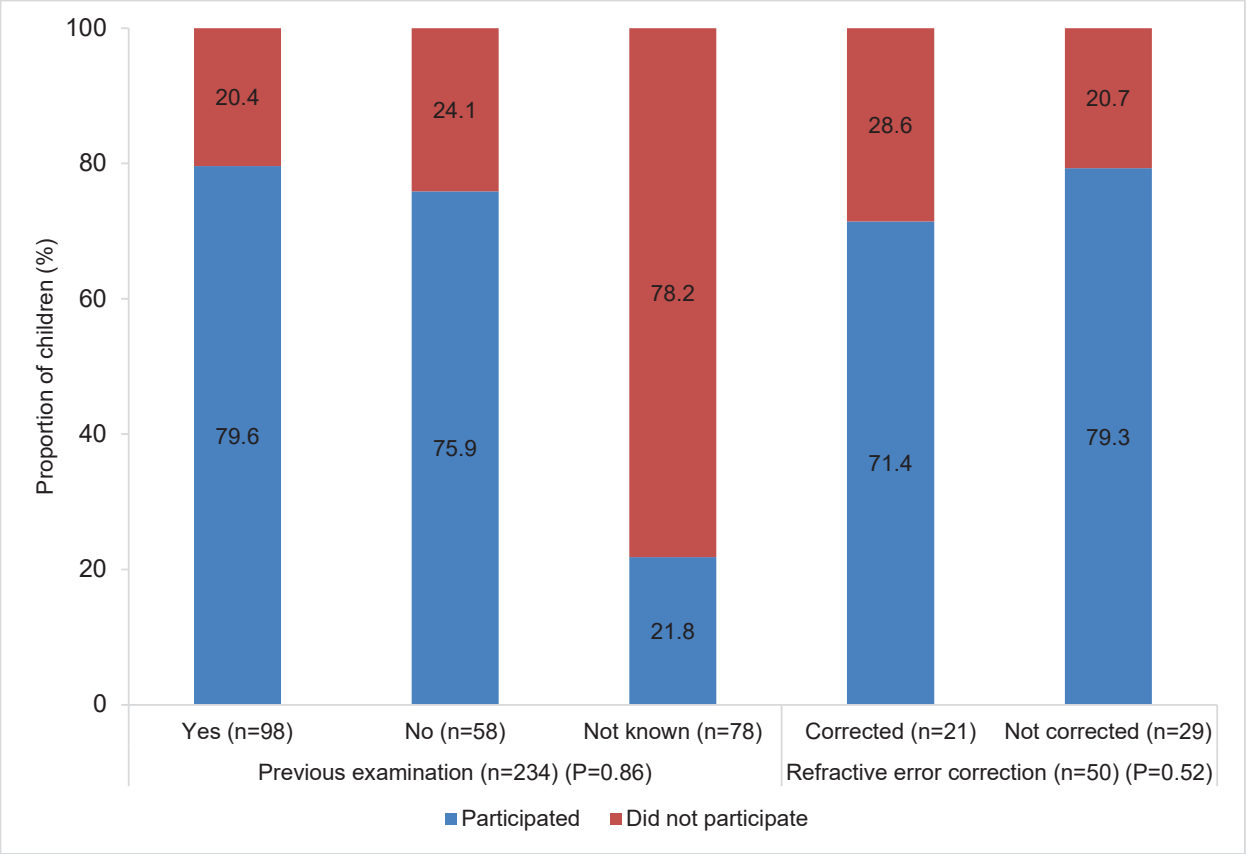

Figure 9-7: Evidence of previous eye examination and correction of refractive error by B4 School Check outcome

There were significant differences in the proportion of children who were referred from vision screening compared with those who passed vision screening among children with versus without significant refractive error ($P < 0.001$) and children with versus without amblyopia risk factors ($P < 0.001$) (Figure 9-8). Compared to children without refractive error or amblyopia risk factors, a larger proportion of children with these conditions had been referred from vision screening.

Among the 24 children referred from the B4SC vision screening, 16 caregivers completed the questionnaire. Eight caregivers (50%) reported being aware of the referral and had taken their child for follow-up. Five caregivers were unsure if their child had received the screening and three caregivers reported that their child had received the screening but were unaware of their child's referral. Of children who were referred from B4SC vision screening (n = 24), 15 (62.5%) had evidence of a previous eye examination.

Of the 24 children referred from the B4SC vision screening, 15 (62.5%) were identified with significant refractive error at our assessment and eight of these (53.3%) were wearing glasses at the time of our assessment. Of the 153 children who had passed the B4SC vision screening, 20 (13.0%) had significant refractive error and five (25%) were corrected at the time of our assessment.

There were also significant differences in the proportion of children who were referred from vision screening compared with those who passed vision screening by attendance at a previous eye examination (P = 0.03) (Figure 9-8). Compared to children had not attended a previous eye examination, a larger proportion of children who had attended a previous eye examination were referred from the B4SC vision screening.

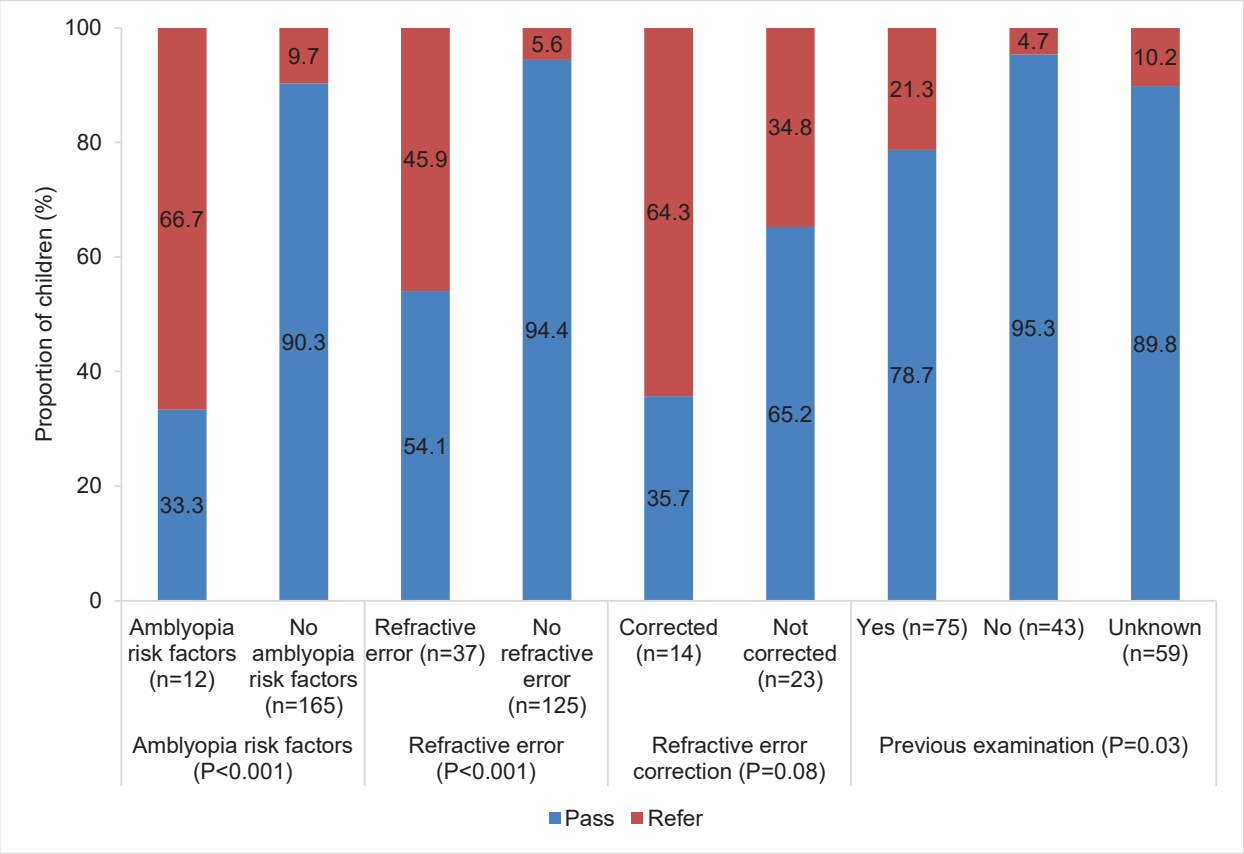

Figure 9-8: Presence of amblyopia risk factors, refractive error, refractive error correction and previous eye examination status by B4 School Check outcome

9.4 Discussion

This study provides contemporary data on vision conditions in NZ children. More than one in five children in this study had significant refractive error and half of these children did not have refractive correction. Significant refractive error was the most common cause of unaided and presenting visual impairment. In contrast, binocular vision anomalies were detected in approximately 10% of children in this study. Half of the children in this study had previously attended an eye examination, however 40% of children with a vision condition and one third of those whose caregivers reported concerns regarding their children's vision had no evidence of a previous eye examination.

9.4.1 Refractive error

Significant refractive error was detected in 23.6% of children in this study. The most common refractive error was astigmatism (15% of children in the study, 63% of all significant refractive error).

The proportion of children with significant refractive error in the current study (23.6%) was lower than seen in WTS (31.6%) which evaluated refractive error and visual impairment of children aged 6-7 years from an area of socioeconomic disadvantage (Chapter 8). Astigmatism was also more prevalent in WTS (25.4%) compared with the current study (15.0%). WTS recruited children to take part in a multidisciplinary study which did not have a specific vision focus. In contrast, for the current study, children were recruited to specifically take part in a study of visual function and reading. Families may have chosen to participate or decline participation based on previous eye care knowledge or experience. Additionally, there were differences in the ages and ethnicities of the children in these studies. Myopia prevalence increases with age, while hyperopia prevalence decreases and astigmatism prevalence reduces or remains stable with age (Fan et al., 2004; McCullough, O'Donoghue, & Saunders, 2016; Zhao et al., 2002). Refractive error prevalence also varies by ethnicity (Hopkins et al., 2016; Kleinstein et al., 2003). Nevertheless, in both WTS and the current study, astigmatism was the most common refractive error in NZ children.

Myopia was detected in 7.7% (17/220) of children, with a larger proportion of Asian children having myopia (15.6%) than children from other ethnic groups. Similarly, a previous study of Australian children aged 12 years found an overall myopia prevalence of 11.5%, with 38.5% of children of East Asian ethnicity having myopia (French et al., 2013). In children in China, a recent meta-analysis of population and school-based studies showed a myopia prevalence of 30.7% in children aged 7-12 years (Dong, Kang, Li, Wei, & Jonas, 2020). Thus, the proportion of children in the current study with myopia was significantly lower both for Asian children and those of other ethnicities. Previous studies have shown higher myopia prevalence for children residing in urban compared with rural areas (He, Zheng, & Xiang, 2009). Although children in the current study resided exclusively in urban areas, NZ children may have increased access to outdoor time compared with children from urban environments in other countries. Outdoor time of more than 120 minutes per day has been shown to be protective against myopia incidence and progression (Ho, Wu, & Liou, 2019).

The proportion of children in this study with myopia was larger than that seen in WTS (Chapter 8). This difference may be due to differences between the studies in terms of age group, ethnicity, socioeconomic status, and study recruitment. A study of Australian children aged 6 to15 years living in socioeconomic disadvantage found myopia prevalence of 3.5 to 4.3% (Fu et al., 2020), lower than that seen in studies of children living in more advantaged urban areas (French et al., 2013; Junghans & Crewther, 2003). Similarly, in an Australian study of children aged 5-13 years from schools with large

numbers of indigenous children, myopia was detected in 1.7% of indigenous children and 4.0% of non-indigenous children (Hopkins et al., 2016).

There are concerns regarding the increasing prevalence of myopia globally and the burden of ocular complications and vision loss resulting from high myopia (Holden et al., 2016). However, studies of Australian children have not shown the same increases in prevalence of myopia seen in some East Asian countries (Fu et al., 2020; Junghans & Crewther, 2005). A previous study of NZ children born in Dunedin in the early 1970s found a prevalence of myopia of 4.3% in children aged 11 years (Williams, Sanderson, et al., 1988). The proportion of children with myopia in our study (7.7%) suggests that, like Australia, myopia prevalence is not increasing in NZ at the same rate as has been observed in some other countries.

Spherical equivalent refraction was used in the current study to classify children with myopia and hyperopia, to enable comparison to other international studies (Negrel et al., 2000). However, for five of the 17 children classified with myopia, their refractive error was primarily astigmatism and they had myopia only in one meridian. The refractive error in these children is likely to be the result of corneal astigmatism (refractive myopia) rather than axial elongation (axial myopia) which is considered to be the primary cause of myopia progression (Flitcroft et al., 2019) and is the major risk factor for the development of ocular pathology (Saw et al., 2019). However, corneal astigmatism in pre-school aged children has been identified as a risk factor for myopia development (Fan et al., 2004; Gwiazda et al., 2000), suggesting that these children require monitoring for axial elongation and myopia progression.

Hyperopia was detected in 7.7% (17/220) of children in the present study. This is similar to the proportion of hyperopia (6.1%) seen in WTS (Chapter 8) and that seen in Australian children aged 5 to 13 years (5.1% in indigenous children and 8.1% in non-indigenous children) (Hopkins et al., 2016). In a study of Australian children in an urban area, hyperopia was detected in 9.4% of children at six years of age and 2.8% in the same group of children at 12 years of age (French et al., 2013). The prevalence of hyperopia seen in population studies of children in East Asian countries is low, and that seen in European countries with largely Caucasian populations is higher. Population studies from China (He et al., 2009; Wu et al., 2013; Zhao et al., 2000), Malaysia (Goh et al., 2005) and Thailand (Yingyong, 2010) have shown hyperopia prevalence of 1.3% to 5.9%. In contrast, studies from Ireland (Harrington, Stack, et al., 2019), Poland (Czepita, Żejmo, & Mojsa, 2007) and Sweden (Grönlund et al., 2006) have found hyperopia prevalence of 8.9% to 38%.

Astigmatism was detected in 15.0% (33/220) of children in the current study. This is lower than seen in WTS, in which 25.4% of children had astigmatism (Chapter 8). In a study in an urban area of Australia, similar levels of astigmatism were found in children aged 6 and 12 years (10.3% and 13.6% respectively) (Huynh et al., 2006; Huynh et al., 2007). Specific populations of children in the Americas

have prevalence of astigmatism of 30 to 40% (Harvey et al., 2010), as do those studies with high myopia prevalence (He et al., 2004; Wu et al., 2013). Astigmatism is associated with reduced scores of early literacy (Orlansky et al., 2015) and reduced reading fluency (Harvey et al., 2016), therefore, it is important that children with significant astigmatism have refractive correction. Furthermore, as increasing astigmatism can be an early sign of keratoconus (Romero-Jiménez et al., 2010), it is important that children with astigmatism receive regular follow-up to ensure early detection and timely treatment.

Refractive error is correctable with glasses or contact lenses and correction results in improved VA and reduced asthenopic symptoms (Abdi & Rydberg, 2005). In the current study, only 44.2% (23/52) of the children with significant refractive error were wearing correction. This is similar to the results of a study of Australian children aged 12 years, which found that just over half of children with significant refractive error had glasses (Robaei, Kifley, Rose, & Mitchell, 2006). Additionally, a recent meta-analysis found overall compliance with spectacle use is 40.1% in children, with reasons for non-compliance including lost or broken spectacles, forgetfulness and parent disapproval (Dhirar et al., 2020). Spectacle coverage in the current study was higher than in WTS where only 13.9% of children living in socioeconomic disadvantage wore glasses for significant refractive error (Chapter 8). Refractive error correction was higher in children nine years and older compared with children who were seven to less than nine years old. Further research is required to determine barriers to caregivers accessing eye care for their children and reasons for non-compliance with spectacle wear in the NZ paediatric population.

9.4.2 Binocular vision anomalies

Binocular vision anomalies were detected in 27 (11.5%) of children in this study. Strabismus was observed in seven (2.6%) children and non-strabismic binocular vision anomalies in 21 children (8.9%).

The proportion of children with strabismus in the current study is similar to that seen in studies of school children from Australia (Hopkins et al., 2016; Robaei, Rose, et al., 2006) and the United Kingdom (Bruce & Santorelli, 2016). In a population-based study of Australian children aged 6 years, 2.8% had strabismus and in another study of Australian children aged 5 to 13 years, 2.7% of non-indigenous children had strabismus at distance and 3.0% at near (Hopkins et al., 2016). A population-based study of children in the United Kingdom found a strabismus prevalence of 2.4% (Bruce & Santorelli, 2016).

There is currently a lack of published data regarding non-strabismic binocular vision anomalies, except for convergence insufficiency. Convergence insufficiency is the most frequently studied binocular

vision anomaly, however, the reported prevalence varies considerably due to differences in study sampling and definitions used for convergence insufficiency. Convergence insufficiency is defined by the presence of one or more of: an exophoria greater at near than distance, a remote near point of convergence and decreased positive fusional vergence at near (Cooper & Jamal, 2012). The reported prevalence of convergence insufficiency varies considerably from 5.2% to 18.3% (Abdi & Rydberg, 2005; Hopkins et al., 2016). The proportion of children with convergence insufficiency in the current study was 3.0% using a definition of two clinical signs. A study of Australian children aged 5-12 years found a higher prevalence of convergence insufficiency of 5.2% in non-indigenous children and 10.3% in indigenous children using all three clinical signs (Hopkins et al., 2016). A study of Indian children aged 7 to 17 years also found higher prevalence of convergence insufficiency using two clinical signs of 16.5% for children living in urban areas and 17.6% for those residing in rural areas (Hussaindeen et al., 2017).

Based on the currently available literature, convergence excess, divergence excess and accommodative insufficiency were present at similar rates in our study sample as in other populations. Convergence excess was detected in 4.3% of children in our study. Similarly, in a study of Australian children aged 5 to 13 years, convergence excess was detected in 5.4% of indigenous and non-indigenous children (Hopkins et al., 2016). Lower levels of convergence excess were detected in Indian children aged 7 to 17 years with 1.4% found in children in urban areas and 0.8% in children residing in urban areas (Hussaindeen et al., 2017). In the same study of Indian children, divergence excess was seen in 0.4% of children in urban areas and none of the children in rural areas. The proportion of children with divergence excess was also 0.4% in the current study. In contrast, the study of Australian children aged 5 to 13 years found divergence excess in 4.8% of indigenous children and 8.8% of non-indigenous children (Hopkins et al., 2016). In the current study, accommodative insufficiency was seen in 1.3% of children compared with 0.2% of urban children and none of the rural children in the Indian study (Hussaindeen et al., 2017). Differences in prevalence between the Australian and Indian studies may be due to differences in population demographics, however the Indian study also established population normative values and determined the presence of binocular vision anomalies based on these values.

In addition to the paucity of comparative data for non-strabismic binocular vision anomalies, there is also a lack of NZ normative data for vergence and accommodation measures. The expected values for vergence and accommodation used to determine presence of binocular vision anomalies are based on international data (Scheiman, 2014). As binocular vision anomalies are diagnosed when a child scores below expected values on more than parameter (Scheiman, 2014), the prevalence of these conditions may have been underestimated or overestimated depending on the true normative values for the NZ paediatric population.

Like non-strabismic binocular vision anomalies, the literature regarding reduced stereoacuity is limited. Additionally, a range of tests are used to evaluate stereoacuity and differing values used to define reduced stereoacuity, making it difficult to compare between studies. In the current study, the Randot Preschool stereotest was used to evaluate near stereoacuity. This test has been shown to have high reliability in children aged 2-12 years (Fawcett & Birch, 2000; Read et al., 2019; Wang et al., 2010). Normative data collected on 1402 children aged 3-18 years for the Randot Preschool stereotest found mean stereoacuity of 40 arcsec for children aged 7-18 years, with a lower limit (two standard deviations from the mean) of 60 arcsec (Birch et al., 2008).

Previous studies have shown children with vision disorders have reduced stereoacuity compared with those without vision disorders (Ciner et al., 2014). Reduced stereoacuity is associated with amblyopia, strabismus and anisometropia (Robaei et al., 2007) and also with lower best corrected VA, higher inter-eye difference in spherical equivalent refraction, higher cylindrical refractive error, higher spherical refractive error and higher inter eye difference in best corrected VA (Guo et al., 2016).

In the current study, a larger proportion of children with significant refractive error and binocular vision anomalies had reduced stereoacuity compared with children without these conditions. However, the proportion of children with reduced stereoacuity was high (82/237, 34.6%) and a significant number of children (40/82, 48.8%) with reduced stereoacuity did not have a vision condition.

In a study of Australian children aged 12 years, the prevalence of reduced stereoacuity (TNO test greater than 120 arcsec) was 3.7% (Robaei et al., 2007). However, a previous study of NZ children using the TNO test, found reduced stereoacuity (greater than 120 arcsec) in 41.0% of children at age 7 years and 9.1% at age 11 years (Williams, Simpson, & Silva, 1988). A recent study of normative data for the Randot Preschool stereotest with children aged 2-11 years in the United Kingdom found higher mean stereoacuity values, and therefore a higher lower limit for stereoacuity (Read et al., 2019). Using a lower limit of two standard deviations from the mean for children aged 6-7 years or 10-11 years gives the criteria for reduced stereoacuity of greater than 200 arcsec. In the current study, 14.3% of children had stereoacuity of worse than 200 arcsec, 73.2% of whom had a visual condition.

Stereaoacuity was measured unaided or with the participant's usual correction in order to evaluate their habitual visual function. Some children may have achieved better stereoacuity with refractive correction in place, however, a proportion of children with reduced stereoacuity did not have a vision condition. Further research is required to determine normative values for stereoacuity in NZ children, as well as the levels of stereoacuity for which visual function is reduced and levels of refractive error requiring correction to improve stereoacuity.

9.4.3 Visual impairment

The proportion of children with unaided and presenting visual impairment in both eyes was low for both distance VA (presenting 11/236, 4.7%, unaided 17/237, 7.2%) and near VA (presenting 10/236, 4.2%, unaided 18/237, 7.6%). The level of distance visual impairment was higher than seen in WTS, likely due to a higher proportion of children with myopia in the current study. Unaided visual impairment was similar to that seen in urban Australian children aged 12 years (7.4%) (Robaei, Kifley, et al., 2006). In contrast, presenting visual impairment was higher than in a study of Australian children aged 5 to 13 years recruited from schools with high proportions of indigenous children (0.6% in indigenous children and 1.7% in non-indigenous) (Hopkins et al., 2016).

Refractive error is considered to be the most frequent cause of visual impairment in children worldwide (Varma et al., 2017) and was also the most common cause of unaided and presenting visual impairment in the current study. There was no child in this study with visual impairment caused by ocular pathology. In contrast, population based studies in South Africa (Naidoo et al., 2003), India (Dandona et al., 2002), Nepal (Pokharel et al., 2000) and Turkey (Caca et al., 2013) have reported visual impairment due to ocular pathology.

Population studies of children in China have found unaided visual impairment in up to 35% of children (He et al., 2004; Wu et al., 2013). The prevalence of myopia was much higher in studies of Chinese children compared to the current study. Myopia is associated with reduced distance VA with children with higher levels of myopia having worse distance VA (Leone et al., 2010). In contrast, some children with high levels of hyperopia (Leone et al., 2010) and astigmatism (Garber, 1981) can achieve VA that is normal or near normal. Each 0.25 D of myopia is associated with a one line decrease in VA (Hirsch, 1945; Luo et al., 2006), whereas for each dioptre of astigmatism a 1 to 1.5 line decrease in VA is observed (Harvey et al., 2006; Wolffsohn et al., 2011). Thus, children in this study who had mainly hyperopic or astigmatic refractive errors, were able to achieve VA above the threshold for visual impairment.

A larger proportion of children had reduced VA (0.1 to 0.2 logMAR) at distance (8.9%) or near (31.6%) in the current study. Children with hyperopia and those with astigmatism had VA that was reduced, particularly at near. This finding is similar to a study of children in the United States aged 4-5 years that found near VA was progressively worse for children with increasing levels of hyperopia (Ciner et al., 2021). In contrast, previous studies have found similar reductions in near VA as distance VA in individuals with astigmatism (Narayanasamy et al., 2015b; Wolffsohn et al., 2011). In the current study, a larger proportion of children without refractive error also had reduced near VA compared with distance VA. This difference between distance VA and near VA in children without refractive error and those with astigmatism may be due to the different testing formats. Distance VA

was tested using the ETDRS protocol presented on an EVA as single crowded letters, whereas near VA was tested using a near chart with the letters presented in linear ETDRS format. Previous studies have also shown differences in VA measured with single crowded letters compared with linear VA (Stewart, Hussey, Davies, & Moseley, 2006). A study of children in the United States aged 4-5 years found near VA that was one line worse than distance VA (Ciner et al., 2021). While distance VA has been studied extensively in children, data regarding near VA is limited. Further research is required to determine normative values for near VA in children and to establish minimum levels of VA required for successful learning.

Children who had visual impairment with their optimal refraction in one or both eyes despite wearing appropriate glasses were considered likely to have amblyopia. Amblyopia was considered the cause of visual impairment in both eyes for one child (0.4%) and in one eye for 2 additional children (0.9%). Amblyopia risk factors were detected in 20 (9.1%) of children. This is consistent with a meta-analysis which showed that that the prevalence of amblyopia risk factors is much higher than the number of children who develop amblyopia (Arnold, 2013). Of the three children in the present study with presumed amblyopia, two caregivers had completed the questionnaire, and both reported a history of previous amblyopia treatment such as patching or atropine penalisation. There was also one additional child with reduced best-corrected VA attributed to refractive error. As this child was not wearing glasses at the time of the study, they may also have had amblyopia due to their older age at time of commencing treatment (Holmes et al., 2011). Nevertheless, the proportion of children in this study with presumed and possible amblyopia was low and previous history of amblyopia treatment suggests that children with amblyopia risk factors are being identified and treated.

9.4.4 Previous eye examinations and ocular history

Half of children in this study had not previously attended, or it was unclear if they had previously attended, an eye examination. This result is similar to that found in a previous study of public knowledge and attitudes to eye health in NZ in which 44% of parents reported that their child had not, or they did not know if their child had, attended an examination (Ahn et al., 2011). In a study of children in the United Kingdom, 35.4% of children had been seen by an eye care specialist (Majeed et al., 2008). While the proportions of children with both significant refractive error and binocular vision anomalies who had a previous eye examination were significantly larger than those without, 39.4% (28/71) children with an ocular condition had not, or it was unclear if they had, attended a previous eye examination.

Of those caregivers who completed the questionnaire, there was a significant difference in the proportion of children with refractive error when their parent reported one or more concerns with their child's vision. A study of parents of children aged 6 to 71 months in the United States found that

parental concern about their child's overall development was associated with some refractive errors (Ibironke et al., 2011). Parents of children who pass their B4SC vision screening are advised to take their child for an eye examination if they have concerns regarding their child's vision. While many children for whom parents report concerns about their vision do not have a visual condition, in the absence of a regular formal vision screening programme, parental concern should be an indication for parents to seek eye care for their child. Only two-thirds of these children for whom their parents reported concerns about their vision had a previous examination. In a study from the United Kingdom, 38% of parents reported barriers to accessing eye care for their children, including 12% of parents who did not know how or where to access an eye examination for their child (Donaldson et al., 2018). Further research is required to determine specific barriers to parents accessing eye care for their children in NZ.

9.4.5 Symptoms

The convergence insufficiency symptom survey (CISS) was administered to children to determine the frequency of visual symptoms reported when completing near visual tasks. The CISS was developed to quantify the severity of symptoms in children with convergence insufficiency (Convergence Insufficiency Treatment Trial Investigator Group, 2009). A total score of 16 or greater is the cut-point for distinguishing children with symptomatic convergence insufficiency from those with normal binocular vision. In the current study, 41.4% (98/236) of children had a total score of 16 or greater and were classified as symptomatic. There was no difference in the proportion of children who were classified as symptomatic versus asymptomatic for those with refractive error or binocular vision anomalies. Similarly, in a study of Australian children aged 10-15 years, 45% of children had a CISS score of 16 or greater and the symptom score was not associated with presence of refractive error (Junghans, Azizoglu, & Crewther, 2020). Furthermore, a study of young adults from the United Kingdom found that 24.5% of participants had a high symptom score, however only 14.6% of these had clinical signs of convergence insufficiency (Horwood, Toor, & Riddell, 2014). These results suggest that while the CISS may be a useful tool in assessing change in children with convergence insufficiency (Convergence Insufficiency Treatment Trial Investigator Group, 2009), it is poor at discriminating between those with a visual condition and those without.

9.4.6 Visual-motor integration

Mean VMI and MC standard scores were lower than the normative population, while the median VP scores were similar to the mean for the normative population (Beery & Beery, 2010). Although the instruction manual reports the test to be culture-free, previous studies have shown ethnic differences with studies of children in East Asian populations having higher VMI scores (Lim et al., 2015; Ng, Chui, Lin, Fong, & Chan, 2015). It has been proposed that ethnic differences could be due to differing

fine motor experiences in early childhood. Girls had significantly higher standard scores than boys for the VP and MC supplemental tests, a finding that has also been seen in previous studies (Coallier, Rouleau, Bara, & Morin, 2014). Additionally, children aged 7 to less than 9 years achieved significantly higher VMI and MC standard scores than those 9 years and older. Further research is required to determine causes of reduced VMI and MC scores in NZ children, particularly for boys and older children. Furthermore, further evaluation is required to determine if changes in the NZ education system are responsible for the difference in standard scores between the younger and older children and if the standardised scores are relevant to NZ children. As VMI can be improved through therapy (Dankert et al., 2003), the reduced VMI and MC scores compared to the normative population suggest that programmes to improve visual-motor integration could benefit NZ children.

9.4.7 B4SC outcomes

B4SC outcomes differed to those seen in previous studies, with lower overall participation and fewer children with rescreen outcomes. The number of children identified for rescreening (6/188, 3.2%) was much lower than seen in WTS (12.7% of children screened) (Chapter 8). This may reflect differences in screening follow-up practises in different district health board (DHB) regions as most children in the current study resided in the Counties Manukau DHB region, whereas those in the Welcome to School study lived in the Auckland DHB region.

One in five children in the current study had no recorded B4SC vision screening outcome. This is higher than seen in previous studies (Findlay et al., 2020; Langeslag-Smith et al., 2015; Muller et al., 2019). This likely results from the older age of this cohort and mobility of families; at the 2018 census, 4.7% of children aged 0-15 year olds did not reside in New Zealand five years previously (Statistics New Zealand, 2020). Children who do not receive vision screening at four years of age are targeted for screening on school entry. However, the cut off for new entrant vision screening is the end of Year 3 (age 7-8 years). Children who move to New Zealand after this age may not have received previous vision screening and do not receive formal vision screening until the Year 7 screening at 11-12 years of age. A larger proportion of children aged 9 years and over had not received vision screening compared with those 7 to less than 9 years. This may be due to a larger proportion of children in this age group having newly entered NZ, or the result of improvements to B4SC protocols improving coverage.

The value and need for continuation of VA screening at 11 years of age in NZ children has been questioned (Ramachandran, Wilson, & Wilson, 2016). The primary aim of vision screening in school-aged children is to detect new conditions that have developed during the school years and any previously undetected vision conditions (Logan & Gilmartin, 2004). Early detection and correction of myopia may reduce myopia progression and reduce potential complications of high myopia (Saw et al., 2019). The lower overall participation in B4SC vision screening in the current study, accompanied by

the higher proportion of children with myopia compared to WTS, which assessed younger children, supports the continuation of screening at a later age following the B4SC.

While the proportion of children who were referred from vision screening was larger for those with significant refractive error and amblyopia risk factors, more than half of children with significant refractive error (20/37, 54.0%) and four children (33.3%) with amblyopia risk factors had previously passed their B4SC vision screening. Due to the time elapsed between the B4SC vision screening (age 4-5 years) and our assessment (age 7-10 years), it is not possible to determine if these children had significant refractive error at the time of their B4SC. However, the majority of refractive error in this population was astigmatism which reduces or stays stable during this age group (Fan et al., 2004; O'Donoghue et al., 2011; Zhao et al., 2002), suggesting that many of the children with significant refractive error detected in this study would have also had refractive error at the time of B4SC vision screening. Furthermore, the proportion of children with significant refractive error that passed screening was similar to that seen in WTS (Chapter 8). VA screening is effective at detecting myopia but not hyperopia or astigmatism (Leone et al., 2010; O'Donoghue et al., 2012). The aim of the current B4SC vision screening programme is detection of amblyopia. However, non-amblyogenic levels of hyperopia and astigmatism have been associated with reduced performance on tests of academic ability (Hopkins, Narayanasamy, et al., 2019). Therefore, improvements to the screening protocol are necessary to ensure that NZ children with significant refractive error that may affect classroom learning are being detected through vision screening. The addition of an autorefractor to the current screening protocol may increase the number of children with refractive error correctly identified by vision screening (Chapter 7).

These results should be considered in view of the limitations of the study. The children recruited for this study are not a representative sample of the NZ paediatric population, which may limit the generalisability of the results. The children in this study all resided in Auckland in an urban setting, however, schools were invited to participate across a range of school deciles to ensure that children from a wide range of socioeconomic backgrounds were included in the sample. Eye care services are likely to be more readily accessed in urban than rural areas of NZ. A previous study found that people residing in remote rural areas of NZ have significantly longer travel times to see their general practitioners (Brabyn & Barnett, 2004). This is likely to be a greater barrier to access for eye care as there are less eye care providers than general practitioners (Medical Council of New Zealand, 2019; Optometrists and Dispensing Opticians Board, 2019) and optometrists are not distributed equally across NZ regions (Chapman, Anstice, & Jacobs, 2020). Additionally, children in this study were recruited to participate in a study specifically examining visual outcomes. Parents may have chosen for their child to participate due to a suspected vision problem or declined participation due to known vision problems that were considered adequately corrected. There is a need for a population-based

paediatric eye health survey in NZ to determine prevalence of refractive error and other visual conditions. This will in turn inform the most appropriate methods and timings for vision screening.

Participation in this study was relatively low for Māori children, who make up 16.5% of the general population (Statistics New Zealand, 2020) but only represented 8.4% of the study population, despite recruitment across a range of school deciles including those with a high proportion of Māori children. Future research should employ *Kaupapa Māori* methodologies to improve Māori participation and thus ensure that future policy changes benefit Māori children and improve equity.

In summary, more than one in five children in this study had significant refractive error, most frequently astigmatism, and half of those children were not wearing correction. Lack of ocular pathology and low levels of amblyopia indicate that screening should be targeted at identifying children with refractive error which, when corrected, will improve visual function. Furthermore, detection and monitoring of children with myopia and astigmatism will allow treatment to reduce myopia progression and early intervention for children with astigmatism who develop keratoconus. Many of the children with significant refractive error had passed their B4SC vision screening, and one in four children in this study had not received screening. The current vision screening protocol is not targeted to detection of non-amblyogenic refractive error which may affect academic outcomes and changes to this protocol may improve visual and academic outcomes. Further research is required to understand and address barriers to eye care and spectacle wear in NZ.

Chapter 10: Visual conditions and their associations with visual-motor integration, reading ability and eye movements while reading

The literature review presented in Chapter 1 identified associations between VA, refractive error and reading ability, however findings from previous studies have been inconsistent. Additionally, the pilot study presented in Chapter 4 demonstrated that reduced near VA caused by induced optical blur resulted in reduced scores on the Beery VMI and its supplemental tests. However, it remains unclear how uncorrected blur, to which children have adapted, affects visual perceptual skills. Furthermore, new eye tracking technology allows the evaluation of eye movements while reading in a clinical setting. This chapter examines the associations between vision parameters and VMI, reading ability and measures of eye movements while reading for the same children in the study described in Chapter 9.

10.1 Introduction

Learning to read is a key early academic outcome (Hulme & Snowling, 2016) and reading ability is a significant predictor of academic success (Cooper, Moore, Powers, Cleveland, & Greenberg, 2014; Lonigan, 2006). Children with poor reading skills are more likely to have social and behavioural issues in school (Miles & Stipek, 2006) and may suffer from psychological and emotional distress (Alexander-Passe, 2006). Most children learn word reading skills in the first two years of school and acquisition of literacy skills is greatest during this time period (Reardon, Valentino, & Shores, 2012). Therefore, early identification and intervention on reading problems is important.

Reading requires sufficient VA to see the text, adequate accommodation and convergence to maintain clear and single vision and accurate saccades and fixations (Handler & Fierson, 2017). Eye movements while reading English language text consist of a series of rightwards saccades of 2 to 4 degrees (7-9 letters) used to move across a line of text, followed by a longer leftwards saccade of about 10 degrees to get the beginning of the next line (Kulp & Schmidt, 1996a; Rayner, 2009; Scheiman & Rouse, 2006). Regressions are small saccades that move backward through the text (Rayner, 1998). Short regressions of a few letters may be due to the reader making a saccade which is too long or due to problems that the reader has processing the currently fixated word. Longer regressions of more than ten letters occur because the reader did not understand the text. Between saccades, fixations with average duration of 200 to 250 milliseconds (ms) are used to obtain new information (Rayner, 1985).

Eye movements develop during the primary school years with reductions in the number of fixations and regressions (Scheiman & Rouse, 2006). These changes are the result of increases in oculomotor

control and improving linguistic processing skills (Scheiman & Rouse, 2006). Less proficient readers exhibit eye movement patterns that are similar to beginner readers with shorter forward saccades, an increased number of regressions and longer fixation times (Handler & Fierson, 2017; Rayner, 1985; Soh, 2016). Therefore, eye tracking has been proposed as a screening tool for dyslexia (Nilsson Benfatto et al., 2016; Smyrnakis et al., 2017).

While there has been extensive research evaluating eye movements while reading (Rayner, 1978, 1998), eye tracking technology suitable for use in clinical practice has only recently been developed (Thomson, 2017). Therefore, the relationship between visual conditions and eye movements while reading has not been systematically explored. Furthermore, although eye movements during reading have been studied extensively, the children in these studies have not had comprehensive eye examinations to assess VA or refractive error. Hence, the influence of these factors is unknown.

Studies of visual conditions and reading outcomes have produced conflicting results (Hopkins, Narayanasamy, et al., 2019). Some studies have found an association between VA and scores of early literacy (Bruce et al., 2016; Chen et al., 2011; Jan et al., 2019) while other studies have found no association between VA and academic outcomes (Dirani et al., 2010; Grisham et al., 2007; Helveston et al., 1985). In preschool children in the United Kingdom, literacy scores were significantly associated with presenting distance VA, independent of cognitive ability, as well as demographic and socioeconomic factors (Bruce et al., 2016). Similarly, distance and near VA were correlated with academic scores in a study of American children aged 6-12 years (Maples, 2003). In contrast, a study of schoolchildren in Singapore aged 9-10 years, presenting distance VA was not related to academic school performance (Dirani et al., 2010). The children in this study were older than in the study by Bruce et al. and it is unknown whether this age difference may have affected the outcomes. Despite the fact that near activities contribute to a significant proportion of classroom learning, studies examining associations of near VA with academic performance are limited (Hopkins, Narayanasamy, et al., 2019). The Vision in Preschoolers study found that children with hyperopia and reduced near visual function had reduced scores on preschool tests of early literacy (Kulp et al., 2016). Further research is required to fully understand the impact of reduced near VA on academic outcomes. Proposed reasons for disparities in study results include differences in criteria for abnormal VA and large numbers of children with normal VA within study populations (Hopkins, Narayanasamy, et al., 2019). Additionally, studies frequently do not analyse these results according to type of refractive error; children with low to moderate levels of myopia frequently have normal VA at near whereas children with high myopia, hyperopia and astigmatism typically have reduced near VA.

Similarly, some studies have demonstrated associations between refractive error and reading outcomes (Harvey et al., 2016; Kulp et al., 2016; Orlansky et al., 2015; Shankar et al., 2007) while others have found no association (Hopkins et al., 2017; Williams, Sanderson, et al., 1988). The discrepancies in these findings are mostly likely due to differences in study populations, methodology, refractive error definitions and criteria for classification of children with and without reading difficulties.

In some studies, hyperopia has been associated with reduced scores on tests of reading, early literacy and other academic measures in preschool and school-aged children (Fulk & Goss, 2001; Krumholtz, 2000; Kulp et al., 2016; Quaid & Simpson, 2013; Rosner, 1997; Shankar et al., 2007; Simons & Gassler, 1988; Williams et al., 2005). In a large scale study, the Vision in Preschoolers study group found that preschool children aged 4-5 years with uncorrected hyperopia (between +3.00 dioptres and +6.00 dioptres) and reduced near visual function (reduced near VA or reduced near stereoacuity) scored significantly lower in a test of preschool early literacy than preschool children of the same age without refractive error (Kulp et al., 2016). Similarly, a study of preschool children aged 3-7 years showed children with hyperopia (+2.00 dioptres or more) had significantly reduced performance on tests used to indicate emergent literacy skills compared with children without refractive error (Shankar et al., 2007). In children aged 7-8 years, those with hyperopia (more than +3.00 dioptres) scored lowest on tests of educational achievement (Williams et al., 2005). In contrast, in a study of Australian schoolchildren, Hopkins et al. (Hopkins et al., 2017), found no difference in reading accuracy and reading comprehension between children with and without uncorrected hyperopia (+1.50 dioptres or more). The authors suggested that other factors affecting educational factors may have coexisted in this population and may have masked the impact of hyperopia in these children.

Studies in preschool-aged children have shown uncorrected astigmatism results in poorer performance on cognitive, language and fine motor tasks (Harvey et al., 2018) and detrimentally affects academic readiness (Orlansky et al., 2015). Additionally, a study of school-aged children found children with uncorrected astigmatism (greater than 1.00 D) had reduced oral reading fluency scores compared with those with low or no astigmatism (Harvey et al., 2016). Reading fluency improved with spectacle correction, with greater improvement in children with higher magnitudes of astigmatism.

Myopia has been associated with average or above average reading and intelligence test scores (Mutti et al., 2002; Simons & Gassler, 1988; Stewart-Brown et al., 1985; Williams, Sanderson, et al., 1988) and children with myopia have increased reading speeds compared with children with hyperopia (van Rijn et al., 2014). In children aged 10-12 years in Singapore, myopia was associated with higher academic achievement, with higher examination scores associated with higher levels of myopia (Saw et al., 2007). However, correction of moderate myopia has been shown to improve self-reported visual functioning in children (Esteso et al., 2007). Furthermore, provision of glasses to children aged 9-12

years in China, of whom 95% of children with refractive error had myopia, resulted in improvement in academic test scores when compared to controls who did not receive glasses (Ma et al., 2014).

Impaired visual perceptual skills have also been associated with reduced academic outcomes (Lowther et al., 2000; Santi et al., 2015; Sortor & Kulp, 2003). However, the effect of uncorrected vision conditions on VMI is unknown.

The hypothesis of this study was that refractive error (hyperopia and/or astigmatism) or reduced near visual function will result in reduced scores of visual motor integration and reading ability. Furthermore, it was hypothesised that children with refractive error refractive error (hyperopia and/or astigmatism) or reduced near visual function will have eye movements more similar to beginner and less skilled readers.

The aim of this study was, therefore, to investigate whether visual conditions are associated with visual-motor integration, reading ability, and eye movements while reading, among school-aged children aged 7-10 years living in Auckland, NZ.

10.2 Methods

The research followed the tenets of the Declaration of Helsinki, ethical approval was attained from the University of Auckland Human Ethics Committee (Reference number: 020926). Parental consent was obtained for each child and assent was obtained from the child.

The same group of children described in Chapter 9 participated in this component of the study. All children received a comprehensive eye examination that was carried out at their school and the results of this have been presented in the previous chapter.

10.2.1 Comprehensive eye examinations

Comprehensive eye examinations were carried out as described in Chapter 9. Distance VA was measured using the e-ETDRS protocol presented on an EVA testing system (JAEB Centre for Health Research) (Beck et al., 2003) at a distance of 3 m. Near VA was measured using the Lighthouse near logMAR acuity chart (Good-Lite Company) at 40 cm. Refractive error was assessed using cycloplegic retinoscopy. Binocular vision assessment included the cover-uncover test and alternating cover test, measurement of positive and negative fusional reserves, and near point of convergence and near point of accommodation. Near stereoacuity was measured using the Randot Preschool stereotest at 40 cm (2012, Stereo Optical Company Inc).

10.2.2 Reading ability

The Neale Analysis of Reading Ability (Neale analysis) was used to assess reading accuracy, fluency and comprehension (Neale, 1999). Form 1 of this test was administered according to the instructions in the manual with the participant wearing their habitual correction. Each child was asked to read aloud passages of text with increasing difficulty. At the end of each passage, the child was asked a series of comprehension questions regarding the text. The time taken to read the text, the number of errors made while reading and the number of comprehension questions answered correctly were all recorded. Accuracy (range 1-94), comprehension (range 1-40) and rate (range 6-122) scores were calculated according to the criteria in the manual. Reading assessment was completed by the thesis author prior to the comprehensive eye examinations.

10.2.3 Visual-motor integration

The Beery VMI (sixth edition) was used to assess visual-motor integration (Beery & Beery, 2010). This test was carried out according to the instructions in the manual with the participant wearing their habitual correction. Raw scores were converted to standard scores using the tables in the manual (range 45 to 153).

10.2.4 Eye movement assessment

The Clinical Eye Tracker (Thomson Software Solutions) was used to assess eye movements during reading. The system comprised a monitor with an attached eye tracking bar that used infrared cameras to detect eye position to within less than one degree and recorded eye position at approximately 60 measurements per second (Thomson, 2017). The Clinical Eye Tracker is a clinically available system that allows direct observation and recording of simultaneous binocular eye movements without the need for a head restraint. The patient was positioned approximately 50 cm from the screen wearing their habitual correction (Figure 10-1).

Calibration was carried out using the calibration routine; a series of four dots were presented on different parts of the screen. The participant was encouraged to keep their head still and look towards the dots, in any order. Each dot was fixated until it “exploded”. Once calibration was completed, the participant was encouraged to keep their head in the same position throughout testing. Recordings for children for whom calibration was unsuccessful (n = 2) were excluded from analysis.

Eye tracking data was recorded for four different stimuli: two non-word tasks and two word-reading tasks.

Figure 10-1: Eye tracking system

10.2.4.1 Non-word tasks

The saccade task comprised alternate presentation of two horizontally displaced fixation targets (red dots) on the screen. The participant was asked to look at each stimulus as it appeared on the screen and eye movements were recorded for twenty seconds.

The letter saccade test presented two columns of randomly generated letters in 16 point Arial font (Figure 10-2). Children were asked to read the letters aloud starting at the top of the left column and reading pairs of letters until they reached the bottom. Eye tracking measures collated from the non-word tasks were average viewing distance, total fixations and median fixation duration. Task duration was also measured for the letter saccade task.

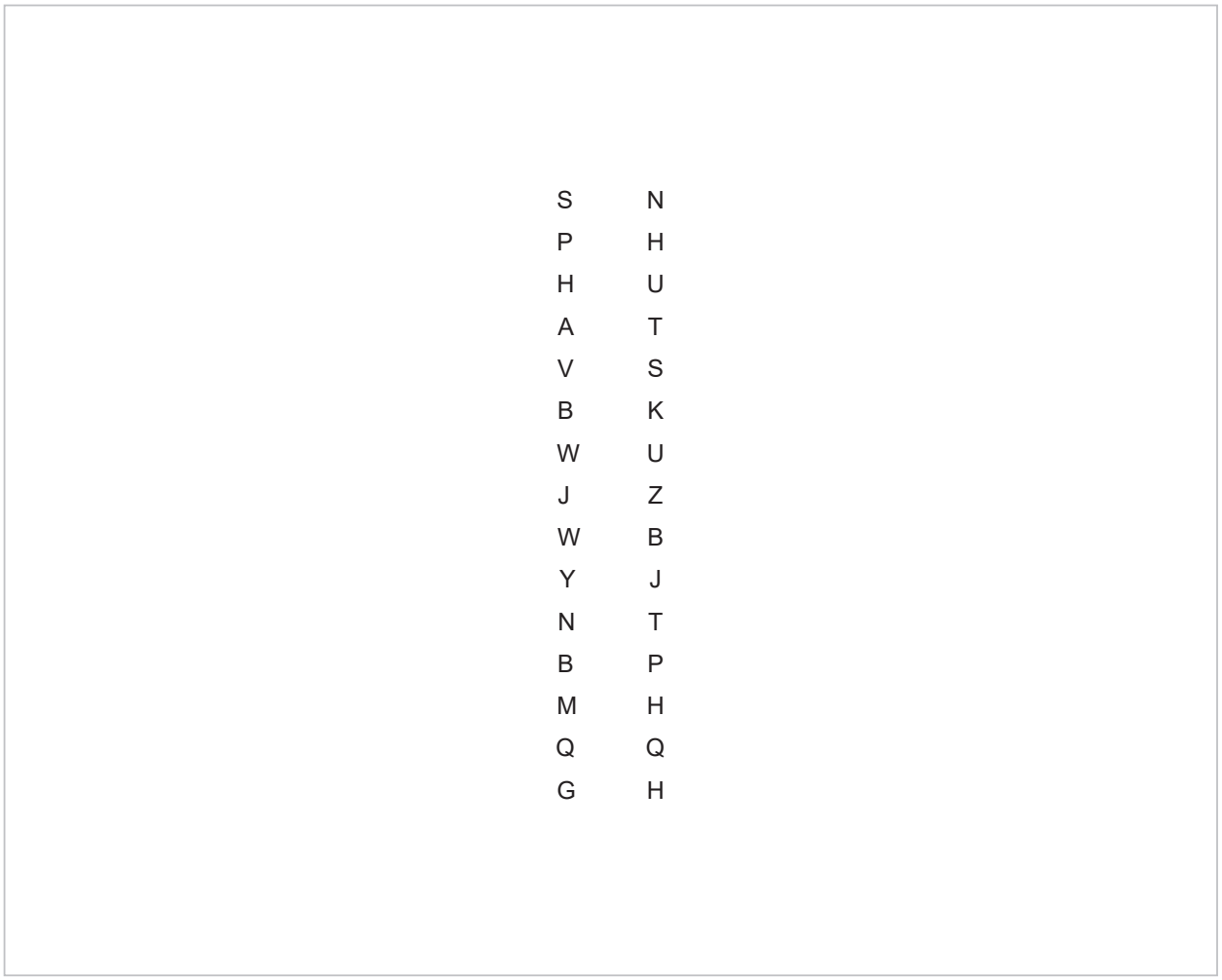

Figure 10-2: Eye tracking stimulus for letter saccade task

10.2.4.2 Word reading tasks

Children completed two word reading tasks. The rate of reading task is a stimulus on the Clinical Eye Tracker which presents a passage of words simulating a normal reading task but without contextual information (Thomson, 2015) (Figure 10-3). Fifteen rows of pseudo-random words were presented on the screen and the children were asked to read the words aloud. The contextual reading task was a custom task created for this study. For this task, children were asked to read aloud a contextual passage, chosen to be age-appropriate text for a seven to eight year old reading level (Fountas & Pinnell, 2012) (Figure 10-4).

Children who were unable to read letters (n=1) or words (n=7) were not asked to complete these tasks and recordings where the child did not read the complete passage (rate of reading n=3, contextual passage n=8) were excluded from the analysis.

Eye tracking measures collated from the word reading tasks were average viewing distance, task duration, total fixations, median fixation duration, total regressions and regressions per fixation.

Figure 10-3: Eye tracking stimulus for rate of reading task.

Once upon a time there were four little Rabbits, and their names were Flopsy, Mopsy, Cotton-tail, and Peter.

They lived with their Mother in a sand-bank, underneath the root of a very big fir-tree.

'Now my dears,' said old Mrs. Rabbit one morning, 'you may go into the fields or down the lane, but don't go into Mr. McGregor's garden: your Father had an accident there; he was put in a pie by Mrs. McGregor.'

'Now run along, and don't get into mischief. I am going out.'
Then old Mrs. Rabbit took a basket and her umbrella, and went through the wood to the baker's. She bought a loaf of brown bread and five currant buns.

Flopsy, Mopsy, and Cotton-tail, who were good little bunnies, went down the lane together to gather blackberries.

But Peter, who was very naughty, ran straight away to Mr. McGregor's garden, and squeezed under the gate!

First he ate some lettuces and some French beans; and then he ate some radishes; and then, feeling rather sick, he went to look for some parsley.

But round the end of a cucumber frame, whom should he meet but Mr. McGregor!

Mr. McGregor was on his hands and knees planting out young cabbages, but he jumped up and ran after Peter, waving a rake and calling out "Stop thief!"
Peter was most dreadfully frightened; he rushed all over the garden, for he had forgotten the way back to the gate.

Figure 10-4: Eye tracking stimulus for contextual reading task

10.2.5 Definitions

Distance and near VA were classified in three categories: visual impairment was defined as VA of 0.3 logMAR or worse, reduced VA was defined as VA of 0.1 to 0.2 logMAR and not reduced (normal) VA as VA of 0.0 logMAR or better. Where single letter scoring was using in VA measurement, the child was considered to have successfully achieved a logMAR level if they correctly named four of the five letters for that level. The Beery VMI, Neale Analysis and eye tracking measures were all completed binocularly with the child wearing their habitual correction. Therefore, presenting VA of the better eye was used to examine whether VA was associated with VMI, reading and eye tracking measures.

Refractive error was classified using the cycloplegic retinoscopy results. Clinically significant refractive error (Table 3-2) was defined according to the Refractive Error Studies in Children group (Negrel et al., 2000). Refractive error was defined as presence of hyperopia or astigmatism (uncorrected and corrected) and as uncorrected hyperopia or astigmatism. Non-strabismic binocular

vision anomalies were defined using the integrative analysis approach (Table 3-5) (Scheiman, 2014). Reduced stereoacuity was defined as near Randot stereoacuity worse than 60 arcsec (Birch et al., 2008).

10.2.6 Analysis

Data analysis was conducted using SPSS Statistics (Version 27, IBM Corporation, New York, USA). A two-tailed $P < .05$ was considered statistically significant. All continuous variables were tested for normality (Kolmogorov-Smirnov and the Shapiro-Wilk tests) to determine if they had a parametric or non-parametric distribution. Descriptive statistics were used to summarise the data and were presented as means and standard deviations (SD) for parametric data, and as medians and interquartile ranges (IQR) for non-parametric data.

Pearson correlation coefficients were used to explore potential relationships between dichotomous vision measures and parametric outcome variables and Spearman correlation coefficients for ordinal vision measures and outcome variables. T-tests and the one-way ANOVA were used to compare means of parametric measures of visual-motor integration, reading ability and eye tracking between children with and without vision conditions. The Mann-Whitney U test and the Kruskal Wallis test were used to compare medians of non-parametrically distributed data for comparisons of measures of reading ability, visual-motor integration, and eye tracking between children with and without vision conditions. Correlation, T-test, one-way ANOVA, Mann-Whitney U and Kruskal Wallis results are all summarised in the results and detailed in Appendix B.

Multivariable analyses using linear mixed models (for parametric outcome variables) and logistic mixed models (median-splits of non-parametric outcome variables) examined whether vision measures were associated with scores of visual-motor integration, scores of reading ability and eye tracking measures. These models were adjusted for sex, age group and ethnicity, with the participant's school included in the models as a random effect. For parametric outcome variables, separate linear mixed models examined whether the predicted scores for children differed (on average) from those without vision conditions; results were summarised using beta coefficients and their standard errors (SE). For dichotomous outcomes (median-splits of non-parametric variables), separate logistic mixed models examined whether children with vision conditions (versus those without) were less likely to achieve scores above the median value. Independent associations were described using adjusted odds ratios (aOR) and their 95% confidence intervals (CI).

10.3 Results

Vision conditions were described in detail in Chapter 9 and are summarised below in Table 10-1.

Table 10-1: Vision conditions

Vision condition	n (%)
Distance visual acuity (n=237)*	
Not reduced	205 (86.5)
Reduced	21 (8.9)
Visual impairment	11 (4.6)
Near visual acuity (n=237)*	
Not reduced	152 (64.1)
Reduced	75 (31.6)
Visual impairment	10 (4.2)
Hyperopia (n=220)†	
Present	17 (7.7)
Absent	203 (92.3)
Uncorrected hyperopia (n=220)	
Present	8 (3.6)
Absent	212 (89.5)
Astigmatism (n=220)†	
Present	33 (15.0)
Absent	187 (85.0)
Uncorrected astigmatism (n=220)	
Present	15 (6.8)
Absent	205 (93.2)
Binocular vision anomalies (n=235)	
Present	27 (11.5)
Absent	208 (88.5)
Reduced stereoacuity (n=237)	
Present	82 (34.6)
Absent	155 (65.4)

* Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

† Corrected and uncorrected refractive error

10.3.1 Visual-motor integration

The Beery VMI was completed by all 237 children. Scores for 9 participants on the VP test and 1 participant on the MC test were below the range for which standard scores were available in the manual. Therefore, the results for these children were excluded from the analysis.

Reduced stereoacuity was significantly correlated with MC standard scores. Mean MC standard scores were lower for children with reduced stereoacuity, compared to those without reduced stereoacuity. In the mixed model analysis (adjusted for sex, age group and ethnicity), reduced stereoacuity was significantly associated with MC standard scores. The adjusted analysis showed that for children with reduced stereoacuity, the predicted MC standard scores were 4.46 (SE = 1.83) points lower than for children without reduced near stereoacuity (P = 0.02, data not shown in the table).

10.3.2 Neale analysis of reading ability

The Neale analysis was completed by 230 children. Rate scores could not be calculated for four children due to incomplete information.

10.3.2.1 Distance VA

Children with reduced distance VA and distance visual impairment had lower median accuracy scores than children without reduced distance VA. In the mixed model analysis (adjusted for sex, age group and ethnicity), distance VA was significantly associated with reading accuracy scores (data not shown in the table). Compared to children without reduced distance VA, children with reduced distance VA were less likely to have reading accuracy scores above the median value (aOR = 0.17; 95% CI = 0.05-0.59, P = 0.01).

10.3.2.2 Near VA

Significant correlations were observed between near VA and reading accuracy, comprehension and rate scores. Children with reduced near VA and near visual impairment had lower median reading accuracy and comprehension scores and lower mean rate scores, compared to children without reduced near VA. In the mixed model analysis (adjusted for sex, age group and ethnicity), near VA was significantly associated with scores of reading accuracy, comprehension and rate (Table 10-2). The adjusted analysis showed that compared to children without reduced near VA, children with near visual impairment were less likely to have reading accuracy scores above the median value (aOR = 0.11; 95% CI = 0.02-0.65, P = 0.02). Additionally, children with reduced near VA (aOR = 0.42; 95% CI = 0.21-0.85, P = 0.02) and near visual impairment (aOR = 0.14; 95% CI = 0.03-0.75, P = 0.02) were less likely to have comprehension scores above the median value. For children with reduced near VA and near visual impairment, the predicted reading rate scores were respectively 10.51 (SE = 3.17, P = 0.001) points and 17.03 (SE = 7.22, P = 0.02) points lower, than for children without reduced near VA.

10.3.2.3 Near stereoacuity

There were also significant correlations between reduced stereoacuity and reading accuracy and comprehension scores. Children with reduced stereoacuity had significantly lower median accuracy and comprehension scores compared to children without reduced near stereoacuity. In the mixed model analysis (adjusted for sex, age group and ethnicity), reduced stereoacuity was significantly associated with both reading accuracy and comprehension scores (Table 10-2). The adjusted analysis showed that children with reduced stereoacuity were less likely to have accuracy (aOR = 0.40; 95% CI = 0.21-0.76, P = 0.01) and comprehension (aOR = 0.45; 95% CI = 0.23-0.88, P = 0.02) scores above the median value, compared to children without reduced stereoacuity.

10.3.2.4 Visual-motor integration

Significant correlations were observed between VMI, VP and MC standard scores and reading accuracy and comprehension scores, and also between VP standard scores and reading rate scores. In the mixed model analysis (adjusted for sex, age group and ethnicity), VMI, VP and MC standard scores were significantly associated with reading accuracy and comprehension scores, and VP standard scores were significantly associated with reading rate scores (Table 10-2). The adjusted analysis showed that for each one-point increase in VMI standard scores, there was an increased likelihood of having scores above the median value for reading accuracy (aOR = 1.07; 95% CI = 1.03-1.11, P < 0.001) and for comprehension (aOR = 1.07; 95% CI = 1.03-1.11, P < 0.001). Similarly, for each one point increase in MC standard scores, there was an increased likelihood of having reading accuracy (aOR = 1.05; 95% CI = 1.02-1.07, P < 0.001) and comprehension (aOR = 1.06; 95% CI = 1.04-1.09, P < 0.001) scores above the median value. Compared to children with VP scores equal to or below the median value, children with VP scores above the median value were more likely to have reading accuracy (aOR = 2.32; 95% CI = 1.25-4.29, P = 0.01) and comprehension (aOR = 2.38; 95% CI = 1.25-4.52, P = 0.01) scores above the median value. Furthermore, children with VP standard scores that were above the median had predicted reading rate scores 6.55 (SE = 3.00, P = 0.03) points higher than children with VP standard scores below the median.

Table 10-2: Associations between vision measures and scores on the Neale Analysis of Reading Ability, adjusted for sex, age and ethnicity

Vision measure	Accuracy			Comprehension			Reading rate
	≤ Median (≤ 52) n (%)	> Median (> 52) n (%)	Adjusted† OR‡ (95% CI)	≤ Median (≤ 20) n (%)	> Median (> 20) n (%)	Adjusted† OR‡ (95% CI)	Beta coefficient† (SE)
Near VA§							
Not reduced	66 (56.4)	82 (72.6)	Reference	68 (56.7)	80 (72.7)	Reference	Reference
Reduced	44 (37.6)	82 (72.6)	0.54 (0.28-1.05)	46 (38.3)	27 (24.5)	0.42 (0.21-0.85)*	-10.51 (3.17)**
Visual impairment	7 (6.0)	2 (1.8)	0.11 (0.02-0.65)*	6 (5.0)	3 (2.7)	0.14 (0.03-0.75)*	-17.03 (7.22)*
Reduced stereoacuity‖							
Present	48 (41.0)	30 (26.5)	0.40 (0.21-0.76)*	47 (39.2)	31 (28.2)	0.45 (0.23-0.88)*	Excluded¶
Not present	69 (59.0)	83 (73.5)	Reference	73 (60.8)	79 (71.8)	Reference	
VP standard score							
≤ Median (≤99)	68 (62.4)	50 (44.2)	Reference	73 (64.6)	45 (41.3)	Reference	Reference
> Median (>99)	41 (37.6)	63 (55.8)	2.32 (1.25-4.29)**	40 (35.4)	64 (58.7)	2.38 (1.25-4.52)*	6.55 (3.00)*
VMI standard score (mean [SD])	86.7 (10.7)	89.6 (10.2)	1.07 (1.03-1.11)**	86.3 (10.3)	90.1 (10.5)	1.07 (1.03-1.11)**	Excluded¶
MC standard score (mean [SD])	86.5 (13.9)	89.9 (13.9)	1.05 (1.02-1.07)**	85.5 (14.0)	91.2 (13.3)	1.06 (1.04-1.09)**	Excluded¶

CI = confidence interval, MC = motor coordination, OR = odds ratio, SE = standard error, VA = visual acuity, VMI = visual-motor integration, VP = visual perception

* P < 0.05, ** P < 0.01

† Adjusted for sex, age and ethnicity

‡ Logistic regression analysis modelling the likelihood that the scores (separate models) are above the median value

§ Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment 0.3 logMAR or worse

‖ Stereoacuity worse than 60 arcsec

¶ Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

10.3.3 Eye movement assessment

Eye movement assessment was completed by 234 participants. One child failed to complete the eye movement analysis and there were two children for whom calibration was unsuccessful.

10.3.4 Saccade task

The saccade task was completed by all 234 participants.

10.3.4.1 Distance VA

Distance VA was significantly correlated with average viewing distance. Compared to children without reduced distance VA, children with reduced distance VA and distance visual impairment had significantly shorter mean average viewing distances. In the mixed model analysis (adjusted for sex, age group and ethnicity), distance VA was significantly associated with average viewing distance (Table 10-3). The adjusted analysis showed that children with reduced distance VA and children with distance visual impairment had predicted average viewing distances of 23.72 mm (SE = 8.83, P=0.01) and 31.25 mm (SE = 12.67, P = 0.01) closer, respectively, than children without reduced distance VA.

10.3.4.2 Astigmatism

Astigmatism was significantly correlated with fixations per minute. Compared to children without astigmatism, children with astigmatism performed significantly more fixations per minute while reading. In the mixed model analysis (adjusted for sex, age group and ethnicity), astigmatism was significantly associated with fixations per minute (Table 10-3) whereby the predicted fixations per minute in children with astigmatism compared to children without astigmatism was greater by 11.1 (SE = 5.00, P = 0.03).

10.3.4.3 Visual-motor integration

MC standard scores were significantly correlated with median fixation duration. In the mixed model analysis (adjusted for sex, age group and ethnicity), MC standard score were not associated with median fixation duration (P = 0.21, Table 10-3).

Table 10-3: Associations between vision measures and eye movement parameters for saccade task, adjusted for sex, age group and ethnicity

Vision measure	Average viewing distance (mm)	Fixations per minute	Median fixation duration (ms)		
	Beta coefficient† (SE)	Beta coefficient† (SE)	≤ Median (≤ 23.6)	> Median (> 23.6)	Adjusted† OR‡ (95% CI)
Distance VA (n=232)§					
Not reduced	Reference	Excluded¶			Excluded¶
Reduced	-23.72 (8.83)*				
Visual impairment	-31.25 (12.67)*				
Astigmatism (n=215)‖					
Present	Excluded¶	11.14 (5.00)*			Excluded¶
Not Present		Reference			
MC standard score (mean [SD])	Excluded¶	Excluded¶	86.63 (14.70)	89.43 (13.44)	1.01 (0.99-1.04)

CI = confidence interval, OR = odds ratio, SE = standard error, VA = visual acuity, MC = motor coordination

*P < 0.05, ** P < 0.01

† Adjusted for sex, age group and ethnicity

‡ Logistic regression analysis modelling the likelihood that the eye movement measures (separate models) are above the median value

§ Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

‖ Corrected and uncorrected refractive error

¶ Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

10.3.5 Letter saccade task

The letter saccade task was completed by 232 participants; one participant was unable to complete the task and one recording was unable to be analysed.

10.3.5.1 Distance VA

A significant correlation was observed between distance VA and average viewing distance. Compared to children without reduced distance VA, children with reduced distance VA and distance visual impairment had significantly shorter average viewing distances. In the mixed model analysis (adjusted for sex, age group and ethnicity), distance VA was significantly associated with average viewing distance (Table 10-4). The adjusted analysis showed for children with reduced distance VA and distance visual impairment, the predicted average viewing distances were respectively 29.71 mm (SE = 9.72, P = 0.003) and 32.33 mm (SE = 13.91, P = 0.02) closer than for children without reduced distance VA.

10.3.5.2 Near VA

Near VA was significantly correlated with task duration and total fixations. Children with reduced near VA and near visual impairment had significantly greater median task durations and total fixations compared to children without reduced near VA. In the mixed model analysis (adjusted for sex, age group and ethnicity), near VA was not associated with task duration (reduced near VA P = 0.21, near visual impairment P = 0.11, Table 10-4) or total fixations (reduced near VA P = 0.11, near visual impairment P = 0.22, Table 10-5).

10.3.5.3 Astigmatism

Astigmatism was significantly correlated with median fixation duration. Compared to children without astigmatism, children with astigmatism had significantly shorter median fixation duration. In the mixed model analysis (adjusted for sex, age group and ethnicity), astigmatism was not associated with median fixation duration (P = 0.40, Table 10-5).

10.3.5.4 Reduced stereoacuity

Reduced stereoacuity was significantly correlated with task duration. Children with reduced stereoacuity had significantly longer task durations compared to children without reduced stereoacuity. In the mixed model analysis (adjusted for sex, age group and ethnicity), reduced stereoacuity was not associated with task duration (P = 0.05, Table 10-4).

Table 10-4: Associations between vision measures and average viewing distance and task duration for letter saccade test adjusted for sex, age and ethnicity

Vision measure	Average viewing distance (mm)	Task duration (s)		
	Beta coefficient[†] (SE)	≤ Median (≤ 23.6) n (%)	> Median (> 23.6) n (%)	Adjusted[†] OR[‡] (95% CI)
Distance VA (n=232)[§]				
Not reduced	Reference			Excluded[¶]
Reduced	-29.71 (9.72)**			
Visual impairment	-32.33 (13.91)**			
Near VA (n=232)[§]				
Not reduced	Excluded[¶]	85 (70.8)	64 (57.1)	Reference
Reduced		32 (26.7)	42 (37.5)	1.48 (0.80-2.75)
Visual impairment		3 (2.5)	6 (5.4)	3.46 (0.76-15.86)
Reduced stereoacuity (n=232)[I]				
Present	Excluded[¶]	34 (28.6)	45 (39.8)	1.80 (0.99-3.28)
Not Present		85 (71.4)	68 (60.2)	Reference

CI = confidence interval, OR = odds ratio, SE = standard error, VA = visual acuity

* P < 0.05, ** P < 0.01

[†] Adjusted for sex, age and ethnicity

[‡] Logistic regression analysis modelling the likelihood that the eye movement measures (separate models) are above the median value

[§] Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

[I] Stereoacuity worse than 60 arcsec

[¶] Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

Table 10-5: Associations between vision measures and fixation measures for letter saccade test adjusted for sex, age and ethnicity

Vision measure	Total fixations			Median fixation duration (ms)		
	≤ Median (≤ 43) n (%)	> Median (> 43) n (%)	Adjusted† OR‡ (95% CI)	≤ Median (≤ 23.6) n (%)	> Median (> 23.6) n (%)	Adjusted† OR‡ (95% CI)
Near VA (n=232)§						
Not reduced	83 (70.3)	66 (57.9)	Reference			Excluded¶
Reduced	32 (27.1)	42 (36.8)	1.63 (0.89-2.98)			
Visual impairment	3 (2.5)	6 (5.3)	2.52 (0.57-11.11)			
Astigmatism (n=215)‖						
Present			Excluded¶	19 (17.4)	12 (11.3)	0.70 (0.31-1.61)
Not Present				90 (82.6)	94 (88.7)	Reference

CI = confidence interval, OR = odds ratio VA = visual acuity

* P < 0.05, ** P < 0.01

† Adjusted for sex, age and ethnicity

‡ Logistic regression analysis modelling the likelihood that the eye movement measures (separate models) are above the median value

§ Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

‖ Corrected and uncorrected refractive error

¶ Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

10.3.6 Word-reading tasks

10.3.7 Rate of reading

The Rate of Reading task was completed by 224 children. Reasons for not completing this task were: child was unable to read words (n = 7), recording was incomplete (n = 2), and recording was unable to be analysed (n = 1).

10.3.7.1 Distance VA

Distance VA was significantly correlated with average viewing distance. Compared to children without reduced distance VA, children with reduced distance VA and those with distance visual impairment had significantly shorter average viewing. In the mixed model analysis (adjusted for sex, age group and ethnicity), distance VA was significantly associated with average viewing distance (Table 10-6) and regressions per fixation (Table 10-8). The adjusted analysis showed that children with reduced distance VA and those with distance visual impairment had predicted average viewing distances of 33.73 mm (SE = 10.45, P = 0.001) and 42.67 mm (SE = 14.59, P = 0.004) closer, respectively, than children without reduced distance VA.

10.3.7.2 Near VA

Near VA was significantly correlated with task duration and total regressions. Children with reduced near VA and those with near visual impairment had significantly shorter average viewing distances and longer task durations than children without reduced near VA. In the mixed model analysis (adjusted for sex, age group and ethnicity), near VA was significantly associated with average viewing distance and task duration but not total regressions (Table 10-6 and Table 10-8). The adjusted analysis showed that children with near visual impairment had predicted average viewing distances of 39.21 mm (SE = 16.75, P = 0.02) closer than children without reduced near VA. Children with reduced near VA (aOR = 2.32; 95% CI = 1.20-4.51, P = 0.01) and near visual impairment (aOR = 9.43; 95% CI = 1.58-56.39, P = 0.01) were also more likely to have task durations above the median value, than children without reduced near VA.

10.3.7.3 Hyperopia

Hyperopia was significantly correlated with total fixations, median fixation duration and total regressions. Children with hyperopia had significantly higher median total fixations, shorter median fixation durations and higher median total regressions, compared to children without hyperopia. In the mixed model analysis (adjusted for sex, age group and ethnicity), hyperopia was significantly associated with total fixations, and total number of regressions but not median fixation duration (Table 10-7 and Table 10-8). The adjusted analysis showed that compared to children without hyperopia, children with hyperopia were more likely to have total fixations and total regressions that were above

the median value (fixations aOR = 3.43; 95% CI = 1.04-11.34, P = 0.04, regressions aOR = 5.92; 95% CI = 1.58-22.08, P = 0.01).

Uncorrected hyperopia was significantly correlated with total fixations and total regressions. Children with uncorrected hyperopia had significantly greater median total fixations and total regressions compared to children without hyperopia. In the mixed model analysis (adjusted for sex, age group and ethnicity), uncorrected hyperopia was not associated with total fixations (P = 0.12) or total regressions (P = 0.10) (not shown in table).

10.3.7.4 Astigmatism

Significant correlations were observed between astigmatism and total fixations, and total regressions . Compared to children without astigmatism, those with astigmatism had significantly higher median total fixations and higher median total regressions. In the mixed model analysis (adjusted for sex, age group and ethnicity), astigmatism not significantly associated with total fixations (P = 0.29) or total regressions (P = 0.26) (Table 10-7 and Table 10-8).

10.3.7.5 Reduced stereoacuity

Significant correlations were observed between reduced stereoacuity and task duration. Children with reduced stereoacuity had significantly longer task durations than those without reduced stereoacuity. In the mixed model analysis (adjusted for sex, age group and ethnicity), reduced stereoacuity was not associated with task duration (P = 0.05, Table 10-6).

10.3.7.6 Visual-motor integration

VMI standard scores and VP standard scores were significantly correlated with median fixation duration. In the mixed model analysis (adjusted for sex, age group and ethnicity), VMI and VP standard scores were not associated with median fixation duration (VMI P = 0.66, VP P = 0.10, Table 10-7).

Table 10-6: Associations between vision measures and viewing distance, words per minute and task duration for rate of reading task

Vision measure	Average viewing distance (mm)	Task duration (s)		
	Beta coefficient[†] (SE)	≤ Median (≤ 160.6) n (%)	> Median (> 160.6) n (%)	Adjusted[†] OR[‡] (95% CI)
Distance VA (n=224)[§]				
Not reduced	Reference			Excluded[¶]
Reduced	-42.67 (14.59)**			
Visual impairment	-33.73 (10.45)**			
Near VA (n=224)[§]				
Not reduced	Reference	82 (73.2)	63 (56.3)	Reference
Reduced	6.14 (6.91)	28 (25.0)	43 (38.4)	2.32 (1.20-4.51)*
Visual impairment	-39.21 (16.75)*	2 (1.8)	6 (5.4)	9.43 (1.58-56.39)*
Reduced stereoacuity (n=224)[I]				
Present	Excluded[¶]	31 (27.7)	44 (39.3)	1.89 (1.01-3.55)
Not Present		81 (72.3)	68 (60.7)	Reference

CI = confidence interval, OR = odds ratio, SE = standard error, VA = visual acuity

* P < 0.05, ** P < 0.01

[†] Adjusted for sex, age group and ethnicity

[‡] Logistic regression analysis modelling the likelihood that the measures (separate models) are above the median value

[§] Better eye presenting VA, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

[I] Stereoacuity worse than 60 arcsec

[¶] Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

Table 10-7: Associations between vision measures and fixation measures for rate of reading task

Vision measure	Total fixations			Median fixation duration (ms)		
	≤ Median (≤ 299) n (%)	> Median (> 299) n (%)	Adjusted† OR‡ (95% CI)	≤ Median (≤ 356) n (%)	> Median (> 356) n (%)	Adjusted† OR‡ (95% CI)
Hyperopia (n=207)[|]						
Present	4 (3.8)	12 (11.9)	3.43 (1.04-11.34)*	11 (10.8)	5 (4.8)	0.43 (0.13-1.43)
Not Present	102 (96.2)	89 (88.1)	Reference	91 (89.2)	100 (95.2)	Reference
Astigmatism (n=207)[|]						
Present	12 (11.3)	17 (16.8)	1.58 (0.68-3.65)	20 (19.6)	9 (8.6)	0.33 (0.13-0.85)
Not Present	94 (88.7)	84 (83.2)	Reference	82 (80.4)	96 (91.4)	Reference
VP standard score						
≤ Median (≤ 99)			Excluded[¶]	50 (46.3)	65 (60.2)	Reference
> Median (> 99)				58 (53.7)	43 (39.8)	0.61 (0.33-1.11)
VMI standard score (mean [SD])			Excluded[¶]	87.1 (10.5)	89.2 (10.6)	1.00 (0.98-1.04)

CI = confidence interval, OR = odds ratio, VA = visual acuity, VP = visual perception, VMI = visual-motor integration

* P < 0.05, ** P < 0.01

† Adjusted for sex, age and ethnicity

‡ Logistic regression analysis modelling the likelihood that the measures (separate models) are above the median value

§ Better eye presenting VA, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

| Corrected and uncorrected refractive error

¶ Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

Table 10-8: Associations between vision measures and saccade measures for rate of reading task

Vision measures	Total regressions		
	≤ Median (≤ 87) n (%)	> Median (> 87) n (%)	Adjusted† OR‡ (95% CI)
Near VA (n=224)§			
Not reduced	78 (67.2)	67 (62.0)	Reference
Reduced	34 (29.3)	37 (34.3)	1.16 (0.63-2.14)
Visual impairment	4 (3.4)	4 (3.7)	1.16 (0.63-2.14)
Hyperopia (n=207)ǀ			
Present	3 (2.8)	13 (13.3)	5.92 (1.58-22.08)*
Not Present	106 (97.2)	85 (86.7)	Reference
Astigmatism (n=207)ǀ			
Present	12 (11.0)	17 (17.3)	1.62 (0.70-3.75)
Not Present	97 (89.0)	81 (82.7)	Reference

CI = confidence interval, OR = odds ratio, SE = standard error, VA = visual acuity

* P < 0.05, ** P < 0.01

† Adjusted for sex, age and ethnicity

‡ Logistic regression analysis modelling the likelihood that the measures (separate models) are equal to or below the median value

§ Better eye presenting VA, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

ǀ Corrected and uncorrected refractive error

¶ Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

10.3.8 Contextual reading

The contextual reading task was completed by 221 children. Reasons for not completing this task were: child was unable to read words (n = 7); recording was incomplete (n = 5); and recording was unable to be analysed (n = 1).

10.3.8.1 Distance VA

Distance VA was significantly correlated with average viewing distance and regressions per fixation. Compared to children without reduced distance VA, children with reduced distance VA and those with distance visual impairment had significantly shorter average viewing distances and higher mean regressions per fixation. In the mixed model analysis (adjusted for sex, age group and ethnicity), distance VA was significantly associated with average viewing distance and regressions per fixation (Table 10-9 and Table 10-11). The adjusted analysis showed that compared to children without reduced distance VA, children with reduced distance VA had predicted average viewing distances that were 64.73 mm (SE = 12.95, P < 0.001) closer and predicted regressions per fixation that were 3.97% (SE = 1.31, P = 0.003) higher.

10.3.8.2 Near VA

Near VA was significantly correlated with task duration, total fixations, total regressions, and regressions per fixation. Compared to children without reduced near VA, children with reduced near VA and near visual impairment had longer median task durations, higher median total fixations and higher median total regressions. In the mixed model analysis (adjusted for sex, age group and ethnicity), near VA was significantly associated with task duration, total fixations, and total regressions (Table 10-9 and Table 10-11). The adjusted analysis showed, compared to children without reduced near VA, children with reduced near VA (aOR = 2.88; 95% CI = 1.41-5.88, P = 0.004) and those with near visual impairment (aOR = 13.85; 95% CI = 2.16-88.96, P = 0.01) were more likely to have task durations above the median value. Children with reduced near VA (aOR = 2.10; 95% CI = 1.10-3.97, P = 0.02) and near visual impairment (aOR = 10.81; 95% CI = 1.23-94.76, P = 0.03) were also more likely to have total fixations above the median value, compared to children without reduced near VA. Compared to children without reduced near VA, those with reduced near VA were more likely to have total regressions above the median value (aOR = 2.24; 95% CI = 1.19-4.21, P = 0.01).

10.3.8.3 Reduced stereoacuity

Significant correlations were observed between reduced stereoacuity and average viewing distance, task duration, total fixations and total regressions. Compared to children without reduced stereoacuity, those with reduced stereoacuity had significantly shorter average viewing distances, longer median task durations, higher median total fixations, and higher median total regressions. In the mixed model analysis (adjusted for sex, age group and ethnicity), reduced stereoacuity was significantly associated

with average viewing distance, task duration, total fixations, and total regressions (Table 10-9 to Table 10-11). The adjusted analysis showed that children with reduced stereoacuity had predicted average viewing distances that were 17.51 mm (SE = 8.21, P = 0.03) closer compared to children without reduced stereoacuity. Children with reduced stereoacuity were also more likely to have task durations, total fixations and total regressions above the median value, compared to children without reduced stereoacuity (task duration aOR = 2.78; 95% CI = 1.40-5.55, P = 0.004, total fixations aOR = 3.14; 95% CI = 1.65-5.96, P < 0.001, total regressions aOR = 2.37; 95% CI = 1.28-4.38, P = 0.01).

10.3.8.4 Visual-motor integration

For the contextual reading task, significant correlations were observed between VP standard scores and task duration and median fixation duration. In the mixed model analysis (adjusted for sex, age group and ethnicity), VP standard scores were significantly associated with task duration but not median fixation duration. Children with VP scores above the median value were less likely to have task durations above the median value (aOR = 0.49; 95% CI = 0.26-0.94, P = 0.03) than children with VP scores equal to or below the median (Table 10-9).

Table 10-9: Associations between vision measures and viewing distance, words per minute and task duration for contextual reading task

Vision measure	Average viewing distance (mm)	Task duration		
	Beta coefficient† (SE)	≤ Median (≤ 161.1) n (%)	> Median (> 161.1) n (%)	Adjusted† OR‡ (95% CI)
Distance VA (n=219)§				
Not reduced	Reference			Excluded¶
Reduced	-64.73 (12.95)**			
Visual impairment	-15.93 (17.71)			
Near VA (n=219)§				
Not reduced	Excluded¶	83 (74.8)	60 (54.5)	Reference
Reduced		26 (23.4)	44 (40.0)	2.88 (1.41-5.88)**
Visual impairment		2 (1.8)	6 (5.5)	13.85 (2.16-88.96)*
Reduced stereoacuity (n=219)ǁ				
Present	-17.51 (8.21)*	29 (26.1)	44 (40.0)	2.78 (1.40-5.55)**
Not Present	Reference	82 (73.9)	66 (60.0)	Reference
VP standard score (n=211)				
≤ Median (≤ 99)	Excluded¶	47 (43.5)	65 (61.9)	Reference
> Median (> 99)		61 (56.5)	40 (38.1)	0.49 (0.26-0.94)*

CI = confidence interval, OR = odds ratio, SE = standard error, VA = visual acuity, VP = visual perception

* P < 0.05, ** P < 0.01

† Adjusted for sex, age group and ethnicity

‡ Logistic regression analysis modelling the likelihood that the measures (separate models) are above the median value

§ Better eye presenting VA, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

ǁ Stereoacuity worse than 60 arcsec

¶ Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

Table 10-10: Associations between vision measures and total fixations for contextual reading task

Vision measure	Total fixations		
	≤ Median (≤ 365) n (%)	> Median (> 365) n (%)	Adjusted[†] OR[‡] (95% CI)
Near VA (n=219)[§]			
Not reduced	84 (75.7)	59 (53.6)	Reference
Reduced	26 (23.4)	44 (40.0)	2.10 (1.10-3.97)*
Visual impairment	1 (0.9)	7 (6.4)	10.81 (1.23-94.76)*
Reduced stereoacuity (n=219)[‖]			
Present	25 (22.5)	48 (43.6)	3.14 (1.65-5.96)**
Not Present	86 (77.5)	62 (56.4)	Reference

CI = confidence interval, OR = odds ratio, VA = visual acuity

* P < 0.05, ** P < 0.01

[†] Adjusted for sex, age group and ethnicity

[‡] Logistic regression analysis modelling the likelihood that the measures (separate models) are above the median value

[§] Better eye presenting VA, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

[‖] Stereoacuity worse than 60 arcsec

Table 10-11: Associations between vision measures and saccade measures for contextual reading task

Vision measure	Total regressions			Regressions per fixation (%)
	≤ Median (≤ 113) n (%)	> Median (> 113) n (%)	Adjusted† OR (95% CI)	Beta coefficient† (SE)
Distance VA (n=219)§				
Not reduced			Excluded¶	Reference
Reduced				3.97 (1.31)**
Visual impairment				2.53 (1.80)
Near VA (n=219)§				
Not reduced	83 (74.1)	60 (55.0)	Reference	Reference
Reduced	25 (22.3)	45 (41.3)	2.24 (1.19-4.21)*	2.20 (0.83)*
Visual impairment	4 (3.6)	4 (3.7)	1.36 (0.30-6.10)	1.04 (2.03)
Reduced stereoacuity (n=219)‖				
Present	28 (25.0)	45 (41.3)	2.37 (1.28-4.38)*	2.16 (0.80)*
Not Present	84 (75.0)	64 (58.7)	Reference	Reference

CI = confidence interval, OR = odds ratio, SE = standard error, VA = visual acuity

* P < 0.05, ** P < 0.01

† Adjusted for sex, age group and ethnicity

‡ Logistic regression analysis modelling the likelihood that the measures (separate models) are above the median value

§ Better eye presenting VA, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

‖ Stereoacuity worse than 60 arcsec

¶ Excluded from analysis owing to no significant correlation or difference in means or medians for the specific variable

10.4 Discussion

Early reading is a key predictor of later reading and overall academic ability (Lonigan, 2006), therefore it is important to identify and address issues that may affect a child's early literacy. In the current study, reduced near VA, reduced near stereoacuity and VMI scores were associated with reduced scores of reading ability. Additionally, hyperopia, poorer near VA and reduced stereoacuity were associated with eye movement patterns that are typical of beginner and less skilled readers (Rayner, 1998).

Current prescribing guidelines for non-amblyogenic refractive error in school-aged children tend to be based on clinical experience due to a lack of high-quality evidence (Cotter, 2007; Leat, 2011). Guidelines for correction of hyperopia and astigmatism are aimed at improving symptoms and visual function. However, correction of mild-moderate refractive errors is still controversial and the minimum levels of hyperopia and astigmatism that require correction to improve visual function are unknown (Leat, 2011). In the current study, reduced near VA (0.1 to 0.2 logMAR), reduced stereoacuity and lower VMI scores were associated with reduced reading scores and eye movement patterns similar to less proficient readers (Rayner, 1998). These findings suggest that children with reading difficulties should receive a comprehensive eye examination and correction of small refractive errors if these are associated with deficits in near VA, stereoacuity or VMI. Eye tracking has the potential to provide eye care practitioners with further data to inform prescribing decisions, by identifying children with eye movement patterns similar to less skilled readers, who may benefit from correction of smaller refractive errors. Further research is required to determine the levels of near VA, stereoacuity and VMI required to optimise educational outcomes.

Near tasks account for nearly half of all academic tasks in the classroom (Narayanasamy et al., 2016). However, there has been little previous research examining the relationship between near VA and academic performance (Hopkins, Narayanasamy, et al., 2019). Studies comparing near VA between children with and without delayed reading skills have found no differences between the groups (Helveston et al., 1985; Vinuela-Navarro et al., 2017). Conversely, similar to the results of the current study, the Vision in Preschoolers study found children aged 4-5 years with uncorrected hyperopia and reduced near VA or reduced stereoacuity had reduced scores on a test of early literacy (Kulp et al., 2016).

The association of reduced stereoacuity with reading scores in the current study is in agreement with two studies of children aged 5-8 years in the United States that found stereoacuity was correlated with scores on standardised tests of reading ability (Kulp & Schmidt, 1996b, 2002). In contrast, in a study of Australian children aged 8-9 years, stereoacuity was not associated with scores on national standardised academic achievement tests (Wood, Black, Hopkins, & White, 2018). Reduced

stereoacuity is associated with refractive error, anisometropia, amblyopia and strabismus (Guo et al., 2016; Robaei et al., 2007) and treating these conditions can improve stereoacuity (Richardson et al., 2005; Stewart et al., 2013). Therefore, the association of reduced stereoacuity with reading scores in the current study suggests that children with reduced stereoacuity require further evaluation to identify and treat any correctable ocular conditions to maximise reading outcomes.

VMI and supplemental test scores were associated with reading test scores. Similarly, in a study of Australian children aged 5-13 years, reduced VMI was associated with lower reading accuracy and comprehension scores on the Neale Analysis (Hopkins et al., 2017). Furthermore, VMI has been shown to be related to reading ability in studies from the United States with children aged 6-8 years (Santi et al., 2015; Sortor & Kulp, 2003) and a predictor of academic success in children aged 5-8 years (Fowler & Cross, 1986; Klein, 1978; Maples, 2003).

In the current study, there was no association between hyperopia or astigmatism and scores of reading ability. Previous studies of the association between refractive error and academic outcomes have produced conflicting results (Hopkins, Narayanasamy, et al., 2019). As in the current study, a study of Australian children aged 5-13 years found no association between uncorrected hyperopia and reading accuracy and comprehension scores on the Neale analysis (Hopkins et al., 2017). Similarly, other studies have found no association between hyperopia (Williams, Sanderson, et al., 1988) or astigmatism (Garber, 1981) and reading ability. In contrast, some studies have found associations between both hyperopia (Shankar et al., 2007) and astigmatism (Harvey et al., 2016; Orlansky et al., 2015) and tests of reading ability. Definitions for significant refractive error, particularly hyperopia, differ between studies. Refractive error was defined in the current study according to established criteria for evaluation of visual impairment (Negrel et al., 2000). The association of reduced VA of 0.1 to 0.2 logMAR with reduced reading outcomes suggests that lower levels of refractive error causing reduced near visual function may be associated with poorer reading outcomes.

Children with hyperopia and astigmatism can achieve different levels of VA. Although hyperopia is associated with reduced VA and amblyopia development (Kulp et al., 2014), the relationship between spherical equivalent hyperopia and VA is not strong (Leone et al., 2010) and for a given spherical equivalent hyperopic refractive error, children can achieve a range of VA (Kleinstein et al., 2021). Astigmatism has a more linear relationship with VA (Wang, Wang, Han, & He, 2018). However, children with moderate levels of astigmatism frequently achieve VA better than 0.3 logMAR (Garber, 1981). The results of the current study suggest that those children who have refractive error and reduced near visual function may require correction to enable acquisition of literacy skills. Further research about children with uncorrected refractive error and good visual function is required to more accurately determine the levels of ametropia that require correction. Additionally, longitudinal

research is required to determine whether correcting refractive error results in improvements in VMI and eye movement patterns.

Distance VA was associated with scores of reading accuracy but not comprehension or reading rate in the current study. Previous studies of children ages 9-10 years in Singapore (Dirani et al., 2010), and ages 6-9 years in the United States (Helveston et al., 1985), found no association between distance VA and academic ability. In contrast, a study of children ages 4-5 years in the United Kingdom found that distance VA was associated with early literacy scores (Bruce et al., 2016), and in a study of children ages 11-15 years in China, presenting VA was associated with academic performance (Jan et al., 2019). Furthermore, a study of children age 8 years in Malaysia, found that children with low academic achievement were more likely to have reduced distance VA compared to children with average and above-average achievement (Chen et al., 2011). The differing results in these previous studies have been attributed to small numbers of children with visual impairment enrolled in the studies and use of non-standardised measures of academic performance (Hopkins, Narayanasamy, et al., 2019). Inconsistent findings may also result from different refractive error profiles of the children in the studies. Children with low to moderate levels of myopia have reduced distance VA but are likely to have normal near VA, whereas children with hyperopia and astigmatism may have reduced distance VA and near VA (Ciner et al., 2021; Narayanasamy et al., 2015b; Wolffsohn et al., 2011).

In the present study, the only association that was demonstrated between vision conditions and VMI scores was between reduced stereoacuity and MC standard scores. Previous studies have shown reduced VMI scores in children with hyperopia and astigmatism (Roch-Levecq et al., 2008), bilateral uncorrected astigmatism (Harvey, Twelker, et al., 2017) and hyperopia with reduced near VA or stereoacuity (Kulp et al., 2017). The pilot study presented in Chapter 4 also found associations between near VA and VMI scores. However, in the present study there was no association between distance or near presenting VA and VMI, VP or MC standard scores. This may be due to the small number of children in this study with habitual near visual impairment in their better eye (10/237, 4.2%), compared to the results in Chapter 4 which blurred all participants back to 0.3 logMAR at near. Further research is required to explore the relationship between visual conditions and VMI in children who are not habitually corrected.

Eye movements while reading are influenced by text difficulty and reading skill (Rayner, 2009). Skilled readers make fewer fixations and regressions and shorter fixations than beginner and less skilled readers (Kulp & Schmidt, 1996a). The increase in fixations and regressions seen in children in this study with reduced near VA, reduced stereoacuity and hyperopia are consistent with eye movement patterns seen in beginner and less skilled readers. Differences between the rate of reading task and the contextual reading task may be due to differences in the two reading tasks. The rate of reading task

consisted of pseudo-random words of approximately equal length and frequency, whereas the contextual reading task was a passage of contextual text with varying word lengths. Word frequency and predictability have strong influences on fixation times with high frequency words less likely to be fixated and longer words more likely to be fixated (Rayner, 1998). Shuffled word reading removes word predictability and slows reading times and results in higher overall number of fixations (Schad, Nuthmann, & Engbert, 2010).

Children in the present study with visual conditions did not demonstrate longer fixation times which have been observed in beginner and less skilled readers in previous studies (Rayner, 1998). Eye movements during reading are affected by low level visual and oculomotor factors as well as higher level cognition related to language processing (Schad et al., 2010). Longitudinal research is required to further understand the development of reading skills and eye movements during reading in children with vision conditions causing reduced near visual function. The association of visual conditions with eye movement patterns similar to beginner and less skilled readers, indicates that children with eye movement patterns suggestive of dyslexia on screening should undergo a comprehensive eye examination to rule out uncorrected vision conditions as the cause. While dyslexia is considered to be a language-based disorder, reduced near visual function may further disadvantage these children when reading (Handler & Fierson, 2011). Thus, it is important to detect and correct vision conditions that result in reduced near visual function in children with delayed reading skills.

No differences in eye movements were observed for children with and without visual conditions for the non-word saccade tasks. These results are similar to studies that have shown that children with dyslexia do not have eye movements that differ from children with normal reading ability for non-word tasks (Olson, Kliegl, & Davidson, 1983; Stanley, Smith, & Howell, 1983). A study of children in the United Kingdom aged 4-11 years found no difference in saccades in response to animal cartoon stimuli between children with and without delayed reading skills (Vinuela-Navarro et al., 2017).

Eye movement patterns observed in the current study suggest that children with reduced near VA, reduced stereoacuity and hyperopia read less efficiently than children without these conditions. Children with reduced near VA and reduced stereoacuity also demonstrated reduced reading rate scores on the Neale Analysis and increased task durations for the contextual reading task. This suggests that children with reduced near visual function will take longer to complete academic tasks that involve reading and may be disadvantaged when completing time-limited tasks in the classroom.

Distance VA is currently the only method employed to screen for vision problems in preschool and early school-aged children in NZ (Ministry of Health, 2014b). The aim of the overall B4SC programme is to identify and intervene on issues that may affect a child's progress in school. Currently, the aim of the vision screening component of the B4SC (to detect amblyopia) does not align

with the aims of the overall B4SC programme (Findlay et al., 2020; Ministry of Health, 2014b). Correction of refractive error resulting in poor distance VA is important for distance viewing tasks which make up approximately one third of academic tasks in the classroom (Narayanasamy et al., 2016). Distance VA becomes increasingly important as children progress through school as the distance VA demand increases with increasing grade level (Langford & Hug, 2010). Furthermore, it is important to detect and initiate treatment for children with low myopia to reduce myopia progression (Saw et al., 2019). However, screening involving assessment of distance VA alone is unlikely to identify all children with reduced visual function, especially at near, and other vision conditions associated with reading. The results of the current study suggest that identifying children with reduced near VA and/or those with reduced near stereoacuity may be more appropriate to detect those who are at risk of delayed reading.

Findings from the present study should be considered in view of several limitations. First, this study employed a clinical eye tracking system utilising software that assessed eye movements and global measures of eye movements were analysed. This approach was chosen as it utilises equipment and methods that are suitable and available for use in clinical practice. However, the software may not accurately discriminate individual saccades for all children. While average fixation duration is a valuable global measure, it does not give accurate information regarding moment-to-moment cognitive processes (Rayner, 2009). Similarly, global measures of regressions do not discriminate between regressions within a word and regressions between words (Vorstius et al., 2014). Additionally, although patterns of eye movements differ between oral and silent reading (Vorstius et al., 2014), in order to confirm that these children were complying with instructions we chose to only assess oral reading in this study. Furthermore, all children completed the same word reading task, therefore the relative difficulty of the reading passage was different for each child. The large numbers of comparisons in this study means that there is some likelihood of false positive results. Therefore, further studies are required to confirm these results. Due to the cross-sectional nature of this study, it is not possible to determine causality between eye conditions, reading outcomes and eye movement patterns while reading. The number of children in the study with visual conditions, in particular binocular vision anomalies, was low. Further research specifically targeting children with vision conditions and tailored to the individual reading level of the child is required to determine the specific patterns of eye movements while reading for these children. Longitudinal research assessing eye movements and reading parameters before and after correction will further clarify the relationship between visual conditions and reading in children.

In summary, near VA, stereoacuity and VMI were associated with reduced reading scores. In addition, reduced near VA, hyperopia and reduced stereoacuity were associated with eye movement patterns that are similar to those seen in less proficient readers. Current vision screening protocols exclusively

employ distance VA screening. Expansion of vision screening protocols to ensure detection of refractive error and other conditions that cause reduced near visual function will improve equity by detecting children at risk of reading problems, who may otherwise remain undetected. Additionally, these results show the importance of comprehensive eye examinations for children with suspected reading difficulties to detect and correct refractive error and other conditions that result in deficits in near visual function.

Chapter 11: Conclusions

Understanding the prevalence of vision conditions and their relationship with reading ability enables the development of vision screening services that are targeted towards detecting conditions likely to impact on a child's academic development, thereby helping to reduce health and educational inequities. Collectively, the studies in this thesis provide data regarding the coverage, efficacy and follow-up from the current NZ B4SC vision screening protocol. Additionally, they give data regarding the prevalence of visual conditions in NZ children and the association between vision conditions and reading parameters.

The current B4SC vision screening has high overall coverage and testability. However, analysis of population data showed that a larger proportion of Māori and Pacific children and those living in high deprivation communities did not receive vision screening, or failed to successfully complete screening, compared with their peers (Chapter 5). Furthermore, compared to children of other ethnicities, a larger proportion of Māori and Pacific children failed to attend follow-up when referred from vision screening (Chapter 6). The current vision screening protocol (VA measurement using the Parr vision test) proved effective in meeting its goal of detecting amblyopia risk factors, but ineffective in detecting significant refractive error (Chapter 7). Children with significant refractive error frequently do not have the spectacles that they require (Resnikoff et al., 2008) which may be because children with uncorrected vision conditions often do not report symptoms (Irving et al., 2016). International research has shown that children from low socioeconomic backgrounds are less likely to see an eyecare professional than those from more advantaged backgrounds (Majeed et al., 2008; Stein et al., 2016). In NZ, children of Māori and Pacific ethnicity and those living in areas of socioeconomic disadvantage experience significant barriers in accessing healthcare (Morton et al., 2017). Therefore, vision screening plays an important role in the detection of ocular conditions in children, particularly for those living in areas of socioeconomic disadvantage.

The studies presented in this thesis provide the first contemporary data on visual conditions in NZ children. Significant refractive error was detected in up to one third of children and binocular vision anomalies in 10% (Chapters 6 to 9). Astigmatism was the most common visual condition observed in the children evaluated in each of the studies presented in this thesis. Children with significant refractive error frequently were not wearing appropriate correction (Chapters 8 and 9). Additionally, children who were referred from B4SC vision screening had lower scores on a test of early literacy than those who passed vision screening (Chapter 6). Furthermore, reduced near visual function (reduced near VA and/or reduced stereoacuity) was associated with reduced reading outcomes and eye movement patterns that were similar to beginner and less skilled readers (Chapter 10).

11.1 Current vision screening programme

Analysis of population data reported in Chapter 5 demonstrated inequities in the B4SC vision screening coverage and testability. Children from Māori and Pacific families and those living in high deprivation areas had reduced B4SC vision screening coverage and testability compared to children of European ethnicity and those living in more socioeconomically advantaged areas, respectively. Children who do not participate in screening may have undiagnosed vision problems that cause amblyopia (Holmes & Clarke, 2006) or that may affect their ability to learn in the classroom environment (Hopkins, Narayanasamy, et al., 2019). Children of Māori or Pacific ethnicity and those living in areas of socioeconomic disadvantage are more likely to have reduced health and educational outcomes compared to their peers (Brabyn & Barnett, 2004; Marriott & Sim, 2015; OECD, 2018). Thus, it is particularly important to detect and treat vision conditions for these children to ensure that they are not being further disadvantaged. Additionally, improving the testability of the B4SC vision screening may improve outcomes by reducing the number of false positive referrals and unnecessary parental concern, as well as personal financial costs including travel and time off work incurred by caregivers of children without a vision problem. Differences in screening coverage and testability were also observed by DHB region. Proposed changes to the NZ health system creating a single nationwide health service and a Māori Health Authority may improve equity by reducing inter-regional differences in health service delivery and improving Māori health outcomes (Department of the Prime Minister and Cabinet, 2021).

While not previously validated, the current NZ vision screening test, the Parr vision test, is a suitable screening tool for the detection of amblyopia in preschool-aged children in NZ. However, while amblyopia may result in permanent vision loss (Holmes & Clarke, 2006), amblyopia prevalence is low and other eye conditions such as mild to moderate hyperopia and astigmatism are more prevalent in the NZ paediatric population. The research presented in this thesis agrees with other studies which have found that VA screening is ineffective in detecting mild and moderate levels of hyperopia and astigmatism (Kleinstein et al., 2021; Leone et al., 2012; O'Donoghue et al., 2012). Targeting vision screening for detection of amblyopia alone may result in children starting school with uncorrected refractive error or reduced near visual function that may affect their ability to learn in the classroom environment (Hopkins, Narayanasamy, et al., 2019). If vision screening protocols are extended to the detection of significant refractive error that may affect academic outcomes, addition of an autorefractor or photoscreener, such as the Spot vision screener, is likely to improve sensitivity of the screening programme.

In Chapter 7, the Parr vision test achieved sensitivity of 50% for children with any ocular condition. When analysed only for significant refractive error, sensitivity was 38.9%. This is consistent with the

60% of children in the study in Chapter 8 and 54% of children in Chapter 9 with significant refractive error who had previously passed the B4 School Check vision screening. This suggests that the results from the study in Chapter 7 are similar to those achieved by vision-hearing technicians in the community.

11.2 Vision conditions in NZ children

11.2.1 Refractive error

Astigmatism was the most common visual condition observed in the children evaluated in each of the studies presented in this thesis, detected in 15-25% of children and accounting for 65-80% of all refractive error. Astigmatism was more common than in a comparable study of children in an urban area of Australia which found similar prevalence for hyperopia (10.4%) and astigmatism (10.3%) in children aged 6 years (Huynh et al., 2006). In children aged 12 years, myopia (12.8%) and astigmatism (13.6%) had similar prevalence (Huynh et al., 2007). Therefore, the visual profile of NZ children appears to differ from children in Australia.

Identification of children with astigmatism is important because it can affect reading and early literacy skills (Harvey et al., 2016; Orlansky et al., 2015) and is related to the development of keratoconus (Romero-Jiménez et al., 2010) and myopia (Fan et al., 2004; Gwiazda et al., 2000). Furthermore, previous studies have found that astigmatism is associated with socioeconomic disadvantage (Dobson, Miller, & Harvey, 1999; Harrington, Stack, et al., 2019). Establishing vision screening protocols in NZ that detect children with astigmatism is important to improve equity by ensuring that all children with astigmatism are wearing appropriate correction to maximise their educational potential. Children with astigmatism in the studies reported in this thesis had reduced distance and near VA, consistent with previous studies (Harvey et al., 2006; Narayanasamy et al., 2015b). However, frequently these children achieved distance VA that did not reach the referral criteria from the B4SC programme. Similar to findings of previous studies (Miller et al., 2001; Nishimura et al., 2019), addition of an autorefractor to the current vision screening protocol is likely to improve detection of children with uncorrected astigmatism.

The prevalence of myopia has increased internationally (Holden et al., 2016) and there have been concerns regarding similar increases in NZ (Petty & Wilson, 2018). It is important to detect children with developing myopia early so they can commence treatment which may reduce myopia progression and myopia related vision loss (Jonas et al., 2021). However, the proportion of children with myopia in the studies in this thesis is low (2.5% to 7.7%). A previous study of children born in Dunedin in the 1970s found myopia prevalence of 4.3% at age 11 years, suggesting that the prevalence of myopia in NZ is not increasing at the same rate as in East Asian countries (Rudnicka et al., 2016). Furthermore,

myopia prevalence in children from an area of socioeconomic disadvantage was very low (Chapter 8). This finding is similar that reported in a study of Australian children aged 6-15 years from an area of socioeconomic disadvantage (Fu et al., 2020) and is consistent with other studies that have found associations between myopia and family income and parental education (Morgan et al., 2021). These results suggest that strategies for detection and correction of refractive error in NZ children should not be limited to the detection and management of myopia. Screening protocols and follow-up from screening programmes should ensure that children with astigmatism and hyperopia are detected and receive appropriate refractive correction. Currently in NZ, children receive vision screening at age 4-5 years with an additional school-based screening at age 11-12 years. Further research is required to determine the optimum timing for the later school-based screening to ensure early identification of children with myopia and detection of vision conditions in children not previously screened.

11.2.2 Binocular vision anomalies

In this thesis, binocular vision anomalies were less common than refractive error and appear to be present in a proportion of NZ children (10.1%) similar to that observed in other populations (Hopkins et al., 2016; Hussaindeen et al., 2017). However, the prevalence and impact of binocular vision anomalies have not been as widely studied as refractive error. The prevalence of reduced stereoacuity was higher than seen in other populations (Lam, LaRoche, De Becker, & Macpherson, 1996; Robaei et al., 2007), but similar to that measured in a previous study of NZ children (Williams, Simpson, et al., 1988). Further research is required to determine normative values for stereoacuity and other binocular vision parameters in NZ children and levels of stereoacuity for which visual function is reduced.

11.2.3 Visual impairment

The proportion of children with unaided and presenting distance visual impairment (0.3 logMAR or worse) was low in the studies in this thesis despite 20-30% of children having significant uncorrected refractive error. Like international studies (Resnikoff et al., 2008; Varma et al., 2017), distance visual impairment most frequently resulted from uncorrected refractive error. The proportion of children with unaided and presenting near visual impairment was also low. Despite nearly half of classroom academic tasks being performed at near (Narayanasamy et al., 2016), there has been little previous research on near VA in children, the prevalence of near visual impairment or its association with academic outcomes (Hopkins, Narayanasamy, et al., 2019). In the studies presented in this thesis, children with astigmatism and hyperopia had VA that was more reduced at near than at distance. The association of reduced near visual function (reduced near VA and/or reduced stereoacuity) with reduced reading outcomes and with eye movement patterns similar to beginner and less skilled readers suggests that even small refractive errors resulting in reduced near visual function may require correction. Further research is required to determine the minimum levels of near VA and stereoacuity

required for reading development. Due to the cross-sectional nature of the studies in this thesis, it is not possible to determine a causal relationship between vision parameters, reading outcomes and eye movement patterns. Furthermore, it remains unknown whether correction of visual conditions results in improvements in reading outcomes and/or influences eye movement patterns while reading. However, the available literature suggests that correction of refractive error results in improvements in academic outcomes (Bruce, Kelly, et al., 2018; Glewwe et al., 2018; Harvey et al., 2016; Ma et al., 2014) and further research to investigate whether this correlates with eye movements during reading is needed.

The association observed between reduced near visual function and reading parameters also supports the need for changes to the current B4SC vision screening protocols. Currently, the aim of the B4SC vision screening (to detect amblyopia) does not align with the intention of the overall B4SC programme (to identify and intervene on issues that may affect a child's ability to learn in the classroom) (Ministry of Health, 2014b). While distance VA screening is effective for detecting visual conditions resulting in distance visual impairment (primarily myopia) and amblyopia (Jonas et al., 2017), it is unlikely to detect children with visual conditions that may result in reduced near visual function. Thus, changes to the B4SC vision screening protocol may be required to identify children with visual conditions that may affect their academic performance. Current vision screening protocols, both in NZ (Ministry of Health, 2014b) and internationally (Hopkins et al., 2013), utilise distance but not near VA measurement. Measurement of near VA has similar reliability to distance VA measurement (Huurneman & Boonstra, 2016). Furthermore, in a study of 6-12 year old children in China, the addition of near VA to distance VA measurement for screening improved detection of high hyperopia and astigmatism (Jin et al., 2015). Addition of an autorefractor to improve detection of astigmatism and hyperopia is likely to detect many of the children with reduced near visual function. Further research is required to determine whether the addition of measurement of near VA will further improve efficacy of screening programmes for detecting children with reduced near visual function likely to result in reduced reading ability.

11.2.4 Visual-motor integration

As a component of this thesis, a pilot study was completed to determine the effect of reduced near VA on VMI (Chapter 4) through the use of simulated refractive error, as VMI had been previously linked with academic achievement (Lowther et al., 2000; Santi et al., 2015; Sortor & Kulp, 2003). However, as children in these previous studies had not received comprehensive eye examinations, it is unknown whether uncorrected refractive error or reduced VA impacted the results. The study presented in Chapter 4 demonstrated that reduced near VA (0.3 logMAR) was associated with poorer performance on the Beery VMI and its supplemental tests. Similar to previous research, the study presented in

Chapters 9 and 10 demonstrated an association between VMI scores and reading outcomes (Hopkins et al., 2017; Santi et al., 2015). However, unlike near VA and stereoacuity, VMI scores were not associated with eye movement parameters in the studies presented in this thesis. This suggests that VMI may be related to reading ability through a different mechanism than VA and stereoacuity. Further research is required to investigate the relationship between VA, stereoacuity and VMI.

11.3 Recommendations for vision screening in NZ

The current B4SC vision screening is effective in detecting amblyopia risk factors. The research in this thesis suggests that the target conditions of the B4SC should be expanded to include the detection of clinically significant refractive error. To enable detection of children with refractive error, the protocol should include a measure of refractive error in a format that is suitable for delivery by lay screeners (eg non-cycloplegic autorefraction or photorefraction) in addition to the current distance VA screening. This screening should still be completed at age 4-5 years to enable detection of amblyopia at age at which it can be treated. Screening at age 4-5 years will also allow detection of refractive errors that may affect reading and academic performance before NZ children commence primary school education and formal reading instruction.

Further vision screening at an older age utilising both VA and autorefraction will enable detection of newly developed myopia (and early treatment to reduce progression) and astigmatism (and allow for monitoring for keratoconus development). It will also allow detection of eye conditions in children who were not previously screened. Further research including population refractive error prevalence and unmet eye care need is required to determine the best time for this screening. Based on the populations and age groups included in the studies in this thesis, the current timing of Year 7 at school (11-12 years) seems appropriate.

Vision screening is only the first step in diagnosis and treatment of childhood vision problems, and vision screening alone has been found to be ineffective in improving academic outcomes (Glewwe et al., 2018). In the study presented in Chapter 6, children who were referred from vision screening had significantly lower scores of letter naming fluency than those who passed vision screening, emphasising the need for follow-up of vision screening referrals in NZ. For a vision screening programme to be effective, services to diagnose and treat vision problems following a screening referral must be available and accessible. Children require timely referral for eye care and spectacles, as well as follow-up and additional treatment where required. Of children referred from vision screening, 20% did not attend an initial appointment at the hospital. A further 20% of those who attended an initial appointment did not attend one or more scheduled follow-up appointments. Non-attendance at both referral and follow-up appointments occurred more frequently among children of Māori and Pacific ethnicities compared with those from other ethnic groups. There is increasing

evidence that cultural factors including institutional and personal racism, lack of trust in healthcare systems and language barriers influence access and utilisation by Māori and Pacific whānau (Ludeke et al., 2012; Paine et al., 2018). Specific interventions are required to ensure that Māori and Pacific children receive culturally safe vision screening and those who are referred or identified for rescreening receive appropriate follow-up, and that whānau receive assistance in accessing these services.

In this thesis, children with significant refractive error frequently did not have appropriate spectacles. Globally, socioeconomic status is associated with uncorrected refractive error (Lou, Yao, Jin, Perez, & Ye, 2016). Previous research internationally has identified financial, logistical, social and perceptual issues that prevent families from obtaining a vision assessment following a failed screening (Kimel, 2006). In this thesis, only 13.9% of children living in an area of socioeconomic disadvantage (NZDep quintile 5) with significant refractive error were wearing correction. Additionally, 42.6% of children from a broader range of ethnic and socioeconomic backgrounds had evidence of a previous examination and 44.2% of those with significant refractive error were wearing glasses. Broken and/or lost glasses are frequently the cause of non-compliance with spectacle wear (Dhirar et al., 2020). Financial barriers to eye care include lack of knowledge surrounding available funding (Holzhauser et al., 2002; Kimel, 2006). In NZ, limited subsidies are available for eye examinations and prescription glasses. However, the process to obtain subsidies can be difficult to navigate and frequently people are unaware of their eligibility. Furthermore, subsidies do not extend to replacement glasses. In a study of American children aged 7-11 years, 66% of children required replacement spectacles in the first year (Huang et al., 2019). Extension of existing subsidies would enable all caregivers to purchase and, when necessary, replace glasses for their children.

In some populations internationally, barriers to follow up from screening have been addressed by provision of immediate comprehensive eye examinations and free glasses at the time and place of vision screening (Ma et al., 2014; Traboulsi et al., 2008). The provision of school-based eye care services may remove some of the financial and logistical barriers to follow-up such as scheduling of appointments and time off work for caregivers. Additionally, this may reduce the burden on hospital-based public eye care services in NZ. Furthermore, provision of eye care services and prescription spectacles within schools may increase the willingness of children to wear prescription spectacles (Dudovitz et al., 2016; Ma et al., 2014). The studies undertaken in this thesis have demonstrated that visual assessment of children in NZ schools is feasible and acceptable. Positioning of eye care services within schools would enable improved participation in vision screening and follow-up care. It would also allow existing support services, such as school nurses and social workers, to assist families to purchase and maintain glasses.

11.4 Strengths and limitations

This thesis provided contemporary data on vision screening and vision conditions in NZ children. This thesis provides insight into the current B4SC vision screening programme and follow-up from the programme. Whole population data was utilised to assess coverage and testability of the current screening programme. Use of *Growing Up in New Zealand* birth cohort data provided a unique opportunity for comparison of B4SC vision screening results with cognitive measures assessed at the same age. The studies in this thesis also provided some of the first contemporary data on vision conditions in NZ children.

The studies presented in this thesis should be considered in view of their limitations. First, children were recruited via convenience sampling. Although the children in the study presented in Chapters 9 and 10 were specifically recruited across a range of school deciles with the aim of having a representative sample, response bias is likely to affect participation. For the studies described in Chapter 6, Chapter 9 and Chapter 10, children were recruited for studies specifically investigating vision. Therefore, caregivers may have chosen for their children to participate based on concerns regarding their vision, or declined participation based on prior knowledge of their child's eye conditions. Secondly, data was collected only within the Auckland region of NZ which generally provides parents and families with good access to eye care services. However, optometrists are not equally distributed within the Auckland region, with fewer optometrists in the Counties Manukau DHB region (Chapman et al., 2020). Access is likely to be worse in rural areas of NZ where access is affected by greater travelling time which adds additional costs to obtain eye care services (Chapman et al., 2020). Classification of children with non-strabismic binocular vision anomalies and reduced stereoacuity were based on normative values from United States populations (Birch et al., 2008; Scheiman, 2014). Furthermore, standard scores for the Beery VMI were also based on normative values from the United States (Beery & Beery, 2010). Ethnic and educational differences between the United States may influence the applicability of these measures to NZ children.

11.5 Future research

Qualitative research is required to determine attitudes toward the B4SC vision screening and potential barriers to participation. These may include the locations for screening, processes used to contact and obtain consent from caregivers and logistical issues with attending screening. Furthermore, as children who are already under care of an eye care practitioner do not currently receive screening, further research is required to determine whether this is adequate or if children are being lost to follow-up.

There is a need for a representative population-based paediatric eye health survey to determine the prevalence of visual conditions in the NZ paediatric population. This will enable planning for

screening and follow-up services and health workforce training to ensure that eye care services are meeting the needs of NZ children. Furthermore, research to determine normative values for vision measures in NZ children will ensure that children with vision measures outside of the normal range can be reliably identified.

11.6 Conclusion

In conclusion, vision screening plays an important role in detecting eye conditions in NZ children. Policy changes are required to improve detection and treatment of vision conditions in NZ children through more appropriate screening targets and protocols, and improved access to follow-up care. Current B4SC vision screening achieves good overall population coverage but inequities in screening coverage, testability and follow-up are evident. In addition, current screening protocols are ineffective in detecting astigmatism, the most common refractive error in NZ children. Distance VA screening is also unlikely to detect children with reduced near visual function which is associated with reduced reading outcomes and poorer eye movements. Therefore, expansion of vision screening protocols to target conditions causing reduced near VA and/or stereoacuity is likely to reduce the number of children entering school with vision conditions which could impact classroom learning. Addition of autorefraction to the current B4SC vision screening protocol is likely to increase the number of children correctly identified with refractive error. Access to eye care in NZ needs to be strategically addressed to improve screening coverage and attendance at follow-up eye care services for all children. Additionally, further research is required to determine specific barriers to eye care and spectacle use in NZ children and interventions that will improve access. Equity-based improvements are required to ensure that Māori and Pacific families and those who reside in neighbourhoods with low socioeconomic status engage in screening and follow-up and obtain vision correction for children where required. Improving access to eye care will reduce inequalities by ensuring that all children have appropriate correction to improve their health and educational outcomes.

Appendix A: Questionnaire

Visual Function and Reading in 7-10 year old children

This project aims to understand the effect of focusing errors and eye movements on reading ability and development, which will be done using standard clinical optometric tests as well as tests of eye movements and reading ability. If your child chooses to participate, their information will be kept confidential. If the information that you provide is reported or published, this will be done in a way that does not personally identify you or your child as its source.

Child's first name

_____

Child's last name

_____

Child's home address

_____

1. Has your child ever had an eye test before?
   - ○ Yes
   - ○ No
   - ○ Don't know

2. I agree for the researcher to contact my child's previous eye care provider for further information
   - ○ Yes
   - ○ No

   Details of previous eye care provider

   Name _____

   Location _____

   Would you like us to send them a report of this examination?

   - ○ Yes
   - ○ No

3. What is your relationship to this child?

- ○ Mother
- ○ Father
- ○ Other

  Please state _____

4. Is your child a girl or a boy?

- ○ Girl
- ○ Boy

5. Which ethnic groups does your child belong to?

   Please choose the option or options that apply to your child

- ○ New Zealand European
- ○ Māori
- ○ Samoan
- ○ Cook Islands Māori
- ○ Tongan
- ○ Niuean
- ○ Chinese
- ○ Indian
- ○ Other such as Dutch, Japanese, Tokelauan.

  Please state _____

6. What is the main language(s) you speak at home?

   Please choose the option or options that apply to you.

   - ○ English
   - ○ Māori
   - ○ Samoan
   - ○ Tongan
   - ○ Fijian
   - ○ Nuiean
   - ○ Cook Islands Māori
   - ○ Cantonese
   - ○ Mandarin
   - ○ Korean
   - ○ Japanese
   - ○ Hindi
   - ○ Arabic
   - ○ Other

     Please state _____

7. Has your child had drops put in his/her eyes to make the pupils big (dilating drops)?

   - ○ Yes
   - ○ No
   - ○ Don't know

8. Was the reaction to the drops normal (sensitive to light, large pupils, blurred vision)?

   - ○ Yes
   - ○ No
   - ○ Don't know

   If no, please describe the reaction to the eye drops

   _____

9. Has your child ever been prescribed glasses?

- ○ Yes
- ○ No
- ○ Don't know

If yes, at what age did your child first get glasses?

- ○ Age _____
- ○ Don't know

10. Does your child wear glasses now?

- ○ Yes
- ○ No
- ○ Don't know

If yes, when does your child wear his/her glasses – select all the options that apply

- ○ All the time
- ○ At school
- ○ For computer/ipad
- ○ For TV
- ○ Other - Please explain _____

If no, why not?

- ○ Advised by eye doctor that glasses are no longer needed
- ○ My child could see without glasses
- ○ Glasses were lost or broken
- ○ Other - Please explain _____

When did your child stop wearing glasses?

- ○ Age _____
- ○ Don't know

11. Has your child ever had to wear an eye patch or use eye drops to improve his/her vision?

- ○ Yes
- ○ No
- ○ Don't know

If yes, at what age did your child start wearing the patch or using eye drops?

- ○ Age _____
- ○ Don't know

And at what age did your child stop wearing the patch or using eye drops?

- ○ Age _____
- ○ Don't know

12. Has your child ever been prescribed eye exercises?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe the eye exercises

_____

13. Did your child receive a B4 School Check Vision screening?

- ○ Yes
- ○ No
- ○ Don't know

If yes, was your child referred for further testing from the B4 School Check Vision screening?

- ○ Yes
- ○ No
- ○ Don't know

If yes, did you take your child for further testing?

- ○ Yes
- ○ No
- ○ Don't know

If no, what is the reason you didn't take your child for further testing?

_____

14. Does your child have an eye that turns or wanders?

- ○ Yes
- ○ No
- ○ Don't know

If yes, which eye turns or wanders?

- ○ Right
- ○ Left
- ○ Both
- ○ Don't know

And in which direction does it move?

- ○ In
- ○ Out
- ○ Up
- ○ Down
- ○ Don't know

15. Does your child blink his/her eyes excessively?

- ○ Yes
- ○ No
- ○ Don't know

16. Does your child rub his/her eyes frequently?

- ○ Yes
- ○ No
- ○ Don't know

17. Does your child squint or narrow his/her eyes to look at things?

- ○ Yes
- ○ No
- ○ Don't know

If yes, does your child squint or narrow his/her eyes when looking at distance or close objects?

- ○ Distance
- ○ Close
- ○ Both
- ○ Don't know

18. Does your child turn his/her head to the side when looking at an object or watching TV?

- ○ Yes
- ○ No
- ○ Don't know

19. Does your child close or cover one eye frequently?

- ○ Yes
- ○ No
- ○ Don't know

If yes, which eye does your child close or cover?

- ○ Left
- ○ Right
- ○ Don't know

20. Does your child complain of difficulty seeing things far away?

- ○ Yes
- ○ No
- ○ Don't know

21. Does your child complain of difficulty seeing things up close?

- ○ Yes
- ○ No
- ○ Don't know

22. Does your child complain of sore eyes?

- ○ Yes
- ○ No
- ○ Don't know

23. Does your child complain of headaches?

- ○ Yes
- ○ No
- ○ Don't know

24. Do you have any other concerns with your child's vision?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please explain/describe

_____

25. On a normal weekday, how many hours per day does your child spend studying or doing homework?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

26. On a normal weekday, how many hours per day does your child spend reading for pleasure?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

27. On a normal weekday, how many hours per day does your child spend using a tablet or smartphone?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

28. On a normal weekday, how many hours per day does your child spend outdoors?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

29. On a normal weekend day, how many hours per day does your child spend studying or doing homework?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

30. On a normal weekend day, how many hours per day does your child spend reading for pleasure?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

31. On a normal weekend day, how many hours per day does your child spend using a tablet or smartphone?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

32. On a normal weekend day, how many hours per day does your child spend outdoors?

- ○ Less than 30 minutes
- ○ 30 minutes to less than 1 hour
- ○ 1 hour to less than 2 hours
- ○ 2 hours to less than 3 hours
- ○ 3 hours to less than 4 hours
- ○ 4 hours or more

33. Has your child ever had an eye injury?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any eye injuries your child has had

_____

34. Has your child ever had an eye operation?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any eye operations your child has had

_____

35. Has your child ever had an eye infection?

- ○ Yes
- ○ No
- ○ Don't know

Please describe any eye infections your child has had

_____

36. Does your child have any general health conditions?

- ○ Asthma
- ○ Eczema
- ○ Diabetes
- ○ Rheumatic heart disease
- ○ Autism spectrum disorder
- ○ Depression
- ○ Anxiety disorder
- ○ Attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD)
- ○ No general health conditions
- ○ Other

Please specify _____

37. Does your child suffer from seizures?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any seizures your child has had

_____

38. Has your child ever had a head injury?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any head injuries your child has had

_____

39. Does your child have any allergies?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any allergies your child has

_____

40. How many weeks of pregnancy was your child born at?

- ○ Number of weeks _____
- ○ Don't know

41. How much did your child weigh at birth?

- ○ Weight _____
- ○ Don’t know

42. Were there any complications when your child was born?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any complications

_____

43. Does your child have any brothers or sisters?

- ○ Yes
- ○ No
- ○ Don't know

If yes, how many brothers and sisters does your child have?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6
- ○ 7
- ○ 8
- ○ 9
- ○ 10
- ○ Don't know

44. Do any of your child 's brothers or sisters have a lazy (turning) eye?

- ○ Yes
- ○ No
- ○ Don't know

45. Do any of your child's brothers and sisters wear glasses?

- ○ Yes
- ○ No
- ○ Don't know

If yes, how many of your child 's brothers and sisters wear glasses?

_____

At what age did your child's brothers or sisters get glasses?

- ○ Sibling 1 age _____
- ○ Sibling 2 age _____
- ○ Sibling 3 age _____
- ○ Sibling 4 age _____
- ○ Sibling 5 age _____
- ○ Sibling 6 age _____
- ○ Sibling 7 age _____
- ○ Sibling 8 age _____
- ○ Sibling 9 age _____
- ○ Sibling 10 age _____

46. Does your child 's mother wear glasses or contact lenses?

- ○ Yes
- ○ No

If yes, at what age did she first get glasses or contact lenses?

- ○ Age _____
- ○ Don't know

47. Has your child 's mother ever been told she has an eye disease or other eye condition?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any eye diseases or other eye conditions that your child's mother has

_____

48. Has your child's mother ever had corrective surgery eg LASIK or PRK?

- ○ Yes
- ○ No
- ○ Don't know

49. Has your child 's mother ever been diagnosed with a lazy (turning) eye?

- ○ Yes
- ○ No
- ○ Don't know

50. What is your child 's mother's highest level of education?

- ○ No secondary school qualification
- ○ NZ School Certificate or National Certificate/NCEA level 1
- ○ NZ Sixth Form Certificate or National Certificate/NCEA level 2 or NZ UE before 1986
- ○ NZ Higher School Certificate or NZ University Entrance from NZ Bursary or National Certificate/NCEA level 3
- ○ NCEA level 4
- ○ Other NZ secondary school qualification
- ○ Overseas secondary school qualification
- ○ Trade Certificate or National Certificated levels 1-4
- ○ Diploma below bachelors level (e.g. teachers or nursing diploma) or National Certificate levels 5 or 6
- ○ Bachelor’s Degree
- ○ Bachelor’s Degree with honours or postgraduate diploma
- ○ Master’s Degree
- ○ PhD
- ○ Don't know

51. What is your child's mother's occupation?

- ○ Occupation _____
- ○ Don't know

52. Does your child's father wear glasses or contact lenses?

- ○ Yes
- ○ No

If yes, at what age did he first get glasses or contact lenses?

- ○ Age _____
- ○ Don't know

53. Has your child's father ever been told he has an eye disease or other eye condition?

- ○ Yes
- ○ No
- ○ Don't know

If yes, please describe any eye diseases or other eye conditions that your child 's father has

_____

54. Has your child's father ever had corrective surgery eg LASIK or PRK?

- ○ Yes
- ○ No
- ○ Don't know

55. Has your child 's father ever been diagnosed with a lazy (turning) eye?

- ○ Yes
- ○ No
- ○ Don't know

56. What is your child 's father's highest level of education?

- ○ No secondary school qualification
- ○ NZ School Certificate or National Certificate/NCEA level 1
- ○ NZ Sixth Form Certificate or National Certificate/NCEA level 2 or NZ UE before 1986
- ○ NZ Higher School Certificate or NZ University Entrance from NZ Bursary or National Certificate/NCEA level 3
- ○ NCEA level 4
- ○ Other NZ secondary school qualification
- ○ Overseas secondary school qualification
- ○ Trade Certificate or National Certificated levels 1-4
- ○ Diploma below bachelors level (e.g. teachers or nursing diploma) or National Certificate levels 5 or 6
- ○ Bachelor’s Degree
- ○ Bachelor’s Degree with honours or postgraduate diploma
- ○ Master’s Degree
- ○ PhD
- ○ Don't know

57. What is your child's father's occupation?

- ○ Occupation _____
- ○ Don't know

Appendix B: Additional analysis for Chapter 10

Table B-1: Correlations between vision measures and Beery VMI scores and Neale Analysis of Reading Ability Scores

Vision measure	Beery VMI standard scores			Neale Analysis of Reading Ability raw scores		
	VMI‡	VP§	MC‡	Accuracy§	Comprehension§	Rate‡
	r (n)	r (n)	r (n)	r (n)	r (n)	r (n)
Distance VA†‖	.08 (n=237)	.05 (n=228)	.08 (n=236)	.13 (n=230)	.08 (n=230)	.04 (n=226)
Near VA†‖	.04 (n=237)	.11 (n=228)	.03 (n=236)	.20** (n=230)	.18** (n=230)	.21** (n=226)
Hyperopia†¶	.03 (n=220)	.11 (n=211)	-.02 (n=219)	-.07 (n=213)	-.01 (n=213)	-.09 (n=209)
Uncorrected hyperopia†	.10 (n=220)	.10 (n=211)	.08 (n=219)	.10 (n=213)	.03 (n=213)	-.04 (n=209)
Astigmatism†¶	-.04 (n=220)	-.02 (n=211)	-.04 (n=219)	-.08 (n=213)	-.05 (n=213)	.01 (n=209)
Uncorrected astigmatism†	-.02 (n=220)	.01 (n=211)	.04 (n=219)	-.05 (n=213)	-.06 (n=213)	-.03 (n=209)
Binocular vision anomalies†	-.10 (n=235)	.05 (n=226)	-.10 (n=234)	.01 (n=228)	.07 (n=228)	.04 (n=224)
Reduced stereoacuity†‡‡	-.12 (n=237)	-.10 (n=228)	-.13* (n=236)	-.15* (n=230)	-.18** (n=230)	-.11 (n=226)
VMI standard score‡	N/A	N/A	N/A	.17* (n=230)	.15* (n=230)	-.02 (n=226)
VP standard score§	N/A	N/A	N/A	.26** (n=222)	.28** (n=230)	.21** (n=218)
MC standard score‡	N/A	N/A	N/A	.16* (n=229)	.18** (n=230)	.004 (n=225)

VA = visual acuity VMI = visual-motor integration, VP = visual perception, MC = motor coordination, N/A = not applicable

* P < 0.05, ** P < 0.01

† Categorical variable, ‡ Parametric variable, § Ordinal variable

‖ Presenting visual acuity in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

¶ Corrected and uncorrected refractive error

‡‡ Stereoacuity worse than 60 arcsec

Table B-2: Mean and median values for Beery VMI standard score and Neale Analysis of Reading Ability raw scores for categorical vision measures

Vision measure	Beery VMI standard scores			Neale Analysis of Reading Ability raw scores		
	VMI	VP	MC	Accuracy	Comprehension	Rate
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Median (IQR)	Mean (SD)
Distance VA[†]						
Not reduced	88.5 (10.8)	99.0 (84.0-107.0)	88.6 (14.0)	56.0 (40.0-77.0)*	20.0 (13.0-28.0)	72.7 (24.3)
Reduced	85.7 (8.0)	91.0 (71.0-106.0)	82.8 (15.7)	43.0 (31.5-51.5)*	17.0 (12.3-24.0)	66.4 (26.8)
Visual impairment	86.0 (7.6)	105.0 (72.5-111.8)	87.6 (9.0)	45.0 (34.0-85.0)*	17.0 (9.0-29.0)	72.5 (19.6)
Near VA[†]						
Not reduced	88.4 (10.6)	100.0 (85.0-108.0)	88.1 (13.5)	58.5 (43.3-78.0)*	21.0 (15.0-29.0)*	76.2 (24.5)**
Reduced	87.7 (10.5)	93.0 (80.0-104.0)	88.2 (15.6)	47.0 (31.0-75.0)*	17.0 (10.5-25.0)*	65.1 (24.8)**
Visual impairment	86.6 (7.6)	105.0 (71.8-111.0)	84.8 (10.8)	45.0 (31.0-66.0)*	18.0 (10.5-28.5)*	64.2 (18.4)**
Hyperopia[‡]						
Present	87.3 (9.3)	98.0 (89.0-108.5)	87.1 (15.4)	47.0 (38.5-77.5)	19.0 (12.0-27.0)	72.0 (24.8)
Not present	87.8 (10.2)	99.0 (82.0-106.3)	87.3 (13.6)	57.5 (40.0-77.0)	20.0 (13.0-28.0)	72.2 (23.8)
Uncorrected hyperopia						
Present	93.0 (9.4)	107.0 (89.5-110.8)	92.6 (12.2)	51.5 (34.2-88.8)	21.0 (10.5-36.3)	66.9 (31.2)
Not present	87.6 (10.0)	99.0 (82.0-106.0)	87.1 (13.9)	52.0 (40.0-77.0)	20.0 (13.0-28.0)	72.4 (23.7)
Astigmatism[‡]						
Present	86.9 (8.5)	96.0 (82.3-106.0)	85.9 (15.9)	46.0 (38.3-74.8)	19.0 (12.0-26.0)	72.7 (23.8)
Not present	87.9 (10.3)	99.0 (83.0-107.0)	87.5 (13.6)	57.0 (40.0-78.0)	20.0 (13.0-28.0)	72.1 (24.0)

Vision measure	Beery VMI standard scores			Neale Analysis of Reading Ability raw scores		
	VMI	VP	MC	Accuracy	Comprehension	Rate
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	Median (IQR)	Mean (SD)
Uncorrected astigmatism						
Present	87.2 (8.1)	99.0 (89.0-106.0)	89.3 (13.7)	46.5 (38.5-75.8)	19.0 (13.25-22.0)	69.5 (19.7)
Not present	87.8 (10.2)	99.0 (83.0-107.0)	87.2 (13.9)	55.0 (40.0-77.0)	20.0 (13.0-28.0)	72.3 (24.3)
Binocular vision anomalies						
Present	85.3 (10.3)	102.5 (82.0-110.3)	83.9 (18.0)	52.0 (38.8-79.0)	23.5 (14.0-29.0)	75.0 (18.9)
Not present	88.5 (10.5)	98.0 (83.0-106.3)	88.5 (13.5)	52.0 (39.0-77.0)	19.5 (12.8-27.3)	71.8 (24.9)
Reduced stereoacuity[§]						
Present	86.4 (10.2)	94.0 (77.0-106.0)	85.5 (14.1)*	46.5 (31.8-75.0)*	16.5 (11.0-25.3)**	25.2 (2.9)
Not present	89.1 (10.2)	99.0 (85.0-108.0)	89.3 (13.9)*	57.5 (42.3-78.0)*	21.0 (15.0-29.0)**	23.6 (1.9)

IQR = interquartile range, MC = motor coordination, SD = standard deviation, VA = visual acuity, VMI = visual-motor integration, VP = visual perception

* $P < 0.05$, ** $P < 0.01$

[†] Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment 0.3 logMAR or worse

[‡] Corrected and uncorrected refractive error

[§] Stereoacuity worse than 60 arcsec

Table B-3: Correlations between vision measures and eye movement parameters for saccade task

Vision measure	Average viewing distance‡	Fixations per minute‡	Median fixation duration§
	r	r	r
Distance VA (n=230)†l	.20**	.08	-.06
Near VA (n=230)†l	.08	-.04	.04
Hyperopia (n=213)†¶	-.10	.04	-.03
Uncorrected hyperopia (n=213)†	-.11	-.10	.05
Astigmatism (n=213)†¶	.04	-.14*	-.13
Uncorrected astigmatism (n=213)†	.02	-.03	.08
Binocular vision anomalies (n=228)†	-.11	.07	-.01
Reduced stereoacuity (n=230)†‡‡	-.04	.02	-.03
VMI standard score (n=230)‡	.03	-.03	.05
VP standard score (n=221)§	.02	.01	-.02
MC standard score (n=229)‡	-.01	-.05	.15*

VA = visual acuity, VMI = visual-motor integration, VP = visual perception, MC = motor coordination

* P < 0.05, ** P < 0.01

† Categorical variable, ‡ Parametric variable, § Ordinal variable

l Presenting VA in better eye, categorised as not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

¶ Corrected and uncorrected refractive error

‡‡ Stereoacuity worse than 60 arcsec

Table B-4: Mean and median values for saccade task parameters for categorical vision measures

Vision measure	Average viewing distance (mm) Mean (SD)	Fixations per minute Mean (SD)	Median fixation duration (ms) Median (IQR)
Distance VA[†]			
Not reduced (n=203)	527.4 (40.7)**	132.2 (26.2)	375.0 (330.0-405.0)
Reduced (n=21)	506.2 (27.9)**	126.5 (27.9)	383.0 (336.0-409.5)
Visual impairment (n=10)	497.8 (38.0)**	125.2 (19.6)	389.0 (347.3-420.8)
Near VA[†]			
Not reduced (n=151)	525.8 (38.6)	130.1 (25.9)	376.0 (332.0-406.0)
Reduced (n=74)	523.4 (44.2)	135.2 (27.3)	373.0 (328.8-400.0)
Visual impairment (n=9)	505.8 (34.8)	124.3 (15.5)	387.0 (362.0-406.0)
Hyperopia[‡]			
Present (n=16)	509.1 (57.6)	133.9 (46.9)	379.0 (288.3-406.0)
Not Present (n=201)	524.4 (39.0)	130.2 (23.4)	380.0 (342.0-406.0)
Uncorrected hyperopia			
Present (n=8)	500.1 (45.3)	118.0 (35.6)	385.5 (359.0-406.0)
Not Present (n=209)	524.2 (40.3)	130.9 (25.3)	379.0 (332.0-406.0)
Astigmatism[‡]			
Present (n=31)	527.4 (47.5)	139.4 (32.7)*	368.0 (297.0-394.0)
Not Present (n=186)	522.6 (39.5)	129.0 (24.1)*	381.5 (344.0-406.0)
Uncorrected astigmatism			
Present (n=15)	526.3 (45.2)	127.2 (15.7)	390.0 (369.0-400.0)
Not Present (n=202)	523.1 (40.5)	130.7 (26.3)	377.0 (332.0-406.0)
Binocular vision anomalies			
Present (n=26)	512.4 (51.9)	136.2 (37.8)	375.0 (315.0-416.3)
Not Present (n=206)	525.9 (38.7)	130.8 (24.4)	378.5 (332.8-405.0)
Reduced stereoacuity[§]			
Present (n=80)	522.3 (42.4)	525.3 (39.3)	385.5 (321.8-402.0)
Not Present (n=154)	132.3 (27.4)	131.0 (25.5)	376.0 (342.3-406.0)

IQR = interquartile range, SD = standard deviation, VA = visual acuity

* $P < 0.05$, ** $P < 0.01$

[†] Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

[‡] Corrected and uncorrected refractive error

[§] Stereoacuity worse than 60 arcsec

Table B-5: Correlations between vision measures and eye movement parameters for letter saccade task

Vision measure	Average viewing distance‡	Task duration§	Total fixations§	Median fixation duration§
	r	r	r	r
Distance VA (n=232)†ǀ	.21**	-.12	-.08	-.07
Near VA (n=232)†ǀ	.05	-.23**	-.22**	-.05
Hyperopia (n=215)†¶	-.06	-.01	.07	-.06
Uncorrected hyperopia (n=215)†	-.10	-.01	.08	-.02
Astigmatism (n=215)†¶	-.06	-.06	.07	.14*
Uncorrected astigmatism (n=215)†	-.09	-.02	.08	-.06
Binocular vision anomalies (n=230)†	-.11	.03	-.05	-.03
Reduced stereoacuity (n=232)†‡‡	-.05	.17**	.08	.05
VMI standard score (n=232)‡	.04	.09	-.02	.10
VP standard score (n=223)§	.04	-.03	-.06	.06
MC standard score (n=231)‡	.05	.07	-.01	.11

VA = visual acuity, VMI = visual-motor integration, VP = visual perception, MC = motor coordination

* P < 0.05, ** P < 0.01

† Categorical variable, ‡ Parametric variable, § Ordinal variable

ǀ Presenting VA in better eye, categorised as not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

¶ Corrected and uncorrected refractive error

‡‡ Stereoacuity worse than 60 arcsec

Table B-6: Mean and median values for letter saccade task parameters for categorical vision measures

Vision measure	Average viewing distance (mm) Mean (SD)	Task duration (s) Median (IQR)	Total fixations Median (IQR)	Median fixation duration (ms) Median (IQR)
Distance VA†				
Not reduced (n=201)	519.6 (43.3)**	23.4 (19.9-28.1)	40.0 (35.0-46.5)	453.0 (382.5-553.5)
Reduced (n=21)	493.8 (40.0)**	26.8 (22.2-32.6)	44.0 (38.5-51.0)	537.0 (379.0-585.5)
Visual impairment (n=10)	487.7 (49.7)**	22.7 (20.5-27.3)	41.0 (36.8-45.0)	448.5 (359.5-576.0)
Near VA†				
Not reduced (n=149)	516.0 (41.3)	22.2 (19.6-27.1)**	39.0 (35.0-44.0)**	450.0 (382.5-554.0)
Reduced (n=74)	519.9 (46.4)	24.6 (21.4-30.8)**	42.5 (38.0-50.3)**	464.5 (368.5-559.8)
Visual impairment (n=9)	482.2 (60.6)	27.3 (23.4-31.8)**	43.0 (37.5-51.0)**	529.0 (413.5-656.5)
Hyperopia‡				
Present (n=16)	505.4 (59.5)	23.4 (19.8-27.3)	43.0 (38.3-49.8)	445.0 (349.0-497.0)
Not Present (n=199)	515.7 (43.3)	23.8 (20.3-28.5)	40.0 (36.0-47.0)	453.0 (383.0-557.0)
Uncorrected hyperopia				
Present (n=8)	493.4 (61.6)	23.4 (19.7-26.8)	43.0 (39.8-47.5)	451.0 (359.5-496.3)
Not Present (n=207)	515.8 (43.8)	23.7 (20.3-28.5)	40.0 (36.0-47.0)	453.0 (383.0-557.0)
Astigmatism‡				
Present (n=31)	508.4 (50.1)	23.0 (19.6-26.9)	42.0 (38.0-51.0)	416.0 (299.0-541.0)*
Not Present (n=184)	516.1 (43.7)	23.8 (20.3-29.3)	39.5 (36.0-46.8)	457.5 (388.0-562.0)*

Vision measure	Average viewing distance (mm) Mean (SD)	Task duration (s) Median (IQR)	Total fixations Median (IQR)	Median fixation duration (ms) Median (IQR)
Uncorrected astigmatism				
Present (n=15)	499.9 (52.8)	23.4 (19.6-26.9)	42.0 (40.0-50.0)	429.0 (329.0-544.0)
Not Present	516.1 (43.9)	23.8 (20.3-28.6)	40.0 (36.0-47.0)	454.0 (383.0-560.0)
Binocular vision anomalies				
Present (n=26)	501.9 (52.6)	23.7 (21.6-27.1)	39.0 (33.0-48.0)	451.0 (353.0-572.8)
Not Present (n=204)	517.5 (42.9)	23.4 (19.9-28.5)	40.0 (36.0-46.8)	457.5 (383.0-554.0)
Reduced stereoacuity[§]				
Present (n=79)	513.0 (46.8)	24.5 (21.7-30.0)**	42.0 (35.0-49.0)	467.0 (371.0-579.0)
Not Present (n=153)	517.4 (42.8)	22.6 (19.7-27.8)**	39.0 (36.0-45.0)	453.0 (383.0-541.5)

IQR = interquartile range, SD = standard deviation, VA = visual acuity

* $P < 0.05$, ** $P < 0.01$

[†] Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment 0.3 logMAR or worse

[‡] Corrected and uncorrected refractive error

[§] Stereoacuity worse than 60 arcsec

Table B-7: Correlations between vision measures and eye tracking measures for rate of reading task

Vision measure	Average viewing distance‡	Task duration §	Total fixations§	Median fixation duration §	Total regressions§
	r	r	r	r	r
Distance VA (n=224)†‖	.25**	-.13	-.04	.05	-.10
Near VA (n=224)†‖	.03	-.17*	-.11	.01	-.15*
Hyperopia (n=207)†¶	-.05	.10	.21**	-.17*	.25**
Uncorrected hyperopia (n=207)†	-.01	.08	.14*	-.08	.15*
Astigmatism (n=207)†¶	-.05	.06	.13*	-.16*	-.15*
Uncorrected astigmatism (n=207)†	-.01	.09	.03	-.002	.08
Binocular vision anomalies (n=222)†	-.18*	-.04	-.01	-.07	-.03
Reduced stereoacuity (n=224)†‡‡	-.08	.15*	.09	.05	.09
VMI standard score (n=224)‡	.04	.13	-.02	.16*	-.04
VP standard score (n=216)§	.04	-.08	.13	-.20*	.09
MC standard score (n=223)‡	.06	.03	-.04	.12	-.07

VA = visual acuity, VMI = visual-motor integration, VP = visual perception, MC = motor coordination

* P < 0.05, ** P < 0.01

† Categorical variable, ‡Parametric variable, §Ordinal variable

‖ Presenting VA in better eye, categorised as not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

¶ Corrected and uncorrected refractive error

‡‡ Stereoacuity worse than 60 arcsec

Table B-8: Mean and median values for measures of viewing distance, words per minute and task duration for categorical vision measures for rate of reading task

Vision measure	Average viewing distance (mm)	Task duration (s)	Total fixations	Median fixation duration (ms)	Total regressions
	Mean (SD)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Distance VA[†]					
Not reduced (n=194)	510.5 (45.6)**	158.2 (135.0-196.3)	299.0 (251.5-349.8)	357.0 (312.8-419.5)	85.0 (64.8-108.0)
Reduced (n=20)	481.2 (45.6)**	189.4 (152.4-221.5)	303.0 (264.5-405.5)	348.0 (294.8-402.3)	97.0 (75.5-134.3)
Visual impairment (n=10)	466.9 (44.8)**	164.4 (138.6-200.6)	302.5 (251.0-354.0)	351.0 (269.8-405.3)	84.0 (67.8-123.0)
Near VA[†]					
Not reduced (n=145)	504.7 (41.8)*	152.8 (132.5-190.4)*	292.0 (248.0-337.5)	356.0 (312.5-419.5)	82.0 (63.0-102.5)
Reduced (n=71)	513.0 (53.0)*	165.8 (140.0-205.5)*	305.0 (252.0-376.0)	353.0 (300.0-406.0)	95.0 (67.0-128.0)
Visual impairment (n=8)	464.6 (60.1)*	198.1 (165.9-216.3)*	310.5 (271.3-350.0)	405.5 (324.3-410.5)	83.5 (67.5-123.5)
Hyperopia[‡]					
Present (n=16)	497.3 (75.9)	175.5 (150.6-235.2)	342.0 (299.3-483.8)**	304.0 (273.0-378.5)*	118.0 (92.5-178.8)**
Not Present (n=191)	505.7 (44.6)	160.6 (135.2-199.2)	291.0 (246.0-347.0)**	360.0 (314.0-419.0)*	82.0 (63.0-107.0)**
Uncorrected hyperopia					
Present (n=8)	502.1 (84.7)	175.5 (145.1-298.2)	342.0 (301.5-417.8)*	313.0 (283.5-393.5)	115.0 (82.8-145.5)*
Not Present (n=199)	505.2 (45.7)	160.6 (135.5-199.2)	292.0 (246.0-348.0)*	359.0 (313.0-418.0)	85.0 (64.0-107.0)*
Astigmatism[‡]					
Present (n=29)	499.5 (49.9)	175.4 (136.7-203.2)	307.0 (285.5-398.5)	329.0 (270.5-397.5)*	91.0 (70.5-143.0)*
Not Present (n=178)	506.0 (47.2)	159.7 (135.4-199.2)	291.0 (246.0-347.0)	361.0 (313.0-419.5)*	82.0 (64.0-107.0)*

Vision measure	Average viewing distance (mm)	Task duration (s)	Total fixations	Median fixation duration (ms)	Total regressions
	Mean (SD)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Uncorrected astigmatism					
Present (n=13)	506.8 (49.6)	187.9 (139.2-226.5)	300.0 (243.5-377.5)	344.0 (306.5-420.5)	95.0 (68.5-134.5)
Not Present (n=194)	505.0 (47.5)	160.1 (135.4-198.4)	295.0 (251.5-348.3)	358.5 (312.0-417.3)	85.0 (65.0-107.3)
Binocular vision anomalies					
Present (n=25)	482.1 (54.9)**	151.6 (138.4-184.9)	305.0 (252.0-337.0)	349.0 (283.5-397.5)	76.0 (70.0-97.0)
Not Present (n=197)	509.0 (45.3)**	160.8 (135.4-200.4)	295.0 (251.5-358.5)	356.0 (312.0-418.5)	87.0 (65.0-112.0)
Reduced stereoacuity[§]					
Present (n=75)	500.5 (48.8)	175.4 (140.0-217.7)*	312.0 (261.0-365.0)	363.0 (314.0-412.0)	91.0 (67.0-118.0)
Not Present (n=149)	508.6 (45.9)	156.9 (134.3-189.8)*	292.0 (246.0-347.0)	346.0 (301.5-413.0)	83.0 (65.0-108.0)

IQR = interquartile range, SD = standard deviation, VA = visual acuity

* $P < 0.05$, ** $P < 0.01$

[†] Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

[‡] Corrected and uncorrected refractive error

[§] Stereoacuity worse than 60 arcsec

Table B-9: Correlations between vision measures and eye tracking measures for contextual reading task

Vision measure	Average viewing distance‡	Task duration§	Total fixations§	Median fixation duration§	Total regressions§
	r	r	r	r	r
Distance VA (n=219)†	.23**	-.04	-.04	.04	-.10
Near VA (n=219)†	.05	-.20**	.24**	-.03	-.24**
Hyperopia (n=203)†	.05	.05	.11	-.11	.11
Uncorrected hyperopia (n=203)†	.10	.02	.05	-.01	.02
Astigmatism (n=203)†	-.03	.09	.08	-.06	.09
Uncorrected astigmatism (n=203)†	.01	.11	.06	.08	.05
Binocular vision anomalies (n=217)†	-.11	-.07	-.06	-.10	-.05
Reduced stereoacuity (n=219)†‡‡	-.14*	.16*	.19**	-.02	.19**
VMI standard score (n=219)‡	.05	-.01	-.06	.07	-.08
VP standard score (n=211)§	.08	-.25**	-.09	-.24**	-.08
MC standard score (n=218)‡	.003	-.05	-.08	.03	-.08

VA = visual acuity, VMI = visual-motor integration, VP = visual perception, MC = motor coordination

* P < 0.05, ** P < 0.01

† Categorical variable, ‡ Parametric variable, § Ordinal variable

| Presenting VA in better eye, categorised as not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

¶ Corrected and uncorrected refractive error

‡‡ Stereoacuity worse than 60 arcsec

Table B-10: Mean and median values for eye tracking measures for categorical vision measures for the contextual reading task

Vision measure	Average viewing distance (mm) Mean (SD)	Task duration (s) Median (IQR)	Total fixations Median (IQR)	Median fixation duration (ms) Median (IQR)	Total regressions Median (IQR)
Distance VA[†]					
Not reduced (n=192)	516.2 (50.2)**	159.1 (126.6-216.0)	362.5 (321.0-435.0)	272.0 (234.3-331.0)	112.0 (86.0-142.8)
Reduced (n=19)	452.7 (87.3)**	207.3 (133.4-248.1)	403.0 (324.0-501.0)	223.0 (271.0-335.0)	105.0 (136.0-176.0)
Visual impairment (n=10)	493.5 (44.4)**	132.4 (118.1-220.9)	340.0 (294.5-381.3)	274.5 (195.5-357.0)	102.0 (84.8-142.3)
Near VA[†]					
Not reduced (n=143)	507.6 (58.1)	150.9 (124.3-202.4)*	357.0 (309.0-415.0)**	267.0 (233.0-329.0)	106.0 (83.0-136.0)**
Reduced (n=70)	517.9 (53.2)	181.4 (135.2-173.9)*	393.5 (338.5-501.0)**	283.0 (231.3-334.3)	123.5 (92.3-167.3)**
Visual impairment (n=8)	476.1 (52.3)	210.3 (139.5-315.7)*	400.0 (375.0-493.3)**	278.0 (268.8-368.0)	120.5 (95.3-173.3)**
Hyperopia[‡]					
Present (n=15)	518.5 (83.5)	175.4 (119.1-290.2)	382.0 (338.0-501.0)	266.0 (192.0-314.0)	133.0 (91.0-194.0)
Not Present (n=189)	508.3 (55.8)	159.1 (127.3-213.5)	363.0 (320.5-429.5)	277.0 (234.5-340.5)	110.0 (86.0-143.0)
Uncorrected hyperopia					
Present (n=8)	538.0 (83.8)	159.9 (119.2-421.0)	379.0 (337.2-477.3)	290.0 (211.5-338.8)	117.5 (90.3-159.8)
Not Present (n=196)	507.8 (56.7)	161.3 (126.9-214.1)	364.0 (321.0-435.0)	276.5 (234.0-334.3)	112.0 (86.0-147.3)
Astigmatism[‡]					
Present (n=29)	505.3 (53.1)	173.4 (132.1-249.1)	367.0 (332.5-475.5)	271.0 (214.5-329.5)	112.0 (96.5-171.0)
Not Present (n=175)	509.6 (58.9)	157.3 (125.7-214.6)	364.0 (321.0-430.0)	277.0 (235.0-335.0)	112.0 (86.0-142.0)

Vision measure	Average viewing distance (mm) Mean (SD)	Task duration (s) Median (IQR)	Total fixations Median (IQR)	Median fixation duration (ms) Median (IQR)	Total regressions Median (IQR)
Uncorrected astigmatism					
Present (n=14)	512.1 (51.8)	211.3 (136.2-266.2)	369.0 (341.5-471.8)	326.5 (227.3-402.3)	114.5 (98.8-163.0)
Not Present (n=190)	508.8 (58.6)	158.8 (126.4-210.8)	364.0 (321.0-435.0)	272.0 (234.0-330.3)	111.0 (86.0-143.5)
Binocular vision anomalies					
Present (n=25)	493.2 (56.7)	159.0 (127.6-184.9)	364.0 (297.0-411.5)	266.0 (225.5-301.0)	109.0 (79.5-142.5)
Not Present (n=194)	511.9 (56.8)	161.6 (127.6-228.8)	365.5 (321.8-446.8)	281.0 (234.0-335.5)	113.0 (87.0-155.3)
Reduced stereoacuity[§]					
Present (n=73)	498.4 (63.3)*	178.4 (134.5-178.9)*	398.0 (337.0-490.5)**	281.0 (219.5-364.5)	123.0 (91.5-169.5)**
Not Present (n=148)	515.3 (52.5)*	151.3 (125.0-206.5)*	356.5 (317.8-416.5)**	271.0 (235.5-328.8)	107.5 (85.3-135.3)**

IQR = interquartile range, SD = standard deviation, VA = visual acuity

* $P < 0.05$, ** $P < 0.01$

[†] Presenting VA in better eye, not reduced = 0.0 logMAR or better, reduced = 0.1 to 0.2 logMAR, visual impairment = 0.3 logMAR or worse

[‡] Corrected and uncorrected refractive error

[§] Stereoacuity worse than 60 arcsec

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