ANGLIA RUSKIN UNIVERSITY

FACULTY OF SCIENCE AND TECHNOLOGY

THE EFFECTS OF COLOUR ON READING AND VISUAL CORRELATES IN CHILDREN AND ADOLESCENTS WHO ARE PROFOUNDLY OR SEVERELY DEAF

RICHARD STEWART HOLLINGSWORTH

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Vision and reading abilities in profound or severely deaf children have consistently been reported to be impaired. Although the nature of reading acquisition in these children has been widely debated, visual functions necessary for reading have rarely been assessed. Coloured overlays have been shown to improve reading in hearing children with reading disabilities, yet no investigation with children who are deaf has been performed. Two visual theories have been proposed to explain the benefit from overlays: visual stress and the magnocellular defect.

Visual functions (refractive state, visual acuities and binocular status for near and distance) were measured and compared between children who were deaf and normal hearing. Intelligence quotient was also evaluated. Reading was investigated with the Wilkins Rate of Reading test and a version specifically adapted for children who are deaf (validated in a pilot study). A clinical assessment using intuitive overlays was performed on all participants. Magnocellular functions were examined with Frequency Doubling Technology and Random Dot Kinematograms.

Convergence and accommodation were significantly reduced in the deaf participants. Reading speeds were increased with colour only for the deaf participants who chose the yellow overlay, and yellow was the most common choice of colour. Magnocellular responses appear increased globally and in specific areas in the Frequency Doubling Technology test, but only if the participant had previously chosen a yellow overlay.

Visual and binocular dysfunction were more prevalent in the deaf participants. This has possible implications with reading difficulties. The most common choice of yellow overlays combined with the selective advantage of yellow in increasing reading speed supported the transient visual stream and the magnocellular defect theory. However, increased sensitivities with the Frequency Doubling Technology test suggest enhancement of the magnocellular pathway which may also be associated with improved peripheral retinal sensitivity and cross modal plasticity of the peripheral retina with children who are deaf.

Key Words: Deaf vison reading colour overlay yellow magnocellular

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Chapter 1

Visual and reading characteristics of children and adolescents who are profoundly or severely deaf

1.1. Introduction

Deaf people are thought to view the visual world very differently from people with normal hearing due to adaptation to their hearing loss and consequential changes to their communication strategy. For example, deaf people who use sign language must be able to quickly discriminate between facial expressions in order to interpret signed sentences. The deaf are therefore more reliant on vision than hearing individuals for both verbal and non-linguistic social cues. This has been shown to lead to altered visual function. The visual system is thought to re-organize and compensate for the lack of auditory input, such that visual skills now take over the functional role performed by hearing in the typically developing child. Change in visual function is believed to occur in pre-lingual deaf children to enhance their visual functions (Neville and Lawson, 1987; Dye and Bavelier, 2010).

Assessment and treatment of ocular conditions, especially refractive errors and binocular vision anomalies, are essential to allow the best possible social and professional adjustment for deaf individuals (Guy et al., 2003). Previous work in typically developing children has indicated that early correction of refractive error may have a significant role to play in their cognitive development; Roch-Levecq, et al. (2008) investigated pre-school children with ametropia of ≥ 4.00D and astigmatism of

≥ 2.00D, whilst the children with ≤ 2.00D of ametropia and ≤ 1.00D astigmatism were considered to be emmetropic. The children with uncorrected ametropia were tested for base line cognitive abilities before correction, and showed significantly lower scores than those with emmetropia. Following a six-week period of visual correction, the ametropic group improved their cognitive scores quicker than that of the emmetropic controls.

It should be noted that when we are discussing deaf children in this thesis we are referring to children who have very little or no hearing before or close to birth, and therefore, have not lost their hearing but never acquired it; that is they are pre lingually deaf and can be categorised as either profoundly or severely deaf.

1.2. Prevalence of childhood hearing impairment

In the UK there are approximately 1-2 per 1000 children born each year with hearing impairment (Fortnum, et al., 2001; Nikolopoulos, et al., 2006). Fortnum et al. (2001) defined hearing impairment as a hearing loss (HL) in the better ear of more than 40dB averaged pure tone thresholds at 0.5, 1, 2, and 4 kHz. Using these data the prevalence of children with severe (71–95 dB HL) and profound (>95 dB HL) losses can be estimated at 0.63 per 1000 children. However, this is nearly doubled by the age of 9 years as more children are identified as being deaf. A child with a severe (71 to 95 dB) hearing loss is only able to hear shouted conversation and can therefore not learn to speak as a normal hearing child. A profoundly deaf child (>95 dB HL) hears only loud sounds, which are generally perceived as vibrations rather than meaningful sounds as a hearing child would perceive (Table 1.1.). The hearing may well be enhanced by electronic aids but the extent to which this enhances the understanding of verbal language is dependent on differing factors, such as speech frequencies and the distortion which remains post amplification (Goldin-Meadow and Mayberry, 2001). Some children may also have Cochlear implants which bypass the physical auditory system by being directly implanted into the auditory nerve. However, even this treatment does not guarantee good spoken language as a pre-lingual deaf child will still need to learn a language via this impeded and impoverished hearing channel producing variable outcomes (Peterson, Pisoni and Miyamoto, 2010).

Assessment of deafness has centred on congenital sensory neural deafness in which deafness is associated with dysfunction of the vestibulocochlear nerve, inner ear, or central processing centres of the brain.

Table 1.1. The British Society of Audiology (2014) classified hearing levels

Mild hearing loss	20-40 (dB)	Able to hear and repeat words spoken in normal voice at 1 metre.
Moderate hearing loss	41-70 (dB)	Able to hear and repeat words spoken in raised voice at 1 metre.
Severe hearing loss	71-95 (dB)	Able to hear some words when shouted into better ear.
Profound hearing loss	>95 (dB)	Unable to hear and understand even a shouted voice.

(British Society of Audiology, 2004)

Research over the past 70 years has established a strong relationship between deafness and ocular abnormalities. Most studies have investigated (almost) exclusively visual acuity when viewing in the distance. Whilst these have shown higher levels of dysfunction in the deaf population when compared with normal hearing groups, surprisingly few investigations of near vision function have been made, and there is little evidence reported in the literature (Hollingsworth, et al., 2013)

Early studies qualitatively grouped deafness into broad levels of moderate, severe and profound without quantifying the degree of deafness that was present (Suchman, 1967), whilst others have associated hearing levels and ocular defects in greater detail having used subjects from audiology or specific deaf centres. For example, Armitage et al. (1995) assessed 83 children, 46 of them having severe hearing loss (>70dB) and 37 having profound hearing loss. They assessed hearing with audiograms and hearing thresholds with octave frequencies of 500, 1000, 2000 and 4000Hz. They found 15 of the severe hearing loss group and 14 of the profound hearing loss group (total 35%) met their criteria for having a visual defect (Table 1.2.). Stockwell (1952) assessed refractive status in acquired and congenital deaf individuals, finding marginally higher levels of ocular defects in the congenitally deaf group, although 13% of the total cohort had an unknown cause of deafness.

Table 1.2. Percentage of deaf individuals with visual defects or ocular abnormalities in 21 studies.

Studies	No of subjects *N*	Male	Female	Age range Years	Visual defects/ Ocular Abnormalities %	Data collection institution	County of origin
Braly 1938	422	†	†	†	38	Deaf School	USA
Stockwell 1952	960	555	405	2-20	46	Deaf School	USA
Suchmaan 1967	104	51	53	4-12	58	Deaf School	USA
Alexander et al 1973	572	†	†	5-20	50	Deaf School	Canada
Pollard et al 1974	511	303	208	5-20	33	Deaf School	USA
Mohindra 1976	77	33	42	5-17	75	Deaf School	USA
Regenbogen 1985	150	92	58	1-14	45	HEC	Israel
Woodruff 1986	460	†	†	†	55	Deaf School*	Canada
Leguire et al 1992	505	†	†	6-22	49	HEC	USA
Siatkowski et al 1994	54	28	26	2-14	61	HEC	USA
Armitage et al 1995	83	41	42	1.3-16	35	HAC	UK
Brinks et al 2001	231	†	†	10-21	48	Deaf School	USA
Mafong et al 2002	114	60	54	1-18	31	HES*	USA
Hanioðlu-Kargý et al 2003	104	68	36	7-20	40	Deaf School	Turkey
Guy et al 2003	122	61	61	0.7-16.8	43	CDC	UK
Khandekar et al 2009	223	142	81	5-15	19	Deaf School	Oman
Bakhshaee et al 2009	50	19	31	†-7	32	Deaf School	Iran
Sharma et al 2009	226	112	114	†-18	22	HEC*	USA
Gogate et al 2009	901	554	347	4-21	24	Deaf School	India
Bist et al 2010	279	154	125	5-20	28	Deaf School	Nepal
Abah et al 2011	608	373	235	5-38	21	Deaf School	Nigeria

†= No data available. HEC= Hospital eye clinic HAC=Hospital audiology clinic. CDC= Child development centre.* = retrospective study. Visual and ocular defects inclusive of refractive, binocular and pathological anomalies.

1.3. Deafness and Vision.

Visual defects in children who are deaf are particularly important due to the social and educational ramifications of having a dual disability (Dammeyer, 2010). The possible effects of visual defects on communication skills has not been adequately researched, although it has been well established that deaf children have difficulties in reading and lag behind their hearing peers (Perfetti and Sandak 2000; Musselman 2000; Goldin-Meadow and Mayberry 2001). This developmental delay has often been attributed to a lack of phonic awareness of the words, making comprehension problematic. Surprisingly there has been relatively little assessment of the levels of near vision function and binocular coordination in these children; visual defects appear to have simply not been considered relevant. Indeed, there are a variety of proposed methods in the literature for reading acquisition in deaf children, with a large proportion dedicated to phonic defects. Less attention has been given to graphical and orthographic (visual) routes to reading (Perfetti and Sandak 2000; Booth et al. 2000).

Measurement of visual acuity in relation to deafness has been arbitrary, for example, (Stockwell, 1952) measured refractive status in participants with acquired and congenital deafness finding marginally higher levels of visual defects in the congenital group with 13% of the total cohort having an unknown cause of deafness. Khandekar et al, (2009) grouped their participants into two groups; profoundly deaf > 81dB and severely deaf 61-80dB and assessed vision with LogMAR charts although no refractive or visual acuity results have been reported. However, no association between the level of deafness and visual acuity was found in some studies (Leguire, et al., 1992; Khandekar, et al., 2009) categorised subjects into; mild hearing loss (30-45dB), moderate loss (45-60dB), severe loss (60-80 dB) with all three groups termed as hearing impaired. Profound loss (> 80dB) was categorised as deaf. Visual defects found by Leguire et al, (1992) were more prevalent in all hearing impaired groups than in their normal hearing group, however, relative refractive defects between the hearing impaired and the deaf groups where minimal (hearing impaired 21.6% deaf 24.54%).Leguire et al, (1992) found an increased level of ocular anomalies related to rubella compared to other associated pathologies. Gogate, et al. (2009) investigated visual impairment in 901 children of varying hearing abilities, categorising the participants with the World Health Organisation's grading for hearing impairment, although no associations between visual abilities and hearing functions were investigated.

Due to the difficulty in recruiting deaf participants, several studies have found themselves reliant on retrospective examination of medical data (Table 1.2.). This methodology reduces the validity of the data (Woodruff, 1986) and is reliant on observations gathered from many different sources, giving results that are at best hypothesis generating (Hess, 2004).

It is surprising that there are so few studies that include direct comparisons between deaf groups and a matched hearing control group (Pollard and Neumaier, 1974). Instead the majority of studies have chosen to compare their data with previous studies on a hearing population (Regenbogen and Godel, 1985; Leguire, et al., 1992; Guy, et al., 2003; Hanioglu-Kargi, et al., 2003), with early studies having simply quoted age range and gender (Suchman, 1967). Some studies have divided gender and ages into year groupings (Pollard and Neumaier, 1974; Mohindra, 1976). One study, conducted in Washington DC, USA specified racial grouping without attributing deafness or visual dysfunction to this factor (Suchman 1967). The racial grouping may or may not be important, but the majority of studies have not directly addressed this issue and have been ethnically biased to the country of origin.

Armitage et al. (1995) also compared ocular defects between congenital and acquired deafness, finding no significant differences between these groups. Moreover, Khandekar et al. (2009) investigated visual defects in the profoundly deaf > 81dB and severely deaf 61-80dB; but did not find any association between visual acuity and contrast sensitivity defects and level of hearing impairment (Leguire et al., 1992)

In summary, no strong relationship between the level of deafness and visual defects has been found (Leguire et al., 1992), due to the lack of comparable data and the variability of definitions of visual defects. Few studies have categorised the level of hearing loss. Whilst the classification criteria differ between studies these have been dependent on the application of international hearing standards, or the use of national standards and experimental preferences. Although there may only be a weak association between the level of deafness and refractive and binocular vision abnormalities, these defects are significantly more prevalent in deaf children when compared to people with normal hearing.

Although refractive error is more common in children who are deaf, there appears to be little consensus as to whether refractive errors are more frequent in the congenitally deaf compared to those who have early acquire deafness (Guy, et al., 2003). Ophthalmological screening regimes have been implemented for deaf children in an attempt to maximise visual abilities and minimise social and educational disadvantages (Siatkowski, et al., 1993; Guy, et al., 2003; Hanioglu-Kargi, et al., 2003)

In the following chapters the British Society of Audiology levels will be used for classification of deaf grouping (Table 1.1.).

1.4. Assessments of Vision

1.4.1 Distance vision and visual acuity

Various methodologies and classification criteria have been used in the assessment of vision / visual acuity. For example, Bist et al. (2011) assessed vision and visual acuity with a Snellen tumbling “E” test chart as this does not require literacy. Whilst most research has used traditional Snellen charts at 6 metres there has been little use of logMAR chart assessment despite it being acknowledged as a superior measurement (Lovie-Kitchin, 1988). Younger children’s distance visual acuity has been assessed with a variety of tests including Sheridan Gardiner cards, Kay pictures, Lea Crowded Symbols (near vision), and for pre-verbal children, Cardiff Acuity Test (Armitage, Burke and Buffin, 1995; Guy, et al., 2003). Crowded Kay pictures and Lea pictures are considered the most appropriate tests for younger children with the LogMAR crowded acuity test and the Sonsken LogMAR chart being the tests of choice for children over 3 years (Saunders, 2010). The reliance on Snellen acuity charts as compared to the LogMAR system may be at least in part due to the location and the clinical nature of the majority of studies in which Snellen charts are more commonly available.

1.4.2. Near vision assessment

Near vision assessments in deaf individuals are a rarity within the literature and when they have been undertaken the reduced Snellen tumbling ‘E’ letter charts have typically been used (Regenbogen and Godel, 1985). For example, (Hanioglu-Kargi, et al., 2003) assessed with a Snellen Reduced E near chart and (Khandekar, et al., 2009) with near Lea symbols, finding 15 participants (total n=223) to have defective near vision though no definition of defect was given. Although measurement of near vision was detailed in Khadehar et al.'s (2009) methodology, near vision results were only reported as 'defective'.

It is evident that many of the deaf studies from developing countries (Khadehar et al. 2009; Gogate et al. 2009; Abah et al. 2011) have greater reliance on non-reading "illiterate" tests possibly indicating the greater difficulties these children have in acquiring basic reading skills when compared to their hearing counterparts or simply that the levels of literacy are much lower in these countries.

Table 1.3. Selection of deaf studies showing variation in criteria used to classify visual defects

Studies	Number of participants		Hyperopia (D)	Myopia (D)	Astigmatism (D)	Anisometropia	Amblyopia	Near vision
Pollard & Nieumair 1974	511	Criterion	>2.25	>0.75	>1.25	>1.25	≤6/12	†
		Number or (%) defect	41(8)	68(13.3)	30(5.9)	30(5.9)	9(1.8)	†
Leguire et al., 1992	505	Criterion	≥3.00	>1.00	≥1.00	≥1.00	<6/9	†
		Number or (%) defect	24(4.8)	39(7.7)	56(11.1)	37(7.3)	22(4.4)	†
Stiatowski et al., 1993	54	Criterion	>2.50	>1.00	>1.50	>1.00	†	†
		Number or (%) defect	17(31.5)	4(7.4)	2(3.7)	1(1.8)	†	†
Armitage et al., 1995	83	Criterion	≥3.00*(≥1.50 §)	≥1.00	>1.50	>1.00	†	†
		Number or (%) defect	12 (14.4)	12 (14.4)	11(13.2)	4(4.8)	†	†
Guy et al., 2003	110	Criterion	≥4.00	≥4.00	>1.50	>1.00	†	†
		Number (%) defect	11 (10)	23 (20.9)	8 (7.3)	1(0.91)	4(3.6)	†
Hanioglu-Kargi et al., 2003	104	Criterion	≥1.50	> 1.00	≥1.50	≥2.00	<6/9	†
		Number or (%) defect	10(9.6)	6(5.8)	15(14.4)	5(4.8)	16(15.3)	†
Gogate et al., 2009	901	Criterion	≥1.00	≥0.50	≥0.50	†	<6/60	†
		Number or (%) defect	41(4.5)	113(12.5)	13(1.4)	†	3(0.3)	†
Khandekar et al., 2009	223	Criterion	†	†	†	†	†	†
		Number or (%) defect	†	†	†	†	†	15(6.5)

† = no data available. § = With esotropia. * = Without esotropia. D = Dioptres.

1.4.3. Review of refractive and binocular anomalies of people who are deaf.

Refractive error has often been assessed objectively using retinoscopy both with, cycloplegic (Mohindra, 1976; Regenbogen and Godel, 1985; Leguire, et al., 1992; Siatkowski, et al., 1993) and without (Suchman, 1967; Pollard and Neumaier, 1974). Evidence of subjective non-cycloplegic refractions having been performed is limited. This is consistent with the accepted viewpoint that cycloplegic refractions are the most accurate method of assessing refraction for children because of the control of accommodative effort (Fotouhi, et al., 2012). Inclusion criteria for refractive errors have considerable variation. For example, Guy et al. (2003) set inclusion for spherical ametropic at ≥ 4.00D whilst Armitage et al. (1995) included hyperopia of ≥ 1.50D with exotropia (≥ 3.00D without exotropia). Outlined below are a few of the most commonly observed refractive and binocular vision abnormalities as documented in deaf individuals.

Refractive and binocular vision abnormalities have typically been the most commonly reported. Studies have shown the prevalence of hyperopia, myopia and astigmatism to be between 18% and 39% (Pollard and Neumaier, 1974; Mohindra, 1976; Regenbogen and Godel, 1985; Guy, et al., 2003) and binocular vision abnormalities (e.g. strabismus) between 5.3% and 18% (Woodruff, 1986; Leguire, et al., 1992; Hanioglu-Kargi, et al., 2003).

1.4.4. Hyperopia

Hyperopic ametropia associated with deafness is the most commonly reported refractive error (Alexander, 1973; Mohindra, 1976; Regenbogen and Godel, 1985; Siatkowski, et al., 1993; Armitage, Burke and Buffin, 1995; Abah, et al., 2011) with the prevalence varying between 8% (≥2.25D; Pollard and Neumaier 1974 - non-cycloplegic refraction) and 44% (≥2.50D; Siatkowski et al. 1993; cycloplegic refraction) as compared to between 4% (≥2.00D (Fan et al. 2004) and 12.8% (≥1.25D; Kleinstein et al. 2003) in a normal hearing population for cycloplegic refractions and 7.7% (≥1.50D; Junghans et al. 2002) for non-cycloplegic refractions.

1.4.5. Myopia

This is the second most frequently reported visual defect. It is acknowledged in the literature that myopia increases with age in hearing individuals (Saw, et al., 2005), yet even controlling for age as a factor, there is still a greater prevalence of myopia in deaf and hearing-impaired children and young adults (Leguire, et al., 1992). In fact the prevalence of myopia in the deaf has ranged from 6% (>1.00D; Hanioglu-Kargi et al. 2003) to 20.9% (Guy et al. 2003).

1.4.6. Astigmatism

There appears to be a greater prevalence of astigmatism in the deaf and hearing impaired, with Pollard and Neumaier (1974) reporting 7.3% in their deaf participants compared to 1.4% in their group of hearing children. Compared to other visual defects, studies have shown far greater agreement with criteria for astigmatism, ranging from ≥1.00D to ≥1.50D (Pollard and Neumaier, 1974; Siatkowski, et al., 1993; Armitage, Burke and Buffin, 1995; Guy, et al., 2003; Hanioglu-Kargi, et al., 2003), although (Hanioglu-Kargi, et al., 2003) used a ≥ 2.00D criterion and reported prevalence in the deaf of 14.4%. Woodruff (1986) in his retrospective study suggested that higher levels of astigmatism (>1.00D) may be associated with congenital rubella, although no associations with disease process or level of deafness have been suggested elsewhere. Mohindra (1976) subdivided astigmatic participants into ‘with the rule’ (steeper corneal curvature vertically) and ‘against the rule’ (steeper curvature horizontally). Corneal curvature was measured using keratometry, and there were twice the number of ‘with the rule’ astigmats than ‘against the rule’. Previous research has shown with the rule astigmatism to be more prevalent in both myopia and hypermetropia in the hearing population (Young et al., 2011), however, to a lesser degree than that reported for the deaf population. Woodruff (1986) also reviewed corneal curvature suggesting congenital rubella subjects show greater curvature and a higher prevalence of microphthalmia.

1.4.7. Amblyopia (unilateral)

A greater prevalence of amblyopia has consistently been shown in individuals who are deaf compared to individuals with normal hearing (with acuity levels for inclusion ranging from < 6/9 (20/30) (Hanioglu-Kargi, et al., 2003) to < 6/60 (20/200) (Gogate, et al., 2009) and prevalence ranging between 0.3% (Gogate, et al., 2009) and 15.3% (Hanioglu-Kargi, et al., 2003). The increased occurrence of amblyopia has variously been attributed to ocular pathology, strabismus, cataracts and anisometropia. In comparison amblyopia (visual acuities of <6/12 – 6/9) in normally developed child populations has been reported to range from 1% to 5% (Thompson, et al., 1991; Powell and Hatt., 2009)

1.4.8. Anisometropia

Anisometropia also has an increased prevalence in the deaf. Definitions of anisometropia have been extremely variable. For example, Pollard and Neumaier (1974) set a criterion of 1.25D differential between eyes whilst Hanioglu-Kargi (2003) used ≥ 2.00D and Regenbogen and Godel (1985) ≥ 3.00D.

1.4.9. Binocular vision abnormalities

Strabismus (heterotropia) and heterophoria have commonly been measured with a simple cover / uncover test (Suchman, 1967; Guy, et al., 2003). Heterophoria has occasionally been quantified using an alternating cover test in association with a prism bar although few studies have reported the magnitude of phoria. (Alexander, 1973; Pollard and Neumaier, 1974; Mohindra, 1976; Leguire, et al., 1992). Deviations of > 10 prism dioptres have been considered significant (Leguire, et al., 1992; Hanioglu-Kargi, et al., 2003) and have been reported as more common in deaf children when compared with normal hearing cohorts. Regenbogen and Godel (1985) found a prevalence of 4.6% compared to 1.8% in a normal hearing population whilst Pollard and Neumaier (1974) found no difference between groups with strabismus in 4.9% of their deaf participants compared to 4.8% in a hearing group, although the criteria in their hearing group was “less rigid”. Accommodation and associated phoria (fixation disparity) have not featured in deaf vision research to date. These assessments would give a greater insight into the coordination of the eyes which is especially important for near vision.

1.4.10. Stereopsis

Stereopsis has been measured in early studies using the wings of a toy butterfly and more recently with the Titmus stereo fly, Wirt dot (Mohindra 1976) and TNO tests (Hanioglu-Kargi, et al., 2003). Normal stereo acuity has been set at ≤100 seconds of arc for the majority of studies. Mohindra (1976), using the stereo fly and Wirt dot tests, found over 70% of the deaf participants with a stereopsis of ≤ 100” (seconds of arc), with 49% having 40” and 30% having no or reduced stereopsis of > 100”. Reduced stereopsis is associated with refractive error and/or an oculomotor abnormality that is in accordance with the greater prevalence of strabismus and amblyopia in deaf children.

1.4.11. Contrast sensitivity (CS)

Contrast sensitivity is mentioned in only one of the papers (Khandekar, et al., 2009) and no methodology or results were published. It would appear unfortunate that assessment of CS has not been conducted as reduced CS can be associated with cataract and retinitis pigmentosa. Research into retinitis pigmentosa, which has high association with Usher syndrome, has found reduced contrast sensitivity in this group (Hartong, Berson and Dryja, 2006). The lack of CS assessment could reflect the unavailability of clinical CS assessment.

1.4.12. Colour vision

Colour vision has been assessed with the Ishihara Colour Test (Regenbogen and Godel 1974; Mohindra 1976), D15 Test (Khandekar et al. 2009) and Farnsworth-Munsell 100 Hue Test (Pollard and Neumaier, 1974; Mohindra, 1976; Hanioglu-Kargi, et al., 2003; Khandekar, et al., 2009). Mohindra (1976) found 2.1% of females (N=43) and 6.9% of males (N=29) to have colour defects using the Ishihara and Farnsworth 100 Hue tests. These levels are consistent with larger scale normative studies and would suggest little variation in the prevalence of colour defects in males who are deaf. Mohindra (1976) had found a greater percentage of females than would have been expected in a hearing population i.e. 0.2% (Birch and Platts, 1993). However, the number of participants in the Mohindra study was small (N=43).

1.4.13. Ocular abnormalities

The retina and the cochlea structures are formed at the same developmental stage and embryonic layer, so any pathological defect within these areas could lead to oculo-auditory defects (Levin, 1974), although the associations between various pathological processes and their impact on vision and hearing are not well described. There is little consensus in the literature regarding which diseases should be considered for inclusion in deaf vision studies with generic terms such as 'hereditary' and 'acquired' conditions being the most commonly reported. Some early studies such as Suchman (1967) examined the external eye and observed the red reflex of the fundus giving little information of posterior segment pathology. Other studies (e.g. Guy, et al. 2003) assessed pathological abnormalities in greater detail, having categorised the pathologies into: genetic syndromal, autosomal recessive, autosomal dominant, infective, metabolic, acquired and unknown causes. Sixty three of the 122 children in the study by Guy, et al. (2003) had a genetic cause of their deafness, 13 were linked to known oculoauditory syndromes such as Usher syndrome, Leigh's encephalopathy and Wildervank's syndrome, and 45 had an unknown cause. This greater detail has given better insight into the associations between deafness, vision and the disease processes, enabling better identification of individuals who may be at risk from these disease processes, whether genetic or acquired, and allowing treatment at an earlier stage of development. In comparison, Regenbogen and Godel

(1985) grouped the pathological conditions into broader areas: fundus, macular, external, pigmentary retinal changes, retinitis pigmentosa and optic disc atrophy but without relating the findings to any specific syndrome.

A diverse range of diseases has been associated to the relationship between deafness and vision defects. For example, Woodruff (1986) reviewed the case histories of 420 children attending schools for the deaf in Ontario, and reported congenital rubella as the most significant pathology and highlighted its association with an increased prevalence of strabismus and amblyopia, secondary to retinopathy and cataracts. Other studies have also found ocular pathologies associated with rubella (Mohindra, 1976; Leguire, et al., 1992; Mitchell, et al., 2001). Fortunately congenital rubella is now a relatively infrequent cause of deafness, particularly within developed countries (Nikolopoulos, et al., 2006). Consequently, it is now more common to attribute deafness and visual problems to genetic causes and the more prevalent infective problems, for example: cytomegalovirus, toxoplasmosis and syphilis (Guy, et al., 2003; Nikolopoulos, et al., 2006). Nikolopoulos et al*.,* (2006) in their review of the ophthalmological abnormalities associated with deafness has 'unknown aetiology' as the largest pathological category in much of the historic research.

The review of the research into the visual deficits found in profound or severely deaf populations has demonstrated a diverse and disparate array of methodology and procedures. Much of the research has been conducted in an individual manner with little assessment of binocular functions. Acuity assessment has generally been measured with Snellen acuity charts whilst little assessment has been made with the more sensitive LogMAR system. The following research outlined in the thesis will attempt to assess visual functions in a method which prevails in current investigations whilst attempting to assess finer binocular functions, with specific reference to near vision functionality.

Despite the awareness that visual abilities are essential in a non-hearing world, it would seem that very little attention has previously been given to near visual function, and in particular reading. Whilst little research has been conducted into near vision in deaf children it has been suggested that deaf children who have reduced dynamic visual acuities may have reduced vestibular responses (Martin, et al. 2012). Children with congenital vestibular abnormalities displayed gross motor developmental problems that the authors suggest may impede the usual ocular motor/vestibular relationship. This in turn could impact on visual stability and hence acquisition of reading (Martin, et al. 2012).

The visual function of a child who is deaf has implications for many aspects of the child's social and cognitive development. An understanding of near visual functions is less well established with very few studies investigating these adequately. Information and knowledge is acquired almost exclusively visually in children who are deaf, whether via sign language, lip reading, facial gestures, reading text, figures or pictorially. The effect of visual defects on communication has also been relatively neglected.

1.5. Visual aspects of reading disabilities

Reading disabilities are not only represented in children who are deaf but are also found within the hearing population who have reading abilities below their matched age groups. Reading requires an ability to convert visual symbols into an orthography and then produce a phonological representation of these symbols to gain meaning. It is not surprising, considering the complexity of the visual and phonological tasks needed for successful reading, that both deaf and hearing children sometimes fail to achieve competent reading levels. Children can present with a variety of reading and learning difficulties including, dyslexia, alexia, dysgraphia and dyscalculia (Lyon, 1996) with some also exhibiting co-ordination problems (dyspraxia). Whilst many of these conditions are associated with reading the visual impact on children who are deaf is not understood or described. However, associations between reading and vision in a hearing population are better described. Amongst the visual problems associated with reading difficulties are the following;

- Uncorrected refractive error
- Reduced visual acuity
- Binocular anomalies
- Convergence and accommodative anomalies
- Colour vision anomalies
- Visual stress
- Aberrant saccadic eye movements
- Magnocellular deficiency
- Visual field defects

1.5.1. Uncorrected refractive errors

Whilst evidence for correcting hypermetropia has demonstrated significantly increased cognitive abilities in hearing children (Atkinson, et al., 2002; Roch-Levecq, et al., 2008), the presence of myopia has not been associated with reduced reading abilities, possibly due to the retention of good near vision and reduced action of the accommodative system. This suggests that hypermetropic children should have early refractive correction to maximise cognitive development.

1.5.2. Reduced visual acuity

Distance visual acuity is routinely measured in vision assessments with the use of suitable charts such as the LogMAR and Snellen. These tests consist of single letter recognition and give a measurement of the visual resolution for a particular eye. The relationship with reading acuity is a more complex task which requires perception and decoding of the graphic symbols which represent speech to acquire meaning (Gibson, et al., 1962). Within the hearing population visual acuity is not generally reduced in children with specific learning difficulties such as dyslexia (Evans, Drasdo and Richards, 2007). However, children with severely reduced acuities will struggle to read fluently without the use of reading aids (Lovie-Kitchin, Bevanm and Hein, 2001).

1.5.3. Binocular anomalies

There is little evidence within the literature as to whether binocular anomalies are the cause of reading difficulties in hearing children, and there is no existing evidence in relation to deaf children. However, some difficulties may be contributory (Scott, et al., 2002; Evans, Drasdo and Richards, 2007). Evans, et al. (1995) investigating the optometric characteristics of children with 'Mears-Irlen syndrome' found participants who reported benefit from coloured overlays had a reduced level of stereopsis and reduced vergence abilities.

1.5.4. Strabismus

Conditions such as strabismus, which can occur in childhood, appear not to be associated with reading difficulties as the visual system is able to adapt to compensate (Ygge, et al., 1993; Evans, 2007). Patients with strabismus have usually undergone adaptation to the deviated eye, either with harmonious retinal correspondences or suppression (amblyopia), to reduce visual perception problems (Evans, 2007).

1.5.5. Heterophoria

Heterophoria is a common condition which occurs with binocular fusion and is identified by a misalignment in a specific direction of the eyes (exophoria, esophoria, hyperphoria / hypophoria or cyclophoria) when one is covered. Although a normal feature of binocularity the ability of the eyes to fuse two monocular images into a single binocular view of the world in turn enables finer depth perception abilities. The visual system will normally compensate for the heterophoria but large deviations or reduced fusional abilities of the eyes may cause the heterophoria to decompensate. This may produce asthenopic symptoms as the eyes struggle to maintain fusion of the monocular images and therefore may reduce visual performance for reading (Karania and Evans, 2006). Although refractive corrections are not perceived as detrimental to reading performance, a child with an uncorrected hyperopia will accommodate more than an emmetropic one. This may lead to an over-activity of convergence and significantly increase the heterophoria (esophoria), possibly resulting in decompensation. Uncorrected myopia may have the opposite effect, this will reduce the accommodative and convergence relationship (exophoria) and consequentially may again decompensate (Evans, 2007). However, the prevalence of significant myopia in younger children is considerably less than that of hyperopia as myopia tends to develop as the child ages. French, et al. (2012) in a study of children's refraction, found children in Northern Ireland between 6 and 7 years old (n=392) had ametropia levels of 2% $\leq$ -0.50D spherical equivalent refraction (SER) and 22% $\geq$ +2.00D SER (O'Donoghue, et al., 2010; French, et al., 2012) . Therefore correction of refractive ametropia would appear prudent for both hearing and deaf children who have decompensating heterophoria and reading difficulties.

1.5.6. Near point of convergence and accommodative difficulties

People sometimes find it difficult to converge on near objects. This in turn, can induce a decompensated convergence weakness or exophoria for near only. Studies of normal hearing dyslexic children and near point of convergence have shown that children with dyslexia have a more remote convergence ability than non-dyslexic children (Latvala, et al., 1994; Kapoula, et al., 2006) although other studies have not found this (Ygge, et al., 1993; Evans, Drasdo and Richards, 2007) whilst only one has associated these convergence problems with reading in deaf children (Hollingsworth, et al., 2015). Difficulties with decompensating convergence causing suppression or diplopia may increase difficulties with reading (Allen, Evans and Wilkins, 2010). The difficulties of convergence movements have been attributed to a possible immaturity of the saccade-vergence mechanisms specifically at near distances and are possibly associated with a defect of the visual magnocellular system (Stein and Kapoula, 2012, p.54). Ray, Fowler and Stein (2005) assessing the near point of convergence of 38 children with reading difficulties and found 15 children had significantly remote near point of convergence of >18cm. They then reassessed the 38 children after using a yellow filter or a placebo filter for three months. After this period the children who had used the yellow filter had increased their reading ability compared to those who had been given the placebo. These findings have been described as showing evidence of a lower visual magnocellular sensitivity in these children.

1.5.7. Accommodation

Accommodation insufficiencies have been associated with reading difficulties. Evans, Drasdo and Richards (1994) investigated amplitude of accommodation in children with reading difficulties and a control group of normal readers. They found a significant reduction in the binocular accommodative amplitudes in the reading difficulties group, whilst this did not appear to affect their dynamic accommodative lags. However, their results suggest there was no association between this and reading visual search abilities. Previous studies have also associated accommodative insufficiencies with reading difficulties (Dusek, Pierscionek and McClelland, 2010), although, other studies have failed to find this association (Kiely, Crewther and Crewther, 2001).

1.5.8. Binocular Instability

Binocular instability is not the same as a decompensating heterophoria as it represents an unstable or variable misalignment of the visual fusional areas and is believed to be most significant clinically when the eyes are under fused conditions, such as viewing the Mallett Fixation Disparity unit. This enables the eyes to be assessed under normal binocular near vision conditions. Fixation Disparity will occur when binocular fixation is not exactly aligned within Panum's fusional areas. This misalignment does not cause diplopia as it is within the binocular fusional area (Panum's area). In previous research, it has been suggested that variable movement of the nonius lines is significant in near vision binocular instability (Karania and Evans, 2006). This instability has been described within the hearing dyslexic population as significant and indicative of a low fusional amplitude and binocular instability (Kapoula, et al., 2006). Stein (1987) has also reported fixation instability and reduced vergence abilities in dyslexic subjects finding 67% of their dyslexic group to have shown poor vergence control (Stein, Riddell and Fowler, 1987). In their subsequent publication reviewing 14 dyslexic children and 24 normal children, who were assessed with an infra-red synoptophore for vergence control "two thirds of the dyslexic children were found to have vergence control that was qualitatively different from normal responses" (Stein, Riddell and Fowler, 1988). It has been suggested that vergence abnormalities are more frequent amongst people with reading difficulties (Kapoula, et al., 2006), although a previous study into the effects of yellow filters in 86 non-dyslexic children with reading difficulties found no change in binocular status or reading ability between the treated group and the non-yellow overlay cohorts

(Palomo-Álvarez and Puell, 2013). However, no such evidence is available for profoundly deaf children.

1.5.9. Visual Pathways

The human pre-cortical visual system is believed to consist of two well defined pathways the Magnocellular and Parvocellular and to a lesser extent the Koniocellular pathway.

1.5.10. Magnocellular

The magnocellular (M) visual pathway is one of the primary visual pathways referred to as the M pathway and represents approximately 10% of the visual stream. It originates from large parasol ganglion retinal cells. These cells have larger receptive fields but are also heavily myelinated facilitating faster signal speeds of 70ms (Baseler and Sutter, 1996) when compared to the slower parvocellular, although the M stream is predominantly sensitive to fast temporal resolution, low contrast and low spatial frequencies (Merigan and Maunsell, 1993). This projects through the lateral geniculate nucleus to areas 4Cα and 6 of V1 in the primary visual cortex. The M stream responds optimally to larger image sizes of 0.5cm when viewed at the participant's reading distance. Despite the relatively large image size required for recognition the M stream it is believed to be able to resolve images about 10 times smaller (Stein and Kapoula, 2012). Although this does not allow for full recognition of individual letters, as some serifs are 0.1mm when viewed at the participant's reading distance, this does allow for rapid positional and some identification of letters within the words. The M pathway is thought to be responsible for important aspects of visual function including; binocular control of eye movements, selective attention, and visual search tasks and is referred to as the "where" stream as it is believed to facilitate directional control of vision (Ray, Fowler and Stein, 2005).

1.5.11. Parvocellular pathway

The parvocellular or P pathway consists of approximately 80% of the visual pathway and is referred to as the “what “stream as it transmits high contrast, high spatial frequency and colour contrast which is processed via the LGN to areas 4Cβ of V1 of the visual cortex. This is then projected via the blobs (colour) and inter-blobs (orientation) to V4 and this information is then sent via the ventral stream to the infero temporal cortex (Atkinson, 1992) for object recognition. An interaction between the parvocellular and the magnocellular pathway during eye movements and saccades when reading is thought to cause suppression in the M pathway enabling vision to be sustained during saccadic movement by reducing blurring and stabilising text. Deficits in the M pathway have been associated with poor saccadic control and as a consequence a reduction in reading performance (Laycock and Crewther, 2008). Although the magnocellular retinal cells show little colour opponency they do receive input from, long wavelength cells (red) medium wavelength cells (green) and short wavelength cells (blue) in equal amounts depending on their retinal distribution. When colour filters are applied to vision they may block light of a specific colour, redistributing the mix of colour across the retinal receptors either enhancing or inhibiting the M pathway (Stein, 2003). Ray, et al. (2005) found enhancement of the M pathway with the use of yellow filters. Chase, et al. (2003) argues that the M pathway could be the dominant visual pathway for text perception and is suppressed by red light slowing reading with individuals with dyslexia.

1.5.12. Koniocellular pathway

The third and less well defined visual pathway the Koniocellular (K) is thought to consist of interlaminar cells in the LGN and comprises approximately 9% of these nucleus cells (Kaplan, 2008). The K pathway is thought to receive input from the blue on cells or short (S) wavelength receptors and project to the layers 1 to 2 in the blob areas of V1 of the visual cortex. The K pathway is still not fully understood but is believed to have many of the properties of the M pathway but colour opponency of blue and yellow (Hendry and Reid, 2000b).

1.6. Visual Stress

People who are susceptible to visual stress find striped patterns uncomfortable. The patterns cause visual perceptual distortions (movement, colour and blur). Many individuals find viewing certain pictures and art works uncomfortable, and this may even lead to headache or seizures in those who have photosensitive epilepsy (Wilkins, 1995). Images which produce this adverse or stressful response, have a spatial structure, which when rendered by a Fourier analysis has a contrast amplitude excess in the mid-range spatial frequencies of 3 cycles per second (Fernandez and Wilkins, 2008). Although extreme responses such as migraine or seizures rarely occur, many susceptible individuals may experience illusions of colour, shape and movement. The number of symptomatic illusions that are seen would appear to indicate the extent to which susceptible individuals are affected by visual stress (Allen, Gilchrist and Hollis, 2008). The regular arrangement of text in literature gives the appearance of regular striped patterns and therefore susceptible individuals may experience discomfort when reading. The patterns that cause most problems are those that most strongly stimulate the visual system (medium spatial frequencies) and have been demonstrated to produce significant responses with neuroimaging studies (Huang, et al., 2003). Juricevic, et al. (2010) has found that when artificial images are produced the mechanism is thought to be an over-stimulation of the visual cortex. These symptoms and distortions can sometimes be reduced with individually chosen coloured filters. It has been argued that precision tints rearrange cortical activity in such a way as to modify strong excitation in hyperexcitable orientation columns of the cortex (Wilkins, Huang and Cao, 2004). The reduction in excitation with the use of precision tints reduces firing of visual neurons that give rise to illusions and distortions allowing increased comfort when viewing these patterns.

1.7. Reading for children who are profoundly or severely deaf

Reduced reading ability within the deaf population has been known for many years. One of the first to address this was the Milan congress of 1880, where oral language was seen as the single pathway to understand a language and education. This theory was taught for many years and sign language, in many cases, banned. This had the effect of isolating people who are deaf as many are unable to communicate orally.

There are multiple factors which contribute to how well deaf children attain reading abilities: were they deaf before birth; how much hearing is preserved; what type of education are they receiving? There is also an extensive range of individual variability in reading achievement amongst the pre-lingual deaf population, with many deaf children achieving age appropriate reading skills (Mayberry, del Giudice and Lieberman, 2011), although this is not the typical outcome for profoundly and severely deaf children who have significantly reduced reading age when compared to their hearing peers.

Musselman (2000) in her paper “How do deaf children who can’t hear learn to read an alphabetic script?” reviewed the literature on reading acquisition in children who are pre-lingually deaf and included an insightful quotation from one deaf child, on how they perceive their ideal world in the future development of new cities on the moon;

> “Eyeth is a special city, that city is on this picture……
>
> Eyeth have all deaf people not even hearing people…….
>
> Earth = a lot of people are hearing in the world. People depend on their ear to listen.

> Eyeth = a lot of people are deaf in the city. People depend on their eyes to listen."

This statement allows us a small glimpse as to how important the visual world is to children who are profoundly or severely deaf, whilst emphasising the importance that is placed on vision in communication with these individuals.

It would appear obvious that deaf children rely on their visual channel for the majority of the information they gather from the world around them. For example, deaf people who use sign language must be able to quickly discern information via: hands, lips (lip reading) and facial expressions to ensure full understanding of what is being communicated. Therefore, a well-functioning visual system would appear essential to facilitate this. Much of the previous research into vision in deaf children has emphasised the need for visual screening to minimise educational and social disadvantages (Siatkowski, et al., 1993; Guy, et al., 2003; Hanioglu-Kargi, et al., 2003). Despite the appreciation that vision is an essential sense in the non-hearing world little attention has been given to near visual function in particular reading.

1.7.1. How do deaf children learn to read?

Profound or severely deaf children have great difficulties in attaining competent reading abilities. Many deaf children leave school having achieved a reading age comparable to an 8-9 year old hearing child (Nielsen and Luetke-Stahlman, 2002; Hermans, et al., 2008), which will significantly reduce their educational opportunities. Many studies have investigated why deaf children find reading difficult to master, citing various impairments to reading sub-skills as causational (Hanson, 1989; Frost, 1998; Harris and Beech, 1998; Perfetti and Sandak, 2000; Musselman, 2000; Wang, et al., 2008; Kyle and Harris, 2010). Language delay in deaf children is considered a hallmark of profound and severe deafness and acquiring this skill may progress slowly or never develop (Musselman, 2000). It has been suggested that one of the primary elements in reading acquisition is phonology with deaf children having no or limited access to this via hearing. Whilst it has also been argued that deaf early readers develop an alternative phonology dependent on visual representations of print, orthographical codes, sign and finger spelling (Aaron, et al., 1998; Kelly, 2003). An impairment in the ability to obtain semantics and syntax from a spoken language for example English can lead to reduced linguistic abilities. These phonological deficits have also been implicated with difficulties in attaining good reading abilities not only for deaf children but also hearing children with reading difficulties (Stanovich, 1998).

Reading for a deaf pre-lingual child is one of the most difficult educational tasks that they encounter. Despite recognition that reading abilities are lower in the deaf pre-lingual population (Harris and Beech, 1998), no single factor has been shown to account for this impairment. Extrinsic factors have been proposed for reduced reading development, for example:

- School language (English or BSL),
- The level of hearing (profound or severe),
- The language used at home (English or BSL)
- Linguistic abilities of parents who may not be deaf and are therefore learning the language themselves (BSL).
- Type of school attended (main stream or specialist deaf school) and the educational program they receive.

As obvious as these factors may appear, visual performance has not been considered as important with one study even stating “it must be made absolutely clear that the effectiveness of the visual channel is not at issue…” (Perfetti and Sandak, 2000). However, some of the first known attempts at recording knowledge was via pictures and pictograms.

When considering the teaching of formal written language, such teaching has been an extremely recent event in human development, having only been taught within the last 250 years for whole populations in the developed world. Fischer makes the analogy that if human development is compressed into one year, written language for everyone has only been available for the last hour (Stein and Kapoula, 2012). Whereas learning to speak a language is an innate ability in the hearing population, reading is not and requires many hundreds of hours of practice and instruction to become proficient. Different languages have been proposed as not requiring a phonological code, allowing greater access of people who are deaf. It has been suggested that Chinese is a pictorial or logographic system which would offer the possibility of gaining information without the use of phonics. This perception has been based on the picture-like characters of Chinese writing. This is a mistaken and misleading belief as though originally based on pictographic symbols the characters are now more stylised and are compounded to include a phonetic element that provides information on the pronunciation of the spoken language (Tan and Perfetti, 1998). This presents the deaf pre-lingual child with an extreme disadvantage as they have no or limited access to phonological interpretation of language (Kelly, 2003). Phonological interpretation is believed to be formed by phonological coding, where words are converted from letters (shapes) or graphemes and then to sounds or phonemes. The deaf therefore do not have these sounds to help them, making speech and reading a more difficult prospect. Whilst reading a formal language is a difficult prospect for children who are deaf communication is not based just on written material; deaf cultures have developed differing methods of communication, whether as a formal language system such as BSL or one which is generally specific to the deaf community.

Many profound and severely deaf children within the United Kingdom (UK) are taught BSL which has a completely different grammatical, semantic and syntax format than that of traditional English. Deaf children then speak (sign) in a different language (BSL) whilst trying to decode another (English) whilst reading. There still remains much disagreement in the literature about the methods in which deaf children learn to read. Musselman (2000) has suggested that there are two main pathways to reading acquisition in the deaf. First reading is achieved in a similar manner to that of normal hearing children, sometimes known as the *qualitative similarity hypothesis* (Paul and Lee, 2010). Secondly deaf children use qualitatively different methods. These methods include speech reading, articulatory feedback, visual phonics and cued speech (Wang, et al., 2008).

As children with >70dB of hearing loss do not acquire functional speech, it should be noted that deaf children have an unimpaired ability to become proficient in sign language especially if exposed to sign language at an early age, for example children who are born to deaf mothers (Strong and Prinz, 1997). There is a strong agreement within the literature that deaf readers acquire some form of phonological encoding but this is less accessible to deaf individuals, consequently driving other methods of reading acquisition. Therefore a combination of differing methods should be considered, including visual / orthographical.

1.7.2. Qualitative similarity hypothesis

This hypothesis considers the acquisition of literacy in pre-lingual deaf children in relation to the strategies which are used to produce a peer equivalent reading ability. The first fundamental premise is that deaf children are not unable to acquire literacy but are delayed and will eventually catch up with individuals with typical hearing. Paul and Lee (2010) suggested that the "*Matthew effect" is* one of the main factors in reading acquisition and that there is a critical period for the development of literacy. For example '*the rich get richer*…' (Paul and Lee, 2010) or good readers become better readers as they continue to advance with their reading abilities, whilst more controversially '*the poor stay the same or become poorer…'* That is*,* poor readers continue to have reduced reading abilities due to their lack of experience, and continue to lag behind as their optimal or critical development period passes, typically before their ninth year. This makes catching up to their hearing peers, a more difficult prospect. It has been suggested that deaf and hearing alike, who have difficulties in attaining proficient reading abilities, have a similar disadvantage. This may also be described as a developmental lag. It should be understood that reading is a complex cognitive process, involving many factors such as converting visual symbols in to graphemes and phonemes and then to word identification (Leybaert, 2000). Therefore children who are deaf may well develop alternate routes to decode texts and may not have a similar understanding of graphemes and phonics as those of hearing children.

1.7.3. The qualitative different hypothesis

In contrast to the similarity hypothesis, the qualitative different hypothesis supposes that there are alternate routes to reading acquisition for profoundly and severely deaf children (Wang and Andrews, 2014). This theory proposes that reading is acquired with alternative methods to those found in hearing children, which include: speech reading, lip reading, facial expressions, sign language and visual phonics (Colin, et al., 2013). Deaf children are unable to access the normal phonic and phoneme meanings from text, which is considered a primary function for good reading. Therefore the question still remains how do deaf children learn to read? Do they bypass the phonological aspects of reading and prefer a visual interpretation? These differing methods are described below.

1.7.4. Visual phonics

Visual phonics has been defined by the International Communication Learning Institute, (1982 cited in Stevenson, 2014) as “a multisensory instructional tool designed to clarify the sound-symbol relationship between spoken English and print” and uses hand cues and written symbols to represent phonic sounds and has been designed to improve reading through the development of phonological awareness. The use of visual cue allows the deaf student to see the sounds rather than hear them,

1.7.5. Speech reading and cued speech

Speech reading and cued speech has been proposed as an alternative sensory coding for “speech-equivalent” phonology. Campbell and Wright, (1989) studied oral training in which the pre-lingual deaf child looked closely at lip movements to convey phonetic meaning which may be significant enough to allow for speech development. The study compared orally trained teenagers with two sets of written syllable rhyming lists:

1 DA,SHA,NA and SA which are perceived as difficult to lip read and

2 BA, THA, MA and VA which are easier.

Their results showed that there was an effect of lip-readability. For example, perceived syllables were simpler to discriminate when movements of mouth tongue and teeth are easily seen (DA,SHA,NA and SA) and have been reported as showing evidence of phonological coding via this method. A previous longitudinal study (Colin, et al., 2013) proposed that profoundly deaf children who are exposed to cued speech (a system to resolve some of the difficulties associated with speech reading) in the children between 5 and 7 years showed enhanced phonological skills compared to later learners.

Perfett and Sadank, (2000) considered the visual role in reading in acquiring a phonology and suggested that a compensation in the visual system may improve phonological access to reading by increasing the use of the visual system as many deaf children make atypical spelling errors when compared to hearing equivalents. Aaron, et al, (1998) found that when deaf children make spelling errors they tend to be transpositional, for example *dook* for *book* and *ture* for *true.* Deaf individuals tend also to make far fewer phonologically acceptable misspellings. For example, hearing children made the spelling error for *blue* as *bloo* whereas *buel* was not considered phonologically acceptable. It is surprising that good profoundly deaf readers do not always have the best oral training (Hanson and Fowler, 1987) as it would seem logical that good oral training would promote phonological proficiency required for fluent reading. Conversely some of the best reading deaf children come from deaf parents who have no verbal linguistic abilities. However, reading English for example, should be considered as a second language to most severely and profoundly deaf children who would usually communicate in a manual (BSL) rather than a verbal one. It would seem that a knowledge of a language whether manual or verbal is essential for acquiring proficient reading skills (Goldin-Meadow and Mayberry, 2001).

In contrast, (Miller and Clark, 2011) in their review of research into phonic awareness in pre-lingual deaf children proposed that these children may not require a phonology to develop good word reading strategies. They questioned the relationship between visual phonics and cued speech as it remains unclear as to whether this yields greater reading comprehension. Miller and Clark, (2011) proposed that deaf readers who become proficient readers without the understanding of phonology, must therefore violate this theory.

The debate into how deaf children finally achieve peer equivalent reading is still on-going as is the contribution that the various methodologies may have on their reading acquisition (Mayberry, del Giudice and Lieberman, 2011). The use of phonological information would appear influential for deaf children to become proficient readers, whilst the type and method of attainment is still greatly debated. However, the fundamental system that enables this understanding is a visual one. Without an accurate representation of the text, any subsequent decoding of the phonology may well be impaired or unachievable. Much of the research that is stated above is related to cognitive interpretation of the written language. The premise of the following investigation into reading and vision function is that the initial constructs of reading are visual. These could be considered the basic elements which describe reading acquisition in profoundly or severely pre-lingual deaf children. In the next experimental chapters an investigation into the visual abilities and specific reading attributes of children who are deaf shall be compared to their hearing peers.

Vision and reading would intuitively appear to be inextricably reliant on one another. Although significant research has been conducted into the visual attributes of people who are deaf this has concentrated on the pathological interaction of vision with disease processes with no research relating to specific reading difficulties, which are highly prevalent. The majority of research investigating reading abilities and achievements in the deaf has simply ignored the visual system, assuming that the process of cognition is of a higher cognitive function. Therefore the premise for this thesis was to assess the visual aspects of children who are profoundly or severely deaf, assessing their visual abilities in relation to the reading functions and investigating specific physical enhancements which may be employed to embellish reading functions for these children.

1.8. Structure of thesis

This thesis will investigate visual function in deaf children and hearing age and intelligence matched controls. In research reported in chapter 2, a complete optometric assessment was carried out, including vision and binocular assessments specifically related to near vision functions. In research reported in chapter 3 intelligence quotient, visual stress and specific reading assessments are made with the use of individually chosen coloured overlays. Chapter 4 introduces a revised rate of reading test for people who are deaf, whilst assessing the repeatability of the revised reading test. Chapter 5 assesses the visual ramifications of coloured overlays. This includes the investigation of the possible associations with reading difficulties, and the restructuring of the visual pathway associated with reading specifically for pre- lingual children who are deaf. Chapter 6 shall review the findings of the previous chapters, and investigate the implications of these findings in relation to the reading abilities of children who are profoundly or severely deaf.

1.9. Research objectives

1. Conduct an extensive literature review of visual and reading characteristics of children and adolescents who are profoundly or severely deaf
2. To investigate the visual function of children and adolescents who are profoundly or severely deaf
3. To assess the effects of individually chosen coloured overlays on children and adolescents who are profoundly or severely deaf
4. Develop and validate a modified Wilkins Rate of Reading test for deaf people
5. Assess magnocellular function of children and adolescents who are profoundly or severely deaf

Chapter 2

Visual function in children and adolescents who are deaf

2.1. Introduction

Children who are deaf have been shown to struggle with reading attainment more often than children who are able to hear (Holt, 1994; Perfetti and Sandak, 2000). This is important as learning to read involves an understanding of the relationship between letters and sound, which in turn involves both auditory and visual cognition. Whilst it is clear that children who are deaf have auditory difficulties, it may also be the case that many children have additional visual deficits, making them particularly vulnerable to difficulties in learning to read.

Whilst phonological awareness is critical for the understanding of letter-sound relationships, the reading process actually begins with an analysis of printed patterns on the page and is intimately tied to visual perception. It is possible then to suppose that reading difficulties may be, at least partially, linked to visual processing. For example, Martin, Jelsma and Rogers, (2012) have found that children with sensorineural hearing loss displayed reduced motor proficiency, which they suggested, may impair the usual ocular motor/vestibular systems. This in turn could impact on their visual stability and hence acquisition of reading (Martin, Jelsma and Rogers, 2012). There is much debate into the acquisition of proficient reading abilities in children who are deaf, with great emphasis being placed on the phonological role in reading. A bias towards a phonological account of reading appears to have resulted in basic visual factors being relatively over looked.

Research addressing the effect of visual anomalies on reading in hearing populations is well established. For example, in normal hearing pre-school children with significant ametropia (≥+4.00 dioptre sphere and ≥2.00 dioptre astigmatism) have shown improvement in cognitive abilities when the ametropia has been corrected (Roch-Levecq, et al., 2008). Therefore, the lack of studies investigating the effect of visual anomalies on deaf children is particularly surprising given the research showing that individuals who are deaf have significant visual problems when compared to their hearing peers (Leguire, et al., 1992).

Refractive and binocular vision abnormalities have typically been the most commonly reported in the deaf. Binocular vision dysfunction is often categorised in terms of manifest eye turns (i.e., heterotropias) or latent eye turns (i.e., heterophorias). For example, studies have shown the prevalence of hypermetropia, myopia and astigmatism in people who are deaf to be between 18% and 39%, and binocular vision abnormalities (e.g. heterotropia) between 5.3% and 18% (Hollingsworth, et al., 2013). This finding is important in the context of reading, because in the hearing population poor readers have inadequate or weak binocular fusion ranges at near, and a more remote near point of convergence (Grisham, Powers and Riles, 2007).

2.2. Participants

Participants were recruited from the student population attending a dedicated school for the deaf, and its partner mainstream school in the UK. All participants and parents gave written informed consent following a written and verbal explanation of the procedures involved. All procedures conformed to the tenets of the Declaration of Helsiki and were approved by the Anglia Ruskin University Ethics Committee.

A total of 33 participants who were deaf (11 female and 22 male aged 7 to 19 years, mean 14 years) were recruited for the study. Sixteen participants were profoundly deaf (hearing loss>95 dB; unable to hear and understand even a shouted voice) and 17 were severely deaf (hearing loss>70 dB; able to hear some words when shouted into better ear). Therefore the deaf sample consisted of children and adolescents who could not hear conversational speech (approximately 60dB) and consequently would not spontaneously learn to talk. All of the participants who were deaf were fluent British Sign Language (BSL) signers. The hearing participants were not BSL fluent and signing was not used. A total of 41 control participants (19 female and 22 male aged 11 to 18 years) were enrolled. All control children had no known hearing problems and no other learning disability.

Inclusion in the research was dependent on:

<u>Deaf participants</u>

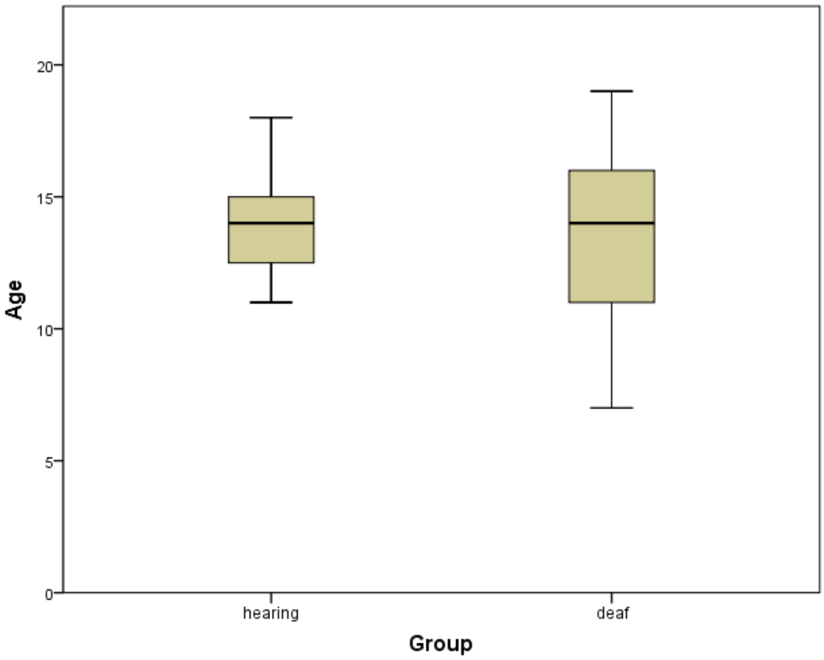
Pre lingual deafness (profoundly or severely deaf)
No specific learning disabilities
Ability to read English
Ability to use British Sign Language
Aged under 20 years
No photosensitive epilepsy

<u>Hearing participants</u>

Normal hearing
No specific learning difficulties
Ability to read English
Aged under 20 years
No photosensitive epilepsy

A total of 70 of the 74 participants who started completed the full range of tests, 31 deaf (20 male and 11 female) and 39 hearing (23 male and 16 female) aged 11 to 18 years. Two children who were deaf and two children who could hear changed schools during the study and were therefore removed from the study. The groups were well matched for age: hearing 13.6 ±1.9 years and children who were deaf 14.0 ±2.9 years and there was no significant difference in age (t_{68} =0.70, p = 0.49). Figure 2.1 shows the distribution between the groups. Experimental procedures were performed at the schools. All optometric procedures were conducted by the author.

Figure 2.1. Comparison between ages of hearing and deaf participants



All children who were deaf had instructions communicated verbally and via British sign language (BSL). The deaf school also provided an experienced BSL translator. Comprehension of the instructions for tests requiring a subjective response was inferred from correct answers to preliminary examples of the test material. PowerPoint presentations were written to aid understanding of the associated and dissociated phoria tests. The PowerPoint presentation in conjunction with verbal and signed instruction maximised compliance and accuracy of the subjective testing. All visual, binocular, accommodative and reading tests were performed with the best corrected refraction worn. The hearing participants were given verbal instructions and confirmation of understanding was received. No further verbal instructions were then given to the hearing cohort. Testing was performed on alternate days i.e. one day in the deaf school followed by one day in the hearing school.

2.3. Vision and Visual Acuity (VA)

Visual acuity is a measurement of the maximum spatial frequency that an eye can resolve. Many of the previous studies have used the traditional Snellen acuity charts and others a LogMAR chart. Although both systems are based on the concept of the minimum angle of resolution, there are fundamental differences between the two systems.

2.3.1 Test chart types

As can be seen from the charts in Diagram 2.1 the LogMAR system (Bailey and Lovie, 1976) contains a logarithmic progression, combined with a constant ratio between the size of each letter and the spacing between them. Each of the lines contains the same number of letters enabling a systematic approach to letter legibility. The Snellen acuity system (Diagram 2.2) does not have a linear progression with differing numbers of letters and spacing per line. Therefore, a LogMAR chart was used for both distance and near vision assessment.

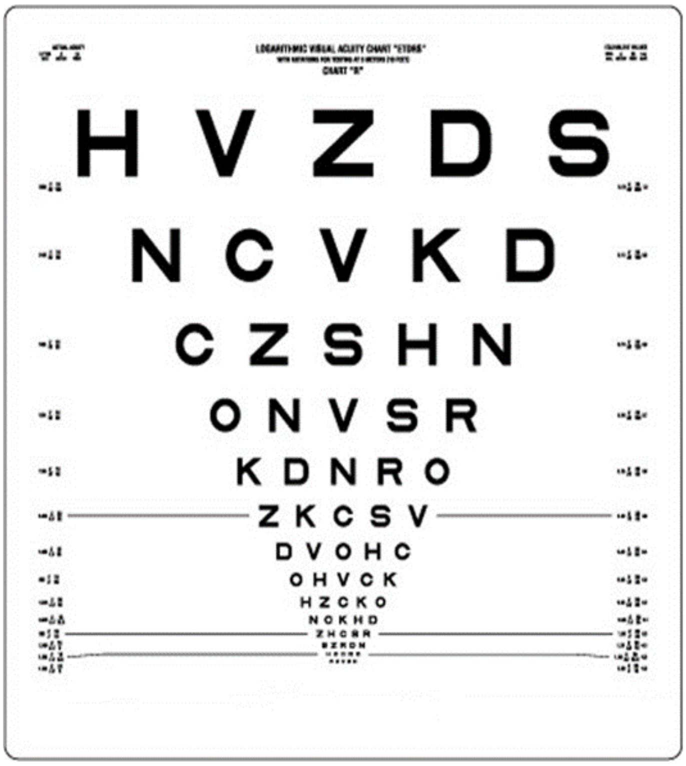


Diagram 2.1. Bailey-Lovie Log MAR chart **(**eyesfirst.Eu, n.d)

Diagram 2.2. Snellen Acuity chart (SSC education, n.d)

The LogMAR chart, due to its design format, produces a finer grading and repeatable assessment of visual acuities than Snellen test charts (Bailey and Lovie, 1976). This improvement in accuracy is increased when the visual acuity is scored per letter (Ferris, et al., 1982).

2.3.2. Near and Distance Visual acuity measurements

Near monocular visual acuity was measured at 0.4 metres with a reduced Log MAR chart for near Diagram 2.3.

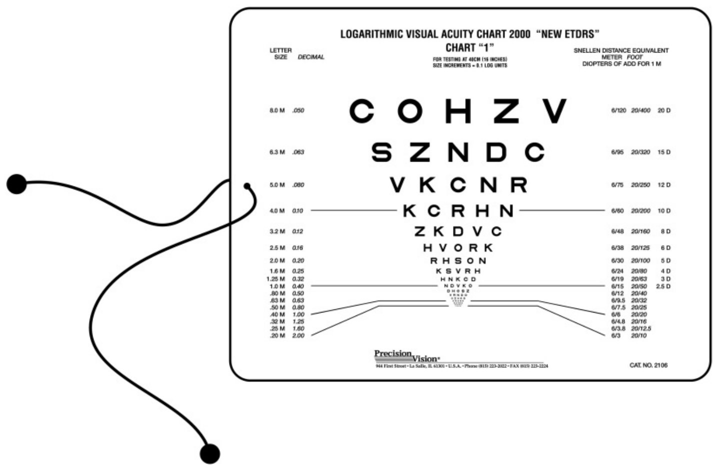


Diagram 2.3. Near ETDRS 0.4m chart (Precision Vision, n.d)

Within this study distance vision (uncorrected) and visual acuity (best corrected) were measured at 4 metres using a 4m Bailey-Lovie Log MAR chart. The charts used the ETDRS letter-by-letter scoring system of 0.02 log units per letter correctly identified. Measures were performed monocularly and the right eye was always measured first.

2.4. Refractive Error

Refractive error was measured objectively with a Nidek AR-600-A (Diagram 2.4) autorefractor (Nidek, Gamagori, Japan); and was compared to the participant's habitual correction. The Nidek autorefractor, using the 'autoshot' and 'autotracking' facilities, estimates the refractive error by averaging three successive readings in each session. The autotracking mechanism enables the machine to follow small losses of fixation by the subject. The autoshot function permits automated serial measurements when the instrument is in focus. Three readings were collected for spherical and cylindrical power and their respective averages calculated and was set to record at the 0.12D level and rounded to the nearest 0.25D. The Nidek AR600-A has given valid and repeatable results when compared to subjective refraction (Allen, Radhakrishnan and O'Leary, 2003).

Diagram 2.4. Nidek AR600-A (Diopsa, n.d)

A cycloplegic agent was not used in the current study, as this can lead to a reduction in visual performance and was therefore considered inappropriate to use in either a school environment or in a group of children who are very dependent on their vision. Other methods of refractive assessment have been utilised for specialist groups, for example the Mohindra retinoscopy technique (Woodhouse, et al., 1997). Although both cycloplegic and Mohindra methods of refraction would have been, arguably, preferable, the extent of the visual investigations and the time which had been allocated by the schools meant a quicker and more efficient method of measuring refractive status was required. The schools did not want a cycloplegic agent instilled into the children's eyes. Furthermore, there was also no provision for a completely darkened room to facilitate the Mohindra retinoscopy technique.

2.5. Binocular assessments

2.5.1 Heterotropia

Initially a cover test with prism bar was performed to identify and measure any heterotropia. A cover test is an objective measure to assess the variations of visual directions to allow for bifoveal fixation of a target (Benjamin, 2006) and was only used to assess binocular participants. Inability to view both nonius lines on the fixation disparity unit was used to determine the binocular status of the participants as suppression was indicated.

2.5.2. Dissociated phoria

Modified Thorington phoria tests (Bernell Corp., South Bend, USA) were performed at distance and near. The measurement of heterophoria is subject to error. These are a result of differing factors such as: luminance levels, accommodation control, patient's co-operation, objectivity and skill of the examiner for example. The Modified Thorington technique has been shown to produce one of the more reliable and reproducible measurements for heterophoria (Rainey, et al., 1998; Wong, Fricke and Dinardo, 2002; Cebrian, et al., 2014). Tests were always conducted in the same order: distance horizontal phoria, distance vertical phoria, near horizontal phoria, and near vertical phoria. The Muscle Imbalance Measure Cards (Diagram 2.5.) and near (Diagram 2.6.) were used at 3 metres (distance) and 0.4 metres (near). The participants were instructed to look at the light in the centre of the card and to keep the numbers on the card clear. A Maddox rod was placed over the participant's right eye and the number corresponding to the red line was recorded. For the benefit of the children who were deaf, a PowerPoint instruction show was developed to enhance understanding of the test (Diagram 2.7) and was used for each deaf student before the test started.

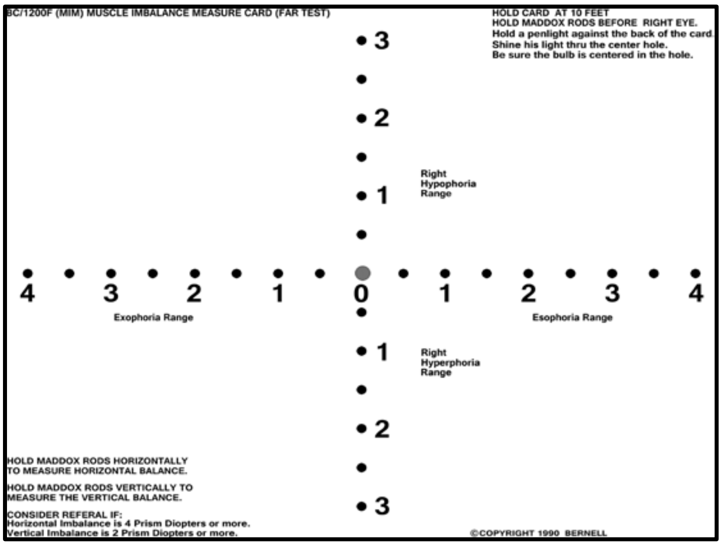


Diagram 2.5. Bernell muscle imbalance measurement card for distance. (Bernell, 2017)

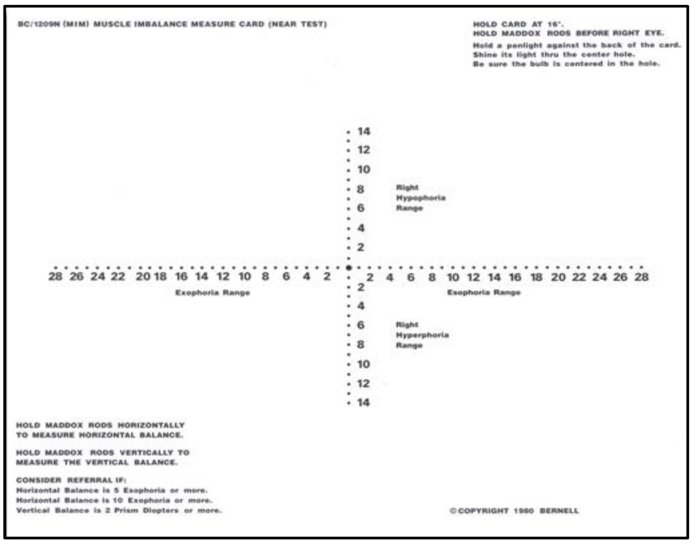
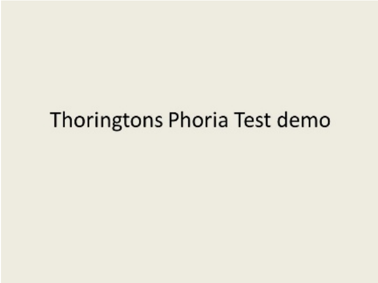
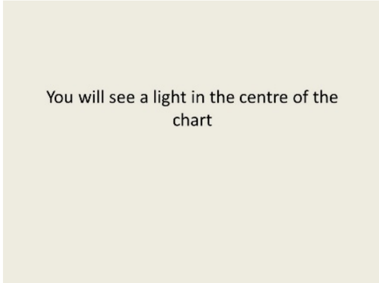


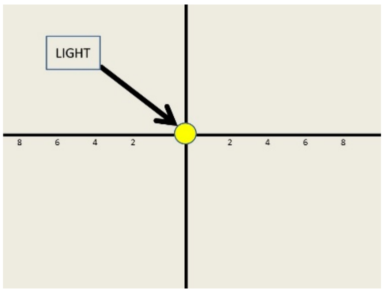
Diagram 2.6. Bernell muscle imbalance measurement card for near. (Bernell, 2017)

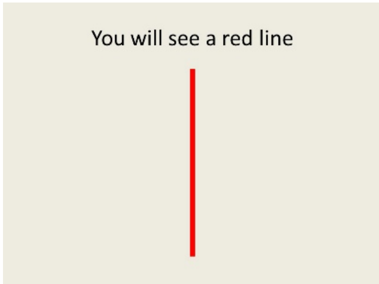
Diagram 2.7. Thoringtons participant demonstration PowerPoint



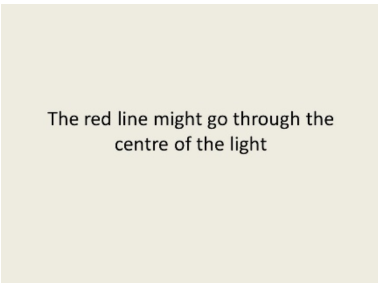


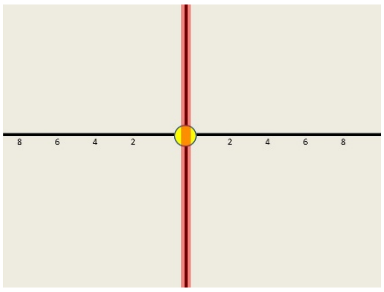
Instructions were initially signed to participants

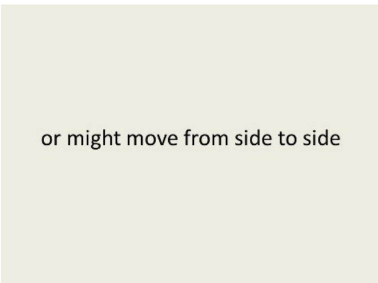


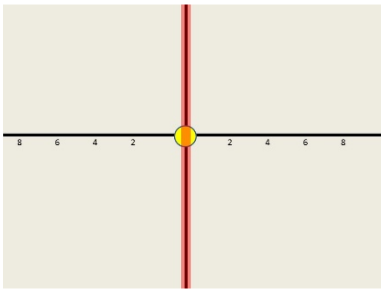


The central light flashed on and off to indicate its position

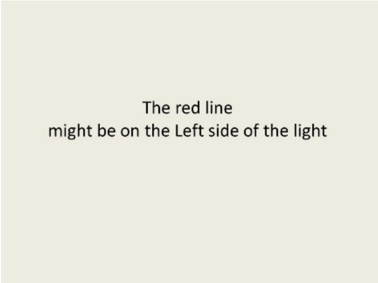


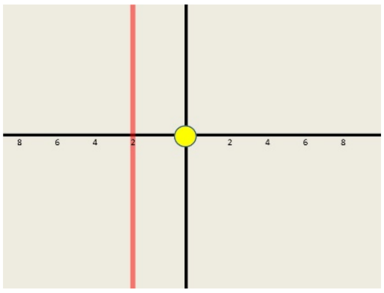


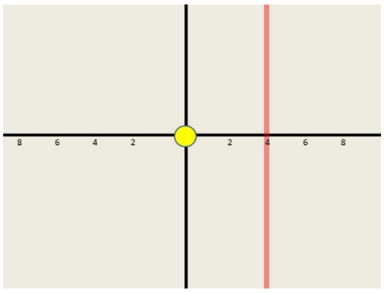


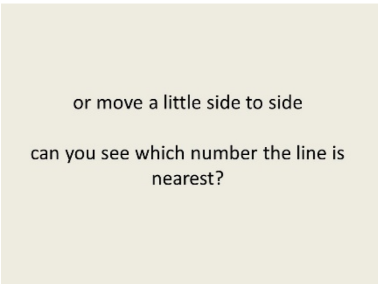


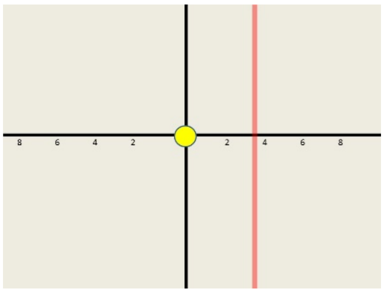
The following slides were animated to show the line moving



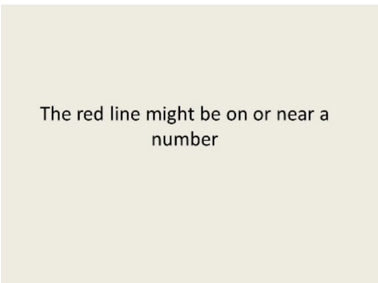


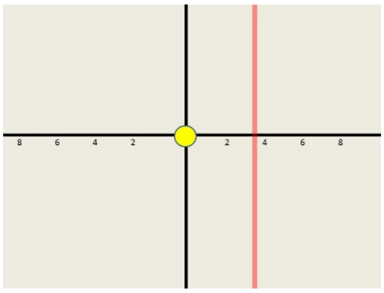


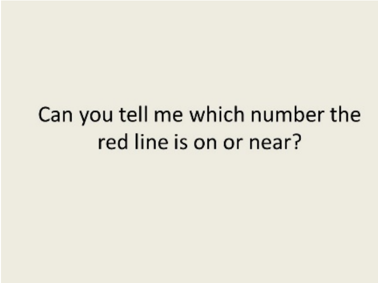


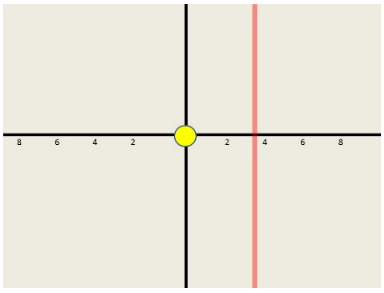


The animation of the line fluctuated from side to side and the participant was asked which number was nearest.

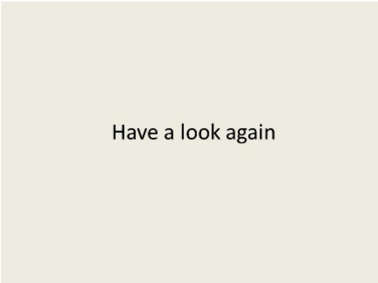


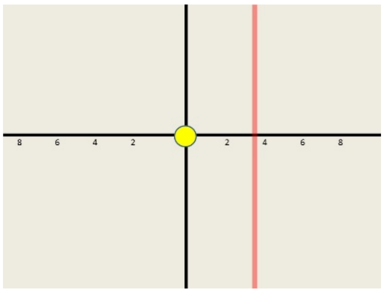




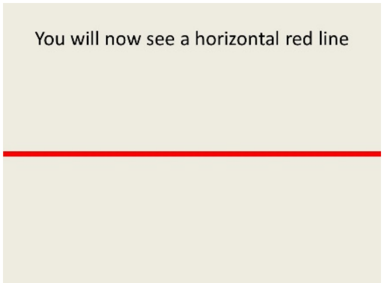


A demonstration animation was given to assess the participant's understanding of the procedure

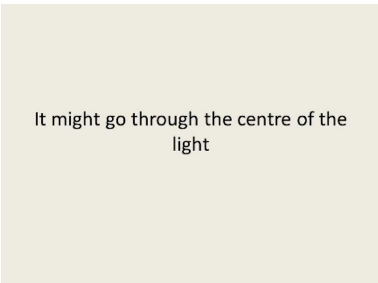


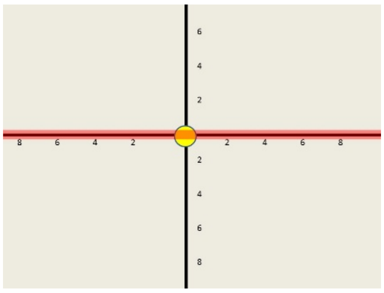


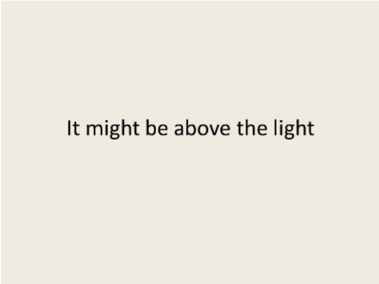
The same demonstration was again presented to confirm choice. This animation moved from side to side a little to represent instability.

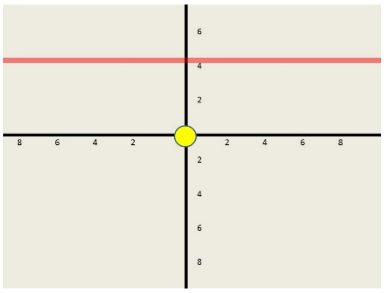


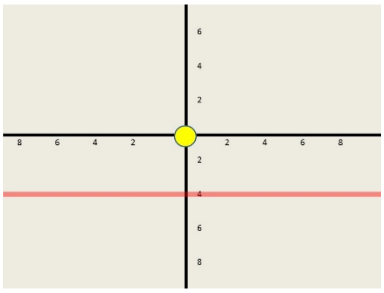
Animated character jumped up and down

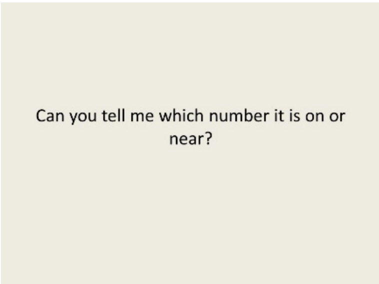


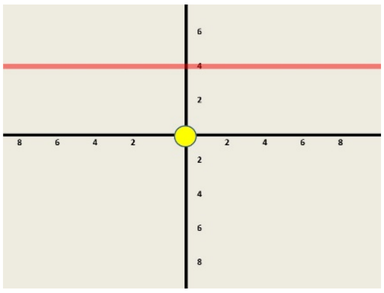




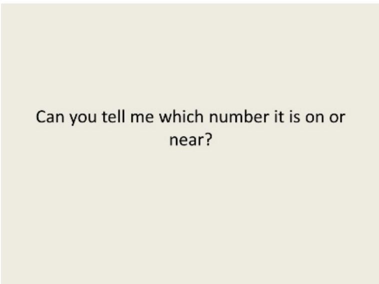


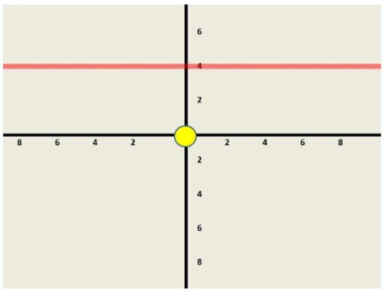




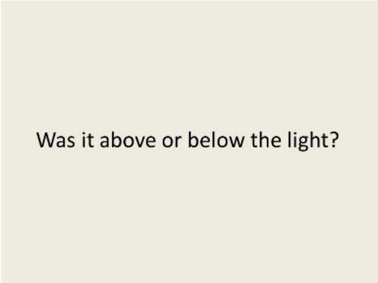


An animated demonstration slide was presented to aid understanding. The line moved up from centre





Again this was repeated with an up and down motion to represent instability

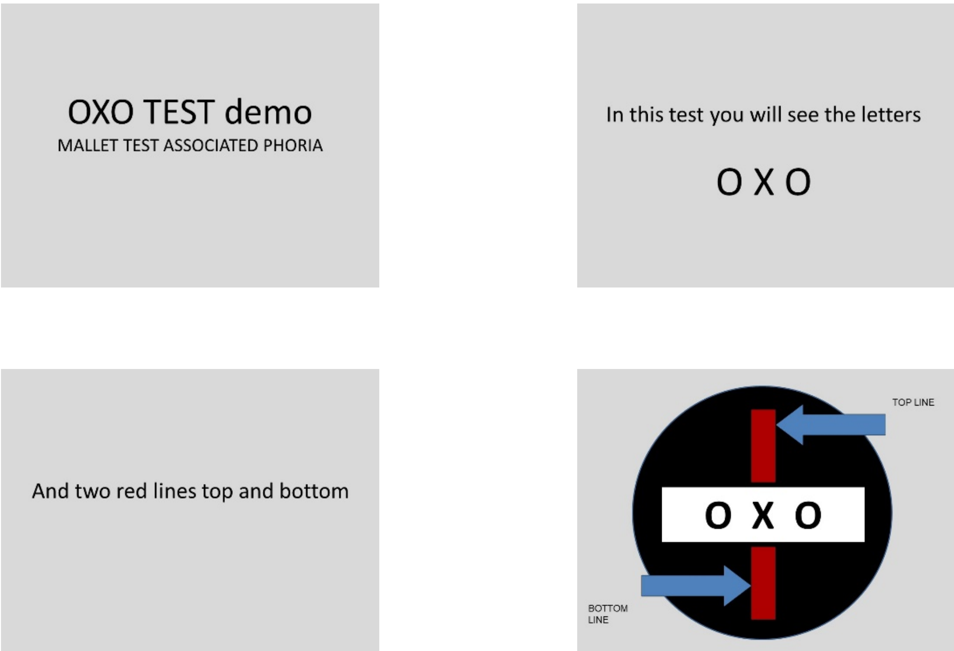


Animated character "danced"

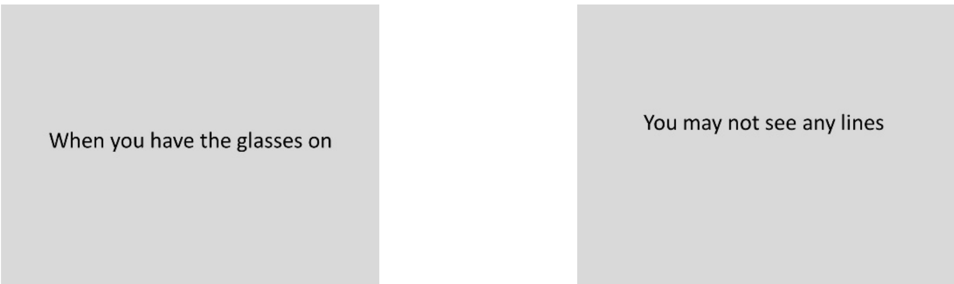
2.5.3. Associated heterophoria

Associated phoria or fixation disparity occurs when images from both eyes are binocularly fixated within Panum's fusional area, but do not stimulate the same corresponding retinal point. This will not produce diplopia as the disparity is within the single vision fusional area (Panum's area). This disparity has been described as a sign of fusional stress as the fusional images from each eye are not perfectly superimposed (Mallett, 1988). The angular value of this fusional area is between 5 and 10 min of arc (Sheedy, 1980). To measure the associated vertical and horizontal phoria (fixation disparity) measurements were conducted at distance (4 metres) and near (40cm) using distance and near Mallet units (I.O.O. Sales Ltd, London, UK). This test is commonly used in optometric practice to assess decompensating heterophoria. There is a central fixation target "OXO" which can be seen by both eyes. Above and below the X are set two monocular targets (nonius strips), which are cross polarized, allowing only one eye to see the top and one to see bottom target. A polarized visor was placed on top of the participants' correction. Any disparity was then aligned with the minimum amount of prism of appropriate base direction. The central "OXO" targets act as a fusional lock, whilst small misalignments can be assessed from the reported misalignments of the nonius strips. The Mallet unit does not measure angular values but indicates the amount of prism or aligning sphere required to realign the nonius strips. Participants who reported only seeing one of the lines, suggesting suppression, were excluded from the fixation disparity data set. For the benefit of the deaf participants a PowerPoint presentation was shown to the deaf children to ensure understanding. Diagram 2.8.

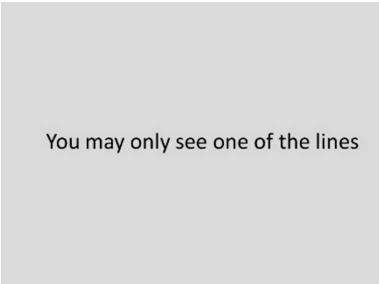
Diagram 2.8. Associated Phoria PowerPoint demonstation test

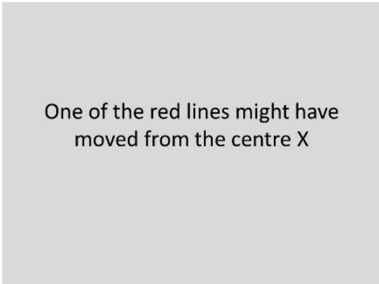


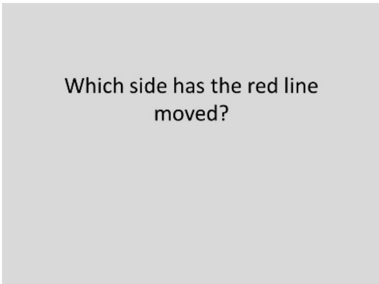
Instructions were also signed to participants.



Although no line would be an unusual finding it was shown as a check for non-compliance.







The following slides were animated and the participants asked to indicate which direction the line had moved.

Which side has the red line moved?

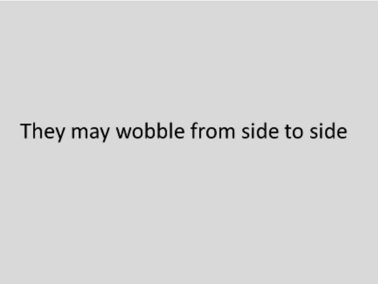
Which side has the red line moved?

Which side has the red line moved?

The top and bottom line may both move from the centre X

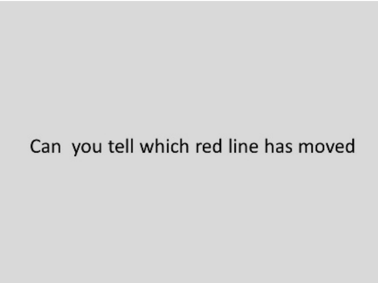
This slide was animated to show movement.

Or they may be twisted



This slide was animated to demonstrate nonius lines may move from side to side a little.

A final demonstration was given at the end of the PowerPoint presentation to assess the understanding of the participant.



This was animated to move to one side.

The participant was asked to indicate the direction the line moved.

Animated character jumped up and down.

2.5.4. Stereo acuity

Stereo acuity was assessed with Randot patterns. These patterns have the advantage of containing no contours and negate monocular clues. Monocular contours aid the fusion mechanism and reduce the effectiveness of the tests. The introduction of a random dot format reduces the ability of the participant to recognise the correct target by monocular clues. Randot tests have been shown to need accurate foveal fusion therefore, subjects with reduced foveal abilities will fail the assessment (Fricke and Siderov, 1997). The Randot® Stereotest A screening plates (Stereo Optical Co. Inc., Chicago, USA) present disparities in the range of 500 to 250 seconds of arc at 40cm and involve a simple recognition of shapes: square, circle, star, triangle, cross and E. The Randot threshold plate presents three monocularly visible circles, one of which has disparity when viewed binocularly through the cross polarised filters. There are 10 sets of three circles presenting a range of disparities from 400 to 20 seconds of arc, and the participants were asked to identify which circle of each set "stood out from the others". Only participants who passed the 500 seconds of arc screening plate progressed to the threshold plates.

2.5.5. Near point of convergence (NPC)

Near point of convergence was measured with a RAF rule (Haag–Streit, Harlow, UK). The ruler measures the near point of convergence and amplitude of accommodation. The ruler is composed of a 50cm long square section rule. Mounted on the rule is an adjustable box which has four different visual targets:

1. A reduced Snellen chart
2. Times New Roman type face (N5, N8, N10 and N12)
3. A reproduction of a page from a telephone directory
4. A vertical line with a central dot for fixation.

When assessing the NPC participants were asked to fixate on the dot located in the centre of the vertical line. The line target was positioned at the far end of the RAF rule and was then moved at approximately 5cm per sec along the RAF rule toward the participant. They reported when (if) the line appeared double and the distance from the participant's cornea was noted. This was repeated 3 times and averaged results were recorded (cm) (Siderov, Chiu and Waugh, 2001; Adler, 2004). Both deaf and hearing groups received instructions at the outset only: no additional prompting was provided during the test due to the deaf participants being unable to hear any spoken instructions.

2.5.6. Amplitude of accommodation (AA)

The clinical measurement of the amplitude of accommodation gives an estimation of accommodative ability (Adler, 2004). Accommodative amplitude measurements were made binocularly using the RAF ruler. The participants were required to read the N5 line of letters and instructed to keep the letters perfectly clear. A combination of push up and push down measurements is advisable as this will reduce any of the over or under estimations which may occur (Rosenfield and Cohen, 1996). The target was moved at approximately 5cm per sec towards the participant until they reported the first sustained blur. This was signalled by a hand movement in the participants who were deaf. This point (in cm) was recorded. No additional instructions to clear the target were given to either group because it was not possible to instruct the deaf participants during the test. The target was then moved away until the participant reported the letters became clear. An average of three measurements were obtained. The six measures were then averaged and converted to dioptres.

2.6. Contrast sensitivity (CS)

A Pelli-Robson chart (Haag–Streit, Harlow, UK) (Pelli, Robson and Wilkins, 1988) was used to measure contrast sensitivity binocularly Diagram 2.9. The Pelli-Robson chart is designed for clinical assessment of contrast sensitivity. This is designed with variable contrast letters of low spatial frequency, subtending 2.8 degree at 1m. The chart consists of 16 triplets of letters composed of Sloan letters, which is read from top left to bottom right. Each successive triplet decreases in contrast by a factor of 0.15 log units and is viewed at a distance of 1 metre. The chart employs a by-letter scoring system of 0.05 log units per letter correctly identified. Reliability of the test is good (Elliott, Sanderson and Conkey, 1990). This test is simple to administer and easily signed to the children who are deaf.

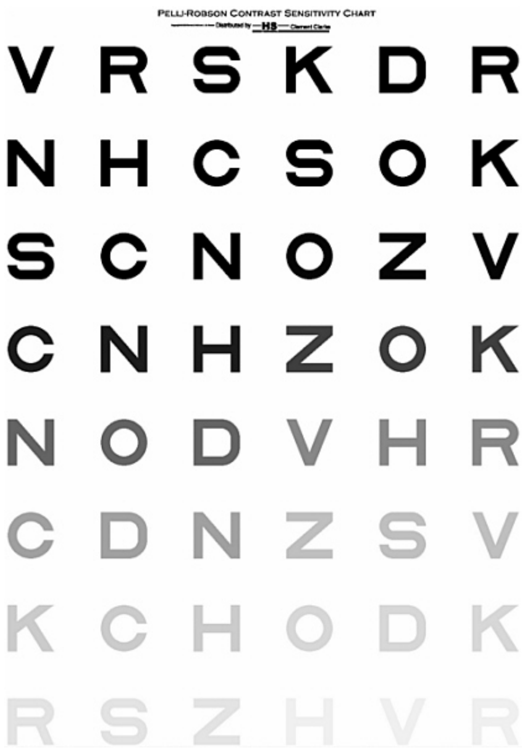


Diagram 2.9. Pelli-Robson Contrast sensitivity chart (psych.ny,edu, n.d)

2.7. Colour Vision

Colour vision was assessed with the 38 plate Ishihara Test (Kanehara Trading Inc., Tokyo, Japan) and the City University Test (Keeler td., Windsor, UK) (Third edition). The Ishihara tests is a development of a pseudo isochromatic plate test (PIC). The test is designed to place a number on a background of the same luminous reflectance as the numbers, to reduce the possibilities of detection by non-colour clues. Each plate on the 25 plate Ishihara test was viewed at 75 cm for approximately 4 sec. The number of errors was noted. If a participant failed the Ishihara test (greater than 3 errors) then the colour deficiency was classified using the diagnostic plates. The City University Test was used at a distance of 35cm. Four differing coloured dots are arranged north, south, east and west about a central test colour. The participant was asked to choose a colour which best matched the central one. Depending on the colour chosen the participant may have no colour deficiency or tend more to a protan, a deutan or a tritan defect. More than two errors constituted a failure.

2.7.1 Data Analysis

Data analysis was conducted using IBM SPSS version 20. Comparisons between hearing and deaf participants for visual and binocular function were conducted using independent sample t tests. Fishers exact test was used to test the relationship between groups with regards to spherical ametropia. A Pearson's correlation was used to assess the relationship between amplitude of accommodation and near point of convergence. For the routine optometric test results the statistical tests for each comparison are presented without a Holm-Bonferroni adjustment, which would require $p < 0.004$.

2.8. Results

Hearing No.	Age	RE V Log MAR	LE V Log MAR	RE VA Log MAR	LE VA Log MAR	RE NVA Log MAR	LE NVA Log MAR
38	17	1.10	1.20	-0.10	-0.16	-0.20	-0.20
39	15	-0.10	-0.24	-0.10	-0.10	-0.24	-0.24
44	15	-0.10	-0.20	-0.10	-0.06	-0.20	-0.20
46	14	0.10	-0.16	-0.10	-0.10	-0.16	-0.16
49	15	0.00	-0.14	0.00	0.00	-0.14	-0.14
51	14	0.00	-0.20	0.00	0.06	-0.20	-0.20
53	13	-0.02	-0.10	-0.02	-0.04	-0.10	-0.10
54	14	-0.02	-0.02	-0.02	0.00	-0.02	-0.02
58	13	-0.16	-0.22	-0.20	-0.16	-0.22	-0.22
68	11	0.14	-0.14	0.14	0.00	-0.14	-0.12
71	14	-0.14	-0.22	-0.14	-0.14	-0.22	-0.22
72	12	1.00	1.10	0.00	-0.02	-0.20	-0.22
52	15	-0.06	-0.20	-0.06	-0.10	-0.20	-0.20
45	14	-0.10	-0.10	-0.10	-0.10	-0.20	-0.20
57	15	-0.16	-0.16	-0.16	-0.16	-0.20	-0.20
59	13	-0.12	-0.12	-0.12	-0.12	-0.16	-0.16
64	12	0.06	0.06	0.06	0.06	0.00	0.00
66	11	0.02	0.00	0.00	0.00	-0.10	-0.10
52	15	0.90	0.90	0.00	-0.02	-0.12	-0.12
36	18	-0.16	-0.14	-0.16	-0.14	-0.22	-0.22
40	17	-0.14	-0.16	-0.14	-0.16	-0.20	-0.20
42	17	-0.06	-0.04	-0.06	-0.04	-0.10	-0.10
60	17	0.00	0.00	0.00	0.00	-0.14	-0.14
61	12	0.04	0.04	0.00	-0.02	-0.10	-0.10
62	12	0.04	0.06	0.04	0.06	0.12	0.14
65	11	-0.16	-0.16	-0.16	-0.16	-0.20	-0.20
43	14	-0.16	-0.16	-0.16	-0.16	-0.24	-0.24
48	14	-0.12	-0.20	-0.12	-0.20	-0.20	-0.20
34	16	-0.10	0.70	-0.10	-0.10	-0.20	-0.12
35	17	1.10	1.10	-0.04	0.00	-0.10	-0.10
55	13	0.12	0.10	-0.02	-0.02	-0.08	-0.06
69	11	-0.06	-0.06	-0.06	-0.06	-0.14	-0.14
70	11	-0.06	-0.06	-0.06	-0.06	-0.16	-0.18
41	16	0.04	-0.06	0.04	-0.06	0.06	-0.18
66	14	-0.04	-0.04	-0.04	-0.04	-0.20	0.00
67	12	0.30	-0.04	0.00	-0.16	-0.12	-0.20
63	13	0.00	0.00	0.00	-0.04	-0.12	-0.12
56	13	1.40	1.40	0.00	-0.02	0.00	-0.02
37	16	-0.10	-0.20	-0.10	-0.20	-0.22	-0.20

Vision(V). Visual acuity (VA**),** Near visual acuity (NVA)

Table 2.1. Vision and visual acuity results of all the hearing participants

Hearing No.	RE Sph SE (D)	LE Sph SE (D)	RE Cyl (D)	LE Cyl (D)	Het Trop	NPC (cm)	AoA (D)
38	-2.75	-3.00	-3.00	-0.25		6	11.10
39	-0.25	-0.25	-0.25	0.00		6	11.10
44	+0.25	+0.25	-0.50	-0.25		6	10.90
46	-0.50	-0.25	0.00	-0.75		6	11.10
49	-0.25	0.00	0.00	-0.25		6	10.90
51	0.00	0.00	-0.25	-0.50		6	11.80
53	0.00	0.00	-0.25	-0.25		6	10.90
54	-0.50	-0.50	-0.25	-0.50		7	10.90
58	-0.75	0.00	0.00	-0.25		7	11.10
68	-0.50	-0.50	-0.50	-0.25		6	12.50
71	-0.25	-0.25	-0.25	-0.25		6	11.30
72	-3.50	-4.25	-0.25	-0.50		6	13.30
52	-0.25	-0.25	-0.25	-0.25		9	11.10
45	0.00	0.00	-0.25	-0.25		6	10.30
57	-0.25	0.00	0.00	-0.25		6	10.90
59	0.00	+0.25	0.00	-0.25		6	11.10
64	+0.25	0.00	-0.75	-0.25		8	9.80
66	-0.25	0.00	-0.50	-0.25		6	11.50
52	-2.25	-2.50	-0.50	-0.50		6	13.30
36	0.00	-0.25	-0.30	-0.50		6	10.70
40	-0.25	-0.13	0.00	-0.25		6	11.10
42	-0.25	-0.50	-0.75	-0.50		7	12.50
60	0.00	-0.50	0.00	-0.25		8	11.10
61	-0.50	-0.50	-0.25	-0.25		6	11.10
62	0.00	0.00	-0.25	-0.50		6	9.20
65	-0.25	+0.50	-0.25	-0.25		6	10.90
43	0.00	0.00	-0.50	-0.25		6	12.50
48	+0.50	0.00	-0.25	-0.25		7	11.10
34	-0.25	-1.75	0.00	-0.50		6	11.80
35	-2.75	-3.50	-0.25	-0.75		9	10.50
55	-0.50	-0.75	-0.50	-0.50		9	8.60
69	0.00	-0.25	-0.25	-0.25		10	10.50
70	+0.25	+0.25	-0.25	-0.50		6	11.50
41	-1.00	-1.25	0.00	-0.50		7	10.50
66	0.00	0.00	-0.50	-0.25		6	10.90
67	-0.75	-0.50	-0.25	0.00		8	11.10
63	0.00	-0.50	-0.50	-0.50		8	11.50
56	-5.00	-5.75	-0.75	-0.75		6	10.70
37	+0.25	0.00	-0.50	-0.50		6	15.40

Right & Left eye spherical equivalent component (RE/LE Sph), Right & Left eye cylindrical component (RE/LE Cyl). Near point of convergence (NPC), Amplitude of accommodation (AoA), Dioptres (D)

Table 2.2. Visual function results of hearing participants

Deaf No.	Age	RE V Log MAR	LE V Log MAR	RE VA Log MAR	LE VA Log MAR	RE NVA Log MAR	LE NVA Log MAR
4	7	0.04	0.02	0.04	0.02	-0.20	-0.20
5	10	-0.10	-0.20	-0.20	-0.18	-0.24	-0.24
6	10	0.30*	0.00	0.30	0.00	0.40	-0.2
7	10	-0.24	-0.30	-0.24	-0.30	-0.24	-0.24
11	17	1.40	1.40	-0.04	1.40	0.02	2.00
13	18	0.60	0.62	-0.10	-0.14	0.02	0.02
14	14	0.44	0.34	-0.06	-0.04	0.04	0.02
17	12	0.12	-0.06	0.02	0.00	-0.04	-0.06
20	14	1.00*	0.30	0.80	0.50	0.70	0.20
21	14	0.50*	0.50	0.30	0.20	0.30	0.30
23	13	0.20	0.16	-0.02	-0.14	0.00	-0.10
24	13	0.06	0.08	-0.06	-0.10	0.02	0.02
25	12	0.04	0.02	-0.10	0.60	-0.12	0.40
31	14	0.50	0.52	0.10	0.12	-0.14	-0.12
3	11	-0.06	-0.04	-0.04	-0.06	-0.24	-0.22
10	10	-0.02	-0.04	-0.04	-0.02	-0.12	-0.14
18	16	0.18	0.18	0.18	0.10	0.02	-0.02
26	15	-0.18	-0.24	-0.20	-0.24	-0.24	-0.18
2	10	-0.10	0.00	-0.10	0.00	-0.10	-0.10
16	16	0.12	0.10	0.04	0.06	-0.02	-0,04
19	17	0.06	0.14	0.06	0.00	-0.24	-0.24
27	16	-0.10	-0.14	-0.12	-0.14	-0.16	-0.14
1	10	0.00	0.00	0.00	0.00	-0.26	-0.26
29	17	-0.20	-0.24	-0.20	-0.26	-0.14	-0.20
8	19	-0.02	-0.24	-0.10	-0.24	0.20	-0.24
9	11	-0.04	0.04	-0.06	-0.10	0.02	0.04
15	13	0.10	0.20	0.10	0.10	-0.14	-0.20
22	15	0.30	0.60	-0.10	0.04	0.04	0.00
30	16	0.04	-0.16	-0.18	-0.18	-0.10	-0.16
12	13	-0.16	-0.14	-0.16	-0.14	-0.10	-0.12
28	18	-0.04	-0.20	-0.04	-0.20	-0.16	-0.14

Vision(V). Visual acuity (VA). Amblyopia (*).

Table 2.3. Vision and visual acuity results of all deaf participants

Deaf No.	RE Sph SE (D)	LE Sph SE (D)	RE Cyl (D)	LE Cyl (D)	Heterotropia	NPC (cm)	AoA (D)
4	+0.25	+0.25	-0.25	0.00		7	10.20
5	+0.25	+0.75	-0.25	-1.00		14	6.90
6	+2.75	+3.25	-1.25	-1.00	Y	NA	8.80
7	+0.75	+0.50	-0.50	-0.25		7	11.10
11	-3.25	-8.25	-2.30	-3.25	Y	NA	14.30
13	-1.75	-1.50	-0.30	-0.50		15	5.10
14	-1.75	-1.00	-0.25	-0.50		8	9.80
17	+0.75	+1.25	-0.50	-0.50		6	9.80
20	-1.75	-1.25	-0.50	-4.00	Y	NA	7.50
21	-1.25	-1.50	-1.50	-1.75		NA	10.00
23	+2.50	+0.25	-4.50	-0.50		13	9.00
24	+1.75	+2.00	-1.00	-1.00		16	6.10
25	+2.00	+2.00	-0.50	-0.50	Y	10	7.90
31	+7.75	+8.00	-2.25	-0.75		9	6.50
3	-0.25	-0.25	-0.50	-0.50		9	10.50
10	+1.75	+1.75	0.00	-0.25		13	11.10
18	+2.00	+1.75	-2.50	-1.75		10	11.10
26	-0.25	-0.50	-1.30	-0.50		8	12.50
2	+0.25	+0.25	-0.50	-0.50		38	6.00
16	+1.00	+1.75	-0.25	-0.25	Y	NA	14.30
19	+0.25	+0.50	-0.50	-0.25		8	6.40
27	+0.25	0.25	-0.30	-0.25		16	6.40
1	+0.75	+0.75	-0.50	-0.75		10	10.50
29	+0.25	+0.50	-0.50	-0.50		9	10.50
8	-0.25	-0.25	-0.25	-0.50		6	8.30
9	+0.50	+1.00	-0.50	-0.50		6	9.70
15	+0.25	+0.75	-0.30	-1.50		8	10.00
22	-1.00	-2.75	-0.30	-0.25	Y	NA	10.30
30	+2.25	+2.25	-0.50	-0.25		9	7.00
12	0.00	0.00	-0.25	-0.25		12	11.50
28	-0.25	-0.25	-0.25	-0.25		14	8.60

Right & Left eye spherical equivalent component (RE/LE Sph), Right & Left eye cylindrical component (RE/LE Cyl). Near point of convergence (NPC). Amplitude of accommodation (AoA), Dioptres (D)

Table 2.4. Visual results from all deaf participants

2.8.1. Refractive error

Forty eight percent (n=15) of the participants who were deaf and 16% (n=5) of the hearing participants had significant spherical ametropia in their RE as defined by ≥ +1.00D or ≤ -1.00D. The difference between the two groups, deaf and hearing, was significant (p =0.02 Fishers exact test). Fifty two percent (n=16) and 18% (n=7) of the hearing participants had significant spherical ametropia in their LE of ≥ +1.00D and ≤ -1.00D. The difference between the two groups was also statistically significant (p =0.02 Fishers exact test). There was a significant strong correlation in spherical ametropia between the two eyes in both groups (r= 0.93, p = <0.001).Twenty six percent (n=8) of the participants who were deaf and 2.5% (n=1) of the children who could hear had a cylindrical error of more than 1.00D for the RE. The difference between the two groups was statistically significant (p =0.003 Fishers exact test). Forty five percent (n=14) of the participants who were deaf wore spectacles compared to only 12.8% (n=5) of the hearing group (p = 0.004 Fishers exact test).

For the participants who were deaf the RE and LE showed greater absolute spherical ametropia when compared to the hearing controls RE (t_{19} = 4.323, p=<0.001) and LE (t_{21} = 3.50, p =0.002).

2.8.2. Cylindrical Ametropia ≥ - 1.00D

Only one of the hearing participants and 8 of the participants who were deaf had a cylindrical value ≥-1.00D for the RE (the difference between the groups was significant, p=0.003 Fishers exact test). Eight of the participants who were deaf and none of the hearing controls for the LE had cylindrical values ≥-1.00D (p<0.001 fishers exact test). The mean astigmatism of the RE of the hearing participants was -0.37 ±0.26 and for the participants who were deaf -0.80 ±0.94 (t_{68}=2.75, p=0.008). The mean for the left eye of the hearing participants was -0.35 ±0.18, and -0.80 ±0.88 for the deaf group (t_{68}=3.01, p=0.003).

2.8.3. Spherical Ametropia ≥ 1.00D

Hypermetropia

Table 2.4 shows a greater prevalence of hypermetropia for the participants who were deaf. The mean of the RE for all the deaf participants was 1.15D ±1.58, whilst none of the hearing participants had hypermetropia ≥ 1.00D (mean = 0.30 ±0.10). The LE of the deaf participants mean hypermetropia was 1.46±1.79 whilst again none of the hearing participants had hypermetropia ≥ 1.00D (mean = 0.30 ±0.10).

Myopia.

There was no significant difference in myopia between the deaf and hearing participant groups (all participants) (RE t_{10}= 1.186, p=0.09. LE t_{10}= 0.36, p=0.73). (Table 2.2. and 2.4.)

2.8.4. Vision (V)

There was no significant differences between V in the children who were deaf and the hearing participants RE (t_{68} =0.39, *p*= 0.71) and LE (t_{68}=.79, p=0.94).

2.8.5. Distance VA

The VAs were not significantly different between groups. The mean RE LogMAR for the participants who were deaf was -0.01 ± 0.20 and for the hearing group was -0.06 ± 0.07 (t_{68} =1.39, p=.17). The mean LE LogMAR for the deaf participants was 0.02 ± 0.32 and for the hearing -0.07 ± 0.08 (t_{68}=1.68, *p*=0.10). (Table2.1. and 2.2.)

2.8.6. Near VA

Near VA in the RE was significantly different between the children who were deaf and the hearing children (t_{68}=2.97, p= 0.01); deaf children mean near LogMAR -0.02 ± 0.24 and hearing children -0.14 ± 0.08 (Table 2.1 and 2.2.). Near VA in the LE also showed a significant difference between the deaf and hearing groups (t_{68}=2.86, p= 0.01); deaf children mean near LogMAR = -0.03 ± 0.21 and hearing children = -0.14 ± 0.08.

2.9. Binocular assessment

2.9.1. Heterotropia

Six of the participants who were deaf (19%) had a heterotropia, all of which were > 10Δ (five in the right eye); 4 (13%) exhibited exotropia whilst 2 (6%) had esotropia (with full refractive correction). None of the participants had vertical deviations. None of the hearing control participants had a heterotropia. Horizontal heterotropia of > 10 Δ was significantly more common in the participants who were deaf (p =0.002 Fisher's exact test).

2.9.2. Heterophoria

Dissociated heterophoria was assessed in 24 participants who were deaf: those without heterotropia (6) and amblyopia (1) and in all the participants who could hear (39).

Distance exophoria (XOP)

Ten (42%) of the deaf group had exophoria ranging from 1.0 to 5.0^{Δ}, mean $2.5(1.3)^{\Delta}$. Five (13%) of the children who could hear exhibited exophoria for distance, ranging from 0.5 to 1.0^{Δ}, mean $0.8 \pm 0.3^{\Delta}$ (t_{13} =2.77, *p* =0.02).

Distance esophoria (SOP)

Five (21%) of the deaf group exhibited SOP at distance and 3 (8%) of the hearing participants. In the participants who were deaf SOP ranged from 1.0 to 2.0^{Δ}, mean $1.7 \pm 0.5^{\Delta}$ and a median of 1.0^{Δ} In the hearing group SOP ranged from 0.5 to 6.0^{Δ}, mean $2.5 \pm 3.0^{\Delta}$ (t_6 =0.61, *p* =0.56) and a median of 1.0^{Δ}.

Near exophoria (XOPN).

Thirteen (54%) participants who were deaf and 13 (33%) of the hearing group showed manifest disassociated heterophoria at near. In the deaf group, XOPN ranged from 1.0 to 14.0^{Δ}, mean 4.9 ± 3.8^{Δ} and in the hearing group from 0.5 to 9.0^{Δ}, mean 3.0 ± 2.5^{Δ} (t_{24} =1.12, p =0.25).

Near esophoria (SOPN).

Four (17%) of the deaf group showed SOPN which ranged from 2.0 to 3.0^{Δ}, mean 2.2 ± 0.5^{Δ}. None of the participants who could hear had SOPN.

Hyperphoria & Hypophoria.

Five (21%) of the participants who were deaf and none of the control group exhibited vertical phoria. Three exhibited hyperphoria and 2 exhibited hypophoria of the right eye, none of which exceeded 0.5^{Δ} deviation. Hyperphoria of $>0.5^{\Delta}$ is regarded as clinically significant (Elliott, 2003).

2.9.3 Associated heterophoria

All participants with binocular vision (excluding those with heterotropia) had associated phorias within normal limits (+/- 2^{Δ}) (Elliott, 2003) Table 2.5. shows the number and distribution of participants who exhibited fixation disparity. None of the participants exhibited or complained of any asthenopic symptoms. The inability to see one of the nonius lines was considered to be indicative of amblyopia, however, this did not occur in any of the participants.

Fixation Disparity	Re Xo		Re So		Re Hyper		Re Hypo		Le Xo		Le So		Le Hyper		Le Hypo	
Aligning prism	D	H	D	H	D	H	D	H	D	H	D	H	D	H	D	H
1 $^{\Delta}$	0	2	0	1	0	0	0	0	0	0	1	0	0	0	0	0
2 $^{\Delta}$	1	2	0	1	0	0	0	0	0	0	1	0	0	0	0	0

Re= right eye, Le= left eye, Xo= exo disparity, So= eso disparity, Hyper = hyper disparity, Hypo = hypo disparity, H= number hearing participant, D = number participants who are deaf

Table 2.5. The number and distribution of participants who exhibited fixation disparity

2.9.4. Stereo Acuity

Only 25 (81%) of the participants who were deaf (those without amblyopic heterotropia but including the one participant who was deaf with non-strabismic amblyopia) could perceive the 500” target whereas all the hearing participants could do so. The mean stereoacuity for the deaf group was 49 ± 19 seconds of arc and for the hearing 41 ±16 seconds of arc (t_{26} =2.10, p =0.05). If the heterotropic participants are included in the analysis then the children who were deaf have significantly lower stereopsis than their hearing peers (t_{31} =3.65, p=0.001).

2.9.5. Near Point of Convergence (NPC)

NPCs averaged 11.3 ± 6.4cm in the deaf group and 6.7 ± 1.1cm in the hearing. The NPCs were more remote in the deaf group (t_{62} = 4.38, p=0.002).

2.10. Amplitude of Accommodation (AA)

The AA averaged 9.3 ± 2.3D for the deaf group and 11.2 ± 1.1D for the hearing group t_{68} = 4.58, p< 0.001). A significant correlation between NPC and AA for the participants who were deaf was found (r_s =.45, p =0.03) whilst the hearing showed little correlation (r_s = .23, p = .16). These correlations may have reflected the binocular nature of both measurements.

2.11. Contrast sensitivity (CS)

There was no difference in contrast sensitivity between the deaf group (mean 2.05 ± 0.10 log units) and the hearing group (mean 2.08 ± 0.04; t_{68} =1.38, p = .17).

2.12. Colour Vision

No colour deficiencies were found in either group of participants

In summary, the optometric examination of the deaf group revealed a high prevalence of heterotropia, greater ametropia, a more remote near point of convergence and reduced amplitude of accommodation. These impairments could compromise reading.

2.13. Discussion

Visual performance in children who are deaf has been investigated for many years and deaf children consistently exhibited greater visual difficulties than their hearing peers, presenting with both visual and ophthalmological problems (Nikolopoulos, et al., 2006). Whilst these studies have reported visual aspects of children who are deaf, the majority of this research has been associated with visual deficits concomitant with pathological processes, for example rubella (Woodruff, 1986). However, research has demonstrated increased levels of refractive, binocular and pathological problems in children who are both severely and profoundly deaf, for a review see Hollingsworth, et al. (2013). The current research has also found increased levels of ametropia in the participants who were deaf. Nearly half of the deaf participants were prescribed spectacles compared to 15% of the hearing controls, although the levels of ametropia were not as great as previously found (Leguire, et al., 1992). It was not possible to undertake cycloplegic refraction because of disruption to teaching, thus, the present findings may underestimate the degree of hypermetropia that exists in this population.

Encouragingly, in the school used for this study, only one child had uncorrected ametropia to a level where, for the first time, spectacles were necessary. One participant whose vision required further investigation (visual acuity less than 0.18 Log MAR without a known cause) was directed via their parents to the community optometrist for a full eye examination.

Research has also shown profoundly and severely deaf subjects to have a high incidence of binocular vision anomalies such as heterotropia (Regenbogen and Godel, 1985; Leguire, et al., 1992; Hanioglu-Kargi, et al., 2003). Six of 31 (20%) participants in the deaf participants had a heterotropia and none in the hearing group. In the remaining 25 without heterotropia, associated heterophoria did not differ between the deaf and hearing groups, which is consistent with previous research in subjects with reading difficulties, that has found little association between heterophoria and reading difficulties (Evans, Drasdo and Richards, 1994). Nevertheless children who were deaf showed a more distant NPC, associated with a reduced amplitude of accommodation, a finding not previously reported within children who are deaf. However, these visual and binocular deficits are often found in children with poor reading skills (Kapoula, et al., 2006) and may contribute to a reduction in reading performance (Evans, Drasdo and Richards, 1994). In addition, visual and binocular deficits are also commonly reported in children who benefit from the use of colour overlays when reading (Stein, Richardson and Fowler, 2000; Scott, et al., 2002).

Whilst reduced visual abilities and reading performance would intuitively appear linked to poor reading skills, the relationship between reading and visual ability for children who are deaf has not currently been investigated. Instead the majority of research into reading acquisition in children who are deaf has centred on the more cognitive aspects of reading acquisition such as their attainment of understanding from written text (see Chapter 3). Although this understanding is essential, the fundamental reading task cannot be achieved unless visual abilities are adequate to allow information to be processed.

Chapter 3 will investigate the reading speed, visual stress and the effect the use of coloured overlays have with children who are deaf when compared to their hearing peers.

2.14. Optometric examination of people who are deaf

Testing people who are profoundly and severely deaf presents a number of challenges to the optometric practitioner. Communication is central to any consultation and it is believed to play a significant role in the satisfaction of patients and treatment outcomes (Beck, Daughtridge and Sloane, 2002). Tests such as Thorington's phoria test and associated phoria tests require a complex level of instruction to enable a participant to perform the test correctly whilst obtaining valid results. Children who are deaf may have significant difficulties gaining understanding, owing to the complexity inherent in some of these optometric procedures. As previously noted BSL (Chapter 1) is not a visual form of the English language and therefore requires translation into sign language (Woll and Lawson, 1987). This presents additional complexity for the deaf participants as many of the signs used to describe the test are not directly related to vision testing. The relevance for the signs used therefore needs to be placed into context within the BSL language. When Thorington's test is used, for example, difficult concepts need to be translated from English into BSL and full understanding of the requirements are difficult to achieve. In the current study a PowerPoint presentation was used to facilitate understanding over and above that of signing alone. These presentations consisted of an animated pictorial representation of the test (see Diagrams 2.7. and 2.8.), in combination with slides of basic written instructions in English. Although many children who are deaf have reduced reading attainment (Musselman, 2000; Wauters, Van Bon and Tellings, 2006) the slides on the PowerPoint presentation were amended by the English teachers at the school for children who are deaf, to ensure the majority of the participants could access the written instruction. Although the instructions for the test were signed to all the participants the written instructions allowed for additional reinforcement of the test.

Many of the assessments performed in the vision testing above are also common in general clinical optometric practice in the UK. When considering the patient who is deaf, vision testing procedures require considerable verbal instructions to elicit a result. When assessing people who have never learnt to speak and find reading and writing difficult, a different approach to vision assessment needs to be considered. This change should be designed to obtain and convey the information and results required for a complete assessment of visual function with people who are deaf.

An example of a child who is deaf and was assessed in optometric practice is included to highlight these issues;

A female child (9 years) who was severely deaf from birth was assessed by the author in general optometric practice for a routine eye examination. The patient attended with their mother who could use basic sign language and the child was a competent BSL user. The mother was extremely anxious as a results of the last vision assessment, which had indicated that the child's vision was considered to be poor and a referral for a low visual assessment had been suggested.

The patient's refraction and vision acuity were noted at the previous test, 3 months earlier as:

R + 6.50 / -1.00 X 90	VA 6/36	N18
L + 6.00 / -1.00 X 90	VA 6/36	N18

Binocular vision and ophthalmoscopy were unremarkable. However, there was little information from history and symptoms, possibly due to the level of communication the previous practitioner achieved with the child.

The child was extremely nervous and did not appear at ease in the test room. The test room environment is extremely intimidating not only for children who are deaf but for many who attend for sight tests. Rooms are filled with unusual equipment for testing sight which are not commonly encountered in everyday life and with a practitioner who may find communication difficult. A basic level of sign language should be utilised by the practitioner with people who are deaf and guides for this are readily available via the internet or the Royal National Institute for the Deaf (RNID), a basic finger spelling alphabet is included in Appendix 1. The child found it difficult to make eye contact and their attention was directed to the mother who was signing. With the author's knowledge of signing, direct communication with the child was established. The direct communication between the practitioner and the child reduced nervousness and calmed the child as the signing became calmer and more fluent with the author and mother. It should be noted that the position of both the practitioner and the translator are important, both should be in direct visual view of the person who is being tested. To gain attention of the person who is deaf either stamping on the floor, waving hands or a gentle touch to the shoulder is advisable. This is uncomfortable for many community practitioners as they are not used to this form of visual and sensory language and they should be encouraged to review these techniques before a person who is deaf attends for a sight test. Should the patient have a translator with them the patient will require time to translate the signing, read written instructions or comprehend diagrams. Only one message can be given at a time, therefore only one person signs or communicates. The translator may need to interrupt you if clarification is needed by the patient. Check periodically that the patient is understanding what is happening and whether communication is adequate. Also ask the patient for feedback on the tests which have been performed and if needed repeat the process. Perception of facial expressions and body language are also of great importance to a person who is deaf and greater emphasis is needed when signing (Muir and Richardson, 2005). The person who is deaf will pick up a great deal of information from body language so the practitioner must be mindful of this and maintain a positive body language. Therefore, the practitioner needs to remain controlled and engaged with the person who is deaf to maintain communication.

History and symptoms revealed that the child was extremely visually active at school and home, having good communications with both her parents and teachers via sign language. The child’s mother had concerns about the reading attainment as the child found this extremely difficult. During the refraction the child was cooperative, having been previously shown and signed what was required for each of the vision tests and these were performed competently with some encouragement and reinforcement of the procedures. For vision assessment the child was able to sign each of the letters on the chart. Letter recognition was assessed by showing the child a number of different single 6/60 (1.0 Log MAR) letters which the child signed easily. When the test started each of the letters were initially pointed at in sequence (left to right) until the child understood what was required and began to sign the respective lines easily on the Snellen chart. Near vision was assessed with a reduced Log MAR chart at 40 cm. This was easily accepted by the child having already been taught how to perform the distance vision test as the same procedure was repeated for near vision. A refraction was performed with the aid of translation from the mother. Sign language for good and bad were used to inform whether there was improvement (thumbs up) or reduced and no improvement (shaking the little finger). Ophthalmoscopy was assessed and a full explanation of the procedure signed to the child. Volk indirect ophthalmoscopy was used as this did not involve too close a proximity, which may have distressed the child. Directions were given by hand gestures to the positions of gaze required. Binocular vision was assessed with the use of basic directional gestures. All tests were performed with consideration for the child and a few minutes rest given between each procedure. However, a longer appointment had been made so the child was not rushed.

The results of the eye examination were significantly different from the previous assessment. Although, ophthalmological and binocular status was unremarkable the visual performance had changed considerably;

R +6.50 / -1.50 X 105	VA 0.2	near VA 0.06 Log MAR
L +6.50 / -1.75 X 85	VA 0.1	near VA 0.02 Log MAR

Refraction had changed in respect of the astigmatic correction and orientation. However, the greatest improvement was achieved in the corrected visual acuity by the child.

The mother enquired as to the level of vision and the author was able to reassure them both that the corrected vision was more than adequate for school and reading use.

The corrected visual acuity from the previous eye examination was much less than that found in the new assessment only three months later. The mother noted that there seemed to be little communication with her daughter during the previous eye examination. She continued to say that the previous practitioner had appeared rushed and a little intimidated about examining her daughter which made the whole experience of the eye examination uncomfortable for all participants.

Whilst guidelines for assessing children with special needs have been addressed in the past (Woodhouse, 1998), special consideration for a deaf patient should also be applied. Karas and Laud, (2014) have suggested a protocol for vision testing in the general deaf population and has been adapted here for profound and severely deaf people (Table 2.6).

Establish the person's attention before speaking, Waving, stamping feet of touching the shoulder
Face the person while speaking
Maintain eye contact. Sit at the same level as the patient, in front of the person so they can see you easily
Be careful not to turn away to take notes whilst speaking, or signing as this can be the main reason for patients confusion with a consultation.
Do not shout as this will only distort the lip pattern, making it more difficult to understand if the person can lip read
Do not cover your mouth when speaking (lip reading)
Do not exaggerate mouth movements. This distorts lip reading
Ensure the person knows what you are about to discuss
Review the person's understanding often. Use easily understood signs such as thumbs up
If the patient does not understand, then try a different method rather than keep repeating the same wording or try a different sign if possible (diagram?)
Tell the person when you are changing to a new part of the assessment because the range of signing is likely to be different
Any cue is useful – use mime, gesture and body language especially if you don't use sign language.
Use visual aids such as models or diagrams especially for persons who are profoundly and severely deaf and have poor reading comprehension
Before carrying out tests on the patient explain clearly, before you begin, what you are going to do and what you require the patient to do.
Use diagrams, If necessary try written instruction if the person is happy to read them
Use closed yes, no questions in testing as these are easily understood
Have patience – check that you have been understood
Consider carefully how to give your advice at the end. If the patient has a translator work with them but always direct your questions to the person being assessed.
Be sure the person has understood the outcome of the consultation and give them written information on their requirements to take with them.

Table 2.6. Protocol for optometric testing with people who are profoundly and severely deaf.

People who are deaf generally have problems communicating with the hearing population (Mohr, et al., 2000) especially those who are pre-lingually deaf as they have little access to spoken language (Dolnick, 1993). Practitioners should develop strategies to help these people to understand the procedures which are being performed. Most people who are deaf have poor experiences with healthcare due to poor communications with health professionals (Ubido, Huntington and Warburton, 2002). The optometric practitioners should prepare themselves in advance of a consultation with profoundly and severely deaf people, being mindful that these individuals may have reading and writing difficult. Whilst consultations may take time to prepare and need longer to perform, the benefits to the individuals being assessed are considerable. Optometric practitioners must understand that the visual channel is the primary communication pathway for profoundly and severely deaf individuals. A testing protocol for profoundly and severely deaf patients as described in table 2.3 should be considered by all optometric practitioners.

Within the hearing population the introduction of specific coloured overlays and precision tinted lenses has increased reading speed performance in those children who have reading difficulties (Jeanes, et al., 1997; Wilkins, et al., 2001; Bouldoukian, Wilkins and Evans, 2002; Wilkins, 2002). This has been associated with visual difficulties such as reduced accommodative and convergence abilities for near. The benefit gained from coloured overlays and precision tinted lenses has been attributed to visual stress and magnocellular dysfunction and binocular instability (Stein, Richardson and Fowler, 2000; Scott, et al., 2002). To further investigate the relationship between vision and reading in children who are deaf, the next chapter will assess reading and the effects coloured overlays have in children who are deaf when compared to hearing children controls. Reading speeds and visual stress will investigate specific reading and visual stress tests which are designed to emphasise visual requirements, whilst assessing the effects coloured overlays have on reading speeds in these children.

Chapter 3

The effects of coloured overlays on children and adolescents who are deaf and hearing.

3.1. Introduction

In hearing children with reading difficulties, their reading difficulties have sometimes been associated with visual distortions and/or discomfort when viewing text. This has been attributed to a condition known as visual stress (Wilkins, 1995). Although visual stress appears to only affect a small percentage of children, the impact on their reading speeds and comfort is significant (Evans and Allen, 2016). This chapter investigates the effect patterns likely to elicit visual stress have on children who are deaf, whilst also investigating the effect of coloured overlays on reading speeds in both deaf and hearing participants.

3.2. Reading for people who are deaf

Approximately 90% of children who are deaf are born to hearing parents who do not know signing and who often have to learn signing alongside their child (Rienzi, 1990). Children who are born to hearing parents generally have greater difficulties with reading compared to those who are born to deaf parents, possibly because of the decreased interaction with signing in the home as communications are basic (Rienzi, 1990). Many children who are deaf therefore enter school with a much lower linguistic base then their hearing peers. When sign language is fluent, students who are deaf learn to read and ascertain academic content in printed English, despite the differences from the sign language used for daily communication (Harris and Beech, 1998). Relative to students who can hear, students who are deaf commonly struggle when learning to recognise words, understand vocabulary, and use comprehension strategies (Andrews and Mason, 1991). The average student who is deaf leaves school at age 18, with a reading age approximately equivalent to that of a 9-year-old child who can hear (Wauters, Van Bon and Tellings, 2006).

Difficulties with reading acquisition in otherwise neurologically, attentionally, and intellectually normal children have often been attributed to two deficits: phonological and visual, with the former being much more common. In the hearing population, deficits in processing the phonology of language have been found to impact reading ability (Liberman and Shankweiler, 1985; Shankweiler and Liberman, 1989). For example, individual differences in phonological awareness and rapid automatic naming ability have been shown to influence the rate at which children who can hear acquire early reading skills (Torgesen, et al., 1997). Importantly, if subtle phonological deficits are associated with poor reading in the hearing population, then the question arises as to how it is possible for profoundly deaf individuals to read.

Sometimes symptoms of visual discomfort are associated with perceptual distortion, usually of text, in which case they are referred to as visual stress (Wilkins, 1995). Visual stress is provoked by images with high contrast stripes such as printed text and is more common in those who have reading difficulties and binocular instability (Evans, Drasdo and Richards, 1996). The individuals who are susceptible can use colour overlays to relieve symptoms and increase reading speeds and visual comfort. Colour overlays have also been shown to benefit other groups; patients with autism (Ludlow, Wilkins and Heaton, 2006), multiple sclerosis (Wright, Wilkins and Zoukos, 2007) and stroke (Beasley and Davies, 2013). The present study is the first to look at the relationship between visual function and reading ability in children who are deaf by conducting a thorough assessment of visual function and rate of reading with and without colour filters.

3.3. Visual stress

An important finding with children who have reading difficulties is an association with distortion and discomfort when viewing stressful visual patterns (Kriss and Evans, 2005). The images which are most likely to induce symptoms of VS include flicker and patterns, in particular stripes with specific spatial frequencies. Symptoms induced by these images include: fading, distortions, flicker and movements of images and blurring. These symptoms are more likely to be shown by individuals who exhibit; migraine, photosensitive epilepsy, and dyslexia (Wilkins, et al., 2001; Ludlow, Wilkins and Heaton, 2006; Allen, Gilchrist and Hollis, 2008; Harries, et al., 2015). For example, people who are subjected to migraines tend to report illusions such as motion, shape and colour. These visual illusions have been related to a inappropriate firing of cortical cells and have been associated with hyper-neuronal activity when viewing visually stressful images (Huang, et al., 2003). Visual stress appears to be sensitive to specific patterns. Stimuli which can induce such symptoms are characterised by images that are high in contrast and have a striped appearance. The pattern which appears to maximise the visual disturbance are stripes which subtend 10” of arc, having a spatial frequency of 3 cycle/deg, an equal width (approximate duty cycle of 50%) and a square-wave luminance profile (Diagram 3.1.).

Please do not look at this pattern on the next page if you have migraine or photosensitive epilepsy because this may induce an attack.

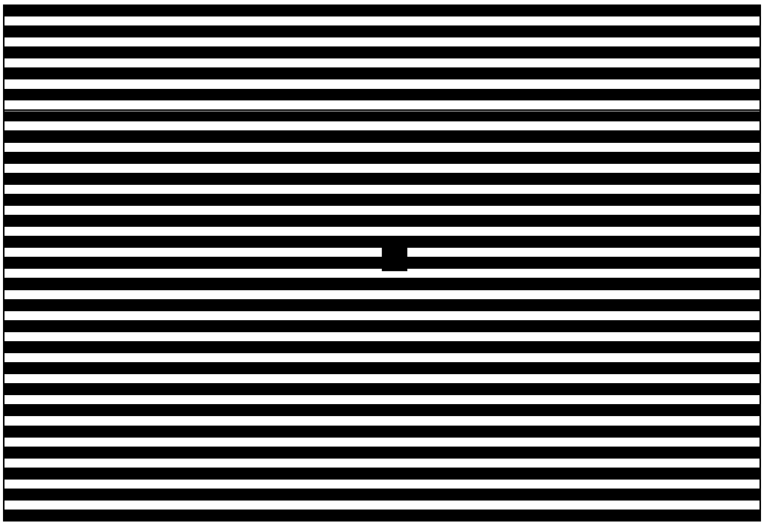


Diagram 3.1. The pattern shows a square wave luminance with a 50% duty cycle with a spatial frequency of 3 cycle/degree (not to scale)

Printed reading material for example books, has the tendency to exhibit a similar frequency to that which causes a visual stress response. These symptoms can be reduced if the reading area is kept to a minimum with the use of a typoscope. Importantly, the use of a typoscope to manage these symptoms suggests that the patterns from the lines of text are responsible for the abnormalities rather than the stripes within the words themselves. Although, it has also been hypothesised that perceptual distortions and headaches associated with reading could occur as a result of the appearance of text in a stripy pattern (Wilkins, 1995). This response has been described as “pattern related visual stress” (Allen, et al., 2010), and has also been described as “Meares-Irlen syndrome” and “Scotopic Sensitivity Syndrome” (as reported in (Allen, Evans and Wilkins, 2010). However, it is noteworthy that most observers, irrespective of being a headache or epilepsy sufferer, will find the pattern at this frequency uncomfortable to look at. Some individuals may even find that they perceive patterns, shapes and colours within the image (Wilkins, Huang and Cao, 2004). Wilkins (1995) described a number of adverse reactions to the pattern which he has listed as:

Colours;

Red, green, blue, yellow

Visual disturbances;

Blurring, bending of the lines, shadowy shapes in the lines, shimmering, flickering of the whole pattern

Physical;

Nausea, dizziness and pain.

Some of these perceptual distortions may also be associated with: micro saccadic movements, changes in accommodation and the relative focusing of various wavelengths of light in the eye (Simmers, Gray and Wilkins, 2001).

3.4. Coloured overlays

There is increasing evidence that colour filters may improve VS symptoms and reading speeds in patients who are susceptible (Jeanes, et al., 1997; Wilkins, et al., 2001; Bouldoukian, Wilkins and Evans, 2002; Ludlow, Wilkins and Heaton, 2006). Although this continues to be a matter of controversy and debate (Ritchie, Della Sala and McIntosh, 2011; Henderson, Tsogka and Snowling, 2013; Elliott, 2016) possibly due to the subjective outcome measures and the individually reported subjective changes to the symptoms when overlays are used. Physical visual function, for example, binocular instability have also been implicated with VS (Allen, Evans and Wilkins, 2010). Weak associations between reduced accommodative ability and uses of coloured overlays have been suggested (Wilkins, Huang and Cao, 2004; Allen, et al., 2010). As VS is hypothesised as having similar characteristics to that of photosensitive epilepsy and migraine which theoretically reduces the efficiency of the cortex, causing illusions and distortions. Wilkins, (2004) has proposed that the firing pattern of neurons in the cortex is changed with the use of coloured overlays, redistributing the excitation within the cortex in the local hyper-excited areas thus mitigating the symptoms of VS and improving reading progression. Mapping of colour responses in the cortex appear to follow the colour sequencing found in the Comission Internationale de l'Eclairage (CIE) colour diagram (Xiao, Wang and Felleman, 2003) within the macaque cortex. It has been argued that the human cortex is arranged in the same manner. The introduction of specific coloured filters are thought to reduce hyper-excitability across the visual cortex, inhibiting the spread of the excitation and impeding misfiring of the visual neurons which produce these visual distortions and illusions (Wilkins, 1995). However, this is a theoretical assumption and there is at present minimal evidence to support this hypothesis, although neuroimaging studies have described a responsive link between cortical hyper excitability with visual stress (Huang, et al., 2003; Chouinard, et al., 2012). Visual disturbances and illusions have also been associated with magnocellular dysfunction (Stein, 2001). Magnocellular defect have also been linked to accommodative and convergence binocular dysfunction in dyslexic children (Scott, et al., 2002; Ray, Fowler and Stein, 2005).

The use of coloured overlays have been combined with a specific reading test developed by professor Arnold Wilkins in the 1990's. The Wilkins Rate of Reading Test (WRRT). The WRRT was designed to be used in general optometric practice to provide an assessment of reading speeds in children who have reduced vocabulary such as children with dyslexia.

Conventional reading tests are designed to assess the educational and semantic abilities of the reader whilst increasing in difficulty. Such tests are also restricted by the child's vocabulary, which is known to be reduced in children who are deaf (Harris and Beech, 1998). The Wilkins rate of reading test (WRRT) has been designed as a simple reading test and is presented and designed to maximise the visually stress aspects of written text. The test also reduces the effects of semantic and grammatical understanding needed by the individual being assessed, whilst also minimising the time required to perform the test. The WRRT is designed to appear similar to horizontal stripes that are most liable to elicit visual stress. This has been achieved by producing a nonsense paragraph of closely spaced words and rows (Diagram 3.2). The words have been randomly placed to reduce the semantic connections between adjacent words. The test has 15 repeated words ordered in ten lines and four sets of differing word sets A, B, C and D. The words were chosen from 110 of the most commonly represented words in children's literature (Wilkins, et al., 1996). The test was derived from research into early reading development in hearing children, where decoding of text into sounds (phonemes) are needed for reading progression. Two font sizes are available and the smaller type should be used unless discomfort or pain is reported (as described in Wilkins, 1996).

Diagram 3.2. Card A of the Wilkins Rate of Reading Test (not to scale)

come see the play look up is cat not my and dog for you to
the cat up dog and is play come you see for not to look my
you for the and not see my play come is look dog cat to up
dog to you and play cat up is my not come for the look see
play come see cat not look dog is my up the for to and you
to not cat for look is my and up come play you see the dog
my play see to for you is the look up cat not dog come and
look to for my come play the dog see you not cat up and is
up come look for the not dog cat you to see is and my play
is you dog for not cat my look come and up to play see the

From (Wilkins, et al., 1996).

3.5. Participants

The participants were recruited from the student population attending a school for the deaf, and its partner mainstream school in the UK. The participants were the same cohort who took part in the initial visual testing and were tested in a separate session. All participants and parents gave written informed consent following a written and verbal explanation of the procedures involved. All procedures conformed to the tenets of the Declaration of Helsinki and were approved by the Anglia Ruskin University Ethics Committee.

A total of 31 (prelingual) participants who were deaf (11 female and 20 male aged 7 to 19 years, mean 13.6 years) were enrolled. Sixteen children were profoundly deaf (hearing loss>90 dB; occasional loud sounds are perceived) and 17 were severely deaf (hearing loss>70 dB unable to hear even shouted conversations). Therefore the deaf sample consisted of children who could not hear conversational speech (approximately 60dB) and consequently would not spontaneously learn to talk. All of the participants who were deaf were fluent British Sign Language (BSL) signers.

A total of 39 hearing control participants (16 female and 23 male aged 11 to 18 years, mean age of 14 years) were enrolled. The mean age did not differ between the groups. The groups were well matched for age: 13.6 ±3.0 and 14 ±11.8 years. There was no significant difference in age (t_{68} =0.70, p = 0.49)

3.6. Methods

Experimental procedures were performed at the schools. All optometric and IQ testing was conducted by the first author. In each school the lighting was a combination of normal background office lighting, and task lighting using an Osram Dulux 11 w 865 lamp (colour temperature 6000K) with an illuminance of 300-500 Lux operated from an electronic ballast at a frequency of 25 kHz. Testing was always performed in the same rooms and under the same lighting conditions in each of the schools.

3.6.1. Ravens progressive matrices (IQ) Test

Non-verbal Intelligence quotient (IQ) was assessed with an open test that could be administered to both deaf and hearing groups: the Raven's Standard Progressive Matrices (RPM) (Raven, Raven and Court, 1992).

The RPM test has been designed as a nonverbal measurement of general mental ability. The test is designed to identify:

Analytical and problems solving from complex information,

Abstract reasoning,

An ability to learn

It is termed progressive as the matrices become more complex and difficult as the test proceeds. As this test is a visual test it is not influenced by language or the inability to hear or read. Therefore, it is suited to both children who are deaf and their hearing peers.

The test is designed with a series of diagrams in which an area is missing. There are a number of options that can be chosen. Diagram 3.3 represents the first test plate (A1) from the RPM standard test series. The participant marks the tab which they think fits the missing area.

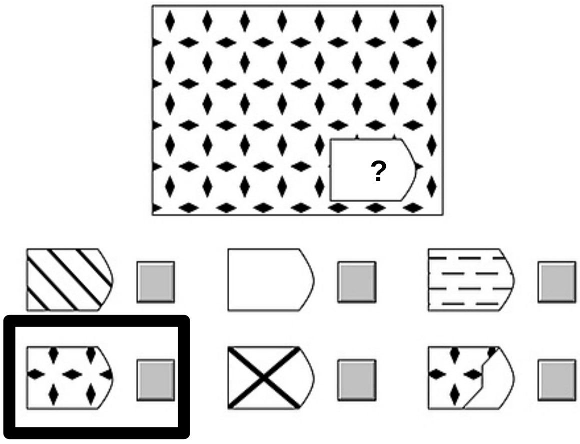


Diagram 3.3. Test plate A1 of the RPM test (Tedaltenberg, n.d.)

There are a total of five sets A, B, C, D and E. Each of these sequences offer the participant opportunity to become familiar with the test, whilst each set becomes progressively more difficult to interpret. (Diagram 3.4. is an example from set E (E1)) (Raven, Raven and Court, 1992)

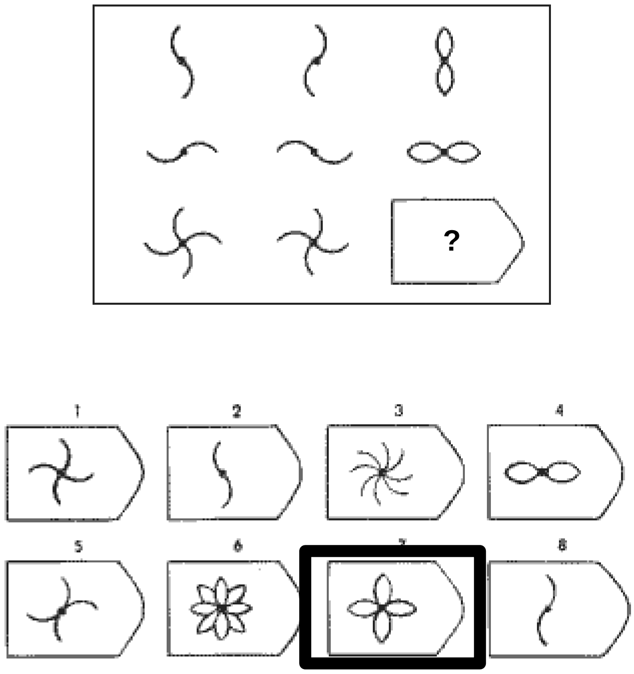


Diagram 3.4. Test plate E1 from the RPM test (Tedaltenberg, n.d.)

3.6.2. Pattern Glare

All participants were assessed for visual stress with the Pattern Glare test (i.O.O Sales Ltd, London, UK) at 0.4m (Evans and Stevenson, 2008).

The tests consist of three plates of square wave patterns of spatial frequency 0.5, 3 and 12 cycles per degree.

Participants were shown a grating with square-wave luminance profile, Michelson contrast about 0.9, spatial frequency 3 cycles per degree, circular in outline, radius 13 degrees. They were asked a series of questions regarding the perceptual distortions that they experienced, each beginning “Looking into the centre of the grid that is in front of you….. Do you see any of the following? Please answer each question with either yes/no (Table 3.1).

Table 3.1. Shows the questions asked of each participant for visual stress.

Questions asked
Pain
Discomfort
Shadowy shapes amongst the lines
Shimmering of the lines
Flickering
Red, green, blue, yellow colours
Blur
Bending of the lines
Nausea
Dizziness
Unease

Each 'yes' answer resulted in 1 being added to the score. Hollis and Allen, (2006) used this technique to identify whether people are likely to benefit (in terms of improved reading) from individually chosen colour overlays. They suggested that individuals with scores of 4 or more indicate a susceptibility to visual stress.

3.6.3. Colour overlays and Wilkins Rate of Reading Test

The Intuitive Overlay system (i.O.O Sales Ltd, London, UK) was used. The colour overlays were presented in the following order: Rose, Lime-Green, Blue, Pink, Yellow, Aqua, Purple, Orange, Mint-Green as suggested in the instructions. This order was adopted in order to reduce the chances of complementary colours being placed next to each other. The top overlay (Rose) was placed to the left of the test page, covering one of the two passages of text (diagram 3.2). When the text covered by the overlay was judged preferable to the uncovered side a second overlay was placed beside the first so that both passages of text were now covered by overlays. The child was again asked which colour made the text clearer and more comfortable. The process of removing the poorer overlay and leaving the best overlay in place was continued until all the overlays had been shown. The final choice of coloured overlay was then compared without a colour. The test was conducted binocularly. Although six participants had heterotopia and associated amblyopia, binocular viewing ensured all participants were reading text that was of a size well above that sufficient to read fluently.

The Wilkins Rate of Reading Test (WRRT) was used to measure participants' rate of reading. The test consists of a paragraph of 10 lines of text, each line comprising 15 common words arranged in different random order as previously described. Individuals were required to read the paragraph aloud or sign as quickly as possible for one minute. The words cannot be guessed from context because of the random order. The words are all high frequency and therefore within the normally developed vocabularies of most children age 7. The words were chosen from 110 of the most commonly represented words in children's literature (Wilkins, et al., 1996). The test was derived from research into early reading development in hearing children, where decoding of text into sounds (phonemes) are needed for reading progression. The WRRT is produced in two sizes and the smaller type should be used unless discomfort or pain is reported (as described in Wilkins, 1996). The smaller of the WRRT was used to maximise visual stress while minimising the linguistic and semantic aspects of reading and is reported to be reliable and valid (Wilkins, et al., 1996). Each of the four paragraphs of the WRRT has a different random order of words. The four paragraphs were given, (A) with the chosen overlay (B) without, (C) again without and finally (D) with an overlay. The ABBA design was used to minimise bias from learning/fatigue effects. Most of the practice effect occurs from the first to the second administration and the ABBA design therefore biases any mean difference against a benefit. An average rate of reading with and without the overlay was calculated. The participants who did not choose a coloured overlay were asked to read the four paragraphs without a colour overlay. The children who were deaf read and then communicated using British sign language (BSL) with the investigator. Any words which were not achievable in BSL a generic sign was used which the participant used to using for these words. No responses were needed during the test and the participants were advised to continue until they finished the paragraph or were asked to stop. All participants were asked not to use fingers as a guide.

3.7. Results

Deaf Participants	Overlay Colour	Reading Speed with Colour (words per minute)	Reading Speed without Colour (words per minute)	Percentage Change in Reading Speed	Pattern Glare
	Yellow	65.0	74	-12	0
	Yellow	64.5	60.5	7	2
	Yellow	84.5	84	1	0
	Yellow	103.0	89	16	0
	Yellow	85.0	60	42	0
	Yellow	120.0	104	15	2
	Yellow	88.0	72	22	0
	Yellow	118.5	103	15	1
	Yellow	31.5	24	31	2
	Yellow	71.5	53.5	34	1
	Yellow	103.5	92.5	12	3
	Yellow	86.5	52.5	65	0
	Yellow	68.0	66.5	2	0
	Yellow	150.0	150	0	1
	Aqua	82.5	88	-6	0
	Aqua	150	150	0	1
	Aqua	59.5	57	4	2
	Aqua	70	68	3	0
	Blue	72.5	75.5	-4	2
	Lime Green	90	81	11	2
	Mint Green	106	117.5	-10	2
	Mint Green	109.5	107	2	2
	Rose	121.5	150	-19	1
	Rose	147.5	120.5	22	0
	Pink	65	74	-12	2
	Pink	100.5	108	-7	2
	Pink	120	107	12	3
	Pink	93	81.5	14	1
	Pink	56.5	41	38	0
	Orange	150	150	0	2
	Orange	123.5	129.5	-5	3

Table 3.2. WRRT reading speeds, colour overlay choice and pattern glare results from participants who were deaf.

Hearing participants	Overlay Colour	Reading Speed with Colour (words per minute)	Reading Speed without Colour (words per minute)	Percentage Change in Reading Speed	Pattern Glare
	No Colour	150	150	0	0
	No Colour	126	127	-1	2
	No Colour	130.5	120.5	8	1
	No Colour	150	150	0	2
	No Colour	150	150	0	1
	No Colour	122	138	-12	1
	No Colour	150	150	0	0
	No Colour	123	111.5	10	0
	No Colour	103.5	105	-1	2
	No Colour	150	150	0	0
	No Colour	75	77.5	-3	1
	No Colour	145	145	0	2
	No Colour	114.5	126	-9	2
	Aqua	147.5	148.5	-1	1
	Aqua	110	108.5	1	1
	Aqua	150	150	0	0
	Aqua	87	90.5	-4	1
	Aqua	123.5	118.5	4	2
	Blue	150	150	0	1
	Blue	130	118.5	10	0
	Blue	141.5	146.5	-3	2
	Blue	139	129.5	7	1
	Blue	135	130	4	1
	Blue	111	125.5	-12	0
	Blue	143	126.5	13	0
	Blue	99	91.5	8	1
	Lime Green	150	150	0	2
	Lime Green	150	150	0	1
	Mint Green	150	150	0	2
	Mint Green	125.5	123.5	2	1
	Mint Green	111	121.5	-9	1
	Mint Green	132	136.5	-3	1
	Mint Green	126.5	117	8	0
	Pink	142.5	150	-5	1
	Pink	120	119.5	0	2
	Pink	97	88	10	2
	Orange	139	129.5	7	1
	Purple	124	123	1	1
	Grey	150	150	0	0

Table 3.3. WRRT reading speeds, colour overlay choice and pattern glare results from hearing participants.

3.7.1. Raven's Progressive Matrices

The IQ (standard deviation) for the deaf and hearing groups were 88.7 ±11.8 and 95.4 ±30.6 respectively and there was no significant difference between groups (t_{68} =1.55, p = 0.13). Comparisons between age and standard scores can be seen in figure 3.1. Only the 13 year old hearing participants had a significantly lower IQ score when compared to the normative data (t_5 =3.28, p= 0.02) (Raven, 1941).

3.7.2. Pattern Glare

There were no significant differences between groups in reported effects of pattern glare when tested with the I.O.O. pattern glare test (t_{68}=0.78, p= 0.44)). Only three participants (who were deaf) scored more than two symptoms, which is below the threshold for visual stress suggested by Hollis and Allen, (2006) see Table 3.2. and 3.3.

3.7.3. Colour overlays

All participants who were deaf chose a colour overlay as improving the clarity of text, yellow being the most popular choice (14 of 31, or 45%; Figure 3.2.). None of the children who could hear chose yellow and 33% preferred no overlay. When the children in the hearing group opted for an overlay a blue overlay was found to be the most popular choice (8 of 39, or 21%; Figure 3.3.). There was no link between refractive error and colour chosen by the deaf group; the mean spherical equivalent of the participants that chose yellow was similar to that of those who chose other colours RE (t_{29}=0.15, p =0.88) and LE (t_{29}=0.2, p =0.83).

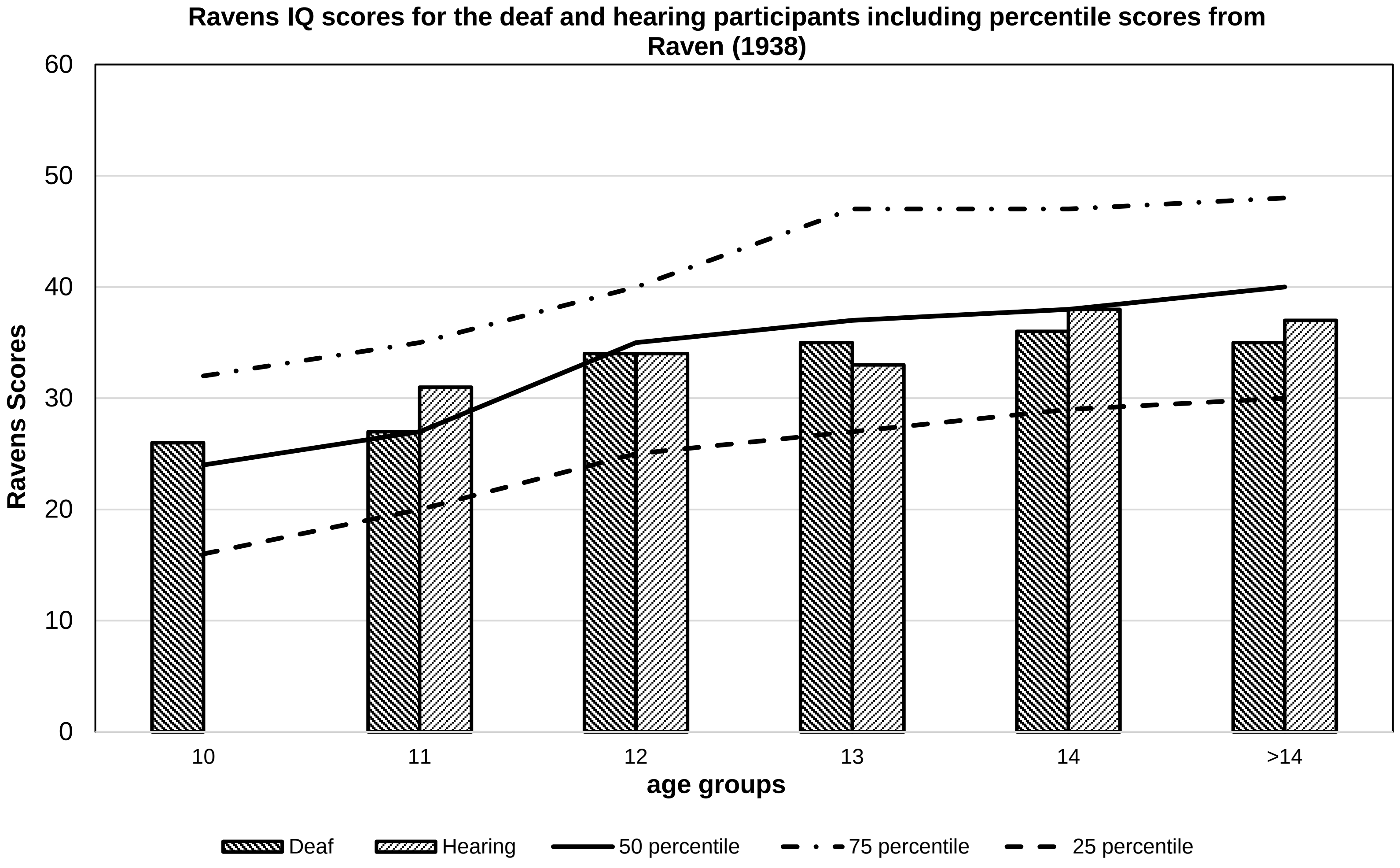


Figure 3.1. Comparison between hearing and deaf participants and normative data calculated from 660 children

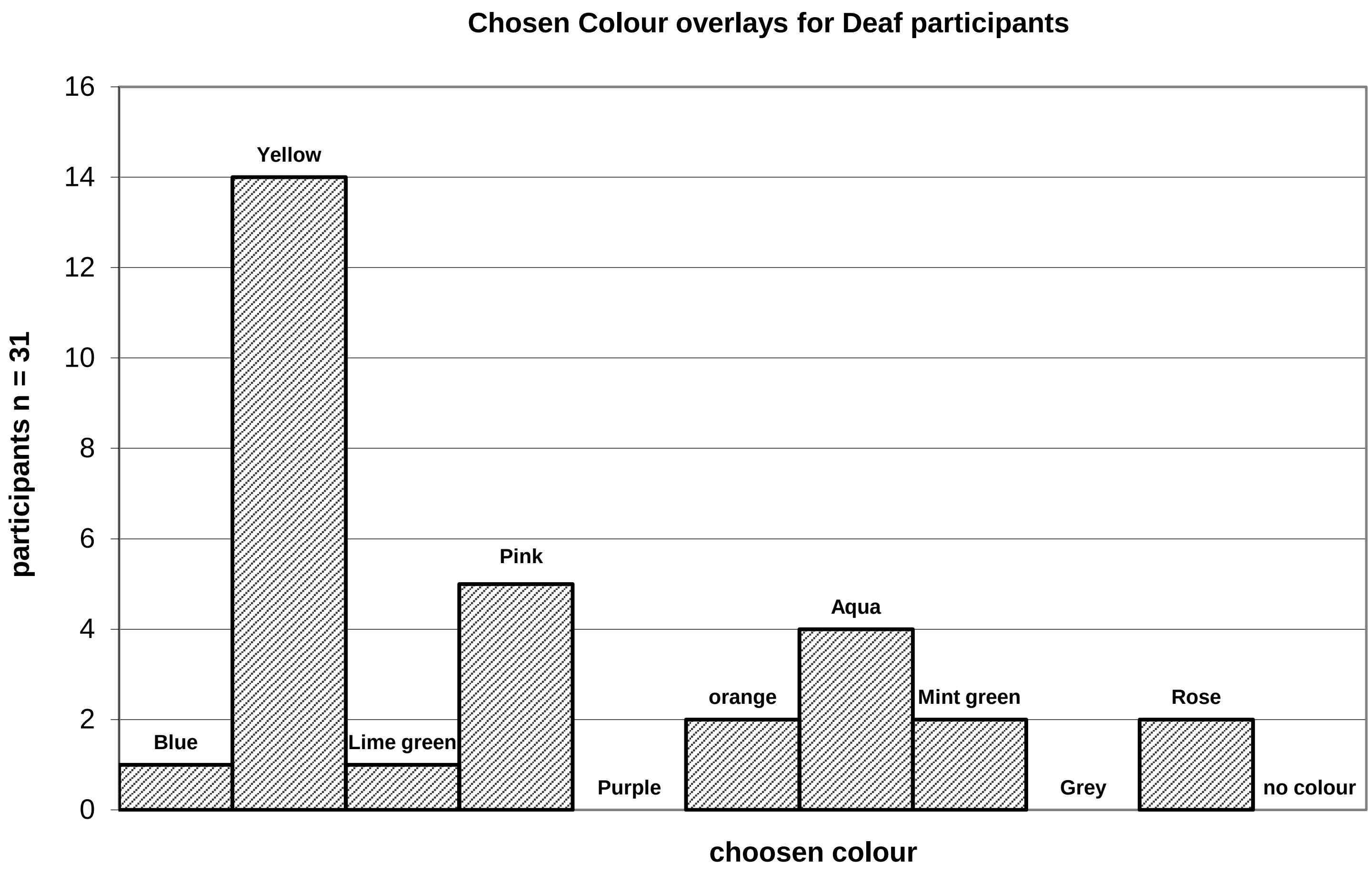


Figure 3.2. Chosen coloured overlays in deaf participants

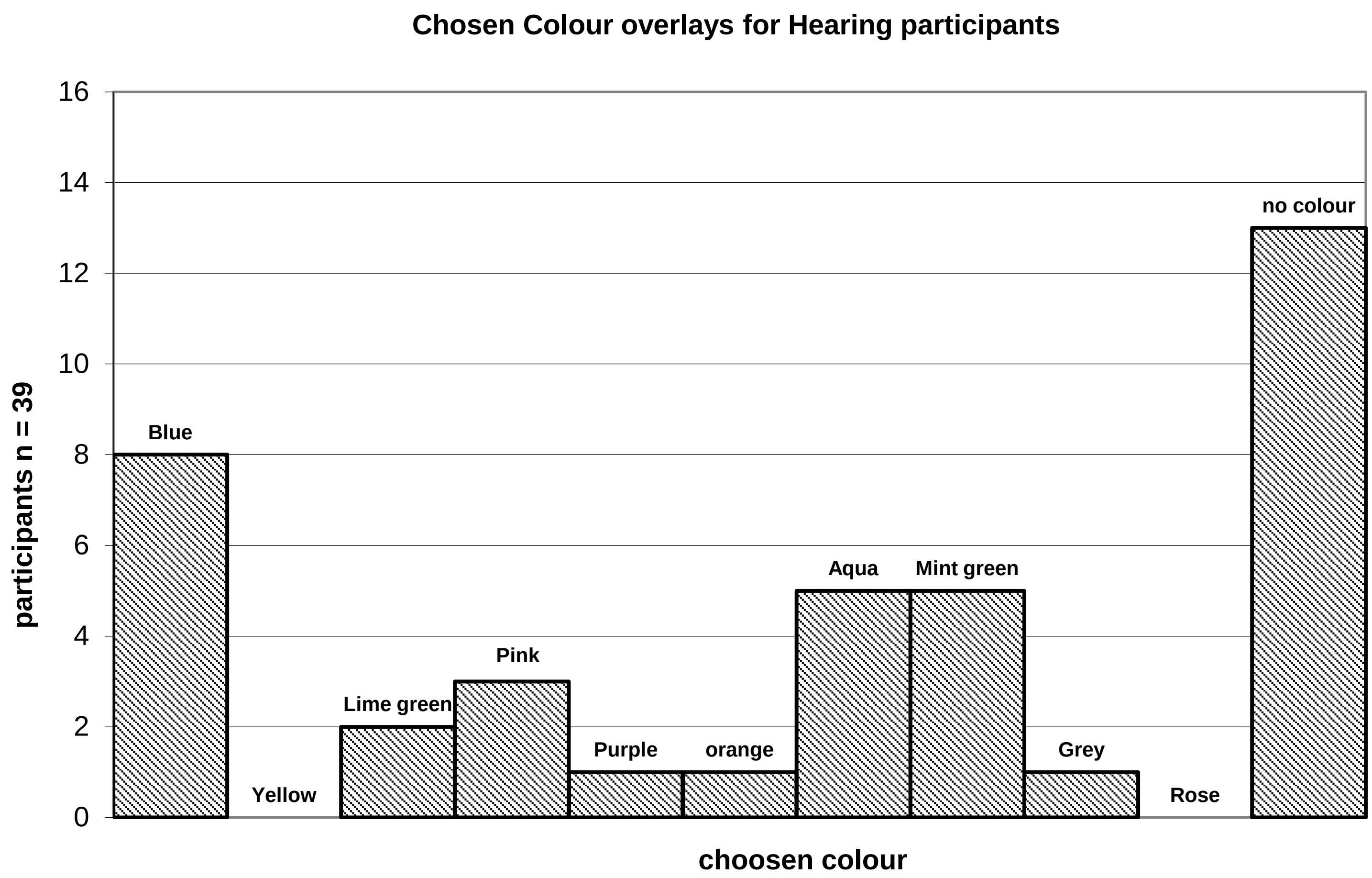


Figure 3.3. Chosen coloured overlays in hearing participants

3.7.4. Wilkins Rate of reading (WRRT)

The rates of reading for each group with and without colour overlays (hearing group) and those who chose a yellow overlay or other coloured overlay (all deaf participants chose an overlay) are shown in Table 3.4. The children who were deaf signed the words, and not surprisingly they did so more slowly than participants who could hear both with (t_{46}.0 =5.5, p =0.001) and without overlays (t_{46}=5.8, p=0.001). Children who were deaf who chose yellow increased their reading speed significantly (t_{13} =3.7, p=0.003). Figure 3.3. shows the percentage change in reading speeds between the groups. The deaf children who chose a different colour increased speeds by only 1% on average whereas those who chose yellow increased by 13% (Figure 3.4.). Importantly, the deaf children who chose yellow increased their reading speed by significantly more than the children who are deaf and chose the remaining colours (t_{29} =2.4, p=0.02). There was no significant change in reading speed for those hearing participants who chose a colour (t_{37}=0.10, p=0.33). Some of the words in the WRRT are not found within BSL and some of the participants who were deaf consequently used a generic sign for some of the words which they could not sign, for example ‘it’, ‘and’, ‘to’, ‘for’. This generic sign was accepted as the correct response.

Table 3.4. Reading speed of deaf and hearing participants with and without their chosen overlay.

Groups	Words per minute without colour overlay	Words per minute with colour overlay
Deaf yellow	77.5 ± 30.2	88.5 ± 29.4
Deaf non yellow	100.3 ± 31.3	101 ± 33.3
Hearing colour	130 ± 18.5	129.5 ± 19.5
Hearing no colour	129.2 ± 22.8	128 ± 23.1

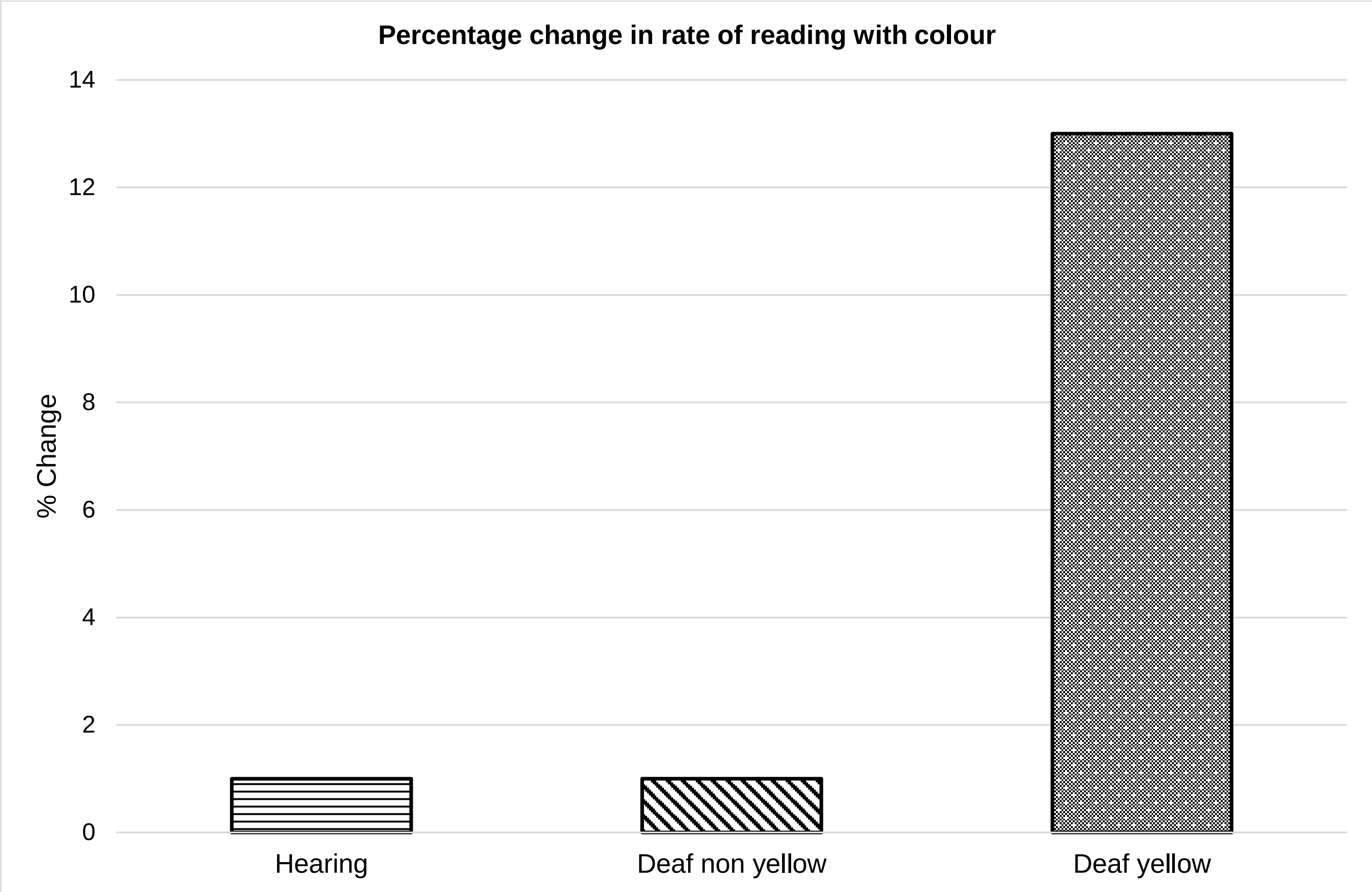
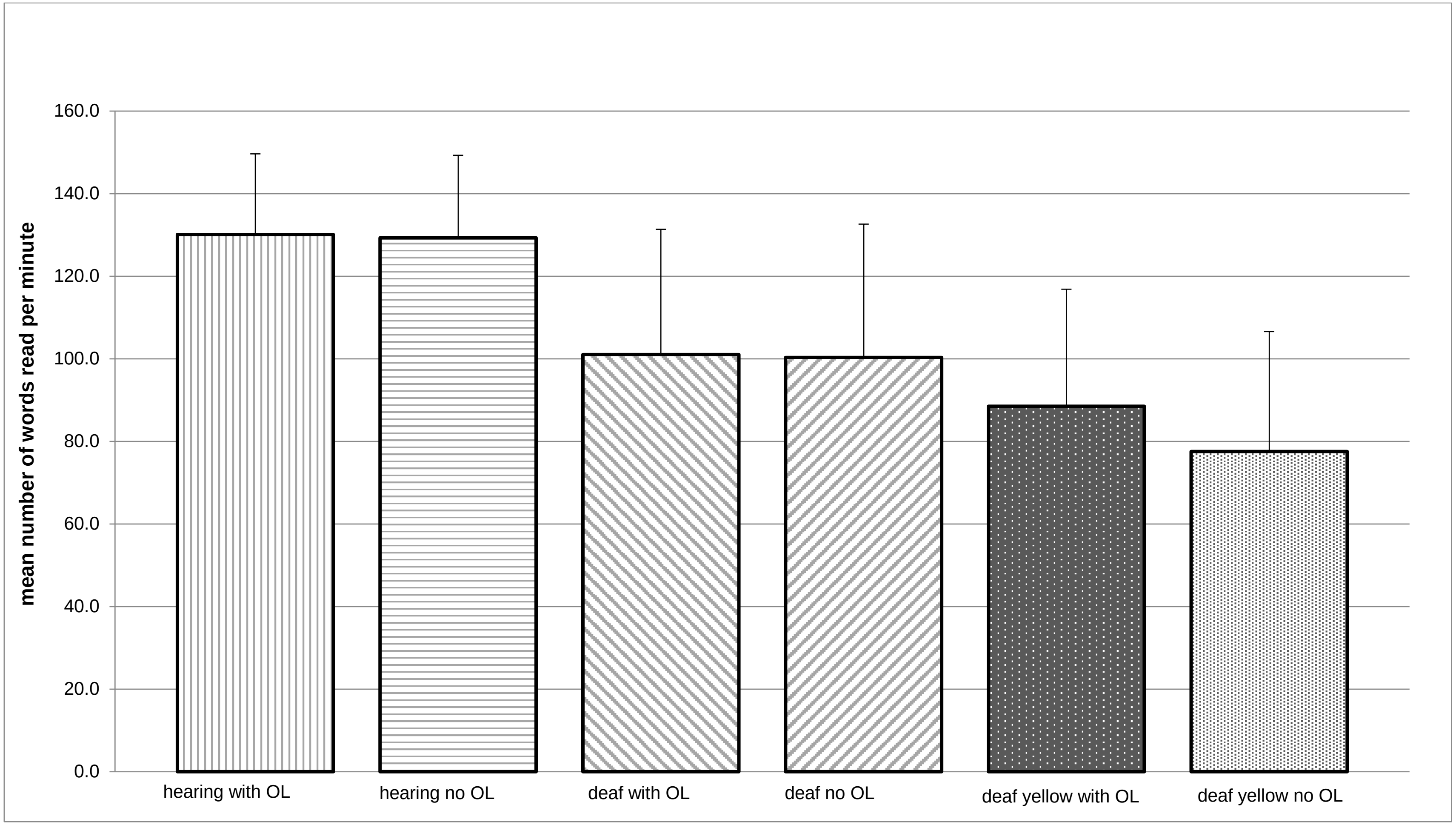


Figure 3.4. Percentage change in reading speeds with coloured overlay



OL= overlay

Figure 3.5. The relative rate of reading between groups with and without coloured overlays

3.8. Discussion

The choice of coloured overlays showed considerable differences between the children who were deaf and the hearing controls (Figure 3.4), with yellow overlay being the most common choice among the children who were deaf, whereas the hearing children preferred no colour. This choice of yellow is unusual and is not typically found in hearing children who have reading difficulties (Wilkins, 2002), although Scott, et al. (2002) suggested an association between the choice of longer wavelength colours (for example rose and yellow) and the accommodative and convergence abilities in a cohort of main stream school children. An association between colour choice and binocular impairment has also been suggested for children who have specific reading difficulties.

The reading speeds between the children who were deaf and the hearing controls show significant differences between the groups. The overall reading speed was much slower in the children who are deaf. This was unsurprising because the time taken to produce a sign for each of the words was much longer than a spoken response given by the hearing children. However, the reading rate for the children who were deaf and chose yellow overlays was lower than the other participants but had the most improvement in reading speed with the overlay.

Both the visualisation of the written word and the acquisition of phonology are important in the development of reading skills (Vidyasagar and Pammer, 2010). The results suggest that children who were deaf were impaired with respect to both the visual and phonological skills (non-lingual participants) necessary for reading acquisition, despite age-normal scores on the Raven IQ test. Various groups of children with learning difficulties have been shown to benefit from the use of colour overlays (Wilkins, 2002) and tend to report pattern glare (Evans and Stevenson, 2008). Their reading speed with the WRRT improves with the use of an overlay (Allen, Evans and Wilkins, 2010) but only when the overlay has a colour previously chosen as optimal for clarity, and the optimal colour differs from one individual to another. In this study, the participants who were deaf differed from previous groups in that few reported pattern glare and nearly half chose a yellow overlay. When chosen, only the yellow overlay increased reading speed significantly (Table 3.4.) Only some (26 of 39) of the participants with normal hearing chose a colour overlay and the chosen colour did not increase the rate of reading. In a sample of 39 of children in mainstream education one would have anticipated that only two would substantially improve their reading speed with an overlay of their chosen colour (Jeanes, et al., 1997). It is therefore unsurprising that the hearing group showed no overall benefit from colour. None of the hearing group or the participants who were deaf had clinically significant pattern glare, which has been shown to indicate a benefit from colour in normal groups (Hollis and Allen, 2006). Although all of the deaf participants chose a colour to read, the lack of pattern glare and VS symptoms indicate that a different mechanism could be responsible for the increase in reading speeds, such as the magnocellular deficit theory discussed in chapter 5.

It should be noted that the participants who were deaf were children attending a school for the deaf and were not specifically screened for reading disabilities. As described in chapter 1, children who are profoundly and severely deaf have a wide degree of reading abilities and levels. There are thought to be many alternative methods to literacy acquisition in children who are deaf, which are still to be fully described (Musselman, 2000; Perfetti and Sandak, 2000). Any assessment of reading disabilities is therefore problematic and bears little relationship to that of hearing peers. The WRRT is a test designed not to measure comprehension and literacy (Wilkins, et al., 1996). The WRRT had been specifically chosen to maximise visual functionality in the absence of semantic understanding. Therefore the WRRT removes the need for competent reading abilities and specialised reading assessments for these children.

The WRRT has been designed as a test of reading speed. The test is presented in a visually stressful format (Wilkins, et al., 1996) and is easily applied to children with a basic vocabulary. However, its application to children who are deaf should not be considered as a direct transfer. The WRRT was designed for hearing subjects consequently not all of the words contained within it are transferable into BSL. The results from Table 3.4. show that the deaf participants were significantly slower in the words read in 1 minute. The children who are deaf did not speak and therefore had to use signs (BSL). This subsequently made responses longer than the hearing children who could verbalise the words. This lack of verbalisation also highlighted another problem which was inherent in the WRRT is that not all of the words contained within the standard test are directly translatable into BSL. The next chapter will address the design issues with the WRRT, whilst reassessing the children who are deaf choice of coloured overlays and reading speeds.

Chapter 4

Modified Wilkins Rate of Reading test for children and adolescents who are deaf

4.1. Introduction

The WRRT was not developed for use by people who are deaf. The WRRT was designed as a reading speed test which is in a visually stressful format. These stressful patterns are produced by randomly placing chosen words in a paragraph which has no comprehension and therefore no understanding can be obtained from reading the text (see Diagram 4.1.). The words which are used have been chosen from words contained in popular young children's literature (Wilkins, et al., 1996). The use of the WRRT is problematic with children who are deaf because some of the words are not directly translatable into BSL i.e. they cannot be signed easily.

The primary method of communication between many pre-lingual deaf individuals in the UK is via sign language, specifically British Sign Language (Emond, et al., 2015). This language is a manual system which utilises: hand gestures, facial expression and body language and has a unique vocabulary and grammatical construct. BSL has been recognised as an individual language since March 2003 (BDA, 2014). Therefore, it should be understood that BSL is not simply English with sign and body language. For example; In English you would say "what is your name?" BSL would translate to "your name, what?" Notice the conjunctive "is" is missing.

Although there are many different signs for common descriptions, processes and objects, signing alone does not attempt to cover all eventualities. Not all words and situations are signed so finger spelling is employed when a specific sign is not available. (See Appendix 1 for a deaf figure alphabet chart). However, some of the more common English conjunctions, such as; and, if, with, is, but, etcetera are not commonly used in BSL but are present in the WRRT. This presents a problem with using the WRRT as a test with people who are deaf as it includes a number of these conjunctions. Therefore, however simple the WRRT may be for hearing children, difficulties still exist for children who are deaf.

In order to be useful in a deaf population some of the words contained within the traditional WRRT that have been specifically selected for hearing children and do not have a direct representation in BSL (Fenlon, et al., 2014) therefore need to be removed. Words in the WRRT which could cause difficulties are:

Old words

is, for, to, and, the,

For the modified WRRT a mixture of common signable words were chosen from those taught in early reading to children who are deaf. Only the word “play” is now evident in both the original and the modified WRRT.

The new words:

hat, bird, cake, sun, play, rain, me, tree, come, fish, read, book, car, ball, like

The original words are especially difficult for younger children who are deaf and struggle to understand English text. They may have only recently started to learn BSL and have not learnt how to ameliorate these non-signable words.

The modified version of the WRRT was developed to remove conjunctive words which are not in common sign language usage. These words were replaced with signable early learning BSL words specifically to enable easier access for deaf children with limited signing ability. Two additional words were also replaced. “look”, and “up” were replaced because “look up” could be combined in a single signing gesture.

The development was assisted by the BSL tutors at the dedicated deaf school in which the participants were students. The criteria for the new replacement words followed the same selection as the original WRRT, and were limited to words which are the most commonly used in early basic sign language. The signed words were also ones that are learnt at stage one BSL. Early sign language contains more descriptive signs of objects and basic informational requirements. The combination of verbs and nouns has been shown to be acquired at an early stage in sign language. Gestures such as movement are thought to be developed earlier than those for meaning of specific objects (Goldin-Meadow, et al., 1984). In hearing children gestures are often the first forms of communicative expressions before language is developed, for example in pointing at a favourite toy (Özçaliskan and Goldin-Meadow, 2005). Children who are deaf quickly acquire local specific signing which only the family may understand and these again are initially directional in nature. For example a child may point at food and then to their mouth (Meier, 1991). When formal teaching of BSL has begun verbs which are described first are those that the child is familiar with and are also represented in early English text.

The passage was designed to the criteria stipulated by Wilkins, (1996) and was produced in four different paragraphs A, B, C and D (Diagram 4.1.). The paragraphs consist of 10 closely spaced lines of text with the words arranged in a random sequence. The letters were in Times 9 point font with a 4 point horizontal spacing between the words. This has been specifically designed to mimic the stripes and spatial characteristics of patterns which produce the greatest perceptual distortions or visual stress (Wilkins, et al., 1996).

The modified WRRT was designed to assess the reading rate of children who are deaf in a more specific fashion. The test was measured as a pilot study on two separate occasions in order to assess the repeatability of the modified WRRT.

Diagram 4.1. The modified Wilkins Rate of Reading Test (not to scale)

Set A

read play book me tree rain cake fish like hat ball come bird car sun
like me hat tree come rain bird fish sun play book ball cake read me
car play tree fish bird ball me sun read like rain come hat book cake
hat bird book like cake play fish come me read tree sun ball car rain
sun rain come tree like book play read ball car fish me cake sun bird
book me book hat play read rain fish come car cake like ball sun hat
cake read me hat tree bird rain sun book like come fish play car ball
like car bird hat fish rain tree cake book come play sun ball me read
rain book fish me tree bird car cake come like ball hat play read sun
bird read me rain sun play fish come tree cake book ball like car hat

Set B

hat fish bird sun book like play ball car cake come read tree me rain
read like sun book hat bird rain car come tree ball cake me fish play
sun like play tree read bird come ball car book hat rain fish cake me
like hat car tree me rain come ball bird sun play fish cake book read
rain sun play me hat read like cake bird come book tree fish ball car
me fish read cake sun hat like ball come rain bird book tree car play
bird play me cake fish car rain read ball sun tree book come like hat
cake sun bird like hat come read tree play book car me fish ball rain
tree rain hat car bird sun like me read ball book fish play come cake
hat book tree rain ball bird cake come car fish play read me like sun

Set C

book come play read me fish ball tree cake like hat car rain bird sun
rain me cake book fish play come tree read hat bird car like sun ball
book me tree like fish sun bird come ball rain read car cake play hat
hat sun read cake play bird tree rain like come book car me fish ball
me tree hat cake read rain car fish bird book play ball like come sun
bird like me read sun tree hat car play fish book rain cake ball come
hat rain sun ball me tree car fish like cake read play come book bird
sun like rain car hat bird cake read me tree book play ball fish come
play sun book come ball rain hat me car tree read bird fish like cake
read car cake sun fish bird me tree hat book ball rain play come like

Set D

rain fish sun tree me car cake like book pay hat bird ball read come
me cake ball rain car tree hat play read book like fish bird come sun
come car sun read hat me play fish like cake bird book rain ball tree
me fish hat cake sun read tree come play bird rain ball book like car
bird car read rain me like come ball tree cake play book fish hat sun
like fish come tree book ball read rain play sun bird car me cake hat
cake car read rain bird tree ball me like come sun fish play book hat
read ball come cake bird sun book tree car like me rain play hat fish
come cake play sun bird rain read hat ball tree like book car fish me
fish cake sun rain hat like come ball tree car play me bird book read

4.2. Methods

4.2.1. Participants

Participants of the modified WRRT were recalled from those who had participated in the original WRRT in chapter 3. Nineteen children who were deaf from the original reading sample were available for this trial. Nine female and 10 male participants with a mean age 14.4 ± 2.3 years took part.

Fourteen (7 male and 7 female, mean age 13.7 ± 2.8 years) of the participants who were deaf and in the original standard WRRT cohort and had participated in the first testing of the modified WRRT agreed to repeat the modified WRRT one week later to measure the repeatability of the new modified WRRT.

The modified WRRT was assessed at the school where the original vision and WRRT tests were performed. The modified WRRT was conducted by the author. In the school the lighting was a combination of normal background office lighting, and task lighting using an Osram Dulux 11 w 865 lamp (colour temperature 6000K) with an illuminance of 300-500 Lux operated from an electronic ballast at a frequency of 25 kHz. Testing was always performed in the same room and under the same lighting conditions.

The Intuitive Overlay system (ioo Sales Ltd, London, UK) was used. The colour overlays were presented in the same order as the original test: Rose, Lime-Green, Blue, Pink, Yellow, Aqua, Purple, Orange, Mint-Green. This order was adopted in order to reduce the chances of complementary colours being placed next to each other. The top overlay (Rose) was placed to the left of the test page, covering one of the two passages of text. When the text covered by the overlay was judged preferable to the uncovered side a second overlay was placed beside the first so that both passages of text were now covered by overlays. The child was again asked which colour made the text clearer and more comfortable. The process of removing the poorer overlay and leaving the best overlay in place was continued until all the overlays had been shown.

Only the smaller print size was produced for the modified WRRT to maximise visual stress while minimising the semantic aspects of reading and has been reported to be a reliable and valid format in the original WRRT (Wilkins, et al., 1996). Each of the four paragraphs of the modified WRRT had a different random order of words. The four paragraphs were given, (A) with the chosen overlay (B) without, (B) again without and finally (A) with an overlay. The ABBA design was used to minimise bias from learning/fatigue effects. Most of the practice effect occurs from the first to the second administration (Wilkins, et al., 1996) and the ABBA design therefore biases any mean difference against a benefit. An average rate of reading with and without the overlay was calculated.

The second administration of the modified WRRT one week later followed the same procedures as above and was conducted in the same environment and lighting conditions.

4.3. Data analysis

Data analysis was conducted with the IBM SPSS version 20 package. Comparisons between hearing and deaf participants were made using an independent sample t test assessing the relationship between reading speeds and colour used. A Pearson's r correlation and a Bland Altman analysis were used to assess the comparability and validity of the modified WRRT.

4.4. Results

The modified tests reduced errors from an average of 1.7 in the original WRRT to 1.1 in the modified WRRT ($t = 2.0$, $p < 0.05$) – see Table 4.1.

First assessment Modified WRRT	Words per minute without overlay	Words per minute with overlay	Second assessment Modified WRRT	Words per minute without overlay	Words per minute with overlay	Mean errors Original WRRT	Mean errors Modified 1st WRRT
Yellow (N=7)	76.9 ± 34.6	83.9 ± 26.9	Yellow (N=5)	73.5 ± 21.6	81.8 ± 25.6	1.7 ± 1.1	1.1 ± 1
Non yellow (N=12)	80.6 ± 18.7	78.8 ± 21.3	Non yellow (N=9)	87.9 ± 17.9	85.4 ± 21.3		

Table 4.1. The mean words per minute between yellow and non-yellow overlays and the errors between original WRRT and modified WRRT

The repeatability of the modified WRRT between the two separate assessments was good (r = 0.82; p < 0.001, Figure 4.1 represents the correlation between first and second application of the modified WRRT) with an overlay. This is consistent with previous research into the validity of the WRRT which showed a similar reading speed correlation of r = 0.94 (Wilkins, et al., 1996) correlations were used to assess repeatability with the modified WRRT as research with the original WRRT had utilised this method. Although the number of participants were low the variability between the means of the first test and the second test were not significant (t_{13} =03, p >0.05). A Bland-Altman comparison was also used to assess the repeatability with the modified test (Figure 4.2).

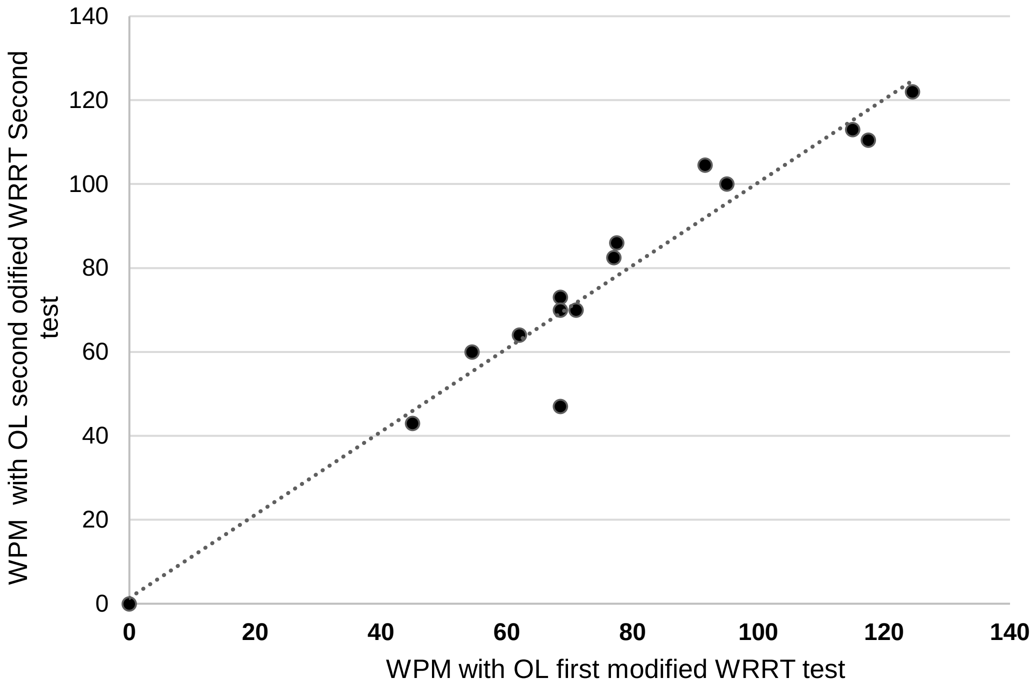
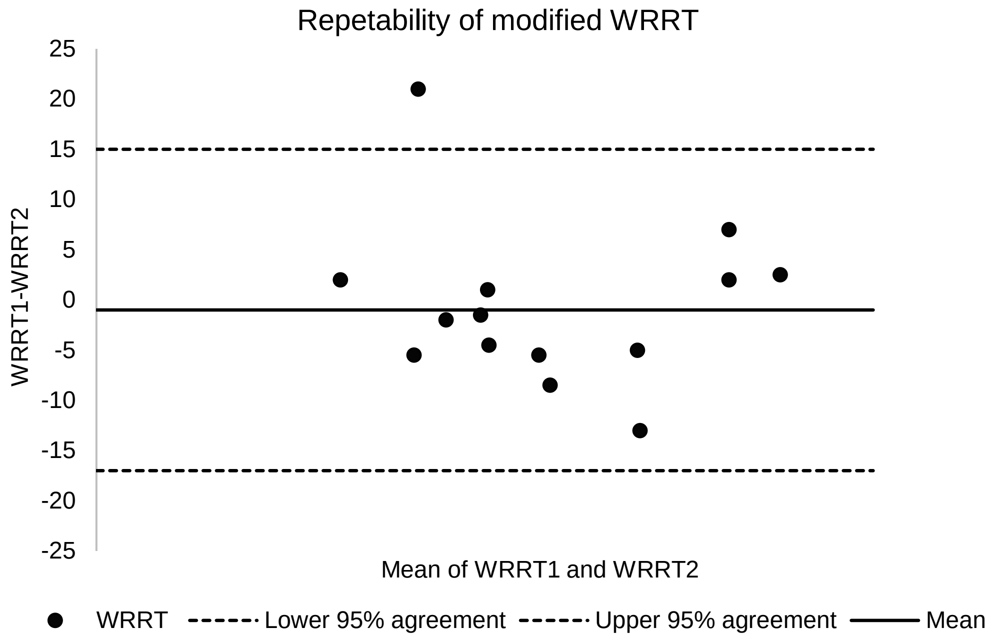


Figure 4.1. Correlation for repeatability with modified WRRT



WRRT= Modified Wilkins Rate of Reading Test

Figure 4.2. Repeatability of the modified WRRT with coloured overlay.

A Bland-Altman plot was used in conjunction with the correlation to demonstrate the good repeatability of the modified reading test. The limits of agreement indicate a variance of 10% change in reading speeds with the modified test. The original WRRT indicated a clinically significant level of 5%, however, this has recently been updated to 15% (Evans, Allen, and Wilkins A.J., 2017). Further investigation of the modified reading test, with a larger sample size, is required to assess the significant clinical level for reading.

In the original WRRT 14 of the children who were deaf chose a yellow overlay. With the modified WRRT 9 of the original participants who chose yellow were available for re-testing. When retested 7 or 63% of the participants again chose yellow as their preferred choice (Figure 4.3.). At the second testing 5 of the children who are deaf again chose a yellow overlay (Figure 4.4.). When using both the original WRRT and the modified WRRT the children who were deaf chose a yellow overlay most frequently.

The average reading rate, on the first testing of the modified WRRT, with and without a yellow overlay and overlays of other colours is shown in Table 4.1. No hearing children were assessed as this test is designed specifically for children who are deaf. The reading rate in the modified WRRT was higher with the yellow overlay than without one (t_{17}=2.3, p=0.01) with the first assessment and again in the second assessment (t_{13}=3.2, p=0.02). However, there was no difference in reading speed or errors with overlays of other colours.

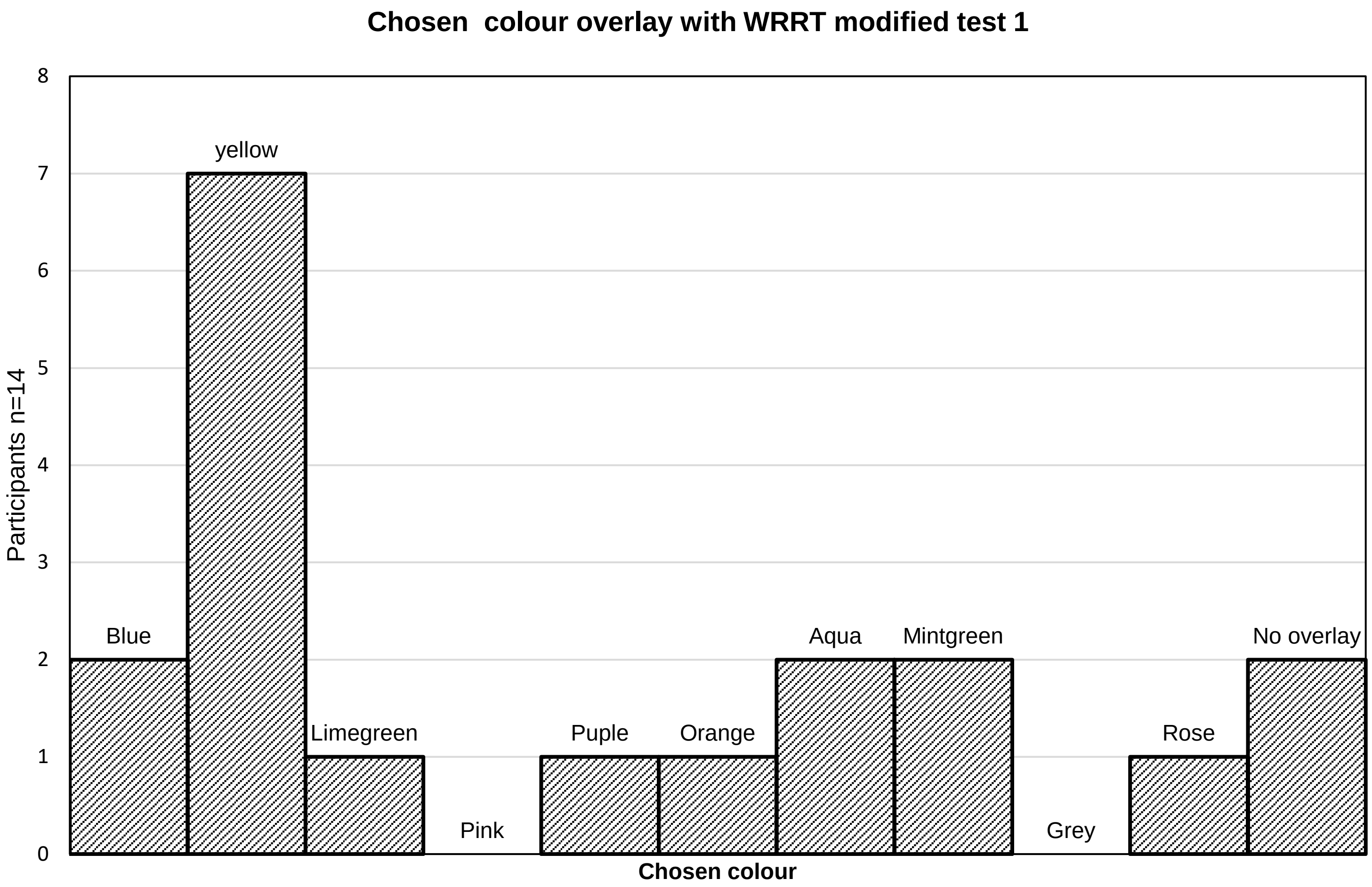


Figure 4.3. Colours chosen by deaf participants with the modified WRRT at the second test

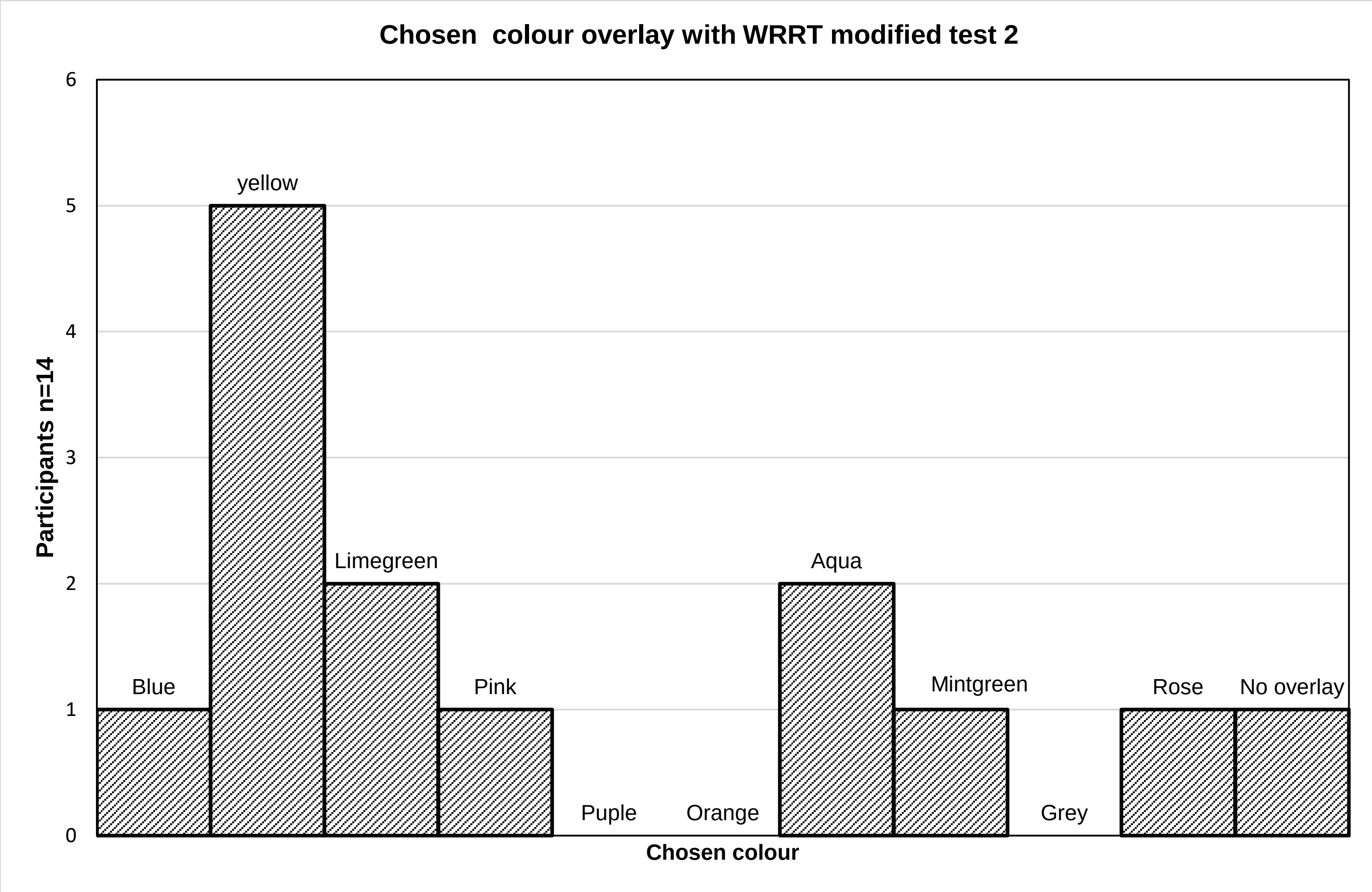


Figure 4.4. Colours chosen by deaf participants with the modified WRRT at the second test

4.5. Discussion

The development of the modified reading test was required due to the difficulties which had arisen in the original testing of the WRRT which highlighted the problems that children who are deaf had in signing some of the words. The modified WRRT is more appropriate for a deaf population as none of the words are unsignable. The new format of the modified WRRT represents early words which are not only learnt at the beginner stage in the formal BSL training but also are encountered in early written English. On re-testing the deaf participants using the modified rate of reading test, yellow was again the most popular choice of overlay. With the yellow overlay an increase in reading speed was achieved whereas with other colours there was no increase. Although repeatability was similar to that found with the original WRRT the number of words read per minute with the modified WRRT (83.6 ±23.7 words per minute with overlay) was reduced by 11% compared to the original (94.8 ±30.6 words per minute with overlay) in the children who are deaf. This reflects the greater accuracy of the modified test as children were able to sign all of the associated words as suggested by the decrease in errors with the modified WRRT (1.7 to 1.1). However this was not clinically or statistically significant (t_{48}= 2.03, p=0.05).

When signing with the original test, participants who were deaf could combine words, for example “look up”, which in BSL can be signed in one movement. Other words such as: it, and, to, have no direct equivalent in BSL and a generic gesture was accepted as the correct response. These gestures were quick sideways movements of the thumb and are consequently much faster than a sign such as hat where the hand is placed above the head. In the modified test every word had a unique meaning enabling the participants to sign each of the words in an unambiguous fashion and not combine signs in a single action for example “look up”.

The modified WRRT has improved the reliability of the original WRRT for people who are deaf. The new words have minimised the possibility of non signable words being misinterpreted. The modified WRRT shows significant improvement in the accuracy. Indicating that more correct signs are being used and fewer words are missed.

Although significance has been found in this sequence of tests only a small population was available for assessment. To increase the validity of these findings further assessment with a larger population will need to be evaluated.

In children with normal hearing, the choice of colour overlay is very variable, and yellow is chosen by fewer than 10% of children who choose overlays (Wilkins, et al., 2001). Previous research with the original WRRT and the use of colour overlays has generally demonstrated improvements in reading rate with any of the chosen coloured overlays. The deaf group were atypical in two respects:

1. They predominantly chose a yellow overlay
2. They improved their reading speed only when the choice of colour was yellow.

Yellow would appear to be the most preferential choice for these participants when asked to choose a colour. The participants were asked why they felt yellow was their colour of choice. The responses included: The words look clearer, easier to see, more comfortable, not as difficult to read, words look nice. Although these responses are anecdotal they give some insight as to why these children find this colour more appealing. The reasonably consistent choice of yellow as an overlay colour would suggest a possible association with magnocellular functions and pathway.

Ray et al., (2001) have shown that in dyslexia, NPC and AA are improved with the application of yellow filters. They also showed that yellow filters improved reading ability over three months in their sample of dyslexic children, and attributed these benefits to the effect of yellow filters on the magnocellular system. Magnocellular discrepancies have been reported not only in dyslexic individuals but also in deaf groups (Samar, Parasnis and Berent, 2002; Samar and Parasnis, 2005). Although the spatial resolution of the magnocellular system is poor, it has been argued that magnocellular function is important for the perception of text (Chase, et al., 2003). However, the role and function of the magnocellular system in reading is controversial (Skottun, 2000).

The results in this chapter have demonstrated that some children who are deaf appear to increase reading speeds with the use of a coloured overlay which is yellow. However, no increase in reading speeds was evident in any of the other colours. The lack of an increase in reading speed with overlays of colours other than yellow would suggest that visual stress is not a significant factor within this group. These findings would suggest an involvement of the M pathway in reading for these children. To further the investigation of these findings the next chapter will assess the relationship between deaf children and the magnocellular visual abilities, specifically in those who prefer yellow filters.

Chapter 5

Assessment of Magnocellular functions in children and adolescents who are deaf

5.1. Magnocellular pathway

Visual information is mediated by two distinct pathways, the parvocellular (P), and the magnocellular (M) and a small less well defined pathway the Koniocellular (K). The M system contains approximately 10% of the retinal afferent fibres and is a defined pathway from the retina to the lateral geniculate nucleus (LGN) (Shapley, 1990). These M fibres are approximately 50 times larger and have a greater thickness of myelination than the smaller P ganglion cells. The P ganglion cells are 10 times more numerous than the M. Both the P and the M pathways are projected to areas 1 and 2 of the LGN and are separated at this point into distinct areas (Livingstone and Hubel, 1988). Experimental lesions of monkeys LGN suggest that when areas 1 and 2 in the LGN are damaged reductions in flicker sensitivity and contrast for low temporal frequencies are observed (Merigan, Byrne and Maunsell, 1991), whereas, parvocellular lesions have revealed reductions in colour and high spatial frequencies Both P and M pathways are well separated until the visual cortex. At V1 the M pathway axons terminate at layers 4Cα and 4B, whilst the P pathway axons terminate at layer 4Cβ. After this point the segregation of the two pathways is less well demarcated and there is greater structural interplay. In the higher visual areas the M pathway is projected to V5 and predominates the middle temporal area (MT) of the extrastriated cortex and then to the parietal areas via the p stream (DeYoe and Van

Essen, 1988). The K pathway is formed of interlinear neurones which are sensitive to blue colour signals (Hendry and Reid, 2000).

The M pathway or dorsal stream has been described as having a transient visual characteristic and is thought to mediate: low to mid spatial frequencies (approximately 0.5 cycle/degree), high contrast sensitivity, peripheral vision, quickly moving objects and is associated with perception of: depth, motion, flicker and brightness (Solan, et al., 1994). Alternatively, the P pathway is maximally stimulated by high contrast, high spatial frequencies of approximately 5 cycles/degree (Diagram 5.1.) and colour. Although there appears to be considerable overlap between the two pathways (Merigan, Byrne and Maunsell, 1991; Chase, et al., 2003) the dorsal stream is thought to mediate attentional eye movements. The M pathway cannot itself identify words, it does however, due to the larger dendritic areas, transmit flicker and movement responses quickly, for which the M pathway is believed to be more sensitive (Vidyasagar, 1999).

Lovegrove (1993) suggested a reduction in function of the M pathway for normal hearing people with dyslexia, having found reduced sensitivity to low spatial frequencies, when compared to controls, whilst high spatial frequencies remained comparable. Stein et al has suggested a modification theory for the M pathway, in which the M pathway plays an important role in the control of eye movements and binocular stability (Stein and Talcott, 1999; Stein, Talcott and Walsh, 2000). The M pathway is claimed to be disorganised or reduced in people with dyslexia causing poor binocular control and hence reduced binocular stability during saccadic movement (Livingstone, et al., 1991) which ultimately causes letters to move around the page, merge and cross (Stein and Talcott, 1999). This has been supported by studies into perceptual movement of coherent dots (random dot kinematograms) to which the MT (V5) area is believed to be extremely sensitive (Tootell, et al., 1996). Individuals with dyslexia have shown poorer perception of these moving dots (Cornelissen, et al., 1995). Other studies have also reported that normal hearing populations with dyslexia have reduced magnocellular function (Lovegrove, 1993; Talcott, et al., 1998; Cornelissen, et al., 1998b; Chase, et al., 2003).

Although the M pathway is not primarily responsible for colour vision it does receive input from the three cone types (long, medium and short wavelengths), each having a peak response near to yellow, suggesting M cells may be most responsive to yellow, the peak summation of these cone types (Ray, et al 2005). The M pathway has been described as being adaptable and enhanced by the introduction of yellow overlays. Ray and his colleagues suggest that reading ability was improved with the introduction of yellow filters to their cohort of 15 children with reading difficulties (Ray, et al., 2005). In addition, convergence and accommodation were shown to improve with the use of a yellow filter. They have suggested the M pathway has a significant impact on binocular and vergence control (Erkelens, 2001). The magnocellular dorsal theory in reading difficulties has been suggested in people with reading disabilities and also in deaf individuals. Reading difficulties have also been associated with the alteration of perceptual processes in people who are deaf. A change or redistribution of peripheral visual abilities has been linked to magnocellular functionality in people who are deaf, although these may differ from individuals who are dyslexic (Dye, Hauser and Bavelier, 2008). The M pathway is believed to be modifiable due to differing developmental experiences (Stevens and Neville, 2006) which could impact reading in children who are deaf.

However, these conclusions are controversial with some challenging the role and functionality of the M channel with reading difficulties (Skottun, 2000; Skottun and Skoyles, 2007; Skottun and Skoyles, 2010). Skottun has suggested that there is no clear evidence that the M pathway is responsible for motion detection and has suggested associations with other conditions, for example autism and schizophrenia, showing it is not specific to reading difficulties.

The relationship between visual deficiencies and reading ability in children who are deaf has only recently been explored (Hollingsworth et al, 2015). Chapters 2 and 3 reported reduced binocular abilities and increased reading speeds when colour filters are introduced, particularly when a yellow overlay is applied. Previous research in the hearing population has found the use of an individually chosen specific coloured overlay increases visual comfort and reading speeds with the WRRT (Jeanes, et al., 1997; Bouldoukian, Wilkins and Evans, 2002; Scott, et al., 2002; Wright, Wilkins and Zoukos, 2007; Monger, Wilkins and Allen, 2015). Hearing controls in Chapter 3 did not choose yellow overlays, either preferring an alternative coloured overlay or no overlay. These choices are more consistent with those chosen by hearing children who exhibit visual stress, where over-excitation of the visual cortex is triggered by contrast or pattern glare, producing hyper-excitation (Wilkins, 1995; Wilkins, Huang and Cao, 2004). Coloured overlays are believed to lessen the effect of the visual cortex over-excitation and reduce perceptual distortion and headache (Wilkins, 1995).

Although the WRRT is not a test of reading comprehension, it is designed to induce a visually stressful image and assess reading progression in a stylised manner. The WRRT in some children who are deaf may induce visual stress. However, the results from Chapters 3 and 4 suggest that the predominant choice of yellow overlays, specifically in the deaf group, could be indicative of modified functionality in the M pathway (Stein, 2001) rather than visual stress. Associations between the M pathway and magnocellular function have been suggested for people who have specific reading difficulties within the deaf population (Samar, Parasnis and Berent, 2002; Samar and Parasnis, 2007; Dye, Hauser and Bavelier, 2009; Bavelier and Hirshorn, 2010). In this chapter we investigate M pathway function with random dot kinematograms (RDK) and a frequency doubling (FD) stimulus, in hearing and children who are deaf, to assess magnocellular responses for defects in children who are deaf.

5.2. Frequency Doubling (FD)

The frequency doubling illusion which was first investigated by Kelly, (1966), describes a visual phenomenon which is a result an activation of the non-linear response of magnocellular visual pathway. Kelly's experiment found that coarse gratings of dark and light bars in a sine wave profile (Diagram 5.1.), appeared to have their contrasts reversed at a relatively high rate which made the number of cycles (bars) to appear doubled. This doubling was dependent on the spatial frequency of the sine wave grating (0.1 to 4 cycles/deg^{-1}) and the temporal frequency at which the contrast is modulated (>15Hz). The magnocellular pathway retinal ganglion parasol cells are subdivided into two groups the $M_{(y)}$ and the smaller $M_{(x)}$ cells. The $M_{(y)}$ cells are responsive to very low contrast of < 2% (Bedford, et al., 1997) and are more responsive than $M_{(x)}$ and P cells to low spatial frequency sinusoidal gratings. When these gratings are flickered with a counter phased high temporal frequency of ≥ 15Hz, they produced an illusion at twice the spatial frequency of the original grating. These specific FD illusions are believed to be only mediated by the nonlinear responses of the M pathway, exclusively the larger $M_{(y)}$ cells and represents between 15 to 25% of the magnocellular cells (Maddess and Henry, 1992). This illusion is known as the frequency doubling illusion (Kelly, 1966). This phenomenon is thought to result from the second harmonic distortion in the M pathway. Studies on monkeys have shown a subgroup of cells the "$M_{(y)}$" (approximately 5 to 20% of the cells in the M pathway) show this harmonic distortion. The P and M pathways combine their receptive fields in a linear fashion. Although this method has been developed for glaucoma detection, as early ganglion cell death is an indicator for disease and is measured by the minimum contrast required for the illusion to be detected. In this study we are investigating relative sensitivities in deaf and hearing children of the $M_{(y)}$ pathway utilising the FD illusion. If there are functional differences in the M pathway, in children who are deaf and hearing children, as previously suggested by Hollingsworth et al (2015) the responses of the $M_{(y)}$ cells may vary. This study will be the first to assess the associated $M_{(y)}$ magnocellular function of children who are deaf.

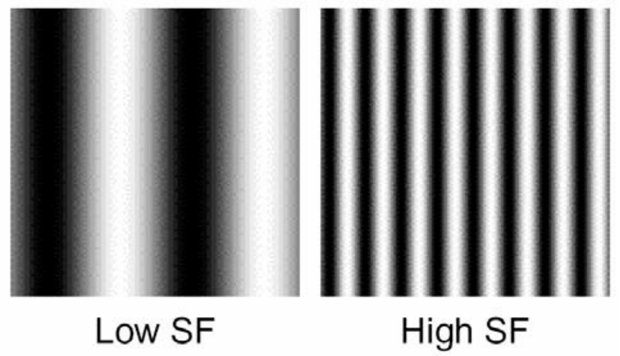


Diagram 5.1. Low and high spatial frequency sine wave gratings. (cns.ny.edu, n.d.)

5.3. Random Dot Kinematograms (RDK)

RDK is a test of coherent dot motion discrimination and has been utilised widely to assess M pathway functionality in both hearing and deaf children with reading difficulties (Lovegrove, 1993; Talcott, et al., 1998; Cornelissen, et al., 1998b; Samar, Parasnis and Berent, 2002; Samar and Parasnis, 2005)

The M pathway dominates the ‘where’ or dorsal visual stream (Goodale and Milner, 1992) and is largely populated by the magnocellular neurones. The middle temporal visual motion area (MT/V5) which is at the centre of the M-pathway appears sensitive to visual motion detection and is strongly stimulated with randomly placed dots moving with the same direction. Several studies have concluded that people with reading difficulties have an altered response to these stimuli, whilst normal readers do not (Cornelissen, et al., 1995; Talcott, et al., 1998; Cornelissen, et al., 1998b). Talcott, et al. (2000) has associated reduced motion sensitivity with visual/orthographic reading ability independent of phonological interpretation and suggested that the M-pathway is important in orthographic skills and detection rather than phonological decoding (Talcott, et al., 2000). Orthographic decoding of words has been correlated with coherent motion thresholds and the authors suggest a relationship between orthography and reading comprehension in children who are prelingually deaf (Samar and Parasnis, 2005).

5.4. Participants

The participants were recruited from student populations attending a dedicated school for deaf children, and its partner mainstream school in the UK and were all children who had previously participated in the vision and reading tests. All participants and parents gave written informed consent following a written and verbal explanation of the procedures involved. All procedures conformed to the tenets of the Declaration of Helsinki and were approved by the Anglia Ruskin University Ethics Committee.

Participants recruited for the FD consisted of 17 deaf participants (7 female and 10 male aged 12 to 20 years, mean 15.2 ± 2.5 years, 5 who had previously chosen a yellow overlay). Nine children were profoundly deaf (hearing loss>90 dB; occasional loud sounds are perceived) and 8 were severely deaf (hearing loss>70 dB unable to hear even shouted conversations). Therefore the deaf sample consisted of children who could not hear conversational speech (approximately 60dB) and consequently would not spontaneously learn to talk. All of the deaf participants were fluent British Sign Language (BSL) signers. None of the participants had any known ocular pathologies. A control group total of 13 hearing participants (7 female and 6 male) aged 13 to 16 mean 13.8 ± 1.1 years was enrolled. All control children had no known hearing problems and no other learning disability or visual problems.

The participants for the RDK test were recruited from the original FD experiment. Twenty three of the FD cohort agreed to participate and consisted of 8 (4 male and 4 female mean age 13.4 ± 1.3 years, including 4 who had previously chosen a yellow overlay) children who were deaf and 15 of the hearing controls (8 male and 7 female mean age 14.1 ± 1 year).

5.5. Methods

Testing was conducted in each of the schools and was always performed in the same room and under the same lighting conditions. All hearing children had instructions communicated verbally and the deaf participants via British sign language (BSL). The deaf school also provided an experienced BSL translator. Comprehension of the instructions for tests requiring a subjective response was inferred from correct answers to preliminary examples of the test material.

5.6. Frequency Doubling Technology (FDT)

5.6.1. Introduction

The Humphrey Instruments (FDT) Visual Field Instrument (Zeiss Humphrey Systems) was used. This instrument tests the monocular central 20° of the visual field. The illumination of the display background mean was 100 cd/m^2. Testing is presented at 17 retinal locations throughout the central 20° radius of the visual field. The central location tested was a 5° diameter area with the remaining locations forming a 4 x 4 area of 10° x 10° squares (see Diagram 5.2.).

Before each test was given to the participants a test program was used to familiarise the subject with each procedure. The training test shows the target at variable locations at 100% contrast (Diagram 5.3.). All subjects had less than 7.00D ametropia and were therefore not required to wear their spectacle correction (as per manufacture's guidelines).

Each stimulus consisted of a 0.25 per degree sinusoidal grating that is modulated at a 25Hz counter phase flicker that is considered optimal for human perception (Maddess and Severt, 1999). Perceptually, low contrast gratings appear to have twice the spatial frequency of the actual stimulus giving rise to the name "frequency doubling illusion". Seventeen retinal areas were tested using a Humphrey Instruments (FDT) Visual Field Instrument (Zeiss Humphrey Systems). The FDT analyser contains age normative data which enables a calculation of overall deviation scores of each participant. The analyser's pre-test program was used with each participant to enable familiarisation with the procedure. At the centre of the field analyser a small black fixation square is produced which remains on throughout the procedure and the participant was advised at the beginning of each session to only look at the black square. The test stimulus duration was 720ms, consisting of 160ms ramped onset and offset, and to avoid anticipatory responses and visual persistence a variable inter-stimulus interval between 300 and 500ms was used. Each eye was tested separately and the testing procedure lasted 4 minutes in total. The participants were able to pause or stop the test at any time and a break of five minutes was taken between each eye. Participants were required to press a response button every time the illusion was seen. To find the threshold, a modified binary search (MOBS) threshold strategy (Tyrrell and Owens, 1988) was used to manipulate the contrast of the stimulus at each retinal location. At least four staircase reversals, plus upper and lower staircase boundaries within 0.3 log units of each other, make up staircase completion. The mean of the last upper and lower presentations satisfying the staircase completion criteria represented the MOBS threshold, which could range between 0 dB (100%, maximum contrast and lowest sensitivity) and 56 dB (0%, minimum contrast and highest sensitivity).

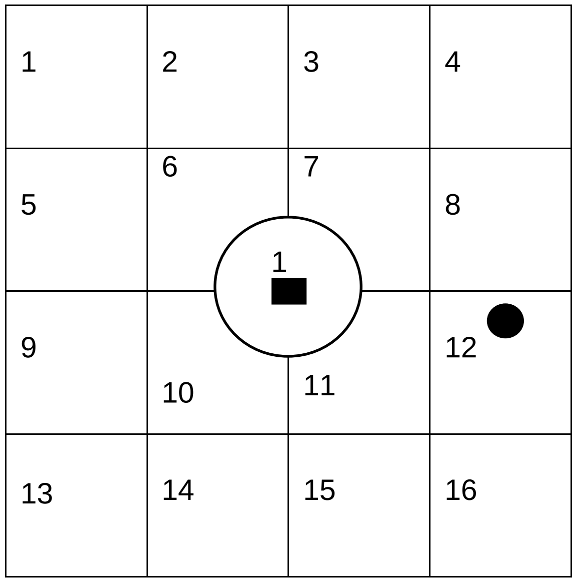


Diagram 5.2. A representation of the 17 areas that are produced by FDT. The central black square represents the central fixation target and the blind spot is shown in box 12

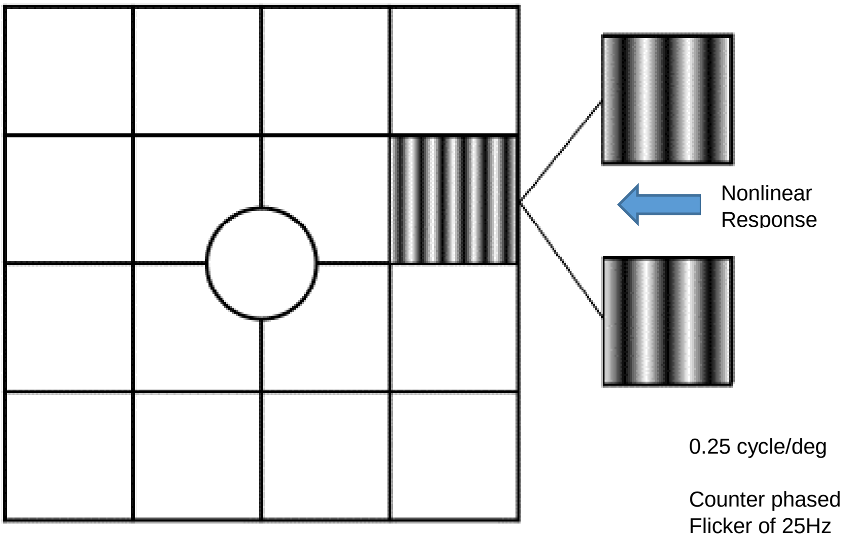


Diagram 5.3. A diagrammatic representation of the frequency doubling

5.7. Random dot kinematograms

A random dot kinematogram (RDK) provides an area of moving dots that move in a linear trajectory. The RDK are made up of two populations of moving dots, signal dots which move in a coherent manner and noise dots which move in random directions (Diagram 5.4.) The percentage of coherent dots is varied to achieve a sensitivity threshold for test participants. RDK motion tests produce strong activation of the media temporal area (MT/V5). RDK moving patches are considered to produce a powerful psychophysical test for M dorsal stream functions (Talcott, et al., 1998; Cornelissen, et al., 1998a; Samar and Parasnis, 2005). Coherent motion detection with RDK tests has been demonstrated to range for presentations of between 200 and 1800ms. Diagram 5.4 shows a pictorial representation of the test and demonstrates the target that was presented to each participant (not to scale). These were viewed binocularly at 0.75m on a 467mm LCD screen. Two circular patches subtending 7° consisting of 150 high luminance dots (0.1deg) per patch and had a horizontal separation of 8°. Both patches were presented simultaneously for 300ms whilst the participant fixated on a centre target (Diagram 5.4.). One patch of the dots moved with Brownian motion whilst the other patch had between 5-90% of dots moving coherently to the left or right. The coherent dots were presented on the left or right patch at random; the participant clicked either left or right mouse buttons to indicate which patch contained the coherent dots. At the start of the test all the participants were given a sequence of three practice tests to familiarise themselves with the test format. The first test sequence consisted of number of demonstration presentations that were presented at 90% coherence. This coherent pattern was always shown to the right on the initial practice test. This enabled the deaf participants to have the information signed to them and both the hearing and children who were deaf were able to visualise the test and ensure consistency with responses. The second test sequence changed to 30% coherence and moved the coherent patch randomly left to right. The final practice sequence then changed to the full testing paradigm for 10 presentations again to confirm participants were conversant with the test. The subjects were then given a five-minute rest before the start of the main test. The test consisted of 180 individual presentations and the subject was allowed to rest between each of the presentations if required. Once the full test started a Quest procedure was used to obtain a threshold for each individual (Watson and Pelli, 1983).

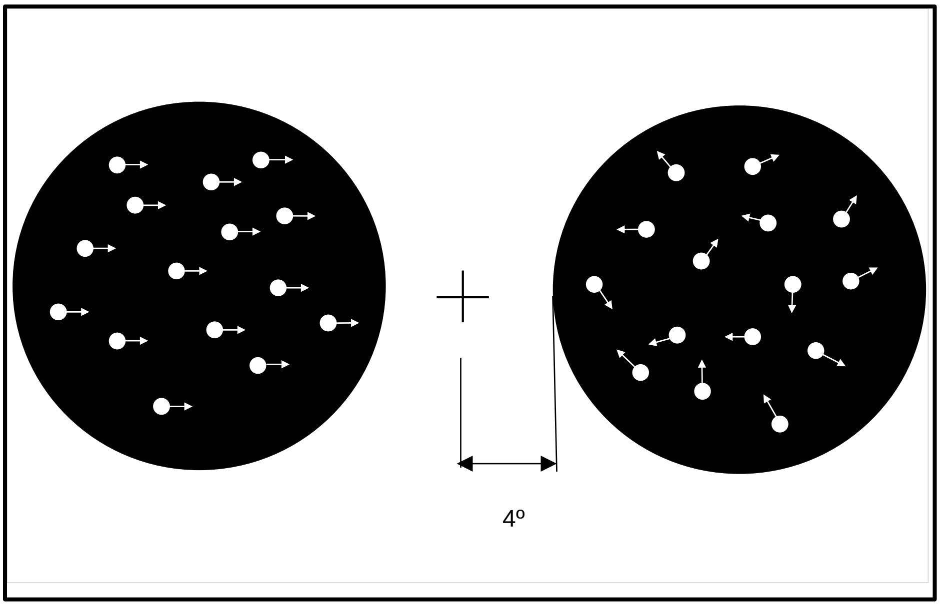


Diagram 5.4. The RDK test. The left patch shows 100% movement coherence right patch 0% movement coherence (not to scale)

5.8. Results

5.8.1 Frequency Doubling Test

As part of the monitoring process during the test procedure a measurement of fixation errors, false positives and false negatives are produced. There were no significant differences between fixation errors (RE deaf participants' Mean 0.65 SD ± 0.89;

hearing controls mean 0.53 SD ± 1.13. (t_{28} =1.53, p= 0.14) and LE deaf participants' Mean 0.54 SD ± 0.66 hearing controls mean 0.82 SD ± 1.01 (t_{28} =1.87, p= 0.39). No false positives or false negative errors were made by either group. This would suggest that the participants in each group performed the task constantly and reliably.

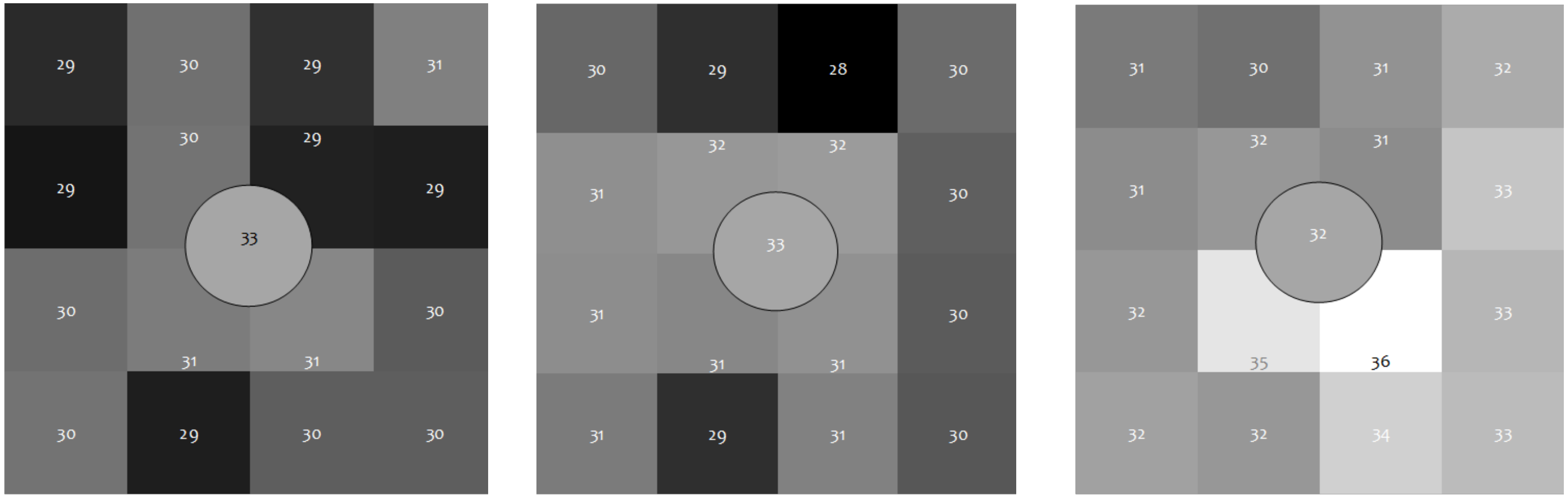
The results also produce a mean deviation index (MDI) which indicates the overall age adjusted response reduction or enhancement. A positive score indicates an average sensitivity above given age, whilst a negative number shows reduced sensitivity.

MDI Hearing (n=13)	MDI Deaf non yellow (n=12)	MDI Deaf yellow (n=5)
-1.86 ± 2.49(SD)	-1.37 ± 1.79(SD)	+1.04 ± 1.04(SD)

Table 5.1. Total mean deviation index

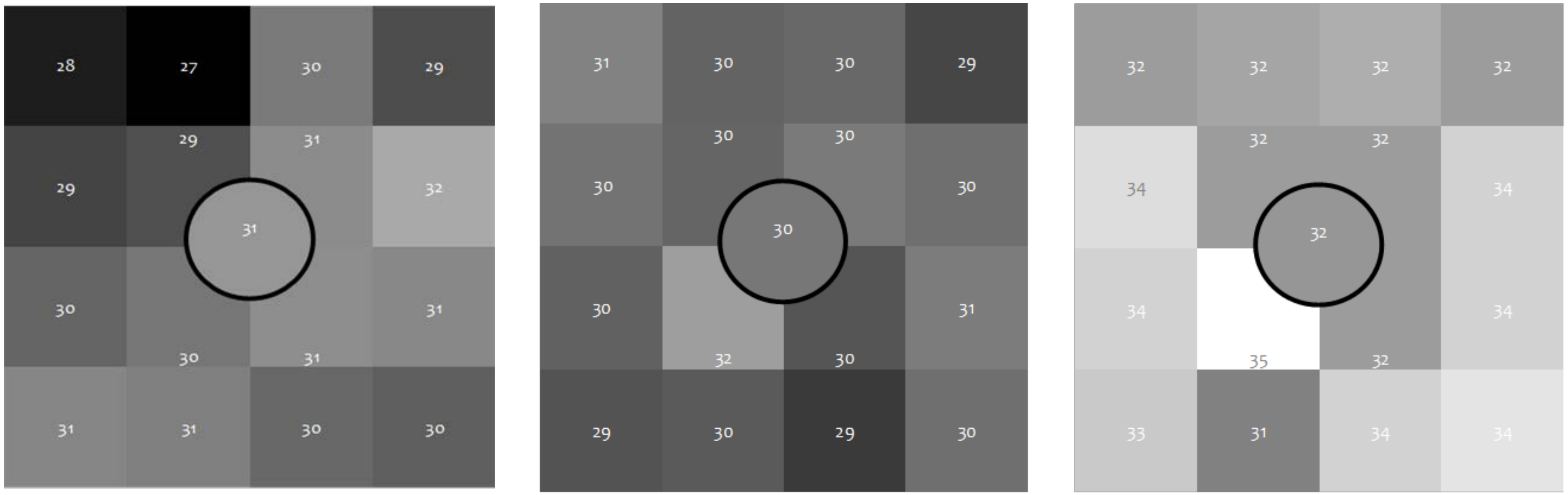
Table 5.1. Shows deaf (yellow) participants had an increased MDI compared to the age matched profile contained in the FDT instrument. However, a between groups ANOVA for both eyes (deaf non yellow x deaf yellow x hearing) showed a significant difference between the participants who are deaf and chose yellow and the hearing participants following post hoc Bonferroni test (deaf yellow x hearing $F(2,57)=4.88$, $p=0.01$). Although significant, the small numbers of participants means this finding should be treated as preliminary.

The participants who were deaf and chose a different colour and the hearing had reduced MDI. The mean responses for all of the subjects in each of the 17 tested areas are represented in Figure 5.1. and 5.2. The mean area responses are shown in Figure 5.3. and 5.4.



a) Right eye Hearing b) Right eye Deaf non yellow c) Right eye Deaf yellow

Figure 5.1. A pictorial representation of the relationship between mean responses in the right eye between the groups. Lighter areas indicate increased sensitivities (dB). Darker areas represent lower responses (dB)



a) Left eye Hearing

b) Left eye Deaf non yellow

c) Left eye Deaf yellow

Figure 5.2. A pictorial representation of the relationship between mean responses in the left eye between the groups. Lighter areas indicate increased sensitivities (dB). Darker areas represent lower responses (dB)

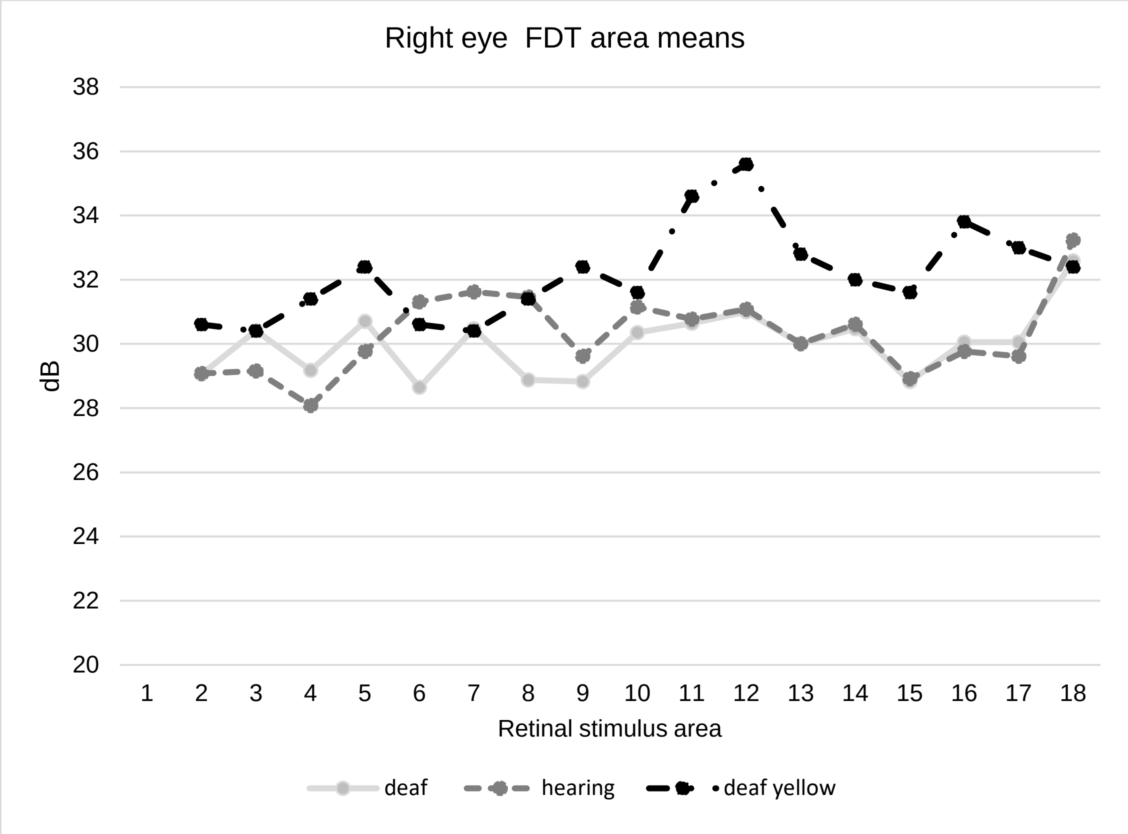


Figure 5.3. Mean global responses between the groups for the right eye

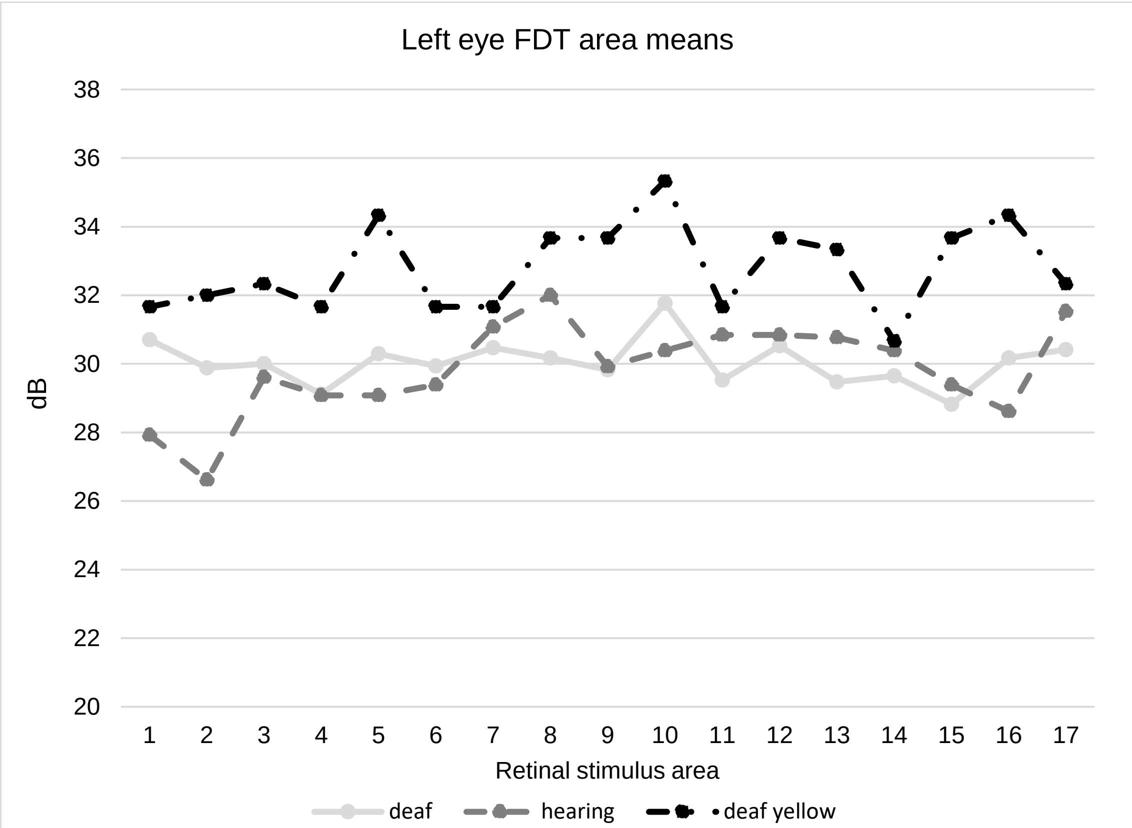
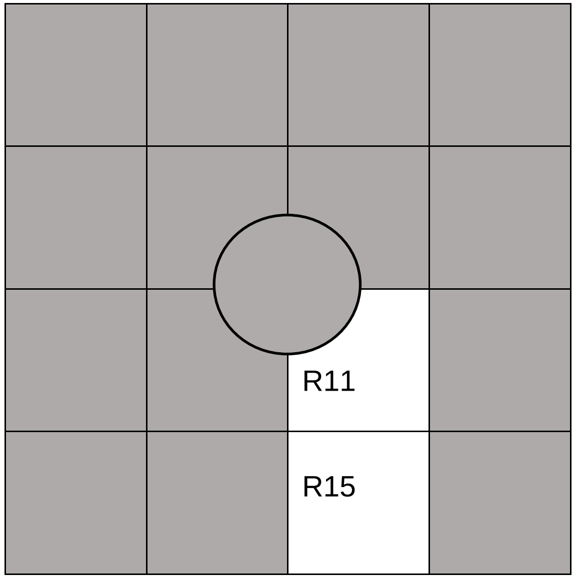


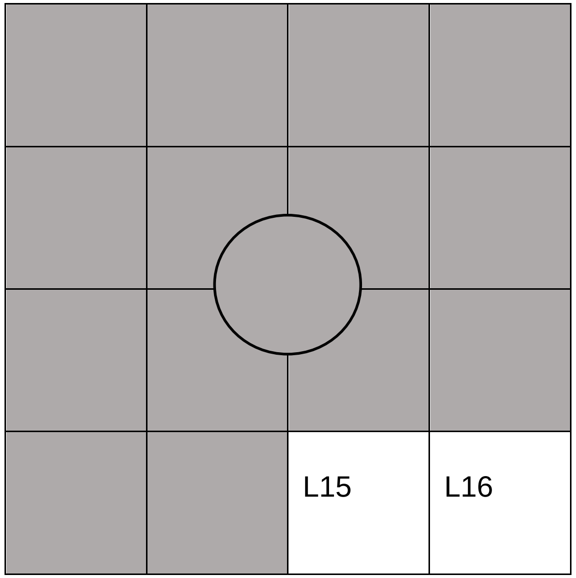
Figure 5.4. Mean global responses between the groups for the left eye

From the responses above several of the FDT areas show areas of greater sensitivity for the deaf yellow group. Following a between groups ANOVA (Hearing x deaf yellow x deaf non yellow) four areas showed increases in sensitivity between deaf yellow and the hearing / non yellow deaf groups; Right eye, R11 $F(2,27) = 5.06$, $p = 0.01$, R15 $F(2,27) = 3.40$, $p = 0.04$ Left eye, L15 $F(2,27) = 5.53$, $p = 0.01$ and L16 $F(2,27) = 7.10$, $p = 0.003$. Figures 5.5. and 5.6. show areas which remained significant following a Bonferroni post hoc test in the deaf yellow group, however, numbers of participants are small especially in the deaf yellow responders (n=5) and further larger scale assessments will be needed to substantiate these findings.



R= Right eye

Figure 5.5.Right eye significant FDT areas



L = Left eye

Figure 5.6. Left eye significant FDT areas

5.8.2. Random Dot Kinematograms

Participant group	Threshold %	Mean	Colour overlay
H	25	6 ± 5	
H	43	3.6 ± 4	
H	19	7.2 ± 10	
H	51	2.9 ± 4	
H	23	6.3 ± 5	
H	37	4.3 ± 4	
H	44	3.6 ± 5	
H	42	3.8 ± 5	
H	60	2.2 ± 4	
H	52	2.9 ± 4	
H	36	4.4 ± 6	
H	30	5.2 ± 5	
H	29	5.3 ± 6	
H	56	2.5 ± 4	
H	30	5.2 ± 5	
D	32	4.9 ± 6	
D	44	3.6 ± 8	Y
D	37	4.3 ± 5	
D	32	4.9 ± 4	Y
D	51	2.9 ± 4	
D	34	4.7 ± 7	Y
D	45	3.5 ± 5	Y
D	33	4.9 ± 4	

H= hearing D=deaf Y= yellow overlay

Table 5.2. RDK mean responses and coherence recognition thresholds

The mean threshold for the hearing group was 44 ± 14.8, deaf non yellow 47 ± 2.8 and deaf yellow 37 ± 8.4 Table 5.2 shows the threshold percentage and the means from the RDK assessments.

A between groups ANOVA (Hearing x deaf yellow x deaf non yellow) showed no significant differences in coherence recognition thresholds F (2,20)= 0.61, p > 0.05 There was also no significant difference in coherence recognition thresholds between all the children who were deaf and hearing controls, t_{21}= 0.08, p= >0.05. However, numbers of participants were small, especially in the deaf yellow responders (n=5 in the FDT study and n=4 in the RDK study) and further larger scale assessments will be needed to confirm these findings. If a Bonferroni correction were applied the above none of these results would be significant.

5.9. Discussion

The FDT has revealed a difference in sensitivity within the $M_{(y)}$ pathway between children who are deaf and prefer a yellow overlay and the hearing controls and the deaf participants who chose a different coloured overlay. The FDT retinal areas which were more sensitive were only found for participants who were deaf and preferred a yellow overlay. The RDK results did not show any significant differences between any of the participant groups. The global sensitivity in the FDT experiment also suggested that participants who are deaf and prefer a yellow overlay have an increase in their mean difference index (MDI) or global sensitivity when compared to the deaf children who chose an overlay of a different colour and the hearing groups. A between groups ANOVA (Hearing x deaf yellow x deaf non yellow) showed no significance between the groups (F(2,27)=1.86, p=0.18) However, a univariate analysis of variance post hoc Bonferroni test did show a significance between the hearing and the deaf yellow groups (F(2,27)=3.30, p=0.04). Although significant the small numbers would limit this finding. The apparent increased global and localised sensitivities with the FDT suggests that the children who are deaf and prefer yellow may have an increased facility in their peripheral vision. In contrast previous research with normal hearing adults, who have specific reading difficulties, have found a reduction in sensitivity in the mean difference index (Buchholz and McKone, 2004). Specific peripheral and parafoveal areas appear to be more sensitive in those participants who preferred yellow overlays. However, a larger population is needed to corroborate these findings.

The implication of increased peripheral sensitivity in children who are deaf and prefer a yellow overlay is one which has resonance for the visual abilities of people who are pre-lingually deaf. Previous research into deaf individual's visual skills has also shown increased performance for peripheral and para-foveal functions (Neville and Lawson, 1987; Bélanger, Mayberry and Rayner, 2013). This performance enhancement has been described as a "compensatory theory" (Bavelier, Dye and Hauser, 2006) or "cross modal plasticity" in which loss of one of the senses increases sensitivities in the remaining. This theory has been well documented in the blind population where hearing has been shown to be enhanced in compensation for the loss of vision (Lessard, et al., 1998; Röder, et al., 1999; Collignon, et al., 2009; Wan, et al., 2010; Vercillo, et al., 2015). Deaf individuals have shown heightened tactile sensory accuracy (Levänen and Hamdorf, 2001) and visual attention enhancements. It is believed people who are deaf are able to process their peripheral vision more accurately than hearing individuals (Bavelier, et al., 2000; Proksch and Bavelier, 2002). This theory has been further supported in research that has shown improved reaction and sensitivities to peripheral and para-foveal tasks (Parasnis and Samar, 1985). Bosworth and Dobkins (2002) assessed peripheral motion in their participants who were deaf and hearing, finding their deaf signing participants had increased peripheral sensitivity to motion distractors compared with the hearing participants. Changes in visual cognition in deaf individuals may be highly specific. These differences and modifications may only be seen when under certain attentional conditions as some visual functions are believed to be comparable to hearing individuals (Finney and Dobkins, 2001; Bosworth and Dobkins, 2002). Therefore specific paradigms such as the RDK experiment which tested areas predominantly in the parafoveal regions (between 2° and 9°), where input from both M pathway and P pathways are mixed could be similar to their hearing peers. In previous studies with people who are deaf, enhancement of coherent motion has been reported at the periphery. Whilst there appears to be enhancement of the peripheral vision in prelingual deaf people, central vision is believed to be unchanged (Codina, et al., 2011). Although visual attention appears modified in deaf individuals it has been proposed that the differences between hearing and people who are deaf are most evident when central and peripheral vision are compared together in rivalry (Bavelier, Dye and Hauser, 2006). Bavelier, Dye and Hauser (2006) have also implied a specialised redistribution of visual resources for prelingual deaf people. This greater emphasis for both peripheral motion and vision, suggests a pivotal involvement of the M pathway. These findings have significant implications for people who are deaf. The redistribution of attentional visual resources from centre to periphery may have repercussions on the educational attainments in these individuals. Prelingual deaf children have a greater tendency to be distracted and find it difficult to concentrate on one task at a time (Mitchell and Quittner, 1996; Quittner, Leibach and Marciel, 2004). This is consistent with research that has demonstrated that children who are deaf appear more responsive to a peripheral distraction with a central task, whereas hearing children are more distracted with a peripheral task and a central distractor (Proksch and Bavelier, 2002). This “conflict” between central and peripheral visual attentions may have significant implications for reading with individuals who are prelingually deaf.

Reading requires eye movement and coordination and so these are of significant importance to reading proficiency (Rayner, 1998; Bélanger and Rayner, 2015). As with any reading task the eyes need to move fluidly between fixation jumps or saccades where the individual words are foveated. These rapid movements induce a suppression of the central visual information that is predominated by the P pathway, due to the speed of each saccade. Each fixation lasts approximately 200 to 250 milliseconds (ms) whilst saccades last between 20 to 50 ms (Reichle, Rayner and Pollatsek, 1999). However, skilled readers do not read every word, skipping those that are small and more frequently used. Each saccade covers 6 to 12 characters although frequent regressions or backward movements to previous text are common (Rayner, 1998). Text difficulty also has an influence on the fixation period with good readers having shorter fixations than poorer ones. Research within the deaf population has found deaf adults who read well, tend to possess a wider perceptual span of up to 18 letters when compared to skilled hearing readers, whilst the span of poorer deaf readers was equivalent to that of skilled hearing readers (Bélanger and Rayner, 2015). This would appear counter intuitive as one would expect skilled hearing readers to perform similarly to skilled deaf readers

Reading text effectively necessities a saccadic progression. This progression entails not only foveation of the word being read but also a parafoveal preview of the next desired word (an area approximately 5° from the fovea to the right in English text).

Parafoveal preview is performed before the next word is foveated and requires the attentional focus to move from the foveated word to next targeted word (Reichle, Rayner and Pollatsek, 2004). This attentional change of focus is believed to require parafoveal cognition of the next targeted word, allowing the eyes to sequence the next saccade and hence foveate the next desired word, therefore implying possible recognition of the targeted word before foveation has occurred (Miellet, O'Donnell and Sereno, 2009).

The structure of the retina changes from fovea to parafoveal areas. These modifications include a variation in the ratio of the differing receptor ganglion cell types the midget and parasol ganglions. The midget and parasol cells project to separate layers of the lateral geniculate nucleus, midget cells being most numerous to the parvocellular areas and the parasol cells to magnocellular area (Shapley, 1990). The central 2° of the fovea is considered to have a ratio of 30:1 midget cells to parasol ganglion cells, changing to 3:1 at the retinal periphery (Dacey and Petersen, 1992). P and M pathways are then projected to separate areas in V1 of the visual cortex (Livingstone and Hubel, 1988) . This change in ratio gives rise to a reduced sensitivity to high spatial frequency (midget cells, P pathway), whilst with increased distance from the fovea there is a greater sensitivity to low spatial frequency images and motion (parasol cells, M pathway). Studies investigating reading performance in normal hearing children and those who are deaf have suggested that performance of the M pathway function is significant in reading performance (Stein, 2001; Samar, Parasnis and Berent, 2002; Samar and Parasnis, 2005) .

The M pathway has a significant influence on the functional input to the parafoveal and peripheral vision and it is thought that hearing individuals with reading difficulties may have subtle changes which may disrupt the normal reading process (Boden and Giaschi, 2007). The disruption may also be associated with poor binocular and vergence control (Stein, Riddell and Fowler, 1988), which in turn affect the attentional focus when fixating or orienting the next word. The sequencing of reading saccades and eye movements are fundamental to the reading process (Rayner, 1998). When considering the physiological changes at the parafoveal retina, magnocellular function must be a consideration in this process. Whilst there is some evidence that hearing dyslexics have magnocellular defect little evidence supports this theory in people who are deaf (Samar, Parasnis and Berent, 2002).

Whilst the current findings are indicative of an increased performance of the M pathway this is only evident in this small sample group. However, yellow appears to be associated with this enhancement. Ray et al, (2005) have associated yellow with a defect in the M pathway arguing that yellow filters normalise the long (L) and medium (M) wave lengths cone responses reducing the inhibitory effect of the L cones, whilst a reduction in the short wavelength cone input may also improve balance in the L/M input to the M pathway. In the current study there already appears to be M pathway advantage possibly due to the plasticity of the visual system to compensate for the loss of hearing. The implications of this M pathway enhancement in children who are deaf are not fully understood and the effects yellow filters have on these children require further investigation to assess the implications of this relationship.

Chapter 6

Discussion and conclusions

6.1. Discussion

The purpose of this study was to assess the visual characteristics of profoundly and severely deaf children. The optometric assessment of children who are deaf have been reviewed, and a reflection on optometric vision testing procedures discussed. Chapter 2 investigated visual performance finding increased levels of ametropia in the participants who are deaf. Binocular and visual function at near were assessed for the first time in this population revealing an increase in binocular dysfunction for children who are deaf especially those associated with reading. Reading speeds, pattern glare and visual stress were investigated in chapter 3 although the WRRT and the use of Intuitive coloured overlays did not indicate visual stress in the deaf. An increased association was found with yellow overlays. Only the participants who were deaf and chose a yellow overlay showed an increase in reading speeds. The WRRT is designed for the hearing population and was found to be not ideal for deaf participants. A modified WRRT was developed to ameliorate the difficulties associated with the original WRRT. The modified test was more specific for early BSL users and facilitated greater compliance and accuracy than the original WRRT. This test was also associated with a choice of yellow and an increase in reading speed was again evident. This lead to an investigation in chapter 5 of the magnocellular visual functions associated with yellow filter choice and indicates an apparent increase in sensitivity within the M pathway, which is contra to the M pathway defect theory. Modification of the peripheral retina due to deafness is implicated by this enhancement.

6.1.1. Vision and binocular function in children and adolescents who are deaf.

Although the vision defects associated with children who are deaf have been investigated for many decades, research into visual function has, in general, been conducted in respect of visual performance and associated pathological defects (Suchman, 1967; Pollard and Neumaier, 1974; Woodruff, 1986; Leguire, et al., 1992). Much of the historic data has been associated with disease processes such as rubella which are now uncommon in developed countries (Nikolopoulos, et al., 2006). Visual assessment and methodologies used have been diverse with little agreement on what constitutes a visual defect or which method of assessment should be performed. However, greater prevalence for example of hypermetropia, (>+ 2.50D of 31.5% Stiatowski, et al., 1993), myopia (≥ 1.00D of 14.4% Armitage, et al., 1995) and astigmatism (≥ 1.50D of 14% Hanioglu-Kargi, et al., 2003) have been shown. There is considerable variance in inclusion criteria in previous studies; this may be due to the previous research having been conducted in the hospital environment. For example, Guy et al (2003), set myopia criteria at -4.00D whereas Armitage et al (1995), set their myopia criteria at -1.00D. Both of these studies were based in hospital clinics and were therefore are more likely to have participants with greater ametropia than that of a general school population. Although visual assessment has been evaluated in previous research, near vision functions have been relatively ignored. This was surprising considering the reported difficulties in acquisition of reading skills in children who are deaf.

Binocular function in deaf populations appears to be associated with increased occurrence of strabismus (Regenbogen and Godel, 1985). Associated heterophoria for near vision had not been measured in the deaf population previously. Although, binocular function has been shown to be reduced in individuals who are deaf, no relationship had been made between reading abilities and these binocular functions.

Chapter 2 described the assessment of heterophoria and showed greater levels of heterophoria in the deaf participants for near vision (1.0 to 14.0^{Δ} XOPN) although the levels of deviation were small for distance (2.0 to 3.0^{Δ}). Near point of convergence was significantly reduced, with many of the participants who were deaf having a more remote NPC (11.3cm), alongside a reduced amplitude of accommodation (9.3D). These near visual anomalies have been related to a reduction in reading performance in typically developing hearing children (Evans, Drasdo and Richards, 1994; Stein, Richardson and Fowler, 2000; Kapoula, et al., 2006) and improved with orthoptic intervention (Kapoula, et al., 2006) and/or the introduction of coloured overlays (yellow) (Ray, Fowler and Stein, 2005). Chapter 2 revealed binocular differences between the hearing and the deaf participants. These appear to be consistent with hearing children who have specific reading difficulties such as dyslexia (Evans, et al., 1996), who also exhibit more a remote NPC and reduced accommodation.

Reading problems have been related to the performance of the binocular system, with some individuals benefitting from closing one eye when reading, preferring a monocular view (Stein, Richardson and Fowler, 2000). For example, Stein, Richardson and Fowler (2000) found that occlusion of one eye could help dyslexic children to achieve stable vision. Binocular foveation of words may be unstable and fine control difficult to achieve with younger children. However, the convergence system is considered to mature with age. Therefore, the inability of many of the children who were deaf to achieve a comparable NPC and accommodation as those of hearing participants, may have significant implications in their ability to perform tasks requiring near vision, especially reading.

Uncorrected refractive error may also impede cognitive and educational progression (Roch-Levecq, et al., 2008; Ibironke, et al., 2011; Orlansky, et al., 2015). Chapter 2 indicated an increase of ametropia with children who were deaf when compared to the hearing controls. The importance of refractive assessment and correction, highlights the need for early intervention in children who are deaf, in order to minimise any associated educational disadvantages. Furthermore, binocular status must also be appraised for near vision tasks, and orthoptic treatment given to maximise accommodative and convergence abilities, all of which have been identified as potential factors in contributing to reading difficulties in children who are deaf. Further work is required to assess the effect of treating these conditions on reading in deaf children.

6.1.2. Reading and coloured overlays for children and adolescents who are deaf

Chapters 3 and 4 have identified potential benefits associated with the use of coloured overlays with children who are deaf. Coloured overlays have been associated with increasing reading speeds in individuals who exhibit symptoms of visual stress. Coloured overlays have been used to alleviate those symptoms and aid reading (Wilkins and Evans, 2010). These symptoms are not only related to reading difficulties, such as dyslexia, but also with visual patterns. These visually stressful patterns, in particular, have been associated with the over stimulation in the visual cortex, giving visual symptoms similar to those experienced with migraine headaches and photosensitive epilepsy (Wilkins, Huang and Cao, 2004). Prior to the studies carried out in the present thesis, the effects of pattern glare in producing visual stress in individuals who are deaf were unknown. However, the assessment of pattern glare in the children who were deaf, led to the finding of minimal symptoms of visual stress (Hollingsworth, et al., 2015). A finding dissimilar to that found in normal hearing children who have dyslexia, where 41% of these children may be highly susceptible to visual stress (Singleton and Henderson, 2007).

The findings surrounding the choice of colour overlay chosen for optimal clarity, also contrasted with other groups with reading difficulties. For example, the children who were deaf had a greater preference for a yellow overlay with 45% choosing this colour. The result was different to that found with hearing dyslexic children among whom only ≈10% chose a yellow overlay. Moreover, the reading speeds were increased in the participants who were deaf by 13%, but only if the coloured overlay was yellow. No other colours in either the hearing or deaf participants who chose a different colour showed this increase.

Chapter 4 described the application of a modified WRRT, which was designed to alleviate some of the language problems between English and BSL. The modified test was produced due to number of non signable BSL words included in the original WRRT, therefore, in the revised version of the WRRT, words were replaced with BSL level 1 signs. Importantly, these revised words were chosen specifically to reflect the first words that all children use when learning to read, and therefore can be used with very young children. Children who are deaf learn sign language to communicate, but they also have to translate from a written text (English), therefore having to use two differing processes to achieve comprehension of a written text. Hearing individuals take for granted the ability to hear the phonemes and phonics of the English language, and when reading apply these sound rules to the written word. In contrast, individuals who are deaf have none or little access to this phonological world, making understanding of written English an immensely more difficult prospect (Musselman, 2000; Perfetti and Sandak, 2000). The application of new signable words enhanced the modified WRRT, as it enabled all of the words to be signed individually. However, even though all the words of the modified WRRT could be signed, it is important to note that the speed of reading was reduced compared to the original WRRT. The reduction in reading speed in the modified test was due to using more hand and arm movements during the signing, and consequently take longer to perform than the original WRRT test. However, the reading speed with the yellow overlay was increased. The choice of a different colour than yellow did not increase reading speeds.

Children who are deaf and have a preference for yellow overlays anecdotally stated “the words are clear” and “more comfortable to see” with their use. Yellow filters have been associated with people who have reading difficulties such as dyslexia (Ray, Fowler and Stein, 2005; Hall, et al., 2013). This association with yellow filters implicates the magnocellular pathway and dorsal visual stream as outlined in Chapter 5. Yellow overlays have been associated with the magnocellular defect theory (Stein and Walsh, 1997). However, the magnocellular theory is based on the presumption that there is a deficiency in the M pathway. Timing of visual processes when reading is thought to be mediated via the M pathway. There are two visual streams beyond the visual cortex; the dorsal stream and the ventral stream. The dorsal stream which is dominated by input from the M pathway and is specialised for motion detection, eye movements and limb movements (Stein, 2001) sometimes called the “where” stream. Whilst the ventral stream is dominant for identifying visual form, sometimes called the “what” stream. The ventral stream allows understanding of the image we are focused on, the dorsal stream is believed to be responsible for the sequencing of eye movements to facilitate the foveation of the desired image. It has been suggested that people who are dyslexic have a reduction in their M pathway either anatomically or functionally (Livingstone, et al., 1991; Talcott, et al., 1998), these reductions or modifications of the M pathway are hypothesised as causational for reading difficulties in a specific subgroup of people with dyslexia (Lovegrove, 1993; Stein and Walsh, 1997; Cornelissen, et al., 1998; Chase, et al., 2003). However, this theory is controversial with others disputing the role of the M pathway in reading (Skottun, 2000; Amitay, et al., 2002; Skottun, 2005).

Results from Chapter 5 indicated an increase in magnocellular function in children who are deaf. Although an enhancement of the M pathway specifically in children who are deaf would appear to be contra to the M pathway deficit theory in dyslexic children. Enhancement of peripheral sensitivity in children who are deaf appears more common, exhibiting enlargements of the peripheral visual fields and faster more accurate processing of peripheral information (Proksch and Bavelier, 2002). However, the implications of the increased sensitivity of the peripheral retinal are not yet fully understood in the deaf population. Although, sequencing of eye movements and perceptual span for reading appear modified for people who are deaf, the role of the M pathway would appear essential to reading performance and has been shown to differ between people who are hearing and deaf (Stevens and Neville, 2006). Stevens and Neville (2006) have attributed increased performance in kinetic perimetry in their participants who were deaf to a possible modification of the M pathway. The M pathway modification has been theorised to compensate for the loss of hearing, consequently enhancing the peripheral visual abilities (cross model plasticity). In comparison, the dyslexic controls in the Stevens and Neville (2006) study showed a reduction in sensitivity to the movement, consistent with the M pathway deficit theory. In the present study, there appear to be indications of improved responses of the M pathway, but only in those individuals who were deaf and had a preference for a yellow overlay. Although M pathway functions are still to be fully investigated, the effect that yellow filters have in influencing M pathway functions may have significant implications with reading sequencing for the deaf population.

6.2. Limitations

The ethical limitations of this study required the participants to be recruited on a voluntary basis, and this was done in one city in the UK, where the dedicated deaf school was located. This may have led to a regional bias between the hearing and deaf participants. Many of the children who are deaf were resident at the school which has a wide catchment area covering most of the central UK. Whereas the hearing school had a typical local catchment area and may not represent as diverse a population cross section.

Numbers of children included in the deaf group were limited due to the school having a much smaller population of children than that of an equivalent hearing school. The school for the deaf is dedicated to those students who are severely or profoundly deaf and have no or little speech, requiring a specific teaching model. The studies included in the thesis were sanctioned by the deaf school involved, with limitations set on both the timing and the classes which could be missed by participating students. For example, participation was not allowed over break or lunch times. These constraints led to significant changes to how the children were tested, with often two assessments being needed to test participants that would ideally be completed in one session, required good cooperation from the participants who could decide not to participate in particular sessions. The schools also refused a cycloplegic test, as the children were at school, and reduction in their visual abilities could have impacted on their learning for the whole day. The inability to use a cycloplegic refraction may have produced an under reporting of the extent of hypermetropia in these children, compared to other studies which did use a cyloplegic. (Armitage, Burke and Buffin, 1995; Abah, et al., 2011). An alternative approach to cycloplegic refraction such as the Mohindra retinoscopy technique could have been performed to confirm results, although this was not possible due to the lighting conditions in the schools, which prohibited this method. However, the Nidek AR-600 auto refractor is considered to be comparable to a subjective refraction (Allen, Radhakrishnan and O'Leary, 2003).

The participation of students in the frequency doubling and random dot kinematograms was reduced following further canvassing of the original participants. The reduction in numbers was in part due to students leaving the schools and some parental concerns with the flickering images. This reduction in participants have reduced the validity of the results in the modified WRRT, FDT and the RDK procedures, and therefore should be considered as pilot studies to assess the potential for future investigations.

The author had learnt basic sign language to communicate with the participants who were deaf. Although this allowed for general basic communication during the assessments, the complexity of the tests being performed both visually and on the reading tasks required a fluent understanding of the task instructions, which was supplied by a school interpreter. A greater and more fluent ability with signing would have improved the interaction between the practitioner and participants who were deaf. Although understanding was mitigated by the use of a demonstration PowerPoint presentation, tests such as NPC could only be explained before it began. No encouragement could be given during the tests as the participants would have to look away from the target to receive the information. Although this method was also employed for the hearing control participants in order to standardise all the assessments.

The tests were only performed by the author. Additional performers would have been preferable to reduce the chance of examiner bias and to confirm the results which have been presented. However, due to the special requirements of the research participants a basic understanding of BSL was a pre-requisite for the deaf school and they would only accept researchers with a basic level BSL. No other researchers were available with these attributes and therefore, research was performed only by the author. The research was alternated between the two schools where possible and data analysed at the end of the collection process.

6.3. Conclusion

There are several key conclusions that can be drawn from studies included in this thesis. Firstly, profoundly and severely deaf children not only have minimal access to the hearing world, they are also predisposed to increased refractive and binocular vision anomalies with: hypermetropia, myopia, astigmatism and strabismus showing increased prevalence. This has a significant impact on these individuals, as the visual pathway is their primary communication channel. Therefore, early identification and correction of refractive error and binocular functions should be seen as a priority for these individuals.

Reading abilities in children who are deaf consistently demonstrate reduced performance when compared with their hearing peers. Reading performance has been widely debated with differing theories being postulated. However, no investigation of visual abilities for reading had been previously investigated. For the first time in this thesis an assessment of near visual and binocular functions revealed reduced convergence and accommodative abilities with children who are deaf. These anomalies have also been associated with some children who have dyslexia and present with symptoms of visual stress. These children have commonly benefited from the use of coloured overlays. However, an assessment of visual stress using a pattern glare test found no association with this anomaly, suggesting children who are deaf are not affected by these visuoperceptual difficulties.

Children who are deaf had not previously been assessed with coloured overlays or the WRRT and were atypical in their choice of colour with a greater preference for yellow overlays. When reading speeds with the WRRT were compared only reading speeds with yellow overlays increased in children who are deaf. This increase was consistent with both the original WRRT and the modified WRRT. The new modified WRRT was developed in this study in response to the difficulties that children who were deaf had with of the some nonstandard BSL words in the original WRRT. The modified test appears to be repeatable and more specific for the deaf population than the original WRRT, although further research in larger cohort populations is required to uphold/confirm these initial findings.

The greater preference and increase in reading speeds with yellow overlays indicated a possible association with the magnocellular deficit theory; a reduction in the effectiveness of the transient stream which is dominated by the M pathway is theorised to impede reading in a subgroup of people with dyslexia. However, contrary to this, the M pathway in this study appears more responsive in the FDT perceptual functions in children who were deaf specifically if they preferred a yellow overlay.

However, these results are for a small pilot studies and further research is required to fully investigate these findings.

This modification in the M pathway may have greater significance for children who are deaf. The peripheral retina is believed to be more receptive and sensitive in these children as a compensation for the loss of hearing. This compensation is theorised to reorder the visual pathways, giving greater emphasis to peripheral tasks and may interfere with the eye movement sequences, therefore disrupting normal reading processes. The possible intriguing association between increased reading speeds and yellow filters suggests a redistribution in functionality of the visual stream, which may indicate an adaptation which could assists eye sequencing for reading.

Further investigation of these new findings is essential to establish its repeatability and functional process found in this research. Firstly, what effects magnocellular enhancement may have on near visual tasks in these children and secondly, why does yellow appear to reorganise these functions?

The results of this research may be of great benefit for children who are deaf and prefer yellow overlays. Children who are profoundly or severely deaf have significant difficulties in their reading ability, which is shown to impact on their social, educational and employment progression. A system or method which may enhance this ability in children who are deaf, must be further investigated to maximise their potential.

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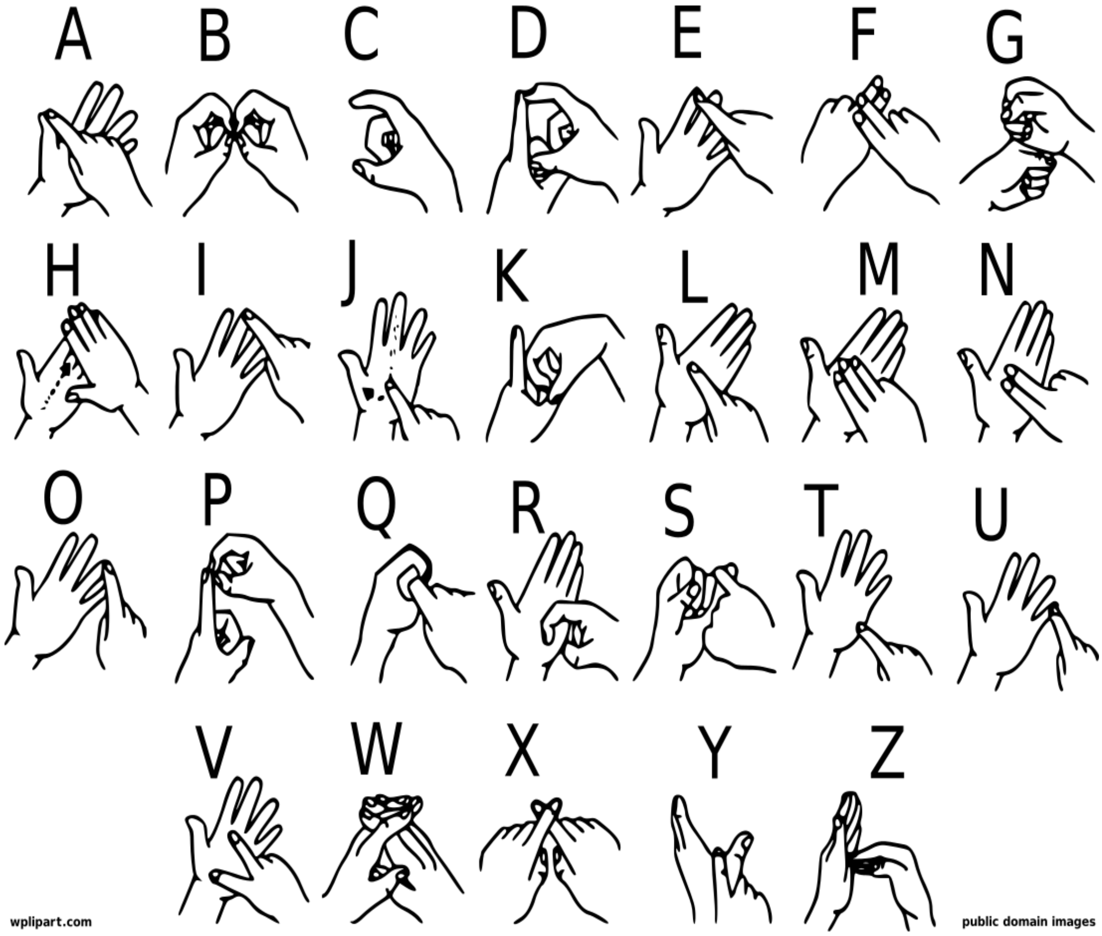
Appendix 1

BSL alphabet



Appendix 2

Publications

Hollingsworth, R., Ludlow, A.K., Wilkins, A., Calver, R. and Allen, P.M., 2013. Visual performance and ocular abnormalities in deaf children and young adults: a literature review. *Acta Ophthalmologica*, 92(4), pp.305-310.

Hollingsworth, R.S., Ludlow, A.K., Wilkins, A.J., Calver, R.I. and Allen, P.M., 2015. Visual performance and the use of colored filters in children who are deaf. *Optometry and Vision Science*, 92 (6), pp.690-699.

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Hollingsworth, R., Ludlow, A., Wilkins, A., Allen, P.M. and Calver, R., 2014. Frequency doubling perimetry and random dot kinematograms in deaf and hearing children. *Investigative Ophthalmology & Visual Science*, 55(13), pp.168-168.

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Hollingsworth, R., Ludlow, A., Wilkins, A., Allen, P.M. and Calver, R., 2015. Visual performance and the use of coloured filters in deaf children. *Annual conference of the college of optometrists* Brighton, UK. 8-9 March

Conference presentation

Hollingsworth, R., Ludlow, A., Wilkins, A., Allen, P.M. and Calver, R., 2013. Visual performance and the use of coloured filters in deaf children. *7th Annual Research Student Conference.* Cambridge. UK. 28 June

Conference Prize

First Prise for presentation

Hollingsworth, R., Ludlow, A., Wilkins, A., Allen, P.M. and Calver, R., 2013. Visual performance and the use of coloured filters in deaf children. *7th Annual Research Student Conference.* Cambridge. UK. 28 June