Studies of Visual Functions and the Effect of Visual Fatigue in Adults with Dyslexia

A thesis submitted to Cardiff University for the degree of

Doctor of Philosophy

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2010

Declaration

This work has not previously been accepted in substance for any degree and is not currently submitted in candidature for any degree.

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Abstract

This thesis has presented a series of studies that examine visual attributes of adults with dyslexia amongst the university student population. The initial literature review has described the prevalence, theories and factors thought to influence dyslexia such as gender and IQ. It is clear that dyslexia is a complex condition and to find correlates is not difficult, but to establish causes and therefore strategies for support is an on-going challenge. Dyslexia is a lifelong condition, and this thesis had at its core a desire to examine visual stress and effect of visual fatigue in adults with dyslexia as almost all the previous research on these areas is either on children or non-dyslexic populations.

This thesis presents the development and validation of a questionnaire to assess visual stress in adults with dyslexia by applying Rasch analysis on a wide range questionnaire. The final 15-item questionnaire is a valid and reliable measure of visual stress in dyslexic across the age range of university students and representing wide range of visual stress levels, a novel finding. The present results established the possible factors that influenced scores of visual stress such as case condition, gender and pattern glare, one of the most commonly considered factor when describing condition of MIS.

This thesis presents the work conducted to address how visual fatigue affects visual performance in adults with dyslexia (with and without MIS. The baseline status of any differences between adults with and without dyslexia was compared to controls. Conventional methods were used to assess binocular vision functions. Binocular instability and reduced vergence reserves at near were demonstrated in dyslexic population with and without MIS. The dyslexia with MIS group also showed reduced amplitude of accommodation and near point of convergence.

Inducing visual fatigue by reading under demanding visual conditions revealed a different effect on certain aspect of binocular vision functions depending on whether subjects have dyslexia or dyslexia with MIS. Increasing near point of convergence appears to be an indicator of visual stress in all subjects, whilst dyslexic subjects with MIS showed decreases in their amplitudes of accommodation and significant exo phoric shift at near – all important features for clinicians to be aware of when managing such patients.

Ocular dominance is a factor referred to frequently in the published literature for dyslexia, but results are often conflicting. This thesis describes the experimental work to develop a quantitative method a new methodology on the synoptophore for assessing sensory dominance that can be applied to the adult population. It was apparent that choice of target was influential in any judgement about dominance. A modified version of this method was then applied to the target cohorts – adults with dyslexia and controls. Crossed eye/hand dominance featured significantly in the dyslexic groups, with also a tendency towards more instability in sensory ocular dominance.

Acknowledgement

I would like to thank the following people for their assistance during this research and the completion of this thesis:

Dr.Chistine Purslow, my supervisor, for her continued and great support and encouragement and for being a sincere supervisor.

Professor Rachel North, for her valuable advice and sharing her great knowledge and enthusiasm.

Dr. Fergal Ennis for his support and encouragement.

Dr. Margaret Woodhouse for being a great advisor.

Dr. Helen Court for her advice and assistance.

Kate Dresser for helping to recruit the dyslexic subjects.

I am extremely grateful to the office staff, who have provided fantastic support over the years, especially to Sue, Leanne, Stephen and Phil who I consider good friends.

A special thanks to my sisters, brothers for their guidance and wishing me all best.

Also to all my friends and colleagues in and outside the school

With a special and great thank to the big heart, my mother, and to my sons Wael and Turki.

And last but by no means least, Saud, my husband for his support, understanding and much more.

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Introduction

Reading and writing provide unique communication amongst human communities, and are necessary to acquire knowledge and education. Extraordinary difficulties in such communication would, therefore, reflect on learning ability and may handicap education or career. This concept of specific difficulties can be described as 'dyslexia'.

The term dyslexia comes from Greek and means 'difficulty with word': for instance, difficulty in decoding visual symbols. Dyslexia may affect persons with normal intelligence and it is a lifelong condition.

Causes of dyslexia are not specific and there is no general agreement about the nature of dyslexia. During reading significant visual symptoms may be experienced by dyslexic individuals that mayor may not be consistent with binocular visual anomalies. These symptoms include visual distortion and asthenopia or visual discomfort which may impede the desire to read and write, and perhaps ultimately handicap the learning process.

When symptoms are alleviated by using an individualized coloured filter then the condition is known as Meares-Irlen Syndrome (MIS), and MIS is often seen amongst children with dyslexia. There appear to be several other visual correlates of dyslexia, but the evidence is somewhat conflicting.

Although dyslexia is not curable condition the associated symptoms may be relieved by orthoptic treatment and coloured filters may also help in dyslexic individuals that are also diagnosed with MIS.

Children with dyslexia appear able to achieve to similar potentials to their peers, including university. Some strategies are required in order to make the full academic field accessible to such groups of the population with dyslexia, e.g. extra time for reading and writing tasks during academic attainment appear useful, and the use of coloured paper in alleviating symptoms in dyslexic subjects diagnosed with Meares-Irlen syndrome.

To date, it appears that many studies on dyslexia and its visual correlates are concentrated on children and there are only a few studies examining adult groups with dyslexia. This PhD introduces new knowledge about an adult population (university students) with dyslexia and those dyslexics who diagnosed with Meares-Irlen syndrome, compared to adults with normal reading abilities. Given that a common support strategy at undergraduate level is the provision of extra time in examinations, studies will focus on the effects of fatigue on binocular instability and ocular dominance amongst these cohorts.

Chapter 1

Literature Review

1.1 Definition of dyslexia

For more than a century, dyslexia has been a subject of controversy, which extends even to its definition. The term "Dyslexia" was first suggested by Berlin in 1887 (Critchley, 1970). The term dyslexia is of Greek origin and means "difficulty with words" (dys- means "difficulty with" or "bad" and lexia refers to "word").

Dyslexia is a complex and subtle neuro-developmental syndrome or disorder (Hynd and Semrud-Clikman, 1989; Galaburda, 1990; Fawcett, Nicolson and Dean, 1996; Fisher et al., 1999; Stein and Talcott, 1999a; Schumacher et al., 2007) and is thought to have a hereditary component (Hallgren, 1950; Critchley, 1970; Owen, 1978). Dyslexia with hereditary, neurodevelopmental aspects has been described as *developmental dyslexia.* The first case was reported in *the British Medical Journal* in (1896) by W. Pringle Morgan, of a "bright and intelligent boy" whose reading ability seemed unusually poor. He described dyslexia as "congenital word blindness" (Morgan, 1896). In 1917, dyslexia was also described as "congenital word blindness" by Hinshelwood (Critchley, 1970). At this time the early history of the condition was terminated. The term "word blindness" was used by Orton in 1925 when describing school children with reading difficulties (Orton, 1925).

An unequivocal definition of dyslexia is difficult (Stein and Fowler, 1981), and can vary according to the discipline, i.e. education, psychology, vision science. The World Federation of Neurology defined it in 1968 as *"a disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence and socio-cultural opportunity"* (Critchley, 1970). Rutter (1978) provided a broader definition: *"a heterogeneous group of reading disabilities characterized by the fact that reading/spelling attainment is far below that expected on the basis of the child's age or IQ"* (Rutter, 1978). Recently, this definition has been modified to *"a specific learning difficulty where reading and/or spelling is markedly below that expected on the basis of age and intelligence"* (Evans, 2002a).

Dyslexia is considered to be synonymous with the term "specific reading retardation" or "specific reading disability". However, "specific reading difficulty" (SRD) is more commonly used (Evans, 2002a; Evans, 2004a). In fact, SRD is the most common type of specific learning difficulty (SpLD) (Evans, 1993a).
The condition can also describe difficulties with the conception of heard language and phrasing in speaking, or with handwriting. People with dyslexia will naturally have different levels of individual difficulty and ability. There are no two dyslexics alike (Snowling, 2000). Moreover, dyslexic people may have a wide range of talents or gifts, for example in mathematics, art, drama and sports, but are often noted to have memory problems (Prior, 1996).

A new (1996) definition of dyslexia has been proposed by the British Dyslexia Association (Crisfield, 1996; Stordy, 2000):

"Dyslexia is a complex neurological condition which is constitutional in origin. The symptoms may affect many areas of learning and function, and may be described as a specific difficulty in reading, spelling and writing language. One or more of these areas may be affected. Numeracy, notational skills (music), motor function and organizational skills may also be involved. However, it is particularly related to mastering written language, although oral language may be affected to some degree".

1.2 Prevalence of dyslexia

Much of the difficulty in assessing the true prevalence of dyslexia arises out of the differences in its definition. Accordingly, prevalence figures vary widely in the literature (see Table 1.1), from 4-10% (Rutter, 1978) to 17.5% (Shaywitz, 1998). A study in Australia (Victoria) found 16% of children aged 7-8 years, with specific reading difficulties (Waring et al., 1996). Approximately 15% of school children were found to have 'SpRD' (Shaywitz et al., 1990). While the incident of reading disability in amblyopic children was reported to be 5% (Koklanis et al., 2006).

Author (Year)	Prevalence (%)	Group	Subjects (n)
Rutter &Yule (1975)	3.7%	Children	2300
Shaywitz et al. (1990)	Approx. 15%	Children	414
Waring et al. (1996)	16%	Children	195
Koklanis et al. (2006)	5%	Amblyopic children	20

Table 1.1: Percentage of dyslexia prevalence

1.3 Factors affecting dyslexia

1.3.1 Age

To date, most studies have concentrated on younger children with dyslexia. Indeed, few studies have been carried out on the adult population. However, longitudinal studies demonstrate that dyslexia is a chronic and lifelong condition (Scarborough, 1984; Bruck, 1992; Francis et al., 1996). Dyslexic persons persist as poor readers during their school life compared to good readers (Shaywitz, Holford and Holahan, 1995). Dyslexic adults with a strong history of childhood reading disability have been examined (Feldman et al., 1995). While, the prevalence in the adult population should mimic that of children, there is little published research to support this idea. Indeed, adults with dyslexia may possess well developed coping strategies (Morris and Turnbull, 2006; White, 2007) which may influence diagnosis. A study carried out to evaluate nursing students (known to have dyslexia) in their clinical experiences found that they managed practice difficulties in different personal ways (e.g. avoiding answering the telephone or handing over reports) in order to overcome their disabilities. Hence, it was suggested there should be more awareness of their practices in order to provide greater support for this dyslexic group and to ensure public safety (Morris and Turnbull, 2006).

Another study showed that dyslexic nursing students have their own strategies to deal with their practical learning difficulties, aimed to reduce such difficulties to meet their specific needs (White, 2007). Thus, while adults with dyslexia try to overcome their deficits, still their reading difficulty persists (Critchley, 1970).

1.3.2 Gender

It has been suggested that dyslexia is more common in boys than girls (Critchley, 1970; Finucc and Childs, 1981; Evans, 2002a). However this has been disputed by several studies.

Some studies have found that the proportion of males in dyslexic samples is higher than females (Rutter and Yule, 1975; Bishop, Jancey and Steel, 1979; Shaywitz et al., 1990; Ygge et al., 1993a). Other studies have postulated that boys and girls are affected almost equally by dyslexia (Flynn and Rahbar, 1994; Feldman et al., 1995; Waring et al., 1996; Moores et al., 1998). Feldman et al. (1998) sampled an equal

number of male and female dyslexics and showed males had lower reading scores than females, suggesting more impairment in reading skills compared to females of the same age (Feldman et al., 1995). Recent studies on twins found no or little significant difference according to gender (Wadsworth and DeFries, 2005; Hawke, Wadsworth and DeFries, 2006a). Thus, insufficient evidence was provided for differential genetic aetiology of reading difficulties in males and females.
(Table 1.2 shows male/female proportion in selected studies).

Author (Year)	**Group**	**subjects (n) (un-selected)**	**subjects(n) (dyslexics)**	**Gender Dyslexic (%)**	
				Boys	**Girls**
Rutter & Yule (1975)	Children	2300	--	76.7	23.3
Bishop et al. (1979)	Children	--	17	64.7	35.3
Shaywitz et al. (1990)	Children A-School B-research	414 (199 boys/215 girls)	--	**a- 2nd grade**	
				13.6	3.2
				3rd grade	
				10	4.2
				b-2nd grade	
				8.7	6.9
				3rd grade	
				9	6
Ygge et al. (1993)	Children	--	86	79	21
Flynn & Rahbar (1994)	Children	708		12.1	8.2
Feldman et al. (1995)	Adults		37	50	50
Waring et al. (1996)	Children	195	--	56	44
Moores et al. (1998)	Adults	--	17	52	48

Table 1.2: Proportion of boys and girls in dyslexic groups.

1.3.3 Intelligence quotient level (IQ)

Many believe that dyslexia is not attributed to low intelligence (Anapolle, 1971; Livingstone et al., 1991; Evans, 2002a; Evans, 2004a). Some authors have studied the IQ of people with dyslexia and found that dyslexia affects subjects with different levels of IQ (Livingstone et al., 1991; Feldman et al., 1995; Francis et al., 1996). However, low IQ scores have been reported in a group of dyslexic children who were

also found to have deficit in working memory (Gathercole et al., 2006).
In another study, it was suggested that IQ test scores are not vital for defining learning disability as IQ tests actually convey an impression of knowledge, verbal language ability and short-term memory, which are usually found to be deficient in any child with learning disabilities. Reading, spelling, language and memory deficits have been found to be similar in subjects with different IQ score levels (e.g. a subject with low IQ may be a good reader (Siegel, 1989)).

It has also been noted that poor readers with different IQ scores (high or low) show the same reading performance, and no causal relationship between IQ and word decoding skills has been found (Gustafson and Samuelsson, 1999).

1.3.4 Language

Different languages may affect reading ability. Some studies report that the reading performance of dyslexic people speaking languages with shallow orthographic properties (where the spelling can be predicted from the sound of the words, e.g. Italian, Spanish) is better than that of dyslexic people speaking languages with deep orthography (e.g. English, French).
Paulesu and colleagues compared reading performance in dyslexic adults speaking English and French with dyslexic adults speaking Italian, and found that Italian dyslexics performed with more accuracy in reading than English and French dyslexic people (Paulesu et al., 2001).
In a study of correlation between the intelligence and reading difficulty in different orthographic languages, e.g. English and Spanish languages, of children with reading disabilities, it was found that IQ as a function of verbal and orthographic performance, e.g. reading and spelling skills, was more related to the orthographic performance in English-speaking Canadian children more than in children speaking the Spanish language. This was suggested to reflect the deep orthographic characteristics of the English language (Jimenez, Siegel and Lopez, 2003). In summary, the impact of language on reading is less in 'transparent' orthographic languages than opaque orthographic languages. It appears that even though the same cerebral deficit may be observed across all language groups at an early age, it is the ambiguous orthography that increases the disability in certain groups (Paulesu et al., 2001).

1.3.5 Memory

Working memory skills are crucial in education in order to acquire knowledge. A correlation between reading and mathematics disability and deficit in working memory (as indicated by complex memory tasks) has been reported in children. Visuo-spatial short term memory (STM) was found to be associated with reading ability whereas phonological STM was found to be associated with mathematics ability (Gathercole et al., 2006).

The DYX1Cl gene has been identified on chromosome 15q as possible genetic cause of dyslexia. The association between developmental dyslexia and DYX1Cl gene has been studied by Marino et al. It was found that linkage disequilibrium in dyslexics explained by the short term memory measured by single letter back ward span (Marino et al., 2007).

1.3.6 Social background

Dyslexia is not attributed to economic, social or conspicuous medical problems (e.g. Down's syndrome) (Evans, 2002a). The concept of dyslexia might sometimes be misused by some people who have considered the condition a matter of "class conspiracy" (Stein and Fowler, 1981). Now it has been proven by many studies that it is a neuro-developmental condition, and not due to bad teaching or cultural differences between social classes (Fawcett et al., 1996; Fisher et al., 1999).

Dyslexia can exist in people of different social backgrounds. The assumption of higher prevalence and diagnosis of dyslexia in the middle social classes, "middle class children are dyslexic, working class children are thick" (Stein and Fowler, 1981) is not, indeed, the case. Rather, the condition in people from lower socio-economic classes appears under-recognized (Evans, 2004a).

1.3.7 Ethnicity

There appears to be no published literature concerning the relationship between ethnicity and dyslexia, other than that which refers to language (section 1.3.4).

1.4 Symptoms in dyslexia

The term dyslexia usually refers to a significant and serious degree of specific reading difficulty, which, in turn, is associated with specific spelling difficulty (Evans, 2004a).

Although dyslexia is a lifelong condition (Critchley, 1970; Scarborough, 1984; Bruck, 1992; Francis et al., 1996; Evans, 2004b), most children growing up create and adapt coping strategies (e.g. try to avoid reading) in order to overcome their difficulty in reading. So, the reading problem will manifest less but the spelling difficulty will last over life (Critchley, 1970; Evans, 2004b).

Verbal memory problems, e.g. difficulty in remembering the just perceived word, and poor phonological awareness, e.g. difficulty to sound out a word, are considered to be symptoms that affect the majority of dyslexic children (Eden et al., 1994).

With regard to response time and accuracy in reading it has been found that dyslexic individuals, children and adults, perform with less accuracy and more slowly when they were examined in computerized sighting word reading and non word decoding tasks, and in spelling discrimination. This problem was noted to be more obvious in dyslexic adults than in the younger group (King, Lombardino and Ahmed, 2005).

1.4.1 Visual symptoms associated with reading

Visual symptoms that some dyslexic people (who are also diagnosed to have Meares-Irlen Syndrome) suffer (with or without the presence of ocular motor function deficits) include:

- Visual stress (Williams et al., 1995; Jeans et al., 1997; Evans et al., 1999; Wilkins and Lewis, 1999; Bouldoukian, Wilkins and Evans, 2002; Singleton and Trotter, 2005 ; Singleton and Henderson, 2007a , 2007b).

- Perceptual distortion (Williams et al., 1995; Jeans et al., 1997; Evans, 1999; Wilkins and Lewis, 1999; Bouldoukian et al., 2002).

- Asthenopia and headache (Williams et al., 1995; Jeans et al., 1997; Evans et al., 1999; Wilkins and Lewis, 1999; Bouldoukian et al., 2002).

- Diplopia (Anapolle, 1971).

• Blurred vision (Eden et al., 1994).

• Visual confusion (Eden et al., 1994; Cornelissen et al., 1998).

Visual confusion is suggested to be as a result of poor binocular control which would cause reading (Cornelissen et al., 1992) and spelling (Cornelissen et al., 1994a) errors.

Eden and colleagues (1994) reported that 64% of dyslexic children, compared to 20% of normal children, appeared to be suffering from visual confusion, represented by losing their place on the page. This was suggested to be attributed to transient system deficit - the sustained system is not inhibited by the transient system and that causes additional eye movements to be necessary in order to bring about the activity of the transient system (Eden et al., 1994). Poor fixation control (unstable fixation) for small targets was also reported in more than 25% of dyslexic children and appeared to be associated with a poor range of vergence (Eden et al., 1994).

Visual confusion is suggested to be as a result of poor binocular control which would cause reading (Cornelissen et al., 1992) and spelling errors (Cornelissen et al., 1994a). The symptom of visual confusion experienced by dyslexics during reading has been attributed to a deficit of the magnocellular (transient) system (see section 1.8) of the visual pathway (Eden et al., 1994; Cornelissen et al., 1998).
In addition, 'faulty vision' symptoms, commonly known as reading errors, occur during reading, such as losing place in reading text, skipping to line below or above, losing place when starting with a new or next line of a paragraph, words and/or letters seeming to move around (Meares, 1980).

1.4.2. Reading errors associated with dyslexia

Reading errors were suggested to be strongly attributed to a visual developmental deficiency (Stein and Fowler, 1981). Dyslexic readers often experience classic diagnostic errors when attempting to read. These errors include: mirror imaging (reverse image appearance), mis-sequencing and/or mis-locating letters and words (Orton, 1925; Stein J and Fowler, 1981). Letters and words have been described as seeming to move around, jump and flip (Cornelissen et al., 1998). This is thought to be due to a lack of precise ocular motor control, which guides accurate visual direction during reading (Stein and Fowler, 1982), dyslexic readers lose their place on a page: they skip, re-read lines, and, to avoid this, they frequently use their finger as a pointer (Anapolle, 1971; Stein and Fowler, 1981; Stein, Richardson and Fowler, 2000a). Eden et al (1994) reported 64% of 'reader-disabled' children showed loss of place whilst reading, compared to 20% of normal readers with this symptom, and this was strongly associated with poor convergence or range of vergence (Eden et al., 1994).

Dyslexic subjects frequently suffer from unstable visual perception and confusion whilst reading in sequence (Eden et al., 1994), and often create words with nonsense meanings termed "non word errors", for small print size (Cornelissen et al., 1991). Types of reading (Cornelissen et al., 1992) or spelling (Cornelissen et al., 1994a) errors may reflect the visual confusion caused by unstable binocular control (Cornelissen et al., 1992), or poor motion perception (Cornelissen et al., 1998) that has been explained by the weakness of the transient visual pathway (Cornelissen et al., 1991).

Causes of dyslexia are discussed later in section 1.7

1.5 Meares-Irlen Syndrome (MIS)

1.5.1 Definition of MIS

Meares-Irlen Syndrome (MIS) has no clear definition in the literature (Evans et al., 1995; Evans et al., 1996b; Evans and Joseph, 2002). Nevertheless, it has been agreed that MIS is the condition that can be described by visual perceptual distortion (VPD) (i.e. illusions of images, colour and motion effects) and symptoms of visual stress (asthaenopia, i.e. eye strain, tired eyes, headache and photophobia), that can be relieved with the use of individually prescribed coloured filters (Evans et al., 1995; Evans et al., 1996b; Jeans et al., 1997; Wilkins et al., 2001; Evans and Joseph, 2002). This visual disorder condition was previously termed "Scotopic Sensitivity Syndrome" (SSS) (Irlen, 1991). Linguistically, this description has been deemed unsuitable (Evans et al., 1996b). Therefore, the alternative name that is currently used is Meares-Irlen syndrome, as this condition was first described by Meares (Meares, 1980) who clearly defined the symptoms of the syndrome and by Irlen (Irlen, 1991) who provided a method of management by using the coloured filters (Evans et al., 1996b).

1.5.2 Prevalence of MIS

It has been stated by Irlen (1991) that MIS affects 65% of dyslexic people and 12% of the general population, but there is no data to support this statement (Irlen, 1991).
The existence of MIS can be indicated by subjective confirmation of persistent benefit from using coloured filters during reading, or immediate benefit that is indicated by increased reading rate (Wilkins et al., 1996 b; Evans et al., 1996b; Jeans et al., 1997; Evans and Joseph, 2002; Kriss and Evans, 2005).
Kriss and Evans (2005) compared a group of 32 dyslexics with 32 control children, based on reading rate with colour overlays, and concluded that MIS is prevalent in the general population but it is a little more common in those with dyslexia: there were no significant differences in the prevalence of MIS between dyslexics and non dyslexic population (Kriss and Evans, 2005). Evans and Joseph reported the prevalence of MIS in unselected adult population is as common as in children (Evans and Joseph, 2002) based on the criteria of 5% improvement in reading rate with coloured overlay reported by Wilkins et al (1996) and by Wilkins et al (2001) (Table

1.3).

Jeans et al reported that up to 20% of unselected school children (undertaken over 6 studies) showed to have visual stress and use their selected coloured overlay for long term use. Of those, 5% show improvement in reading rate (they read 25% faster with overlay) (Jeans et al., 1997).

Table 1.3 shows the prevalence of MIS based on different criteria such as immediate benefit of coloured filters, improvement of reading rate and sustained benefit of coloured filters (Wilkins et al., 1996 b; Jeans et al., 1997; Wilkins et al., 2001; Evans and Joseph, 2002; Kriss and Evans, 2005).

Author (Year)	Sample	Criterion	(%)
Wilkins et al. (1996)	77 Unselected school children.	Initially selected overlay	49
		>5% faster at WRRT	20
		Continue using coloured filter (8 weeks)	20
Jeans et al. (1997)	152 Unselected school children.	Initially select an overlay	53
Wilkins et al. (2001)	426 Unselected school children	Initially select an overlay	60
		>5% faster at WRRT	36
		>25% faster at WRRT	5
		Continue using coloured filter (8 months)	31
Evans & Joseph (2002)	113 Unselected university students	Initially select an overlay	88
		>5%faster at WRRT	34
		>25% faster at WRRT	2
Kriss &Evans (2005)	32 dyslexic /32 control Children	>5% faster at WRRT	47/25
		>8% faster at WRRT	34/22
		>10% faster at WRR T	31/12.5

Table 1.3: Prevalence of MIS from the published literature, based on different criteria. (WRRT: Wilkins Rate Reading Test).

1.5.3 Possible causes of MIS

The pathogenesis of MIS is not well defined in the literature, and several possible causes have been suggested:

a. Pattern glare:

The term 'pattern glare' refers to the description of visual perceptual distortions, e.g. motion of the reading material, change in the spacing between letters and coloured halos, which in turn can cause visual discomfort, and asthaenopic symptoms, by viewing certain "striped" pattern stimuli with spatial characteristics (Wilkins et al., 1984), such as lines of the text on a page (Wilkins and Noimmo-Smith, 1984; Wilkins, 1995).

Pattern glare is the factor most commonly considered when explaining the mechanism of MIS (Evans et al., 1996b). It is suggested that it is attributable to the hyper-excitability of the visual cortex (Wilkins, 1995; Evans et al., 1996b). Neurons of the visual cortex may be oversensitive to the trigger produced by the striped pattern stimuli and the degree of visual distortion may reflect the degree of cortical hyperexcitability (Wilkins, 1995). It is suggested that the visual cortex in people with MIS exerts more energy in processing the image during reading than normal readers, resulting in visual stress symptoms and headache (Nandakumar and Leat, 2008). This may explain why patients with MIS derive benefit from using coloured filters, since their use reduces or redistributes the hyper-excitation of the neurons in the visual cortex (Wilkins, 1995).

b. Accommodative and binocular vision anomalies

Specifically, oculomotor anomalies (accommodative insufficiency and binocular instability) are another dominant consideration frequently associated with MIS (Evans et al., 1995; Evans et al., 1996b; Scott et al., 2002). It has been reported that reduced amplitude of accommodation and fusional reserves can cause fluctuating vision via the link between accommodation and vergence, which is correlated to visual stress (Scott et al., 2002). It has also been suggested that symptoms of visual stress in MIS might be attributed to the reduction of accommodation amplitude and/or decompensating heterophoria (Lightstone and Evans, 1995; Scott et al., 2002). Poor sensory and motor binocular stability (demonstrated by instability of nonius lines in the Mallet test) has also been shown in subjects with MIS (Scott et al., 2002). It has been suggested that although optometric correlates of MIS can cause visual stress, they are unlikely to be the major cause of dyslexia, rather, they are most likely to be correlates of MIS (Evans et al., 1996b).

Clinical management of binocular anomalies (e.g. accommodative insufficiency and decompensated heterophoria) in patients with visual stress and suspected to have MIS, is highly recommended before colour filter investigations (Lightstone and Evans, 1995), in order to avoid misdiagnosis of MIS (Evans, 2005). Some dyslexics, whose symptoms seemingly cannot be helped with orthoptic treatment, can be relieved with individually prescribed coloured filters. In this condition, 'reading-disabled' people can be identified as having MIS (Evans et al., 1996b; Evans et al., 1999).

c) Magnocellular deficit theory

The magnocellular and parvocellular systems are responsible for visual processing (Lovegrove, Martin and Slaghuis, 1986). The magnocellular (or transient) system is stimulated by rapid object movement (e.g. flickering light) and peripheral stimuli, whereas the parvocellular (or sustained system) is mainly responsive to slow or static central stimuli and colour (these are explained in more detail in section 1.8).

It has been suggested that the magnocellular deficit theory of dyslexia is a possible explanation of MIS and the reported benefit from coloured filters (Solman, Cho and Dain, 1991; Irlen, 1994; Scheiman, 1994). On the other hand, several studies have found that the function of the magnocellular system in MIS subjects is normal, based on contrast sensitivity tests (Evans et al., 1995; Evans et al., 1996b; Simmers et al., 2001).

1.5.4 MIS and coloured filters

1.5.4.1 Coloured Overlays

Colour overlays are coloured transparent plastic sheets designed to be placed over a text on a white page (Figure 1.1). They alter the colour of the page beneath but they do not affect the clarity of the text. Their particular colour can reduce visual symptoms experienced by Meares-Irlen syndrome people during reading, for example, perceptual distortion and headache (Jeans et al., 1997; Wilkins and Lewis, 1999; Bouldoukian et al., 2002; Wilkins, 2002; Wilkins et al., 2002).

Coloured overlays not only change the colour of the text but they also decrease the contrast of the text. This may be advantageous for reading in some subjects with MIS (Williams et al., 1995), since they reduce the symptoms of pattern glare and visual stress and hence, increase reading rate (Wilkins et al., 2001; Evans and Joseph, 2002; Evans, 2005). They can be used by optometrists and teachers alike to screen the subjects with visual stress (Wilkins, 1994).

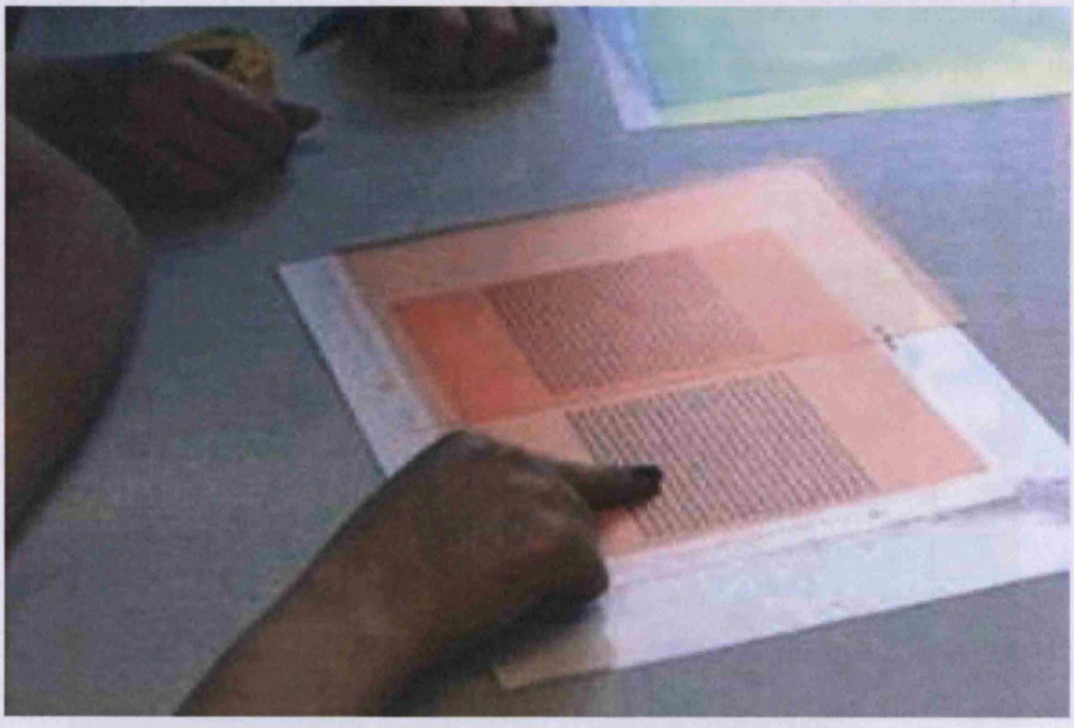

Figure 1.1: Coloured overlay (Taken from: www.Edinburgh-eyetests.co.uk).

1.5.4.2 Intuitive Overlays®

This brand of coloured overlay has been designed and used extensively by Wilkins (Wilkins, 1994; Wilkins et al., 1994) and in many studies on MIS (Evans et al., 1996b; Jeans et al., 1997; Bouldoukian et al., 2002; Evans and Joseph, 2002; Scott et al., 2002; Waldie and Wilkins, 2004). Irlen postulated that the colour of the required filter is individual, differs from one person to another, and always needs to be highly specific (Irlen, 1991). The optimum coloured filter can be prescribed using an Intuitive Colorimeter (Figure 1.2).

1.5.4.3 Intuitive Colorimeter

The Intuitive Colorimeter is an optometric instrument designed by Arnold Wilkins (Wilkins, Nimmo-Smith and Jansons, 1992), and has been used to subjectively assess the precise colour required to reduce visual stress (asthenopic symptoms) and perceptual distortion. This is achieved through an effective and inclusive coloured light mixing mechanism by which the characteristics of colour, e.g. hue, saturation, and brightness, can be changed freely and continuously. Once the optimum colour is determined, precision tinted lenses can be provided using special dyes prepared for a distinct colour, consistent with the optimum colour chosen subjectively in the Intuitive Colorimeter (Lightstone and Evans, 1995).

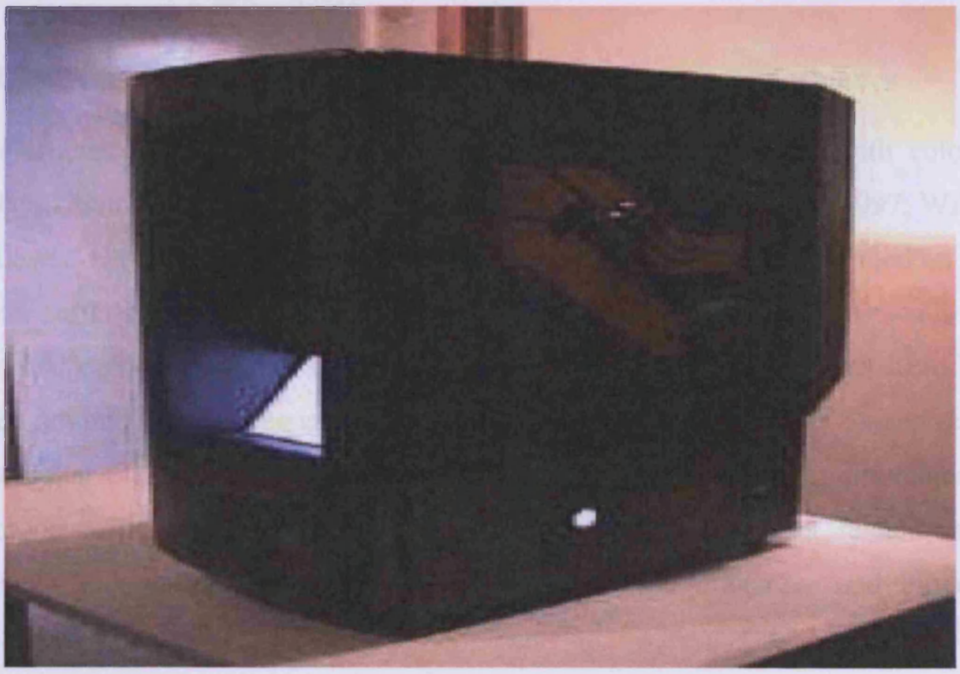

Figure 1.2: Intuitive Colorimeter (Taken from: www.wanganuieyecare.co.nz).

1.5.4.4 Wilkins Rate Reading Test (WRRT)

This test (Figure 1.3) was designed by Wilkins (Wilkins et al., 1996 a1996 b) to measure the effect of coloured overlay on the rate of reading performance objectively in subjects suffering from visual stress. It consists of simple and common words, familiar to children and poor readers, but which cannot be estimated from the text. The words are repeated and ordered randomly in a small and closely-spaced text, in such a manner as to cause visual distortion. The test does not depend on reading skill or intelligence, nor does it measure the cognitive ability in reading skills. In the test, the subject is asked to read the words loudly and quickly (Wilkins et al., 1996 b; Evans and Joseph, 2002).

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 scc thc

Figure 1.3: Example of text in WRRT. In the test, there are four samples of text, each similar to that in the figure, with different (random) order of words in each (Evans and Joseph, 2002).

1.5.4.5 Effect of coloured filters on symptoms and reading performance

Some studies have demonstrated that the increase in reading rate with coloured overlays cannot simply be attributed to the placebo effect (Jeans et al., 1997; Wilkins and Lewis, 1999; Bouldoukian et al., 2002). The WRRT has been performed on poor readers suffering visual stress and visual distortion under two situations: with their individual coloured overlay and with a control colour filter. Such trials have been carried out on both children and adult subjects (Bouldoukian et al., 2002), and results suggest that the increases in reading speed and performance, and improvement of symptoms with individually prescribed coloured overlays are not related to the placebo effect nor to optometric factors such as accommodative and binocular anomalies.

In a double-masked, placebo-controlled trial of precision spectral filters in children with reading difficulty, who used coloured overlays, it was concluded that reduction in symptoms (headache, eye strain) from the use of coloured lenses in MIS subjects could not be explained in terms of the placebo effect and, consequently, an increase in reading speed and performance also could not be attributed to common clinical binocular anomalies (Wilkins et al., 1994; Wilkins et al., 1996 b).
It has been reported that reading speed improved to more than 25% faster with the appropriate coloured overlays in at least 5% of the school children (Wilkins et al., 2001). This advantage probably also takes place in an adult population (Evans and Joseph, 2002). Evans and Joseph studied the effect of coloured filters on reading rate among a university student population and found that 38% of subjects read more than 5% faster with coloured overlays and 2% of subjects read more than 25% faster with overlays (Evans and Joseph, 2002). Comparing results of the two aforementioned studies it was concluded that MIS is equally common in children and adult population.

Coloured filters have usually been investigated in people with reading difficulty with symptoms of asthenopia and visual perceptual distortion. After all parts of the ocular motor function, (i.e. associated and dissociated hetrophoria, amplitude of accommodation and facility, accommodative lag, fusional vergence reserves, stereo acuity, foveal suppression, near point of convergence and ocular motility), have been evaluated, and any anomaly treated, if symptoms persist then intuitive coloured overlays are initially prescribed and, after confirming benefit is gained from them, tinted spectacle lenses are then prescribed using the intuitive Colourimeter (Lightstone and Evans, 1995).

1.6 Relationship between dyslexia and MIS/Visual stress

It has been reported that the condition of MIS, that characterized by visual stress or unpleasant visual symptoms in reading, is more common in dyslexic individuals (Irlen, 1991; Grant, 2004). However, the relationship between dyslexia and MIS remains inconclusive (Singleton and Trotter, 2005; Evans, 2005b; Singleton and Henderson, 2007a, 2007b). Although MIS is considered to be one of the visual correlates of dyslexia (Evans, 1998, 1999) it is not synonymous with dyslexia (Evans, 2005b). An aetiological link between the two conditions may be attributed to the magnocellular deficit theory of dyslexia (Lovegrove et al., 1986; Livingstone et al., 1991; Cornelissen et al., 1994b; Stein, 2001) where some studies results suggested a consistency between MIS in terms of benefit from colour filters and the deficit of the transient system (Livingstone et al., 1991; Solman et al., 1991; Williams, LeCluyse and Rock-Faucheux, 1992; Irlen, 1994) where magnocellular system may explain the benefit from colour filters in reading in subjects with reading difficulties (Robinson and Foreman, 1999 ; Chase and Stein, 2003). The involvement of visual stress in MIS appears quite obvious but the nature of the relationship between visual stress and dyslexia remain unclear.

Kriss & Evans (2005) concluded that dyslexia and MIS are two different conditions and should be diagnosed and treated separately. They reported that the two conditions may present in a person in conjunction or may present separately. The authors found whilst the incidence of MIS was a little higher in dyslexic children than non dyslexics, there was no significant difference between groups in the reading improvement (using WRRT) with colour overlay (Kriss and Evans, 2005).

Based on the reported visual stress symptoms it has been suggested that dyslexic subjects with high scores of visual stress are more likely to benefit from colour filters in improving reading rate compared to non dyslexic subjects with similarly high visual stress (Singleton and Trotter, 2005).
Singleton and Henderson (2007a) also investigated visual stress in dyslexic and non dyslexic children using a bespoke, computerized visual stress screening test (ViSS). They found that the incidence of high level visual stress in dyslexic children was almost twice that in control children, and reported that dyslexic children who showed high visual stress reported more than 20% improvement in reading speed with colour

overlay in WRRT, compared to control children with high visual stress who showed between 5% and 10% improvement. For children with lower visual stress scores, those with dyslexia showed at least 5% improvement compared to controls who showed <5% when using coloured overlays (Singleton and Henderson, 2007a).

Based on visual stress symptoms, Singleton and Henderson reported that high visual stress was found in 41% of dyslexics, whilst only in 23% of a matched control group (Singleton and Henderson, 2007a). This may infer a relationship between dyslexia and the prevalence of visual stress.

1.7 Possible Causes of Dyslexia

1.7.1 Hereditary

In his series of studies on 112 families to determine the presence of a hereditary form of specific dyslexia, Hallgren (1950) found that dyslexia runs in some families more than in others. He believed that dyslexia is genetically determined by a dominant character chromosome, 'the autosomal dominant' (Hallgren, 1950). It has also been suggested that a large number of genes may determine certain types of dyslexia (Owen, 1978). Critchley also believed that the genetic factor plays an important role in dyslexia (Critchley, 1970).

Some genetic evidence has been generated from family histories of dyslexia. A study of 37 dyslexics adults with a three generation family history of dyslexia suggested that dyslexia is a hereditary condition (Feldman et al., 1995). Recent studies on twins provide strong evidence of a genetic factor in dyslexia: however, no or little significant difference in the genetic factor has been found between males and females (Wadsworth and DeFries, 2005; Hawke, Wadsworth and DeFries, 2006b). Thus, insufficient evidence has been provided to indicate differential genetic aetiology of reading difficulties in males compared to females.

DCDC2 and KIAA0319 are the most convincing genes described to-date to understand the molecular basis of dyslexia (Schumacher et al., 2007). The nature of recently identified genes indicates that there is disorganisation of neural migration and decreased activity in the left hemispheric area to which patho-physiological dyslexia is related.

As previously mentioned, the DYXICl gene has also been identified on chromosome 15q. The association between developmental dyslexia and DYXIC1 gene has been studied by Marino and colleagues (Marino et al., 2007). They found that the linkage disequilibrium in dyslexics explained by the short-term memory which measured by single letter back ward span.

1.7.2 Cerebral

It has been hypothesized that the cortical system is divided into fast and slow parts, and the fast part (the magnocellular visual system in the brain) is affected in dyslexic subjects. A greater reduction in size and disorganization of magnocellular (but not parvocellular) lateral geniculate neurons in dyslexic subjects than normal subjects has been reported (Livingstone et al., 1991).

It has been proposed that dyslexia is caused by sub-clinical brain damage at the parietal occipital area (Goldberg and Sims, 1960).
It has also been suggested that dysfunction of the cerebellum-vestibular causes dyslexia (Frank and Levinson, 1976). In a study of brain morphology in dyslexia it was suggested that there are some abnormalities in the cerebral system of dyslexic people, and that subtle lesions may be present in some focal areas, especially in the left cerebral cortex (Hynd and Semrud-Clikman, 1989).
Stein (1989b) proposed that disorder in development of right posterior parietal zone in dyslexic children with poor or unstable binocular control can be indicated by particular signs - including imprecise localisation of dots in the left hemi field, tendency to left negligence and fixation instability of the left eye during convergence. Stein believed that precise vergence control was the hardest functional task of right posterior parietal cortex and therefore any disorder or impairment to right posterior parietal region can cause dyslexia. He concluded that developmental disorder or impairment of the right hemisphere visuo-motor or visuo-spatial function processing functions was experienced by many dyslexic children and led to their reading difficulties (Stein, 1989 b).

Galaburda (1990) also reported cerebral abnormalities in dyslexia. Cerebral asymmetry was found to be absent in dyslexics, and tiny focal abnormalities ('ectopia' or 'brain warts') distributed over the cerebral cortex surface were noted. These microscopic cortical abnormalities were particularly noted in the perisylvian language areas in the left cerebral cortex. Galaburda hypothesized that these abnormalities are caused by foetal developmental abnormalities (Galaburda, 1990). Structural abnormalities of dyslexic brain have also been reported by Habib (Habib, 2000). Reduced activity in the left hemisphere, left middle, inferior and superior temporal cortex and in the middle occipital gyrus has been reported in dyslexic adults and described as a universal weakness in the neurocognitive network (i.e. language system) in dyslexic individuals, thereby resulting in the slower processing of spoken and written language (Paulesu et al., 2001).

1.7.3 Phonological

Studying the sound in a language is referred to as phonology. During reading, in order to translate the written words into the sound of the verbal language, phonological processing is highly required (Evans, 2002a). Deficiency in phonological processing skills that are needed to interpret the perceptual visual images of the letters and words while reading into sounds, is considered to be the main cause of dyslexia (Rack, 1997).

Evidence of deficient phonological processing in dyslexics has been reported in many studies. The brain activation pattern of dyslexic children indicates a deficit of orthographic representation and deficits in mapping between orthographic and phonological representations in the inferior parietal cortex (Cao et al., 2006). Cognitive skills such as coding and decoding symbolic targets are also important for reading. Core deficits of phonological function will lead to difficulty in learning decoding, and hence naming speed dysfunction (Wolf and Bowers, 2000).

Legein and Bouma suggested that ineffectual coding skills and recoding deficiencies are strongly associated with dyslexia and may actually cause dyslexia (Legein and Bouma, 1981). Manis and colleagues found deficiency of phoneme awareness in dyslexic children, and suggested that their speech difficulty may be associated with reading skills (Manis et al., 1997). Impairment of phonological processing in dyslexic adults has been described as a universal dyslexia problem regardless of the spoken language and can also influence orthography. However, the orthography problem is more apparent in languages with ambiguous orthography, e.g. English and French (Paulesu et al., 2001).

It has also been suggested that poor syntactical processing in dyslexic children contributes to impairment of phonological ability (Sabisch et al., 2006).

Investigation of speech-in-noise perception was found to be significantly reduced in pre-school children with a high family risk of dyslexia compared to control children, and speech ability showed a close correlation with phonological awareness and low level auditory processes (Boets et al., 2007 a).

1.7.4 Auditory

It has been hypothesized that a low level auditory problem in pre-school children with high family risk of dyslexia can cause speech perception difficulties and the latter might then handicap development of phonological ability as well as reading and spelling performance (Boets et al., 2007 a).

Recent longitudinal research (Boets et al., 2007 b) compared phonological ability, speech perception, and low level auditory processing of preschool (5 year old) children with a high risk of hereditary dyslexia, with those of a matched group of control subjects; deficits were found in phonological awareness, rapid automatic naming, speech-in-noise perception, and detection of frequency modulation. The aforementioned study suggested that auditory and speech problems are common in cases of learning disability, and may inhibit the phonological and learning process, but are unlikely to be the main cause of the latter problem. Furthermore, high level neurological evidence of auditory processing dysfunction along the auditory-to-articulation stream was provided by Boets and colleagues (Boets et al., 2007 b). Other direct neural evidence of auditory processing abnormalities in poor readers has been supported by an electrophysiological study of the auditory cortex in adults with reading difficulties. These difficulties were attributed to abnormal neural representation of short and fast successive sensory inputs (Nagrajan et al., 1999).

1.7.5 Visual

Visual factors that can be contributory to dyslexia have been broadly divided in to the following categories (according to Evans, 1998, 1999).

1- Sensory factor: deficit of the magnocellular (or transient system) visual pathway.

2- Ocular-motor factors which are represented by binocular instability evidenced by reduced amplitude of accommodation and low fusional reserves.

Evans and colleagues found a link between sensory and motor visual correlates in dyslexic people. Subjects found to have binocular instability (reduced fusional reserves) were likely to have sensory deficit (magnocellular visual deficit) identified by reduced ability to detect a flickering light (Evans, Drasdo and Richards, 1996a).

3- Meares Irlen Syndrome (Kriss and Evans, 2005).

Each of these theories is now discussed separately.

1.8 The Magnocellular deficit theory of dyslexia

Magnocellular deficit theory, originally known as 'transient system deficit theory' (Skottun and Parke., 1999) is derived from the fact that the visual pathway connecting the eyes to the visual cortex consists of a combination of two corresponding neural systems. These are the magnocellular system (the two ventral layers of anatomical disposal of the lateral geniculate body (nucleus) (LGN)), which represents the transient system that has been hypothesized to be the fast subdivision of the cortical system (Livingstone et al., 1991), and the parvocellular system (the most dorsal layers of (LGN)), that represent the sustained system (Figure 1.4). The prefixes magno- and parvo- mean large and small, respectively, based on neuron size. The magnocellular system consists of large neurons that have high speed properties in conducting visual signals and strongly respond to movement and rapid temporal stimulus changes. On the other hand, the parvocellular system is made up of small neurons that are responsible for detecting smaller objects, their details and for colour vision (Livingstone and Hubel, 1987; Livingstone et al., 1991; Skottun and Parke., 1999; Skottun, 2000). The properties of magno- and parvo- cellular systems are summarised in table 1.4.

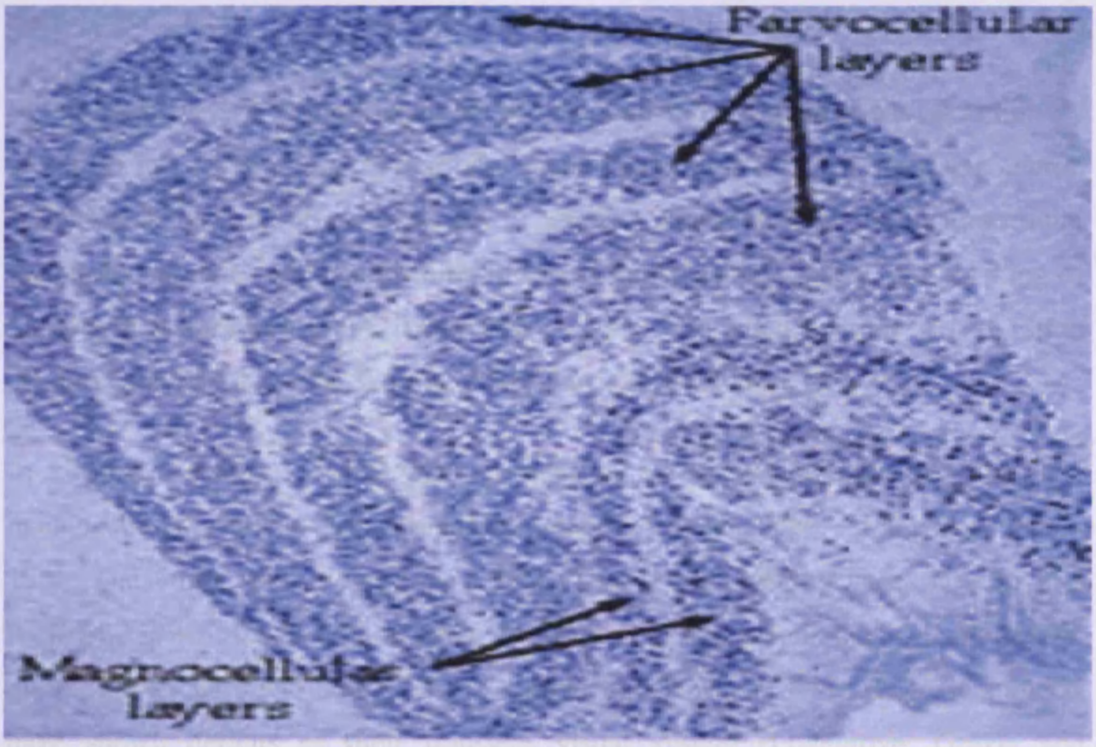

Figure 1.4: Cross section from the Lateral Geniculate Nucleus (LGN), illustrating the Magnocellular and the Parvocellular system of the visual pathway (Hubel, 1988).

Property	Transient (Magnocellular)	Sustained (Parvocellular)
Layer of LGN	The two ventral	The four most dorsal
Size of neuron	Large	Small
Response property	Long	Short
Retinal location	More peripheral	More central
Temporal condition for maximum response	Moving objects, low flicker frequency	Static object, high flicker frequency
Spatial condition for maximum response	Low spatial frequencies	High spatial frequencies
Colure sensitivity	No	yes
Shape discriminating	Contour lines	Detailed shape

Table 1.4: Properties of mango and parvo cellular systems.

In the course of reading, it has been suggested that for an accurate and perfect reading process, the fast subdivision of visual pathway is required to be intact (Stein and Talcott, 1999b). Reading activity is characterized by a series of brief fixations separated by saccades; a series of small rapid eye movements, rather than a continuous sweep (Kulp and Schmidt, 1996), and only about 90% of the reading time is spent in fixation (Solan, 1985). Based on magnocellular deficit theory, the magnocellular system is stimulated by saccades while the parvocellular system stimulation occurs during fixations (Skottun and Parke., 1999; Skottun, 2000; Farraj, Kheder and Abel-Naser, 2002).

In normal readers, it is postulated that the magnocellular system elicits an inhibitory effect on the parvocellular system and hence, suppression of parvocellular neuron activities at the time of each saccade. Therefore, stimulation of the magnocellular system by saccades will result in inhibition of the sustained system and blocking of its activities, preventing one fixation from being continued into the next fixation (Skottun and Parke., 1999; Skottun, 2000; Farraj et al., 2002).

In dyslexic readers, it has been suggested by many authors that the fast magnocellular pathway is disordered (Lovegrove et al., 1980; Livingstone et al., 1991; Galaburda and Livingstone, 1993; Lovegrove, 1993; Evans, Drasdo and Richards, 1994b; Evans et al., 1996a; Evans et al., 1996b; Stein and Talcott, 1999b; Stein, 2001; Chase and Stein, 2003). A high prevalence (75%) of dyslexic subjects have shown deficits of their transient visual system (Lovegrove, Grazia and Nicholson, 1990). Furthermore, the magnocellular system deficit has been found to be highly correlated with dyslexia, and an etiological role of the transient system deficit in reading disability was suggested as it seems that a deficit of the transient system precedes the reading disability (Lovegrove et al., 1990). A delay of the magnocellular system has also been suggested to be present in dyslexic children (Lehmkule, 1993). Histologically, Livingstone and colleagues found a reduction in size of the magnocellular neurons of dyslexic individuals (Livingstone et al., 1991). Based on magnocellular deficit theory it is assumed that the inhibition of parvocellular system by magnocellular system is reduced (Skottun and Parke., 1999), and this is demonstrated in a failure to maintain separate parvocellular neural activity that produces different fixations. The activity of the parvocellular system is therefore confused and this drives the dyslexia problem (Skottun and Parke., 1999).

However, this theory of dyslexia has been disputed. Evidence suggests that magnocellular system rather than the parvocellular system (as has been postulated) is the target of saccadic inhibition (Skottun and Parke., 1999; Farraj et al., 2002), indicating that the magnocellular theory of dyslexia is incorrect (Skottun and Parke., 1999).

Moreover, abnormalities have been found within the parvocellular visual system and this seems to be consistent with the normal physiological function of the parvocellular system demonstrating that detecting the fine details of viewed objects, for instance, proper reading activity, depends on ability of the parvocellular system to distinguish fine details (Farraj et al., 2002).

Recently, in order to close the gap between reading disability and the theoretical magnocellular deficit hypothesis, a string processing task, that consists of 5 or 6 constant letters (e.g. "RHNBM, QDWKSX" as experimental stimuli and "NNNML, HHXGL" as target stimuli), has been used. The strings are considered to have functionally similar visual characteristics to reading material (words and/or letters), therefore requiring visual perceptual and ocular motor performances similar to those required in the reading process. This test was carried out on dyslexic and normal subjects, and no differences were found in respect of eye movement patterns. Absence of difference in eye movements between the two groups provides strong evidence that dyslexics' perceptual accuracy and eye movement control during reading do not appear to be related to reading problems. Thus, no relationship between functionality of the magnocellular system and coherent eye movements was found. In the same study, a pseudo-word (e.g. liribi) experiment was carried out and higher number and longer fixation durations were shown by the dyslexic group. This indicated that dyslexics have difficulty in perceiving strange letter components (Hutzler et al., 2006).

1.9 Visual correlates of dyslexia

1.9.1 Visual Acuity

Several studies have examined the correlation of visual acuity with reading ability. Some of studies have found no significant relationship between distance visual acuity and reading ability in school children (Bishop et al., 1979; Aasved, 1987; Buzzelli, 1991). Bishop et al tested visual acuity in 147 unselected school children and found monocular and binocular visual acuity was within the normal range (6/9) (Bishop et al., 1979). Similarly, Aasved (1987) studied 3000 unselected school children and found no correlation between reading ability and visual acuity (Aasved, 1987). Buzzelli compared distance Visual Acuity (VA) in dyslexic children with normal children and found no significant difference between the two groups (Buzzelli, 1991).

In contrast, Ygge et al (1993) reported a significant difference between dyslexic children (n=86) and a matched control group (n=86), in regard to distance and near visual acuities (Ygge et al., 1993b). Evans et al. found corrected and uncorrected visual acuities were worse in a dyslexic (n=39) group of children compared to the control group (43 matched age children) (Evans et al., 1994b). Moreover, it has been postulated that dyslexic individuals always have discrepant visual acuities (Anapolle, 1971). However, no significant difference between visual acuities in dyslexic children described to have Meares-Irlen Syndrome and a matched control group has been reported (Evans et al., 1995). It seems no study has evaluated VA in adults with dyslexia.

1.9.2 Refractive errors

Many studies have assessed the refractive errors among dyslexic children (Farris, 1936; Norn, Rindziunski and Skydsgaard, 1969; Anapolle, 1971; Fowler and Stein, 1983; Aasved, 1987; Evans and Drasdo, 1990; Evans, Drasdo and Richards, 1992b; Ygge et al., 1993b; Evans et al., 1994b; Evans et al., 1996a).

Some studies have suggested that a high incidence of hypermetropia is particularly associated with learning disability (Evans et al., 1992b; Evans, 2002a). Because hyperopia is usually related to symptoms of blurred vision, eye strain and headache, this may limit the child's desire to read and continuation of learning performance may be markedly affected. Hence, hyperopia may be a contributory factor in dyslexia, but it cannot be a causal factor (Evans, 2002a).

Norn found mild hyperopia and astigmatism were slightly more common in a dyslexic group (Norn et al., 1969). A link between hyperopia and poor accommodation in a sample of dyslexic children has also been reported (Evans et al., 1992b).

Farris investigated non-selected school children of the seventh grade (n=1685) and found that hyperopia appeared to have a negative effect on progression in reading ability due to the symptoms associated with hyperopia during reading. A positive correlation with reading ability was shown in the myopic and myopic astigmat population (Farris, 1936).

Studies comparing reading performance between 117 non-selected hyperopic and myopic school subjects found subjects with myopia had significantly better reading performance and higher intelligence scores than hyperopic subjects of correlation of higher IQ level in subject with myopia and from (Young, 1963).

In contrast, many authors have reported little association between refractive errors and reading ability (Anapolle, 1971; Aasved, 1987; Ygge et al., 1993b; Evans et al., 1994b). Anapolle has postulated that there is no single type of refractive error that can 'interfere' with the reading process (Anapolle, 1971).

Evans, Drasdo and Richard compared dyslexics (n=39) with control (n=43) children, and found no difference in the distribution of refractive errors between the two groups (Evans, Drasdo and Richards, 1994a). A similar finding was reported by Ygge and colleagues (Ygge et al., 1993a).

Furthermore, it has been postulated that refractive error is not considerably correlated to MIS either. For instance, Evans found that the refractive errors in a MIS group and control group were similar (Evans et al., 1995), and normal refractive errors were noted in dyslexic children with MIS (Evans et al., 1996b).

1.9.3 Binocular vision functions

The relationship between binocular vision functions and dyslexia have been a subject of controversy in the optometric literature (Evans and Drasdo, 1990; Evans, Drasdo and Richards, 1992a; Evans et al., 1994a, 1994b; Evans et al., 1995; Evans et al., 1996b; Evans, 1999). Optometric correlates that could contribute to reading difficulty mainly include ocular motor deficits, and have been described as "low level" visual correlates of dyslexia (Evans et al., 1996a). It is well established that dyslexic people have greater prevalence of ocular motor anomalies than the norm. Ocular motor anomalies, such as low vergence reserves, reduced amplitudes of accommodation, and unstable heterophoria have been shown to manifest more in dyslexic children than a control group (Evans et al., 1994a).

Many studies agree that binocular vision dysfunction (defined as reduced amplitude of accommodation and convergence insufficiency) and exophoria at near contribute to reading difficulty, and, perhaps dyslexia is also associated with poor stereopsis.

In 1934, Eames found 88 children with poor reading performance (presumed dyslexic) exhibited reduced fusional convergence reserves, particularly to small targets, compared to 52 normal readers (Eames, 1934). In 1988 this was supported by Stein who also found poor positive and negative relative fusional reserves, especially with a small target, in a dyslexic population (children) through an objective measurement of eye movements using the Synoptophore instrument test (Stein, Riddell and Fowler, 1988).

Riddle et al found reduced stereopsis in dyslexic children (n=74) compared to controls (n=80) (Riddle, Fowler and Stein, 1987).

Hung found static accommodation and vergence performance (range and dynamic velocity) were reduced in two dyslexic subjects (one child and one adult) when compared to normal subjects of matched age. This may indicate abnormalities of underlying ocular motor (vergence) control function (Hung, 1989).
Buzzelli (1991) compared 13 dyslexic children with 13 matched age and IQ normal readers and found that vergence facility in dyslexics was significantly worse than control subjects. However, performance of accommodative facility and stereopsis were similar in both groups (Buzzelli, 1991).

Evans et al. (1992) reviewed the optometric correlates of dyslexia in children and found relevant factors included accommodative dysfunction, reduce vergence reserves, poor convergence, and exophoria at near to be common in dyslexic children (Evans et al., 1992a). In another study Evans investigated accommodative and binocular function in dyslexia and by comparing dyslexic children (n=39) with control subjects (n=43). It was found that the positive and negative vergence reserve and amplitude of accommodation were significantly lower in the dyslexic group. In the same study, similar results were recorded for both groups for accommodative lag and facility. However, dyslexics tended to show a slightly slower response in the accommodative facility test (Evans et al., 1994a).

Eden et al found that vergence amplitudes, convergence and divergence, were reduced in dyslexic children (n=26) compared to normal readers of matched age (n=39). The authors reported poor stability of fixation for small targets in dyslexic children (Eden et al., 1994).

Latvala et al (1994) compared dyslexic children (n=55) with control children (n=50) and found that only near point of convergence showed significant difference between the two groups, while there were no differences in heterophoria (distance and near), accommodation or stereopsis. They stated that ophthalmic factors constitute part of dyslexic syndrome (Latvala et al., 1994).

Morad et al (2002) failed to ascertain the hypothesis that reading required sustained convergence, where no correlation between near point of convergence and reading performance was found in dyslexic children (Morad et al., 2002).

Kapoula (2007) evaluated binocular vision functions in dyslexic children (n=46) compared to normal children (n=57) and found a more distal near point of convergence and reduced divergence capacity at distance and near. However, stereopsis and phorias at distance and near were similar in both groups (Kapoula et al., 2007).

Bucci and Kapoula compared binocular vision measures in dyslexic children (n=18) with non-dyslexic children (n=13) and found reduced divergence capability in dyslexic children compared to non-dyslexics while there were no significant difference in convergence amplitude, near point of convergence and heterophoria at distance and near between the two groups (Bucci and Kapoula, 2008).

More recently, Dusek et al (2010), evaluated retrospective clinical data of binocular status and accommodation functions in dyslexic children (n=825) compared to

control children (n=328) and found significant differences between the two groups, as demonstrated in reduced convergence (NPC), exophoria at near, lower amplitude of accommodation, reduced accommodative facility and vergence facility in the dyslexic group (Dusek, Pierscionek and McClelland, 2010).
It has also been reported that oculomotor dysfunctions (reduced amplitude of accommodation, low vergence reserve and poor stereopsis), are contributory to dyslexia in people who have also been diagnosed to have MIS but they are not a major cause of the problem (Evans et al., 1995; Evans et al., 1996b). Authors reported that reduction in vergence reserves arguably results in an inability to overcome the heterophoria (Evans et al., 1995).

Evans et al (1995) compared 16 children with MIS with 25 control and found slight but significant reductions in stereoacuity and in vergence and accommodative amplitudes in subjects with MIS. However there was no significant difference between the two groups in associated and dissociated heterophoria (Evans et al., 1995).

Scott et al (2002) investigated dyslexic children who showed symptoms of MIS and found slight but significant reduction of binocular amplitude of accommodation and fusional reserves in MIS subjects compared to control children (Scott et al., 2002).

Evans et al (1996) investigated binocular vision functions in children with symptoms of visual stress and distortion who got benefit from colour filters (MIS subjects) and found slightly but significantly reduced amplitude of accommodation and vergence, and poor stereopsis in MIS subjects compared to the control subjects. However there was no significant difference in near point of convergence (Evans et al., 1996b).

Anapolle reported some of the reading symptoms suffered by dyslexics (i.e. eye strain, double vision) and/ or reading errors (losing the place in the reading material, skipping and re-reading the reading line) are attributed to the presence of exophoria and lack of accurate convergence during reading (Anapolle, 1971).

Another possible explanation for ocular motor factors contributing to reading difficulties is that characteristics such as low amplitude of accommodation, poor fusional reserves may cause blurred vision, diplopia, confusion, headache as well as visual discomfort, (Evans et al., 1992a; Evans et al., 1994a; Evans et al., 1996a; Evans, 1998, 1999). However, binocular vision anomalies such as accommodation and vergence anomalies have not been accounted as a major cause of dyslexia (Hung, 1989; Evans et al., 1994a).

The studies above provide evidence to confirm there is a correlation between accommodative dysfunction, low fusional reserve, convergence insufficiency, exophoria at near and perhaps poor stereopsis on one hand and dyslexia on the other hand. However, there is no absolute evidence to show that conventional ocular motor visual anomalies are a cause of dyslexia.
Indeed a conflict of opinion regarding the correlation of dyslexia with binocular visual anomalies has been suggested by other authors (Norn et al., 1969; Aasved, 1987; Adler and Grant, 1988; Ygge et al., 1993a).

Norn et al (1969) compared 117 dyslexic children with 117 control children and found no relationship between reading disability and binocular vision functions (Norn et al., 1969). A similar conclusion was reported by Aasved (1987) who found no relationship between reading performance and ocular motor condition where ocular motor findings were similar in the different levels of reading performance in a studied group of 3000 children (259 of whom were dyslexics) (Aasved, 1987). Similarly, Ygge et al. (1993) found no significant difference between dyslexic children (n=86) and a matched age and sex control group in regard to ocular alignment, suppression, stereopsis, accommodative and vergence abilities (Ygge et al., 1993a).

Adler and Grant suggested that 50% of children with reading difficulties may get benefit from treatment of binocular instability at near (Adler and Grant, 1988).

Grisham et al found that subjects with normal binocular vision and those with poor binocular functions perform equally in reading task (Grisham, Sheppard and Tran, 1993)

Kiely et al reported a lack of correlation between binocular visual functions (stereopsis, near heterophoria, NPC, and accommodative facility) and reading performance (Kiely, Crewther and Crewther, 2001).

1.9.4 Binocular instability

Binocular instability as described by unstable heterophoria at near and demonstrated by an excessive movement of arrow in the Maddox Wing test (Giles, 1960; Evans et al., 1994a) has been widely reported to be common in dyslexic population (Evans et al., 1994a; Evans et al., 1996a; Evans, 1998, 1999, 2002a, 2004b). Binocular instability is the ocular motor condition that reflects poor vergence stability, reduced convergence and divergence fusional reserves and unstable heterophoria (Evans et al., 1994a; Evans et al., 1996a; Evans, 1998, 1999).

Stein et al (1988) hypothesised that poor vergence control shown by dyslexic children can cause problems for precise visual localisation process, therefore creating errors in reading (Stein et al., 1988). They believed that unstable vergence control is strongly associated with reading disability (Stein et al., 1988; Stein, 1989 b). Riddle et al investigated vergence eye movements to small targets in dyslexic children (n=74) compared to their matched reading age and IQ of control subjects (n=80), and found poor vergence control which would affect accuracy of spatial localisation in dyslexic children and therefore impair their reading performance (Riddle, Stein and Fowler, 1988).

Stein (1989) reported that dyslexia was associated with disorder of vergence control, dysfunction of visual localisation signals and poor (unstable) binocular fixation: all reflected in the symptoms experienced by dyslexic children during reading, e.g. letters are moving around and blurring of small letters (Stein, 1989 b).

Stein et al. (1988) suggested a correlation between unstable or poor vergence control for small target and reading difficultes (Stein et al., 1988). Similarly, Eden et al. found reduced fixation control (poor stability of fixation) for small targets in dyslexic children (Eden et al., 1994).

Further, Stein & colleagues have suggested that reading difficulties due to perceptual distortion are attributed to poor ocular motor and/or visual motor control and, hence, poor binocular localisation, based on the Dunlop test (See section 1.5.9) as shown in 2/3 of their dyslexic children (Stein and Fowler, 1981; Stein and Fowler, 1982; Stein et al., 2000a).

1.9.5 Instability of ocular dominance

Ocular dominance is defined as a condition in which there is a tendency to prefer visual input from one eye over the input from the other (Porac and Coren, 1976). The perceived image appears larger (Porac and Coren, 1976) and clearer (Porac and Coren, 1984) when sighted with the dominant eye. Hence, visual performance is more perfect when subjects use their dominant eye (Coren, 1999).

The dominant eye may not be the eye that sees best but is the eye used for sighting (Portal and Romano, 1998) or the eye that is used to perform task (Mapp, Ono and Barbeito, 2003). Although accommodation innervations and responses are considered to be equal in both eyes, the dominant eye has been shown to play an essential role in accommodation. Moreover, under normal binocular viewing status, since the dominant eye is the one that tends to address a task, the static tonus of its ciliary's muscles and accommodation process will be stimulated more than those of the non dominant eye. This difference in accommodation responses between the two eyes might indicate a more myopic shift of the dominant eye than the non dominant eye (Ching et al., 2004).

Conventionally, for mono-vision cases in presbyopic subjects, the dominant eye is determined by sighting test and corrected for distant tasks while the non dominant eye is corrected for near viewing (Handa et al., 2005) because at distant sight the dominant eye can easily suppress the blur induced in the non dominant eye (Schor and Erickson, 1988).

Despite the large number of studies on this topic, the substantial function of ocular dominance is still confusing.

Several claims about ocular dominance have been reported (Mapp et al., 2003):

1) "Eye dominance is related to handedness or hemispherical dominance"

The notion that "right-handed humans are one sided, i.e. they are right-eyed, right-footed, and right-handed" is a fallacy (Pointer, 2001). The eye consists of, mainly, sensory and motor components and its perceptual outputs are perceived and interpreted binocularly and equally in the brain (both hemispheres of the visual cortex).On the other hand, handedness as a motor aspect is represented contra-laterally to the brain. Therefore, hemisphere laterality can include hand dominance

but not eye dominance, because retinal signals from each eye project to both hemispheres (Portal and Romano, 1998).
Statistically, hand dominance (handedness) and eye dominance are certainly correlated. A meta-analysis of the relationship between handedness and eye dominance indicated that about 35% of right-handed individuals had left eye dominance whereas 57% of left-handers had left eye dominance (Bourassa, McManus and Bryden, 1996).

Lack of correlation between eye and hand dominance has been reported (Porac and Coren, 1975, 1976; Pointer, 2001) while others have found an independent correlation between both writing hand, throwing hand and eye dominance (McManus et al., 1999).

The term "uncrossed eye hand dominance" is a description for the agreement between hand and eye dominance, e.g. right handedness and right eyedness, whereas "crossed eye hand dominance" refers to lack of laterality between hand and eye dominance (Portal and Romano, 1998). Ching (2004) found consistent (uncrossed) eye-hand dominance in 60% of subjects and 40% showed crossed eye-hand dominance (Ching et al., 2004).

2) "The sighting dominant eye is the egocentric"

It is important to keep in mind that visual inputs are provided to the visual cortex as a summation of the retinal images of the two eyes. An imaginary big eye sited almost at the middle line of visual directions, the Cyclopean eye, has been termed the egocentric centre (Walls, 1951; Mapp et al., 2003), i.e. the centre of visual direction, and represents the combination of the visual output under conditions of normal binocular vision and fusion. It is assumed during determination of ocular dominance using sighting tests that the cyclopean eye is located either superimposed on or closer to the dominant eye rather the non-dominant eye (Portal and Romano, 1998), thus slanted towards the right eye in most people. Based on sighting dominance it has been reported that 65% of people prefer to use their right eye for sighting (right eye dominance) (Chaurasia and Mathur, 1976; Portal and Romano, 1998) and eye dominance is not affected by sex or handedness (Chaurasia and Mathur, 1976; Bourassa et al., 1996).

Using a sighting test, Rengstroff (1967) found 62% of his sample (5500 subjects) were right handed and right eyed and 29% were right handed and left eyed. Robboy and Erickson (1990) found almost three-quarters (70%) of subjects showed a right sighting eye or the same eye dominance at distant and near using the blurred suppression test . Ching et al (2004) found 63.6 % of their sample to be right eyed. However, in addition to right or left eye sighting dominance, subjects defined to have no ocular dominance have also been reported, and it was hypothesised that in these cases the two hemispheres may dominate equally (Cei, Bergerone and Ruggieri, 1982).

3) "There is a single dominant eye for each person"

Consistence in eye preference has been reported with different sighting tests (Walls, 1951; Coren and Kaplan, 1973; Porac and Coren, 1976) implying that there is a single sighting dominant eye for each person. Therefore, a sighting test is considered to be the most reliable and substantial method for ocular dominance determination (Porac and Coren, 1976).

4) " For a given test there is a dominant eye"

Many authors of early studies reported disagreements or conflicting results between different eye dominance tests (Walls, 1951; Gronwall and Sampson, 1971; Coren and Kaplan, 1973; Porac and Coren, 1976).

Recently, it has been reported that the sighting test is correlated with the binocular rivalry test (Handa et al., 2004 a). However, Ooi et al. (2001) reported no positive correlation between sensory eye dominance (in the binocular rivalry test) and motor dominance (determined with the sighting test) (Ooi, Optom and He, 2001).

For determination of ocular dominance three criteria have been suggested (Coren and Kaplan, 1973):

a) The eye with better visual acuity

It had been reported that the eye used for sighting tended to be the eye with better near point monocular visual acuity (Porac, Whitford and Coren, 1976). However, although Pointer (2001) contended that there was no worthy correlation between sighted eye dominance and visual acuity, they nevertheless argued that in normal (non strabismus) subjects, the eye manifesting sighting dominance is simultaneously more likely to be the better sighted eye (Pointer, 2001). A review of studies carried out by Pointer showed that the aforementioned belief is not absolutely right, since there is no predictable association between sighting eye dominance and visual acuity. Rather, an association between the eye used for sighting and the eye with better visual acuity is a chance occurrence at the statistical level. Accordingly, sighting dominance should be considered as a separate entity from the visual acuity dominance. Thus, testing monocular visual acuity and recording the dominant (sighting) eye should be important clinical considerations (Pointer, 2001; Pointer, 2007).

b) *The eye that responds more frequently to a stimulus in the binocular rivalry test.*

The original function of binocular rivalry is sensory, that is when viewing unrelated (dissimilar) images presented simultaneously in front of both eyes i.e. one image is observed with the right eye and another, different image, is observed with the left eye, the two eyes will be in a competing status in perceiving either image (Coren and Kaplan, 1973; Handa et al., 2004 a). Sensory ocular dominance is described as 'the controlling eye of binocular perception', whereas sighting eye dominance is derived from motor origin (Walls, 1951; Handa et al., 2004 a) and is described as the centre of visual directions (Walls, 1951; Portal and Romano, 1998; Mapp et al., 2003) or the directing eye in binocular vision (Walls, 1951).

c) The eye that performs tasks in the sighting test (the eye used for sighting).

Sighting eye dominance has been defined by Walls as "one-eyed expressions of an asymmetrical but binocular phenomenon" (Walls, 1951), for instance, when an observer looks with both eyes open at a distant target through an aperture on the midline of the visual axes at arms length (Mapp et al., 2003).

Sighting dominance is of motor origin, i.e. is related to the motor visual system, and is required for a defined motor eye movement in order to direct or combine monocular visual directions of right and left eyes into a single binocular visual direction which can be represented by the cyclopean eye. There is a wide range of ocular dominance sighting tests, for example, observing a near target, a finger or pencil, so that it appears collinear with a distant target (Porta test) (Walls, 1951;

Crovitz and Zener, 1962; Porac and Coren, 1976).

In the Hole in the Card (HIC) test (Durand and Gould, 1910) an observer views a distant target through a small hole in the middle of a card (Figure 1.5), whereas in the Miles test (Miles, 1928) a subject extends both hands at arm's length and brings them together to create a small aperture, at the middle line of visual direction, through which a distant target is viewed (Figure 1.6). Then the subject closes either eye in turn or draws his hands towards his face to determine by which eye the target is viewed (Mendola and Conner, 2007).

Figure 1.5: Hole in the Card (HIC) test

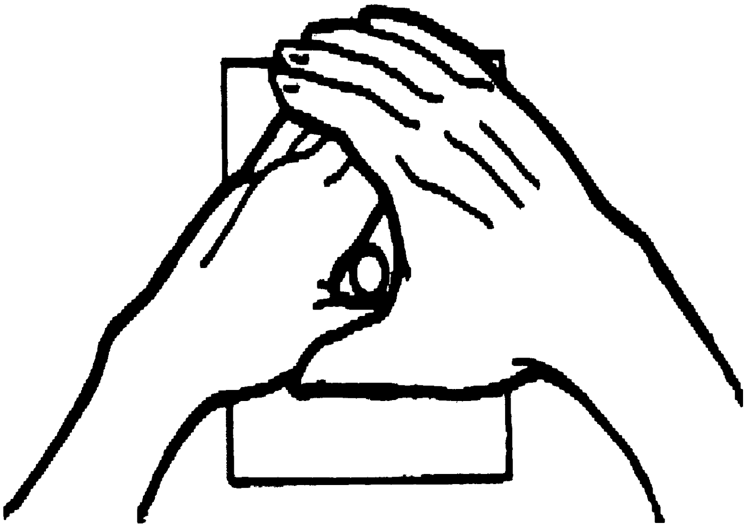

Figure 1.6: Miles test (Taken from: www.archeryweb.com/archery/eyedom.htm).

Ocular dominance can be determined by another common test of motor origin, using the near point of convergence. When the target appears double, the eye that maintains fixation is defined as the dominant eye (Walls, 1951; Porac and Coren, 1976; Ching et al., 2004).

In central binocular viewing in primary gaze, the tendency to change from one referent eye to another is known as unstable ocular dominance (Bigelow and McKenzie, 1985). Failure to establish a stable dominant eye may play an important causal role in visual dyslexia, as it has been reported that developmental dyslexia is the sequence of failures to develop cerebral lateralization of reading activities (Critchley, 1970).

Bigelow and McKenzie hypothesized that unstable ocular dominance can directly cause delay in discriminating left-right or mirror-image visual inputs and hence result in reading errors (Bigelow and McKenzie, 1985).

These errors may be attributed to the fact that each hemisphere receives information from the opposite visual field (Blakemore and Pattigrew, 1970; Fowler and Stein, 1980). Retinal information transfers to the visual cortex by means of ipsilateral and contralateral fibres; temporal retinal images are delivered through ipsilateral fibres and the nasal retinal images are delivered through contra-lateral fibres (Blakemore and Pattigrew, 1970). In other words, in the situation of non central binocular fixation, the image that falls on the temporal retinal side of one eye and the nasal retinal side of the other eye will be analyzed in either the right or left cerebral cortex (Bigelow and McKenzie, 1985). However, in each retina there is a small central vertical strip, approximately 1 degree wide, where visual fields overlap (Stone, Leicester and Sherman, 1973). This is served by both ipsilateral and contralateral fibres. In the case of central binocular fixation, the image from the fovea is carried out to both hemispheres of the cortex by ipsilateral and contralateral fibres. Information moves from one hemisphere to the other and left-right inversed images are produced (Bigelow and McKenzie, 1985), so that a real sensory image and a mirror memory representation are received by both cerebral cortices. Contralateral neural activity impulses to one visual cortex acts as a reference with which the mirror-image memory traces from the other visual cortex can be compared.

This complex sensitive central retinal image analyzation is critical in reading, because, in the course of reading, it is essential to discriminate between real and mirror-image memory traces to avoid visual confusion. Since the strip in the central retinal area is served by both ipsilateral and contralateral visual neural fibres, this discrimination is difficult and complex (Bigelow and McKenzie, 1985).

'Referential engrams' (monocular images) (Orton, 1925) are sited in only one hemisphere where interpretation of the reading process occurs in the final stage of cerebral activities (Fowler and Stein, 1980). Visual signals from the other hemisphere are transported to the reading hemisphere through the commissures of the forebrain. The majority of these commissural linkages are homotopic (Fowler and Stein, 1980; Stein and Fowler, 1981) that is, they possess a regular manner in connecting left and right mirror image sites, i.e. they are distributed 1 degree, 2 degrees left and right of midline and so on (Fowler and Stein, 1980).

In the course of transposition from one hemisphere to the other, reversal outcomes may have an effect on image forms of letters and words, where it is essential to discriminate left or right sides and sequences (Orton, 1925; Bigelow and McKenzie, 1985). Such commissural arrangement will mix them up, resulting in a jumbling effect. Unstable ocular dominance in dyslexia will, therefore, demonstrate as visual confusion or visual reversal errors in dyslexics (Fowler and Stein, 1980). This is the basis for Orton's reversal theory from the 1920s; he believed that one of the two "engrams" must be dropped off or suppressed during reading to avoid confusion and the imperfect crossing of one of the two images will cause confusion of the reading material (Orton, 1925; Orton 1928).

A causal relationship between crossed eye to hand dominance and reading difficulty (in terms of reversals and faulty eye movement) has frequently been reported.
Orton noted that many children with poor reading skills exhibited crossed dominance. Some of those children examined were able to read or write backwards as easily as forwards. He concluded that they appear to be using their right hemisphere for language and that confusion in cerebral dominance is the major cause of dyslexia (Orton, 1925).
Zangwill and Blakemore also describe a case of crossed dominance who frequently showed reversal errors of letters or words. This subject also showed higher tendency to move the eyes or to read from right to left rather from the correct direction of reading (from left to right) (Zangwill and Blakemore, 1972).
Rengstroff (1967) investigated sighting eye and handedness in their group of 5500 and found that subjects with crossed dominance (right-handed and left eye or vice versa) were more likely to show slower reading speed and comprehension (Rengstroff, 1967).
Dearbon (1931) reported that left eye dominance and crossed dominance was common in his clinical cohort of children with reading difficulties. He believed that left eye dominance was the major cause of their reading difficulty; as the children with left eye may show a tendency of right to left movement and make them to read in the wrong sequence for word ('boy' as 'dog') and reverse orientation for letters ('b' as 'd') (Dearbon, 1931).
Monroe (1932) reported a correlation between left eye preference and the accuracy of mirror reading. She suggested that children with crossed eye hand dominance may show opposite directions of eye and hand movement, therefore, left to right eye movement may be more difficult for left eyed children (Monroe, 1932).
Other studies have not found such a link. Spitzer (1959) assessed sighting ocular dominance in 103 reading disabled children and 288 control subjects and found similar results in both groups regarding the incidence of right, left, and mixed eye dominance and handedness (Spitzer, Rabkin and Kramer, 1959). Another study examined the relationship between the pattern of eye/hand dominance and reading proficiency in 100 children with reading problems compared to 80 control children and found no association between crossed dominance and reading ability in comprehension and tendency to make reversal errors. Similarly, they did not find a relationship between sighting eye preference and reading proficiency (Witty and

Kopel, 1936). In 1973 Dunlop examined for the controlling eye, with the Dunlop test, in 15 poor readers and 15 good readers and found higher incidence of crossed dominance (Dunlop, Dunlop and Fenelon, 1973). Similarly, more recent studies have not found a relationship between sighting eye or pattern of eye/hand preference and the reading proficiency in unselected school children (Fagard, Monzalvo-Lopez and Mamassian, 2008). Castro et al (2008) found the incidence of right or left eye motor dominance in dyslexic children was similar to that in controls (Castro et al., 2008).

During reading at near, the eyes are converged and the visual directions of eyes are not precisely identical. Different ocular motor signals provided by each eye may lead to visual confusion. Developing stable eye reference to guide visual direction will overcome this problem (Walls, 1951; Stein and Fowler, 1982).

Formation of stable eye preference may support controlled eye movements while reading and avoid perceptual visual jumbling that is created when ocular-motor system signals from both eyes are not identical. In fact, dyslexics show unstable ocular dominance even in non-reading tasks when assessed with the Dunlop test (Stein and Fowler, 1981; Stein and Fowler, 1982).

The Dunlop test of ocular dominance has received much attention in studies of dyslexia (Fowler and Stein, 1980; Stein and Fowler, 1981; Stein and Fowler, 1982).

The Dunlop test is usually performed with a standard synoptophore using slides F69 and F70 that represented a small house with two trees, a small tree seen by one eye and a big tree by the other eye (each image subtend 3.25°). The tubes of the synoptophore are adjusted to attain fusion. Then, while subjects maintain fixation at the central door, the tubes are diverged steadily until fixation disparity occurrs, i.e. when subjects reported one of the trees was moved. The eye that continues seeing the non-moved image is considered the dominant eye (Dunlop et al., 1973)

However, other authors have found the test to be less useful (Bishop et al., 1979; Newman et al., 1985; Aasved, 1987; Ygge et al., 1993a; Evans et al., 1994a; Goulandris et al., 1998).

Stein and co-workers believed that visual dyslexia is caused by lack of the stable ocular dominance (i.e. unstable reference eye) using the Dunlop test found the majority of dyslexic children exhibited unstable ocular dominance (Stein and Fowler, 1981; Stein and Fowler, 1982). This suggested a causal relationship between dyslexia and instability of ocular dominance (Fowler and Stein, 1980; Stein and Fowler, 1981; Stein and Fowler, 1982).

In their studies (Stein and Fowler, 1981; Stein and Fowler, 1982) using the modified Dunlop test, the dominant eye was identified as the eye whose ocular motor and retinal signals showed accurate correlations. Stein and Fowler defined dominance stability when the dominant eye was consistent in at least 8 out of 10 trials. They proposed a neurophysiology theory of the Dunlop test. They stated that *"in the test the eyes were made to move in opposite directions. Ocular motor signals about lateral movements of each eye are probably organized in the hemisphere contralateral to that eye. In our test the trees were viewed in the nasal field of each eye; hence retinal signals about the trees were projected to the ipsilateral hemisphere. Yet for most people movement information deriving from one eye was successfully associated with retinal signals about the tree seen by that eye, presumably employing interhemispheric connections. This gave rise to the consistent illusion that one, but only one, of the trees moved. Retinal and ocular motor signals derived from the other eye were not associated in this way, and the tree seen by the other eye did not appear to move. Hence (this version of) the Dunlop test seems to be able to identify the eye whose ocular motor and retinal signals are successfully associated (i.e., the eye contralaeral to the tree that appeared to move) as the dominant one"* (Stein and Fowler, 1982).

Stein and Fowler compared dyslexics (n=80) with normal child readers (n=80). They found two thirds of dyslexic subjects had unstable ocular dominance whereas only one of 80 children from the control group exhibited unstable ocular dominance. This difference was highly significant (Stein and Fowler, 1982). Dyslexics showed unstable ocular dominance even in non-reading tasks when assessed with the Dunlop test (Fowler and Stein, 1980; Stein and Fowler, 1982). These authors concluded that Dunlop test is a reliable method to identify the stability of motor ocular dominance and to diagnose 'visual dyslexia' (Stein and Fowler, 1981; Stein and Fowler, 1982; Stein and Fowler, 1985).

Not all studies agree with this finding. Newman and colleagues found a significant preponderance of stable right eye dominance over the left eye dominance (Newman et al., 1985). However, they did not find significant differences between dyslexics (52%) and control group (54%) regarding to the instability or "unfixed ocular dominance". Thus they concluded that ocular dominance assessment using the

Dunlop test does not provide sufficient evidence of reading and spelling performance rate (Newman et al., 1985).

Bigelow & McKenzie (1985) used a portable device (tranaglyph), to assess the ocular dominance in 14 poor readers and 14 control subjects. They found high incidence of ocular dominance instability in dyslexic group but a causal relationship was not supported (Bigelow and McKenzie, 1985).

In assessment of the correlation between ocular dominance stability identified with the Dunlop test and vergence response, Stein et al (1988) measured vergence eye movement during forced vergence using 2 different sizes targets (2.5 and 7.5 deg.) and found that the dyslexic group (39 dyslexic children) with unfixed referent eye (n=24) have significantly lower vergence responses (fusional reserves) for the small target than both those dyslexics with fixed ocular dominance and control subjects (n=24) (Stein et al., 1988).

Ygge et al (1993a) used the Dunlop test and found no significant difference between dyslexics (n=86) and normal readers of children regarding ocular dominance instability (Ygge et al., 1993a).

In another study using the Dunlop test Bishop et al. (1979) reported inconsistent ocular dominance results in 147 randomly selected children. Crossed dominance dominated in their study, but was not associated with reading problems (Bishop et al., 1979).

Bishop (1989) reviewed the literature concerning the Dunlop test and reported that the Dunlop test performance depended on the subject's intelligence. Bishop reported that the Dunlop test does not precisely differentiate between dyslexics and good readers in terms of stability of ocular dominance- in fact, 24% of the good readers in Stein et al's study in 1986 showed unstable ocular dominance (Bishop, 1989).

Furthermore, using the Dunlop test, Bulkey and Robertson compared the test results between 100 dyslexic children and 100 controls and found that control children showed more unstable ocular dominance than dyslexic children. The authors also noted that the children's responses changed between visits and were unreliable (Bulkey and Robertson, 1991). Evans also reported that the Dunlop test is an "unreliable" method to provide clinical binocular vision data and that conventional methods can assess this type of instability (Evans, 1993b). Evans et al used the near Mallet unit target with polarized filters and fixation disparity was forced with rotary prisms. The test was repeated 10 times and the eye that maintained fixation in 8 trials was declared the dominant eye. Authors referred to this test as a modified Dunlop test and went on to find no significant difference between dyslexic and control groups. Dyslexics showed a slight tendency towards less stable eye dominance and their responses to the Dunlop test were significantly less credible than the matched age. and IQ control subjects. Accordingly, they concluded that the traditional Dunlop test appeared to be unreliable in discriminating between dyslexic and control groups (Evans et al., 1994a). Gouladris et al similarly compared 20 dyslexic children and 20 control children and found that the Dunlop test failed to discriminate between dyslexics and normal readers, although dyslexic subjects performed harder in the test (Goulandris et al., 1998).

Interestingly, in 1985, Stein and Fowler investigated the effect of eye patching on ocular dominance stability in 148 children with visual dyslexia. They reported improved stability and reading performance of ocular dominance after wearing occluded spectacles for 6 months. They concluded that only dyslexics with visual-motor problems could be helped with such occlusion therapy (Stein and Fowler, 1985) attained. In a later study, Stein and Fowler reported improvement in reading performance resulting from eye patching in poor readers of children with unstable ocular dominance (20%) (Stein, Riddell and Fowler, 1986). However, Aasved reported that logically no scientific foundation could explain the treatment of ocular dominance instability by occlusion (Aasved, 1987).

Bishop's review also concluded that a scientific causal relationship between improvement of reading performance and monocular occlusion therapy in children with visual dyslexia and unstable ocular dominance had not been demonstrated (Bishop, 1989). However, a subsequent study by Stein in 2000 reported ocular dominance stability and reading performance improvements after 3 months of patching in 59% of 143 unselected school children in comparison to 36% of children who did not receive patch treatment (Stein et al., 2000a). The controversy continues but studies that occlude are not always considered favourably from an ethical viewpoint.

In conclusion, the literature on the Dunlop test for detecting unstable motor ocular dominance is equivocal, and may reflect the 'dominance instability'.

1.9.6 Eye movements

The fovea subtends only 1° (Bigelow and McKenzie, 1985) and in order to locate the selected reading information such as a letter onto the fovea precise saccadic eye movements are required (Kulp and Schmidt, 1996). These details are processed during fixation whereas the successive eye movements are stimulated and directed by the peripheral target information such as word length (Bouma and Legein, 1977; Kulp and Schmidt, 1996) in the para-foveal or macular visual field (about 3°-4°) (Stein and Fowler, 1981). Therefore, continuous visual perception will be performed by the brain (Boden and Giaschi, 2007). Hence, for the reading process to be integral, accurate eye movements are required.

In the course of reading it is important to have an accurate identification of visual direction in order to maintain fixation. Exact correlation between the central retinal image and ocular motor signals derived from the ocular motor system to control suitable eye movements during reading is highly demanded (Stein and Fowler, 1982; Cornelissen et al., 1991).

In dyslexia, a lack of such precise association may cause abnormal eye movements (Stein and Fowler, 1982) characterized by small regressed saccades, termed erratic eye movements (Pavlidis, 1978). Stein and colleagues believed that precise eye movements such as those in reading require fine vergence control which in turn is based on accurate identification of macular signals. They reported poor vergence responses during forced vergence to a small target (2.5°) in a dyslexic group (n=39).

It has been claimed that there is a correlation between reading difficulties and abnormal sequential eye movements, i.e. while trying to pursue flickering lights (Pavlidis, 1985a).

Riddle also investigated vergence eye movements to small targets in dyslexic children; dyslexic subjects showed poorer vergence eye movement compared to controls (Riddle et al., 1988).

Whether the abnormal eye movement seen in dyslexics during reading reflects difficulty in reading which requires re-reading the text in order to understand the meaning of the word, or whether it is the key to reading difficulty, is not clear from the literature.

Three hypotheses that could explain eye movement abnormalities in dyslexic individuals have been stated (according to Pavlidis, 1985b):

1-"Erratic eye movement reflects the problems dyslexics have with the reading material".

2-"Erratic eye movement may cause dyslexia"

3-"Erratic eye movements and dyslexia are usually the symptoms of one or more commonly shared or independent, but parallel deficits in central processing".

Stain and Fowler (1982), who postulated the association between reading disability and unfixed ocular dominance, suggested that this may be attributed to unusual regressed eye movement which can be the reason for visual confusion, and hence leads dyslexics to lose the exact position of letters or words on the page (Stein and Fowler, 1982).

In non reading tasks, dyslexics' dynamic visual performance showed fixation instability at the end of saccades and poor smooth pursuit when compared to normal readers. It was concluded that the abnormalities in eye movements were the result of neurological deficit rather than a cause of reading disability (Eden et al., 1994).

Dyslexics have also exhibited an excessive number of regressions and fixation pauses during target tracking tasks. This suggests that the successive eye movement ability in dyslexic subjects is reduced (Hung, 1989).

Further, in non-reading tasks, dyslexics have shown excessive saccades while viewing peripheral stimuli (Fischer and Weaber, 1990). Fischer and Weaber concluded that the erratic eye movements exhibited by dyslexics are a result of visual attention dysfunction of oculomotor control and, therefore, inconsistent saccadic eye movement timing. An excessive number of regressions has also been reported in dyslexic subjects when tested with sequential non-reading tasks that still require side to side following (Pavlidis, 1985b).

During reading, dyslexics have been reported to exhibit more saccades than normal readers and more frequent regressions, termed "reversed staircase pattern" (Zangwill and Blakemore, 1972). An excessive number of regressions, fixation pauses (Hung, 1989), and un-required saccades to other lines, coupled with a higher tendency to move the eyes from right to left rather from the correct direction for reading (from left to right), have also been shown by dyslexic readers. This was attributed to "an irrepressible tendency to move the eyes from right to left" (Zangwill and Blakemore, 1972). Moreover, compared to normal readers, it has been reported that dyslexic people expend longer durations fixating in the reading process, implying that a longer time is required for dyslexics to comprehend words or a group of letters. However, when words or groups of letters are presented tachistoscopically (separately) with very short duration, dyslexics showed no difficulty in comprehending them (Zangwill and Blakemore, 1972).

Similarly, Williams and Lecluyse (1990) reported that when a reading process required spontaneous eye movement to be used 'disabled readers' showed decreases in ability in comprehending it, compared to when the text was presented word by word or with guided reading, where no eye movement was required, as they suggested. However, the control group didn't show significant differences between the two test conditions (Williams and Lecluyse, 1990).

Pavlidis further tested the saccadic eye movements in dyslexic children using a simple visual tracking test by following consecutive sources of illuminating light. He suggested defective eye movements represent difficulty in consecutive tracking performance and could indicate the key to dyslexia. He concluded that the abnormal sequential nature of dyslexic eye movements which occur during reading were not due to difficulty with the text but due to a central deficit, that he termed "sequential order disability" (Pavlidis, 1981). This therefore suggests that the defective eye movement shown by dyslexics in the course of reading could be the cause and not the result of dyslexia. However, Ygge et al. did not find any difference between dyslexics and normal readers' eye movements in non-reading tasks (smooth pursuit and saccadic). Accordingly, he contended that inconsistent eye movements shown by dyslexic readers refer specifically to decoding difficulties while reading the text (Ygge et al., 1993a).

Rightward and leftward directions of saccades and saccadic re-fixation eye movements tested with simple re-fixation tasks were found to be normal in dyslexic children when compared to normal, age matched subjects, and slight differences in eye movement pattern during reading were found between dyslexic and normal children (Black et al., 1984).

Recently, in order to investigate the theoretical magnocellular deficit hypothesis a string processing task test has been utilised that consists of 5 or 6 constant letters (e.g. "RHNBM, QDWKSX" as experimental stimuli and "NNNML, HHXGL" as target stimuli, considered to have similar visual characteristics to reading material). No differences were found between dyslexic and control readers in respect of eye movement patterns with these targets. This provides strong evidence that dyslexics' perceptual accuracy and eye movement control during reading do not appear to be related to reading problems. Thus, no relationship between functionality of the magnocellular system and coherent eye movements was found (Hutzler et al., 2006).

1.10 Aims for this PhD

Almost all the literature examining visual correlates in dyslexia considers children, yet the condition of dyslexia is life-long, and we continue to make adjustments and considerations for dyslexic adult learners in higher education. Binocular instability appears to be a key correlate, and yet nothing has been reported about the effects of fatigue on binocular function in people with dyslexia. Given that much of the educational support for dyslexics involves extra time for examinations, etc., this may be important. The clinical evidence for unstable ocular dominance in dyslexia is equivocal, despite increasing physiological evidence to suggest that it would explain eye movement problems: this may be due to the current methods used to assess ocular dominance, particularly as they give no measure of strength of dominance, and they address different aspects of visual processing. Meares-Irlen Syndrome (MIS) is frequently diagnosed in dyslexic individuals, and the affects of using coloured filters on ocular dominance testing is also unknown.

This PhD will investigate and compare several aspects of dynamic binocular stability and the effect of visual fatigue in three cohorts:

1- Students diagnosed with dyslexia

2- Students diagnosed with dyslexia and also with MIS

3- 'Normal' students as controls

Specific aims include:

a) To evaluate visual stress in dyslexia by developing a specific visual stress questionnaire for dyslexic subjects.
b) To evaluate binocular vision functions in dyslexic subjects with or without MIS compared to control group.
c) To evaluate the effect of induced visual fatigue, by means of reading tasks, on binocular vision functions in dyslexic subjects with or without MIS compared to control group.
To evaluate sensory ocular dominance in dyslexic subjects with or without MIS compared to control group.

Chapter 2

Developing the Cardiff Visual Stress Questionnaire for Adults with Dyslexia (CVSQAD)

It is apparent that visual stress plays a part in MIS, and seemingly also in dyslexia, but the assessment of visual stress is subjective and no universal method appears to exist, nor have any been validated in the literature. One of the principle aims of this thesis is to compare the characteristics and responses to fatigue in groups of subjects with dyslexia. The ability to measure their level of perceived visual stress prior to such experiments is vital and the next two chapters report the development of a novel tool for this purpose, and its application amongst the groups.

2.1 Introduction

2.1.1 Definition of visual stress

Visual stress (VS) has been defined most simply as "the inability to see comfortably without distortion and discomfort" during reading and some other visual tasks and it affects both dyslexics and non dyslexic individuals (Wilkins, 1995; Singleton and Henderson, 2007a, 2007b).

In the published literature however, the term 'visual stress' may imply four different conditions (Singleton and Trotter, 2005).

(1) A condition that can be described by repulsive visual symptoms of perceptual (i.e. illusions of images, colour and motion effects) and somatic (asthenopia, i.e. eye strain, tired eyes, headache and photophobia) natures, that are suffered during reading and can be relieved with the use of individually prescribed coloured filters (Wilkins et al., 1994; Evans et al., 1995; Evans et al., 1996b; Evans and Joseph, 2002).

(2) Individuals whose reading speed increases with the use of coloured filters (overlay or lenses) for reading (Jeans et al., 1997; Wilkins and Lewis, 1999; Wilkins et al., 2001; Bouldoukian et al., 2002): the condition in which subjects visual symptoms and reading performance improved with the individually prescribed coloured filters is known Meares Irlen Syndrome (MIS) which was reviewed in Chapter 1.

(3) When a group of visual stress symptoms (perceptual and somatic) that may be experienced by some people are stimulated by bright or flickering light and grating patterns such as striped or lines of the text on a white page, referred to as cortical hyper-excitability (Wilkins, 1995; Conlon and Hine, 2000; Singleton and Trotter, 2005).

(4) A condition that describes the cases of cortical hyper-excitability caused by pattern glare and that is specifically related to photosensitive epilepsy and migraine (Wilkins and Noimmo-Smith, 1984; Wilkins, 1995; Evans, 2002a; Wilkins, 2003).

It has been argued that symptoms of visual stress may interfere with reading performance in MIS and hence cause reading difficulties (Williams et al., 1995; Jeans et al., 1997; Evans et al., 1999; Wilkins and Lewis, 1999; Bouldoukian et al., 2002; Singleton and Trotter, 2005)

2.1.2 Factors affecting visual stress

2.1.2.1 Reading for prolonged periods

It is well established that visual stress is typically associated with prolonged visual tasks (Sheedy and Saladin, 1978; Ehrlich, 1987; Iribarren, Fornaciari and Hung, 2002). Tyrell et al (1995) reported that long periods of reading aggravate the visual stress condition (Tyrrell et al., 1995). Another study suggested that reading difficulty exaggerated with prolonged reading tasks was then associated with visual discomfort anomalies (Kiely et al., 2001). Grisham reported a correlation between long reading periods and symptoms of visual stress, and observed reduced reading efficacy in non dyslexic university students (Grisham et al., 1993). Singleton and Hindreson reported that, in dyslexic children, a longer reading time and more difficult reading task was associated with visual stress symptoms (Singleton and Henderson, 2007a). However, until recently, the effect of prolonged near work on visual stress symptoms has remained inconclusive. For example, Borsting and colleagues studied visual discomfort symptoms in college students over one year and found stable scores of visual symptoms (Borsting et al., 2008).

2.1.2.2 Environment and working distance

Furthermore, working under demanding visual conditions is thought to be an essential factor in inducing visual stress (Pickwell, 1984). For instance, it was reported that reading at unusually close viewing distances may cause near vision fatigue in young adults with normal binocular vision function. Reducing viewing distance from 60 to 30 cm (Jaschinski, 1998) or reading at distance of 20 cm (Pickwell, Jenkins and Yekta, 1987c) appeared to cause weakness of the disparity vergence system and increase the magnitude of fixation disparity towards exo-deviations. Working under poor room illumination (Pickwell, Jenkins and Yekta, 1987b; Pickwell, Yekta and Jenkins, 1987d; Yekta, Pickwell and Jenkins, 1989a; Jaschinski-Kruza, 1994) also caused visual stress in a group of symptom-free subjects, and was also indicated by an increase in the magnitude of associated phoria and fixation disparity (Pickwell et al., 1987b). Simonson and Brozek also reported reduced visual performance and induced visual fatigue associated with working under poor illumination. However, the effects of fatigue were not shown in optometric measures, such as near point of convergence and accommodation (Simonson and Brozek, 1948). Glare from lighting (Guth, 1981; Sheedy, Hays and Engle, 2003) and flickering stimuli such as computer displays (Wilkins et al., 1989) appear to also cause visual stress. Further, perceptual features of the text such as small size can lead to visual stress (Cornelissen et al., 1991; Singleton and Henderson, 2007a).

2.1.2.3 Print characteristics

Some authors have reported that print size has a conceivable effect on reading performance, particularly in dyslexia (Cornelissen et al., 1991; O'Brien, Mansfield and Legge, 2000; Skottun, 2001; O'Brien, Mansfield and Legge, 2005).
O'Brien et al indicated that the effect of print size on reading performance manifested more in dyslexic subjects compared to control and that for dyslexic

children to achieve the highest reading speed, larger print size is required (O'Brien et al., 2000).
Cornelissen and colleagues reported reduced reading errors with increased print size in dyslexic children with known poor binocular co-ordination (Cornelissen et al., 1991). These findings may reflect that reading impairment can be attributed to a 'stressed' visual system, and suggest a relationship between dyslexia and visual processing that is affected by the visual characteristics of the text.
Small and closely spaced print can induce visual distortion of the text and interferes with reading, especially in children, reducing reading speed and performance. Irlen suggested that the print characteristics may affect visual perception of the text and therefore may contribute to reading difficulty in some children (those with MIS) (Irlen, 1991). Meares reported symptoms of perceptual distortion of the text such as doubling, blurring and moving or jumbling of the letters or words were caused due to the spaces between words and lines (Meares, 1980). Studies that change text characteristics, for example the print size and spacing, showed significant improvement in reading performance and rate in dyslexic children, confirming a marked link between dyslexia and visual processing (Wilkins, 2003; Wilkins, Huang and Cao, 2004; Singleton and Henderson, 2007b).
As the print size gets smaller it makes the identification the sequential letters and/or localization of letters within words, and therefore coding, more difficult. It is logical that this makes reading more incomprehensible for people with dyslexia (Cornelissen et al., 1991; Irlen, 1991), particularly those subjects with binocular instability (Cornelissen et al., 1991).

Furthermore, clustered and crowded letters reduce the ability to perceive and/or comprehend words, even when a subject has good vision (Chung, 2002; Tripathy and Cavanagh, 2002). However, dyslexic individuals appear more sensitive to a stressed reading task (induced fatigue), causing impairment of reading performance (O'Brien et al., 2005). Using large size letter and widely space text has been recommended to reduce the difficulty in reading by reducing the potential effect of distortion (Wilkins et al., 2004).
A possible explanation for the improved reading in dyslexic subjects with increasing the print size is that the larger print size facilitates perceptual discrimination of letters with defined spatial frequency (more than 2 cycles per letter) (Legge et al., 1985;

Solman et al., 1995) and therefore, improve reading performance (Legge et al., 1985). When reading, the middle letters are complicated by the flanking letters of words (Spinelli et al., 2002) hence, the advantage of large print size is that it may promote reading performance by reducing the crowding effect (Geiger and Lettvin, 1987; O'Brien et al., 2005), and hence distinguishing more letters in a time or 'visual span' (Legge et al., 1997; O'Brien et al., 2005).

The uses of coloured filters can improve the reading performance and rate in dyslexic subjects. The beneficial effect of coloured filters appears maximal when the print of the text is small and closely spaced; the increase in reading rate with conventional text print is low (Wilkins, 1996).

It has been assumed that the successive lines of printed text resembles that of a striped pattern and therefore may provoke pattern glare and visual distortion leading to visual stress and/or discomfort (Wilkins et al., 1984; Wilkins and Noimmo-Smith, 1984; Wilkins and Nimmo-Smith, 1987; Wilkins, 1995; Wilkins et al., 2004). Lines of the text have a spatial frequency and may cause perceptual distortion in some people who are susceptible to pattern glare and symptoms of visual stress, such as (perceptual) distortion illusions of stripe and colours, movement of letters, blurring, diplopia and somatic symptoms (eye strain, sore or tired eye and headache), may be provoked during reading (Wilkins and Noimmo-Smith, 1984; Wilkins and Nimmo-Smith, 1987; Irlen, 1991).

Successive letter strokes within words also create striped patterns that may cause discomfort and increase the reading time, however if the space between letters is increased it increases reading speed in poor readers (Wilkins et al., 2007).

Repetitive striped patterns are unpleasant/uncomfortable to view and may provoke perceptual distortion, i.e. illusions of colour, motion and shape (Wilkins et al., 1984) in individuals who are sensitive to pattern glare and therefore susceptible to visual stress; particularly in subjects with migraine (Wilkins et al., 1984; Wilkins, 1995) and subjects with visual discomfort (Singleton and Henderson, 2007a , 2007b).

Gratings stimuli with specific spatial characteristics were particularly shown to induce strong anomalous visual effects (perceptual distortion and visual discomfort) when the spatial characteristics include square wave and high contrast repetitive striped patterns with almost equal width of dark and bright areas (i.e. a duty cycle of 50%) (Conolon et al., 1998; Wilkins et al., 2004) and a spatial frequency range between 2 cycle per degree (c/d) to 8c/d that subtended at least 3 degrees (Simmers et al., 2001).

2.1.3 Measuring Visual stress

Visual stress can be evaluated using two different methods, one objective and one subjective.

2.1.3.1 Objective evaluation to the visual stress

Increasing rate of reading in the WRRT with coloured overlays (Wilkins et al., 1996 b; Evans et al., 1996b; Jeans et al., 1997; Evans and Joseph, 2002; Kriss and Evans, 2005) can be an objective indicator for the presence of MIS-related visual stress.

Tyrrell and colleagues screened for visual stress in non-selected school children by applying searching tasks where children were asked to search for the letter 'x' in a text of random letters, and found that the response time in children who had a preference for using coloured overlays was impaired after 10 minutes, but improved when the coloured overlays were used (Tyrrell et al., 1995). Conlon et al (1999) found adults with higher susceptibility to visual stress performed less efficiency in copying and reading tasks (Conlon et al., 1999).

Recently, an objective diagnostic criterion for visual stress has been developed by Singleton and Henderson (Singleton and Henderson, 2007a). They used a computer based screening test for visual stress to show the level of visual stress in dyslexics and control children. The test consisted of a visual search task which required the children to locate a random three-letter word in a matrix of 'distracter' three letters words; no spaces separated the words and the background was either non-visually stressful (normal 10 point letter size and grey background) or visually stressful (letters were bolded and the background was striped with black and white in horizontal successive pattern). All children showed significantly worse response time with the visually stressful searching. Dyslexic children who experienced higher levels of visual stress demonstrated significantly worse response times than dyslexic children with low visual stress, and were more likely to show significant benefits from coloured overlays (having higher percentage of reading performance or speed in WRRT with coloured overlays). Furthermore, comparing to the control group, the susceptibility of dyslexic children to visual stress was markedly higher in the dyslexic group identified with higher percentage of visual stress. This would give rise to an important point which indicates that predominance or incidence of visual stress in dyslexics is higher than non-dyslexics.

2.1.3.1 Subjective measurement of visual stress

There are several questionnaires that have been used as diagnostic tools for subjects who report symptoms of visual stress. For example, the questionnaire adopted by Irlen (Irlen, 1991) and the one used by Conlon et al (Conlon et al., 1999). Examples of these questionnaires are included in appendix I (1.1 & 1.2). However, almost all symptom questionnaires have been used to identify visual stress when children read, especially in those who may benefit from coloured overlays (Irlen, 1991; Evans et al., 1995; Evans et al., 1996b), and one concern would be that responses about symptoms may be under-reported due to a lack of understanding (Evans, 2004a). Children who always experience symptoms of visual stress during reading may not identify the symptom as unusual and therefore they might accept it as normal, except perhaps if these symptoms are relieved by use of coloured overlays (Wilkins et al., 1994). Wilkins at al (1994) reported improvement symptoms (headaches and eye strain) during reading in 68 children who use colour filters (Wilkins et al., 1994).

Evans et al. also used a symptoms questionnaire (Appendix 1.3) in children with MIS (whose reading rate increase with coloured filters) to evaluate the incidence of symptoms experience during reading (Evans et al., 1996b).

Data regarding visual stress symptoms from 323 patients (age range 4 -73 years) in optometry and specific learning difficulty clinic were reviewed and it was found that visual symptoms and headache were common, and a high percentage (73%) of sufferers were issued for colour filters to reduce visual stress symptoms and improve reading rate (Evans et al., 1999).

Wilkins at al (2001) assessed improvement of visual symptoms with coloured filters in 426 children with reading difficulty. During the Wilkins Rate of Reading Test children were asked about some visual/perceptual symptoms such as; "Do the letters stay still or do they move?"; "Are they clear or are they blurred (fuzzy, difficult to see)?"; "Are the words too close together or far enough apart?"; "Does it hurt your eyes to look at the page or it is OK?". Wilkins found visual symptoms and, therefore, reading rate improved in 60% of subjects using coloured filters (Wilkins et al., 2001).

For older subjects, a symptoms questionnaire has also been applied to unselected university students including dyslexics (Evans and Joseph, 2002) (Appendix 1.4) to find out the effect of coloured overlays on symptoms and reading rate. They reported improvement in visual distortion and discomfort symptoms with coloured overlays.

Singleton and Trotter (2005) investigated the relationship between visual stress and dyslexia in university students (ten were diagnosed with dyslexia and ten without) where they compared the reading rate with and without colour overlays. Visual stress was evaluated by means of a rating scale called Visual Processing Problems Inventory (VPPI). The test consisted of 24 questions about visual stress related symptoms. Each question was ranked into 5 scores to show subject's response from 0 (never) to 4 (always), resulting in a wide total range of symptoms scores (0-96). Based on this methodology, the authors found a significant difference between dyslexic (mean of high VS score= 56.4, mean of low VS score = 25.8) and non-dyslexic subject (mean of high VS score= 41.8, mean of low VS score = 16.6) in the total scores of VPPI, and they found that only dyslexic subjects with high VS scores reported significant improvement in reading rate with their optimal colour overlays. The authors concluded that, based on reported symptoms, dyslexic students with high levels of VS are more likely to show an improvement of reading rate with colour filters than non-dyslexic students with high VS (Singleton and Trotter, 2005).
A shorter questionnaire has been used to assess the visual stress in children (Singleton and Henderson, 2007a, 2007b). The questionnaire consisted of nine questions relating to stress during reading: six "critical" questions related to symptoms of perceptual distortion (e.g. print seems to be unstable 'move about', blurry or fuzzy print, patterns problems from lines of the text, glare from the white page against the black letters, sore or tired eyes when reading for a long time, headache when reading for a long time) and three "non critical" questions related to other symptoms that may be experienced during reading and may be associated with visual stress (e.g tiredness, reading gets harder as time of reading is increased, losing the place when reading). Each of the nine questions were scored on a five point scale (0=never to 4=always) so the total scores ranged from 0 to 36. They found that

dyslexic children with high scores of visual stress reported significantly higher improvement of reading rate with coloured filters than those with low levels of visual stress (Singleton and Henderson, 2007a).

Grisham et al assessed non visual and visual asthaenopic symptoms (Appendix 1.5) in 78 non dyslexic university students after one hour of reading task and found that the number of symptoms increased after reading (Grisham et al., 1993).

Conlon et al developed a visual discomfort questionnaire which consisted of 23 questions with a four point scale (from 0 to 3 scores). The questionnaire was administered to 518 non-dyslexic college students and the reliability of the questionnaire was assessed by using Rasch analysis (Conlon et al., 1999).

Boreting at al used the questionnaire developed by Conlon et al to measure the distribution of visual discomfort symptoms in 594 college students and found three levels of visual discomfort; low (score of 0-35%), moderate (score 35%- 69.5%) and high (score of 70% or greater) (Borsting et al., 2008).

2.1.4 Principles of questionnaire design

It is apparent for the published literature that questionnaires have been designed based on need, and little attention seems to have been given to the construction. This PhD required a valid tool to assess visual stress that was fit for purpose. In order to achive this it was necessary to review the principles behind questionnaire design.

There are two distinct response categories to a questionnaire that can reflect a person's agreement to a specific question (known as an 'item') in a bulk of items (the questionnaire). The first is qualitative and non-parametric, and is associated with discreet epidemiological data, such as gender or race and is assessed on a *nominal scale*. The second category is usually applied to the health sciences: it is parametric, and quantitively measures the degree of a subject's response to a continuous variable, such as severity of pain or anxiety, and is measured on an *ordinal scale* (Huskisson, 1974).

To obtain the quantitative data about a respondent's attitudes (known as the latent variable character) in a questionnaire, two rating scales are commonly applied – visual analogue Likert scales.

2.1.4.1 Visual analogue scale

Visual analogue scale (VAS) can be used when a subject is required to precisely describe the degree of response to an item. This scale is represented with a 100mm horizontal line with defined ends to describe the extreme response status (anchors), and the subject is required to mark on the line according to the degree of response reflect his condition (Huskisson, 1974). Despite the implied precision of the response this scale can not actually illustrate the underlying latent character on a linear interval scale, and this may create misleading results (Wewers and Lowe, 1990).

2.1.4.2 Likert scales

Likert scales are a popular method to allow a quantitative measure of the subjects' attitudes to a particular characteristic, presented in a continuous ordinal scale. Likert scales are commonly used to evaluate perceptual visual difficulties in visual function questionnaires (Conlon et al., 1999; Massof, 2002 , 2004; Borsting, Chase and Ridder, 2007) as they are more understandable than VAS (Shield et al., 2003; van Learhoven, Van der Zaag-Loonen and Derkx, 2004). Each response would assign the degree of subject endorsement according to a given indicator on the scale (Likert, 1932). This type of scaling is considered to be the finest data collection strategy as it allows the researcher to clearly quantify opinion based on expressed items (Bond and Fox, 2007). However, it is proposed that that there is no difference between scales which have each category labelled and those that have only end labelled (Streiner and Norman, 1995a). Furthermore, it was reported that a maximum of seven points of nonlabelled numbers can be discriminated (Miller, 1956). Many methods of analysis in validation of questionnaires assumed this type of ordering (Massof and Ahmadian, 2007).

An example of 7-point scale is shown in figure 2.1 (Bond and Fox, 2007):

Strongly disagree 2 3 4 5 6 Strongly agree

Figure 2.1: An Example of 7-point scale

The example shown in figure 4.1 expresses a subject's endorsement ordered from least to most difficult. This is called a Guttman pattern (Andrich, 1985). This scale typically ranges in order from one extreme to the other with intermediate ratings that would express the level (degree or severity) of subject response or opinion (Streiner and Norman, 1995a; Massof, 2004).

The number of categories along the scale design can vary from 2 to 10 categories (Stelmack et al., 2004). For example, several exist in the vision science literature: there have been 3-point (Court, Greenland and Margrain, 2007), 4-point (Conlon et al., 1999; Borsting et al., 2007), 5-point (Pesudovs, Garamendi and Elliott, 2004; Court et al., 2007; Singleton and Henderson, 2007b), 6-point (Khadka et al., 2010) or and 7-point (Pesudovs and Noble, 2005; Bond and Fox, 2007; Pesudovs et al., 2007) scales. Intuitively, more reliability of subject responses would be expected with increasing number of response catogories (Wright and Linacre, 1992; Linacre, 1995), however it has been reported that the reliability of response is not related to number of response categories (Brown, Widing and Coulter, 1991; Bond and Fox, 2007).

Also, it is important to offer even numbers of categories allowing the participant to provide a certain decision in describing their opinions (Streiner and Norman, 1995b; Bond and Fox, 2007).

2.1.5 Aims of this study

Currently available questionnaires designed to assess visual stress in dyslexic individuals vary widely in their design and none appear to have been mathematically validated in order to assess the suitability of the questions being asked (Irlen, 1991; Wilkins et al., 1994; Evans et al., 1996b; Evans et al., 1999; Wilkins et al., 2001; Evans and Joseph, 2002). Whilst it is relatively easy to design questions that one would think will be relevant to visual stress (print difficulties, missing words out), there are other questions which are a common feature in many areas (for example, headaches). The relative worth of these types of question in dyslexia individuals (particularly in adults) is unknown and has not been validated. For this project, a detailed questionnaire will be designed and applied amongst dyslexic university students in order to determine which are the most appropriate questions to be used in order to identify visual stress when reading in this population. This will be achieved by applying mathematical analysis (Rasch; reviewed in the following section) on this detailed questionnaire about reading in an adult student population.
Therefore the end goal is to develop a short, validated visual stress questionnaire for dyslexic adults.

This questionnaire will also aid grouping for analysis in future studies on subjects who are known to have reading difficulties associated with a diagnosis of dyslexia, with or without MIS.

2.2 Rasch Analysis

Rasch (Rasch, 1980) analysis is a probabilistic mathematical model which is used for questionnaire development and validation (Conlon et al., 1999; Court et al., 2007; Keenan et al., 2007; Massof, 2007; Khadka et al., 2010). It is based on item response theory (Wright and Stone, 1979; Coster, Ludlow and Mancini, 1999; Hays, Morales and Reise, 2000). The Rasch model is a one-parameter model, indicating that it can construct one parameter models describing the difference between 'person position of ability' and item difficulty by evaluating both the test taker's ability and the test item's difficulty. The Rasch model facilitates a clearer image of information than the observed raw scores, where it converts the raw scores into measures of ability, and isolates the impact of the degree of item difficulty, item discrimination, item quality and personal ability. This is in contrast to the raw scores, where no clear explanation of low scores can be given - for example low scores may reflect that the test was too hard, or the person was not skilled, or the test items were ambiguous.

Several advantages of Rasch model have been reported:

1- The Rasch model provides a researcher with a clear idea about a particular questionnaire measurements: thus, it is a statistically proven interval scale (Rasch, 1980; Bond and Fox, 2007).

2- The Rasch Model deals with missing data appropriately, as the Rasch algorithm compares each observed item score to an expected score, i.e. in case of missing data expected score information is accounted, based on overall scaling model.

3- Rasch analysis is a sample-free method in evaluating the person and item measures. This means that it holds for every sample and not only the sample under consideration (the sample population).

4- The Rasch model presents statistical fit information about the different items and persons to the expected model.

Substantially, probabilistic aspects of the Rasch model emphasize that the outcome scores represent ability of the persons and the difficulty of the questionnaire items (Bond and Fox, 2007). Hence Rasch analysis frequently uses the terms 'ability' and 'difficulty' – this has an educational origin as the achievement level was evaluated through exercises of varying complexity using item response theory (Wilson and Scalise, 2006).

2.2.1 Person and item measure

Rasch model evaluates two principal measures:

- Person ability (described as person position) and
- Item difficulty (i.e. item measure),

Both are measured on a common scale, using a log-odd unit called "logit": an interval scale in which all logit units are of the same size (Bond and Fox, 2007). Each logit is the natural logarithm of the odds of success (the ratio of probability of success and failure) (Bond and Fox, 2007). The scale explicates the raw scores (Wright and Stone, 1979; Wright and Master, 1982; Bond and Fox, 2007). The model allows the interaction between person ability and item difficulty to be characterized in an additive way, i.e. "the response probability for any person *n* attempting any item *i* is a function of the difference between the ability of the person (Bn) and the difficulty of the item (Di)" (Bond and Fox, 2007). The model may then be created that predicts the likelihood that each person will respond correctly to each question.

The probability of a person selection for a specific item response category depends on functional reserves of the person for the item (Massof, 2007) i.e. a person's ability may be equivalent to his/her functional status (e.g. functional vision or visual stress, in the present research).

Item difficulty is calibrated and person ability is measured, and both are illustrated correspondence to a continuum interval scale (Wright and Stone, 1979; Wright and Master, 1982; Bond and Fox, 2007). The description of item difficulty on a continuum is from less difficult to more difficult and is measured in logits. Zero represents the average item logit. Positive logit score given for the above-average item difficulty while those of below the average difficulty receive a negative logit score. Person ability is defined as 0 logits when a subject has a 50% chance to succeed. For example, a person with a logit score of 2.0 has a 0.5 probability of "passing" an item with a difficulty level of 2.0 logits (Figure 2.2) (Bond and Fox, 2007).

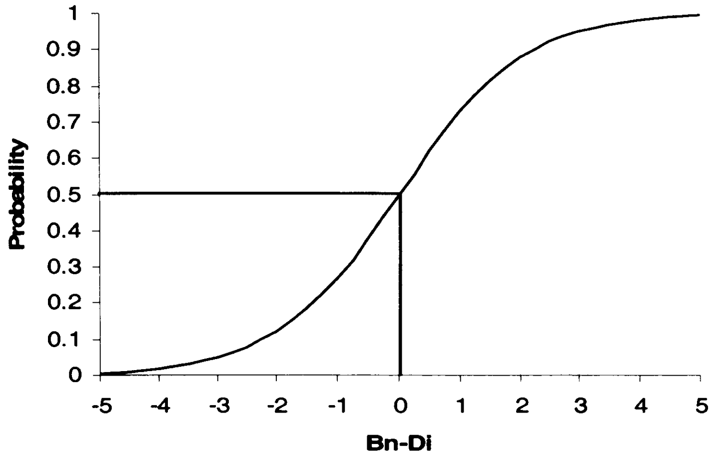

Figure 2.2: The probability curve of success response to items constructed by Rasch model.

2.2.2 Person-item map

A person-item map is constructed to from the measures to illustrate the simultaneous distribution of the persons and items on the same continuum measurement scale. The scale is located vertically with both the most difficult items and most able persons at the top. Item difficulty is placed in the right-hand column, calibrated and reported in logits. Person ability is placed in the left-hand column, also measured in logits (Figure 2.3). Two advantages of the combined map are; firstly, this map would allow the researcher to visually observe the function of items and ability measures of subjects as a whole. Secondly, it provides visualizations of inspection of item distribution along the scale.

Item separation is the distance between items of different difficulty levels measured in logits. Items are considered as being distinguishable when the separation distance between items is 0.15 logits or more (Wolfe and Kong, 1999). Researchers can more easily distinguish between items when the separation between items is larger: however, no considerable gaps of separation between items should be created (>0.30) as this would develop zones (steps) in the map that require further investigation, with the consideration for additional items that might cover the gap in the range of item difficulty, hence improving the questionnaire design.

```
PERSONS MAP OF ITEMS
         <more>|<rare>
    3          +
               |
               |
               |
               |
               |  Q40
    2        X +
               |
               |T
              T|  Q35J   Q41
               |
             X |  Q32    Q39
    1       XX +  Q27    Q30    Q33
               |S Q25
               |  Q21    Q28
               |  Q31
          XXXX |  Q35F   Q42    Q43
           XXX |  Q26
    0     XXXX S+M Q22   Q35D
          XXXX |  Q17    Q18    Q34
             X |  Q14    Q29    Q35H   Q35I   Q35K
          XXXX |  Q19    Q24    Q35E   Q37
            XX |  Q35C
        XXXXXX |S Q15    Q16    Q35A   Q35G   Q36
   -1       XX +  Q23    Q38
          XXXX |
               |  Q35B
          XXXX M|
             X |T
          XXXX |  Q20
   -2        X +
           XXX |
             X |
           XXX |
         XXXXX |
             X |
   -3        X S+
           XXX |
        XXXXXX |
             X |
               |
            XX |
   -4          +
            XX |
             X |
              T|
               |
             X |
   -5          +
         <less>|<frequ>
```

Figure 2.3: An example of person/item map

2.2.3 Goodness of fit statistics

Perfection (or goodness) of fit statistics of the item parameters can evaluate the uni-dimensional Rasch model scale. Uni-dimensionality means that all included items in the instrument (questionnaire) are consistent (i.e. fit) with a single underlying construct (Pesudovs et al., 2007) (i.e. measured a single latent trait). The fit statistics for an item express the differences between the actual item scoring in the data and the corresponding predicted or expected scores (according to person and item estimation of Rasch model). This determines item residuals and this is actually stated by mean square (MnSq), the weighted average of the squared item residuals. Therefore, the Rasch model will assess the association between the predicted item responses and the observed item functioning performed by respondents.

Considering residuals, two references of fit statistics can be accounted for in each item to express the correlation between the actual data and expected Rasch model scores (parameters):

i) Outfit statistic is sensitive when residuals between the data set (observed data) and predicted Rasch model are large. This indicates that the level of person ability is unexpectedly outlying beyond the difficulty level of an item score. This can be computed for both persons and items, according to the residuals. Outfit is based on the conventional sum of squared standardized residuals (residual variance). If X is an observation, E is the predicted value based in Rasch model estimates, and σ its modelled variance of expectation, then the squared standardized residual is: (Bond and Fox, 2007).

$$Z^2 = (X-E)^2 / \sigma$$

Outfit is the mean of summed squared standardized residuals;

Outfit $= \Sigma (z^2)/N$, where N is the sum of the number of observations.

ii) The other reference of fit statistics is "Infit statistics"; it is an informative type and gives more weight to the residuals of persons whose ability level is close to the difficulty level of the item. Infit is an information-weighted additive statistic in which each square residual of items is weighed by its variance *(a^2).* Infit can be calculated, by dividing that value by the total sum of variances, as;

$$\Sigma (Z^2 a^2)/ \Sigma (a^2) = \Sigma (X-E)^2/ \Sigma (a^2)$$

Item Outfit or Infit MnSq with expected values of 1 are considered to be perfectly fitted to the unidimensional scale and ideal by Rasch model specifications and their value range from 0 to infinity (Wright and Linacre, 1994; Massof and Fletcher, 2001; Court et al., 2007). Values substantially less than 1.0 reflect the over-fitness of the item to the model indicate subsidiary in the data, i.e. additional information. Values substantially more than 1.0 reflect under-fitting of item to the model and indicate the item may evaluate unrelated outliers which their presence may be unexpected to the rest of the scale (measuring some thing different form the underlying issue) and this can cause noise (Bond and Fox, 2007).

For both the outfit and infit statistics, the Z (standardize) or (t) is the MnSq normalized to approximate a theoretical mean of 0.0 and a SD of 1.0. A Zstd (t value) of infit and outfit greater than ± 2.0 (more than 2; MnSq of 1.3, or less than -2; MnSq of 0.70) indicates that the MnSq surpasses the predicted value of the model by more than 2 (Smith and Suh, 2003; Bond and Fox, 2007), and the agreement of infit and outfit statistics with the model is less accurate (Bond and Fox, 2007). However, it was proposed that the MnSq value between 0.5-1.5 Logits can be considered to be effective in evaluation or measurement (Wright and Linacre, 1994; Wolfe and Kong, 1999; Linacre, 2005). Although the misfit statistics, the residuals i.e. difference between the Rasch model expectation and actual data empirically available, may be estimated, fit statistics are conventionally applied (Bond and Fox, 2007). Thus, values of infit or outfit that do not match the model predictions condition are usually described as misfits to Rasch model conditions and are to be considered for omission from the context of a particular construct (Wright and Master, 1982; Linacre, 1995; Bond and Fox, 2007). The uni-dimensionality of an instrument can be conventionally assed by Cronbach' alpha value, that explain the correlation of each item with every item in the instrument: when this value is nearer to 1 this would reflect consistency of the scale (Pesudovs et al., 2007).

2.2.4 Separation and Reliability

For the construction of a valid questionnaire, precision person and item reliability should be clarified. The 'person estimate reliability' describes how accurately the sample of individuals can be discriminated by the questionnaire in terms of person ability. The person reliability implies perfection of the instrument. The item reliability estimate describes how accurate the items along the scale can be distinguished by the sample of individuals in terms of item difficulty. For operative investigation and measurement, items spread along continuum required good separation (Wright and Master, 1982; Bond and Fox, 2007). Item separation reliability can be defined as sufficient level of item spread and standardized along the continuum required to determine discrete persons ability level measured in logits (Bond and Fox, 2007).

For item and person reliability statistics various indices were provided by Rasch Model: the item and person reliability indices.
Item indices - Item reliability index and the item separation index (also called item separation reliability coefficient).
Person reliability - person separation index and the person reliability index (also called person separation reliability coefficient).

The person reliability index indicates the "the reliability of person ordering that could be expected if the particular sample of persons were given another parallel set of items measuring the same construct".
The item reliability index indicates "the reliability of item placements along the pathway if these same items were given to another sample of the same size that behave the same way", i.e item difficulty estimate would have the same level of difficulty (Bond and Fox, 2007). The reliability index (of item and person separation) is similar to Cronbach's alpha (Andrich, 1982; Bond and Fox, 2007), and both are assigned on a 0 to 1 scale; therefore they have similar understanding value, i.e. above 0.8 is very good (Bond and Fox, 2007).

Index figures give the degree of the true disparity in person ability or item difficulty and can be described by the ratio of variation, i.e. the actual spread of item difficulty or person ability separation and their standard errors. Degree of item difficulty or person ability is more recognizable when separation index is high. The Person Separation Index (PSI) describes the ratio of standard deviation that explains the different item difficulty levels evaluated in a group of subjects. It can be calculated by the square root of true difference (variation or disagreement) divided by the error difference due to person measurement imprecision (PSI = (True Variance N/ Error Variance N) ½. The value for both person and item should be more than 2.00 logits (Bond and Fox, 2007).

2.3 Methods

2.3.1 Participants

The participants in this study were 351 volunteers (University students) recruited from Cardiff University. The sample included 39 students with reading difficulties (38 had been diagnosed with dyslexia and one had received a diagnosis of dyslexia Meares-Irlen syndrome).

32 of the dyslexic group were recruited via online questionnaire survey through the Student Support Centre at Cardiff University, and 7 dyslexics were from those who filled recruitment questionnaires amongest the general non-selected student population.

Ethical approval was obtained from Cardiff School of Optometry and Vision Science Ethical Committee and all procedures follow the tenets of the Declaration of Helsinki.

Opportunity was given to the subjects to ask further questions, and their completion of the questionnaire implied informed consent. Contact details for investigators were available on the questionnaire.

2.3.2 Questionnaire design (Materials)

An extensive set of questions were collated: the questionnaire had a wide range of questions which were designed to subjectively identify the type and the degree of symptoms associated with reading, and whether those symptoms hinder the learning process or are associated with a specific reading and/or spelling difficulty. The detailed questionnaire consisted of 6 pages containing 40 questions about symptoms related to visual distortion at near and at distance and to the binocular visual dysfunction, in addition to questions about reading or writing errors that may be experienced by subjects diagnosed with dyslexia and or MIS. Items of the questionnaire were derived from previous studies on dyslexics, MIS and visual discomfort (Wilkins et al., 1984; Irlen, 1991; Evans et al., 1995; Evans et al., 1996b; Conlon et al., 1999; Evans et al., 1999; Evans and Joseph, 2002; Evans, 2004a; Singleton and Henderson, 2007a). Some of the questions have been adopted from Dyslexia Diagnostic Manual currently used by the Dyslexia Support Centre at

Cardiff University. Additional questions related to the participant's optometric experience, handedness, age and gender were also included.

Items regarding visual symptoms (asthenopia and visual stress) associated with reading or writing, and questions about reading or writing errors that may be experienced by students (from question 14-43) were rated on seven point scales from 0 (never) to 6 (always) (see Appendix 1.6). This number of categories was primarily used to provide more distinction than an even number of categories and because seven point response categories reflect the lower limit of people's discrimination ability and proposed that it is ideal for multiple characters (Miller, 1956). This may provide flexibility in options for subjects to express their feeling and hence, add more significance to subject response scores (Bond and Fox, 2007).

2.3.3 Experimental Procedure

Two versions of the questionnaire were circulated to facilitate maximum participation. A paper version of the questionnaire was randomly distributed amongst students from the disciplines of social sciences and optometry at Cardiff University.

Visual conditions for volunteers were unscreened by the researcher prior to their participation. Each volunteer was recruited by invitation from the investigators, who described the process and requirements. Volunteers were required to select the most appropriate score for each of the items (questions). The online version of the questionnaire was distributed by the Student Support Centre at Cardiff University.

2.3.4 Statistical analysis

In the present study a one parameter item response theory model was utilized, commonly known as the Rasch model embracing the uni-dimentionality, i.e the construct or the questionnaire is targeting only one underlying measured variable. Rasch analysis was based on Andrich's rating scale model (Andrich, 1978; Stelmack et al., 2004) which expresses the probability of subject response to a response category along a Likert-type scale for each item.

Winsteps software version 3.85.1 (Linacre, 2005) was used to develop a valid visual stress questionnaire. Winsteps uses an unconditional maximum-likelihood estimation routine to provide the optimum number of categories of subject response measuring scale that subject being able to discriminate and to delete unrelated item that may measure different thing rather than the underling issue or topic (visual stress in the present study).

2.4 Results

Respondents from our questionnaire were 351 participants (university students), 39 of them were dyslexics (Figure 2.4). For Rasch analysis we included all dyslexic subjects and their age and gender matched control participants. Hence, the sample included 78 participants, 39 dyslexic and 39 age and gender matched control subjects are shown in table 2.1, and mean age is 23.42±5.66 years. No person had more than 33% of missing data (more than 33% missing data indicates that the questionnaires were unreliable and should be excluded (Pesudovs et al., 2004; Court et al., 2007)).

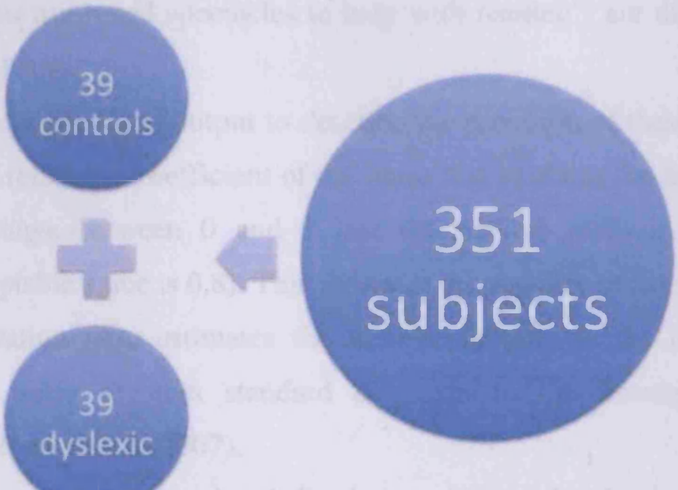

Figure 2.4: Total number of subjects.

	Male	Female	Age Mean (SD)	Range
All Subjects n=351	108	243	22.00 (5.43)	17-56
Dyslexia n=39	13	26	23.42(5.66)	18-46
Control n=39	13	26	23.42(5.66)	18-46

Table 2.1: Demographic data of groups of population.

Ten people were potential 'misfits' according to the Rasch model (infit and outfit >1.4). Questionnaire responses were individually analyzed to verify whether any subjects had used the same response category for every item. All questionnaires of the 'misfit' subjects were therefore retained in the analysis: 78 questionnaires were included in the analysis.

2.4.1 Person and item estimates

The Person-item map (Figure 2.5) shows how the distribution of each item calibration is visualized compared with the range of person ability estimates. The range of item measure were -1.00 (the most difficult question; Q40) to 0.97 (the easiest question; Q20) Logits. Question 26 had the mean item difficulty and therefore is located at 0 Logits. Items located at the bottom of the map, e.g. item 20 "How often do you get tired eyes when reading for long time" discriminate between those people with lower visual stress. Conversely, items located at the top of the map, e.g. item 40 "Do you use tinted spectacles to help with reading", are discriminating for high level visual stress.

Winsteps provides statistical output to describe the precision of these estimates. The item separation reliability coefficient of the items that explains the reliability of item ordering and range between 0 and 1, for the present analysis was high 0.94 (minimum acceptable value is 0.8). This indicates the stability of item estimates.

The item separation ratio estimates the item separation on the continuum. It is defined as the ratio of item standard deviation to the average error of the measurement (Bond & Fox, 2007).

Item separation reliability can be defined as sufficient level of item spread and standardized along the continuum required to determine discrete persons ability level measured in logits (Bond and Fox, 2007). The item separation for this study was 4.01 (the recommended value of separation should exceed 2) (Pesudovs et al., 2004; Bond and Fox, 2007; Court et al., 2007).

The items are more targeted to the high end of visual stress. The mean of the person estimates was -0.79±0.83 Logits with a range from -3.17 (more able or least visual stressed persons, i.e. least dyslexic or non dyslexic) to 0.94 (the least able or more visually stressed person, i.e. more dyslexic) Logits.

The person separation ratio expresses the reliability of the scale to discriminate between people with different abilities (different levels of visual stress in the present study). It is defined as the ratio of the adjusted person standard deviation to the standard error of the measurement (Bond and Fox, 2007) measured in standard error units. Recommendation is that the separation ratio should exceed 2. It was 4.08 for this sample and this is a relatively high (good) value and the person reliability coefficient which illustrate the reliability of person ordering (Bond and Fox, 2007) was relatively high (good) in this studied population (0.94) i.e. minimum acceptable value for both item and person separation reliability coefficient is 0.8 (Bond and Fox, 2007).

```
PERSONS MAP OF ITEMS

Less able people                                                    Items discriminating high levels of VS
(more dyslexics)

         <more>|<rare>
 1            +  Q40
            X T|T
              |
              |  Q32    Q35J   Q41
          XXX |  Q25    Q27    Q30    Q33    Q39
              |S Q21    Q28
          XXX |  Q31    Q35F
        XXXXX |  Q42    Q43
 0      XXXXX S+M Q17   Q22    Q26    Q34    Q35D
          XXX |  Q14    Q18    Q29    Q35H   Q35I   Q35K
       XXXXXX |  Q19    Q24    Q35E   Q37
       XXXXXX |S Q15    Q16    Q35A   Q35C   Q35G   Q36
        XXXXX |  Q23    Q38
           XX |  Q35B
          XXX M|
       XXXXXX |T
-1         XX +  Q20
          XXX |
           XX |
          XXX |
          XXX |
          XXX S|
         XXXX |
         XXXX |
-2         XX +
              |
              |
          XXX |
             T|
              |
              |
              |
-3            +
            X |
              |
              |
              |
              |
              |
-4            +
         <less>|<frequ>
more able people                                                    Items discriminating low levels of VS
(least dyslexics)
```

Figure 2.5: Person visual ability (with different levels of visual stress)/ item difficulty (items discriminating different levels of visual stress) map. On the left of the continuum, each subject is represented by "x" and on the right of the continuum items are represented as Q and number of the questions (i.e.Q20). M=means, S=1 standard deviation from the mean, T= 2 standard deviation from the mean. The more dyslexic persons and items discriminating high levels of visual stress are located at the top of the map.

The person-item map shows the sequenced distribution of items and persons. Visually the map shows that the questionnaire located above the mean of persons and targeted the more dyslexic population and dyslexic population having higher levels of visual stress. Further, the means of items and persons are relatively widely separated, by about 0.8 Logits. In order to move the two means close to each other it was required to develop a more suitable questionnaire by reducing the response categories options and reducing the number of items (Pesudovs, Garamendi and Elliott, 2006a).

2.4.2 Response scale analysis

Rating scale categories defined as "the average of ability estimates for all persons in the sample who chose that particular response category with the average calculated across all observation in that category (Linacre, 1995; Bond and Fox, 2007).

The diagnostic statistics of Winsteps illustrate the functioning of the response categories Figure 2.6 shows the probability curves for the seven utilized categories that explain the estimated response probability function for each presented response category, as a function of item difficulty. The curves show that categories 1, 2, and 3 are disordered, i.e. the peaks are overlapping. Therefore, these categories are never the most probable to be selected (Court et al., 2007).

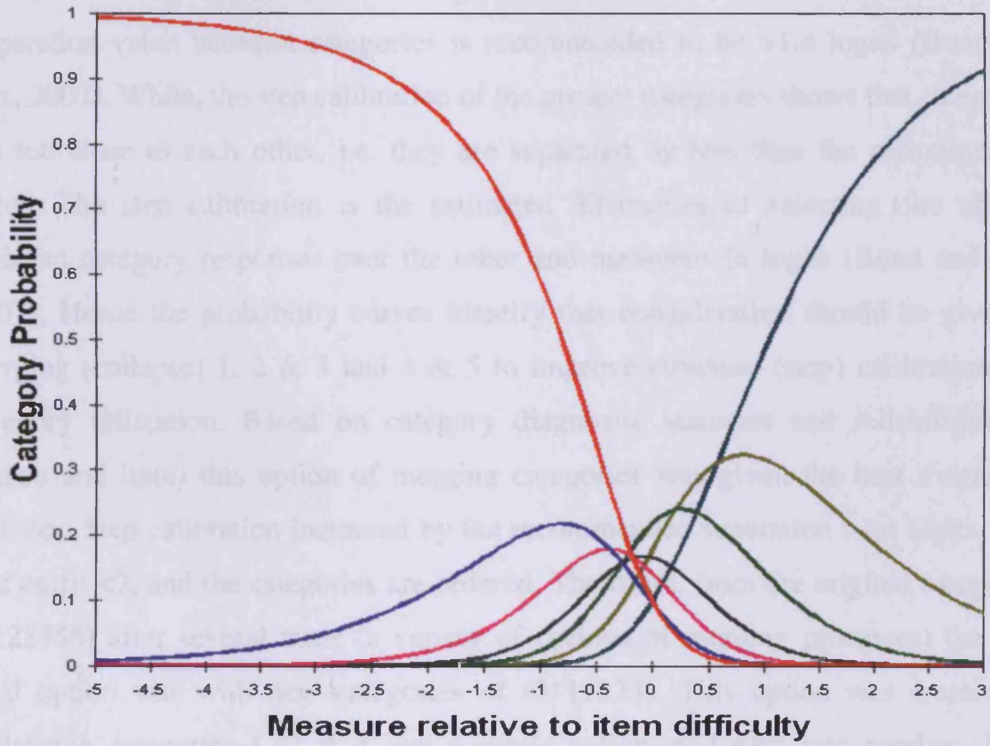

Figure 2.6: Category probability curves for the seven response categories (0, 1, 2, 3, 4, 5, and 6).

Category label	Category utilization (%)	Infit (MNSQ)	Outfit (MNSQ)	Step calibration (logits)	Category measure (logits)
0	45	1.00	1.09	NONE	(-1.71)
1	14	0.09	0.85	0.02	-0.81
2	10	0.99	0.81	-0.38	-0.38
3	8	0.91	0.92	-0.16	-0.07
4	9	1.19	1.23	-0.27	0.26
5	8	1.07	1.30	-0.21	0.81
6	6	1.03	1.11	-0.58	(2.04)

Table 2.2: Category diagnostic statistics for the seven response categories for 40-items questionnaire.

Categories 3, 4, 5 and 6 have less than 10% of responses that means they are underutilized and their frequencies are not enough to estimate stable threshold values (Linacre, 1999; Bond and Fox, 2007). Therefore, these categories are superfluous and can be collapsed into adjacent categories.

Separation value between categories is recommended to be >1.4 logits (Bond and Fox, 2007). While, the step calibration of the present categories shows that categories are too close to each other, i.e. they are separated by less than the recommended value. The step calibration is the estimated difficulties of selecting one of two adjacent category responses over the other and measured in logits (Bond and Fox, 2007). Hence the probability curves identify that consideration should be given to merging (collapse) 1, 2 & 3 and 4 & 5 to improve structure (step) calibration and category utilization. Based on category diagnostic statistics and reliabilities (of person and item) this option of merging categories was given the best diagnostic statistcs. Step calibration increased by the recommended separation >1.4 logits, infit and outfit <2, and the categories are ordered. Therefore, from the original categories (0123456) after several trials (a variety of options of merging processes) the best final option was with new categories of (0111223). This option was created by collapsing categories 1, 2 & 3 into a single option, and 4&5 into another single option. This gave the best diagnostic statistics. Step calibration increased by the recommended (>1.4 or 1.4-5) Logits, infit and outfit was < 2 and all categories are ordered (Table 2.3). Ordered category values means that the categories are distinguishable among the different persons difficulties and have probability of being selected (Bond and Fox, 2007; Court et al., 2007).

Category label	Category utilization (%)	Infit (MNSQ)	Outfit (MNSQ)	Step calibration (logits)	Category measure (logits)
0	45	1.01	1.02	NONE	(-2.79)
1	31	0.96	0.81	-1.56	-0.84
2	17	0.99	1.03	0.06	0.86
3	6	1.11	1.16	1.50	(2.75)

Table 2.3 Category diagnostic statistics for the four response categories for 40-items questionnaire.

This option stabilized the item reliability (0.94) while there was a very slight reduction in item separation from 4.01 to 4.00. Person reliability was improved from 0.94 to 0.96 and the separation from 4.08 to 4.61 (recommended values of separation and reliability are >2 and >0.8 respectively) for both item and person as shown in table 4.4 (Pesudovs, Garamendi and Keeves, 2003; Bond and Fox, 2007; Court et al., 2007). The category probability curves for the successful retained four categories solution are shown in figure 2.7.

	Person separation	Person reliability	Item separation	Item reliability
0123456 (all categories)	4.08	0.94	4.01	0.94
0111223 (4 categries)	4.61	0.96	4.00	0.94

Table 2.4: Person and item reliability and separation for before and after category reduction.

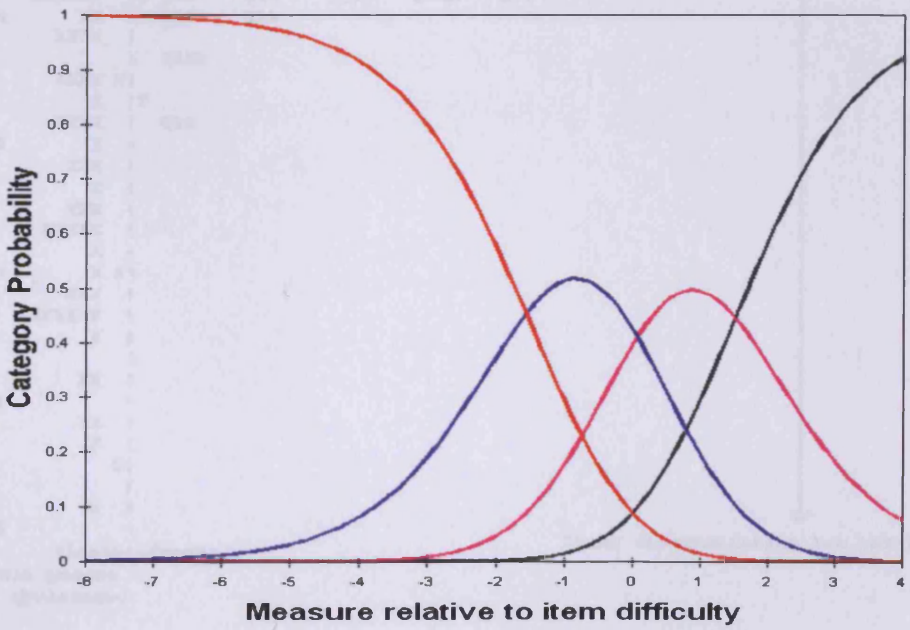

Figure 2.7: Category probability curves of the four retained response options (category 0= never, Category 3= always).

2.4.4 Person and item estimates

Person-item map shows the sequenced distribution of items and persons. After category reduction means of item and person are separated more widely (from 0.79 to 1.53), i.e. 0.74 Logits difference of separation. This indicated that this questionnaire is not suitable for this population as a whole. This is probably due to the mixed nature of sample, i.e. two different groups (dyslexic and the matched age and gender normal population) being evaluated with the same questionnaire.

```
PERSONS MAP OF ITEMS
 Less able people
 (more dyslexics)
           <more>|<rare>                                   Items discriminating high levels of VS
 3             +
               |
               |
               |
               |
               |  Q40
 2           X +
               |
               |T
              T|  Q35J  Q41
               |
             X |  Q32   Q39
 1          XX +  Q27   Q30   Q33
               |S Q25
               |  Q21   Q28
               |  Q31
          XXXX |  Q35F  Q42   Q43
           XXX |  Q26
 0        XXXX S+M Q22  Q35D
          XXXX |  Q17   Q18   Q34
             X |  Q14   Q29   Q35H  Q35I  Q35K
          XXXX |  Q19   Q24   Q35E  Q37
            XX |  Q35C
        XXXXXX |S Q15   Q16   Q35A  Q35G  Q36
-1          XX +  Q23   Q38
          XXXX |
               |  Q35B
          XXXX M|
             X |T
          XXXX |  Q20
-2           X +
           XXX |
             X |
           XXX |
         XXXXX |
             X |
-3           X S+
           XXX |
        XXXXXX |
             X |
               |
            XX |
-4             +
            XX |
             X |
              T|
               |
             X |
-5             +
          <less>|<frequ>                                   Items discriminating low levels of VS
more able people
(least dyslexics)
```

Figure 2.8: Person visual ability (with different levels of visual stress)/ item difficulty (items discriminating different levels of visual stress) map.

2.4.5 Item reduction

Items (questions) are considered for removal from the scale when they fulfil the highest number of criteria in order of priority (Pesudovs et al., 2003; Court et al., 2007):

1. Infit mean square outside 0.80 to 1.20

2. Outfit mean square outside 0.70 to 1.30

3. High proportion of missing data (50%)

4. Skew and kurtosis outside –2.00 to 2.00.

Rasch fitting statistics for the 40 items with the retained 4 category response scale are shown in the appendix 1.7 that showed the items (highlighted) which were likely to be removed on the basis of infit and outfit statistics.

However, items were removed one by one, because fit statistics change as each removal takes place, removal of items will probably reduce the person separation below 2 (after Court et al., 2007), until all items provide good infit and outfit values, with no significant missing data and with good person separation i.e. >2. Person separation reflect the ability of the items (questionnaire to discriminate between people with different levels of visual stress (Bond and Fox, 2007).

Rasch fit statistics and item measures for the final 16 items of visual stress questionnaire are shown in table 2.5. Items with higher positive item measure discriminate higher levels of visual stress.

Items	Missing data (%)	MnSq Infit (ZSTD)	MnSq Outfit (ZSTD)	Item measure (SE)
14. particular difficulties with reading	0	0.86 (-0.8)	0.78 (-1.2)	-0.55 (0.20)
15. any difficulties with spelling	0	1.08 (0.5)	1.00 (0.1)	-1.12 (0.19)
20. tired eyes when reading for a long time	0	1.19 (1.2)	1.19 (1.2)	-2.55 (0.19)
21. double vision when reading for a short time	0	0.99 (0.0)	0.89 (-0.3)	0.75 (0.23)
25. words fade or disappear when reading	0	0.94 (-0.2)	1.17 (0.6)	1.13 (0.24)
26. words jump around or move when reading	0	1.11 (0.7)	0.92 (-0.3)	0.08 (0.21)
27. words get smaller or bigger when reading	0	0.95 (-0.2)	0.72 (-0.7)	1.24 (0.24)
28. words get faint colour around when reading	0	0.93 (-0.3)	0.79 (-0.6)	0.91 (0.23)
29.words go blurred when copying from a white board	0	1.10 (0.7)	1.09 (0.5)	-0.47 (0.20)
30. words fade or disappear when copying from a white board	0	1.17 (0.9)	0.98 (0.1)	1.30 (0.25)
32. words get smaller or bigger when copying from a white board	0	0.88 (-0.6)	0.77 (-0.5)	1.49 (0.25)
33. words get faint colour around when copying from a white board	0	0.86 (-0.7)	0.80 (-0.4)	-0.55 (0.20)
34. difficulty in changing focus from near to distance and vice versa	0	0.99 (0.0)	0.99 (0.0)	-0.22 (0.20)
35A. skip or omit words or lines during reading or studing	0	0.98 (-0.1)	0.96 (-0.2)	-1.12 (0.19)
35E. use finger as a marker during reading or studing	0	1.07 (0.5)	1.11 (0.7)	-0.78 (0.20)
38. crossing out in writing	0	0.91 (-0.5)	1.01 (0.1)	-1.34 (0.19)

Table 2.5: Rasch fit statistics and item measures for the remaining16 items of visual stress questionnaire. Items with higher positive item measure discriminating higher levels of visual stress.

For the present sample, the final 16-item construct showed excellent reliabilities (high item and person separation coefficient) for item (0.96) and person (0.91) and good item (5.15) and person (3.18) separation ratio (See table 2.6)

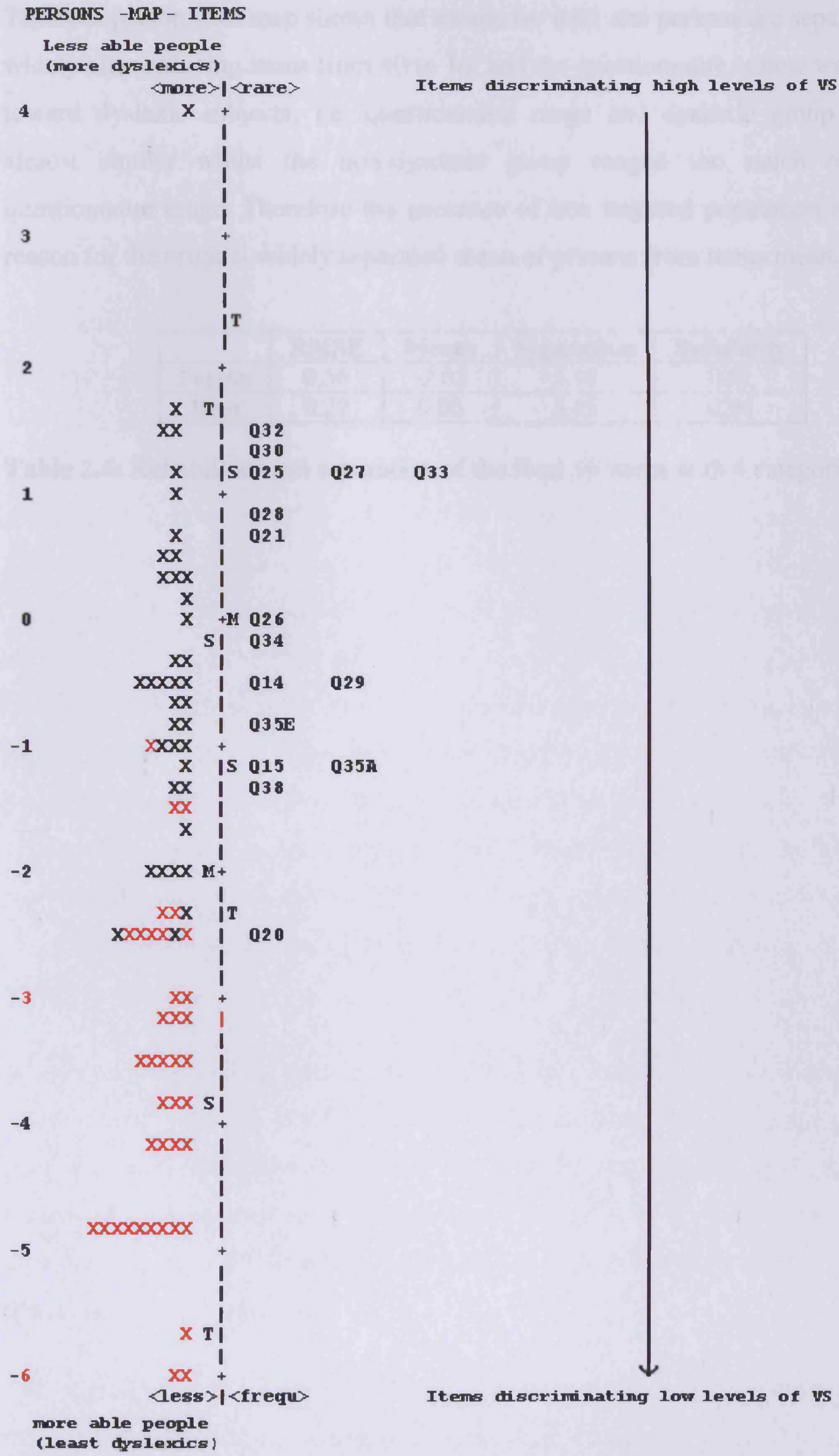

Figure 2.9: The final person/item map shows this questionnaire is well targeted to dyslexics and also those dyslexics have more visual stress. (Non dyslexic persons are highlighted in red).

The final person item map shows that means for item and persons are separated more widely after reducing items from 40 to 16, and the questionnaire is now well targeted toward dyslexic subjects, i.e. questionnaire range and dyslexic group range are almost similar whilst the non-dyslexic group ranged too much out of the questionnaire range. Therefore the presence of non targeted population may be the reason for the original widely separated mean of persons from items mean.

	RMSE	Means	Separation	Reliability
Person	0.56	-2.02	3.18	0.91
Item	0.22	0.00	5.15	0.96

Table 2.6: Reliabilities and separation of the final 16 items with 4 categories.

2.5 Discussion

In the present study the principle aim was to develop a suitable questionnaire measuring visual stress in dyslexic population. Non-dyslexic of matched age and gender were included to the studied sample to identify the sub-group population that the proposed questionnaire is targeting.

The initial 40 item questionnaire was created from questions used or suggested by previous studies on dyslexics, MIS and visual discomfort (Wilkins et al., 1984; Irlen, 1991; Evans et al., 1995; Evans et al., 1996b; Conlon et al., 1999; Evans et al., 1999; Evans and Joseph, 2002; Evans, 2004a; Singleton and Henderson, 2007a). However, it appears the strategy of these studies on dyslexia and/or MIS was to identify the presence and the incidence of different visual stress and asthenopia symptoms but they didn't evaluate the effective weight of symptoms as an explicated performance measure of a single underlying trait, i.e. visual stress. Only two published studies have applies Rasch analysis on visual discomfort questionnaires, but these were both in normal population (Conlon et al., 1999; Borsting et al., 2007) to identify the uni-dimensionality of the construct applied on adult students (Conlon et al., 1999) and to validate the same construct proposed by Conlon et al in non-dyslexic college students (Borsting et al., 2007). Therefore their aims were entirely different from the aim proposed in the present study and the definition of the visual stress was adopted in the present study.

A large number of items were included in the present study to ensure content validity (Streiner and Norman, 1995b) that was designed to measure a particular trait in a given group of subjects (dyslexics). Content validity explains the scope to which the content of the construct meet the intended concept that primarily hypothesised, to measure a particular trait (visual stress in the present study) in a given population (Pesudovs et al., 2007).

The offered number of categories were merely and primarily developed to provide more distinction between ordered even number categories where the seven point response categories reflects the lower limit of people discrimination ability and proposed that it is ideal for multiple characters (Miller, 1956). This may provide flexibility in options for subjects to express their feeling and hence, more significance of subject responses scores (Bond and Fox, 2007). Because different people may have different thought in understanding different item categories, only the terminal points of the scale were categorized (0 equivalent to Never and 6 equivalent to Always).

Examining the category statistics for the original seven categories revealed overlapping probability curves, indicating that subjects could not discriminate well between categories of difficulty, and noise in the construct results would occur (Bond and Fox, 2007). Accordingly some categories were merged with each other in a sensible manner that improved structure calibration and fit statistics of the recommended person and item separations and reliabilities. Although the end category was still under utilized (< 9%) (Linacre, 1999; Bond and Fox, 2007), this was probably due to presence of non-dyslexic subjects who represented 50% of the examined sample. The decision was not to remove the end category as any further collapsing to the categories may affect future fit statistics. Thus the resultant response scale was a 4-point scale from 0 (Never) to 3 (Always).

The initial person-item map where 40 items included with 4 categories showed wide difference between item and person means (1.53 Logits, i.e.> 0.5 Logits). It is known that close (similar) means of item difficulty and person ability indicate proper targeting of items to the subjects. However, in the present study, this wide separation may be attributed to the presence of the non-dyslexic population in the examined sample. In addition the questionnaire range is covering subjects on the top of the map (mainly dyslexics). This indicats poor targeting of item difficulty to the person ability for those subjects who are represented lower in the map as items are clustered higher in the map. This means that the present questionnaire is unlikely to discriminate people defined as least dyslexic or non-dyslexics. This result is not unexpected as the items were developed essentially from studies on dyslexia.

The outcome of this study was a shorter questionnaire which is desirable. Clinically, such long questionnaire versions may exaggerate a patient's effort and time burdens regardless of subject motivation and performance. Therefore it is required to develop a trait-targeted shorter questionnaire with the minimum number of items (Stelmack et al., 2004). Another major key in developing a suitable satisfied questionnaire to measure the intended trait, is the sensitivity of items to the underlying trait (Court et al., 2007). In addition it is essential for a questionnaire aimed at assessing a single trait not to contain items measuring something else. For example frequent blinking and eye-rubbing may be related to eye dryness or allergy, and blurred words, covering one eye and tilting the head when writing or reading and holding the reading material unusually close or far away could also all be attributed to the presence of uncorrected refractive error. It is also important to avoid items of ambiguous meaning, i.e. have you ever been told that you read slowly and your handwriting is difficult to read? These approaches help to reduce inaccurate information obtained from subjects (Massof, 2002). Applying Rasch analysis is a method to remove redundant items that are not related to the underlying measured trait, those items defined as misfitting the Rasch model, that may disable the construct validation (Massof, 2002). Removal of misfitting or redundant items is a process based on standard criteria excuted in several papers (Pesudovs et al., 2003; Pesudovs et al., 2004; Pesudovs, Garamendi and Elliott, 2006b; Court et al., 2007). In this study, prioritizing of item reduction was given to those with highest infit and outfit, or lowest infit or outfit, to improve goodness of fit statistics for the assessment scale of the developed questionnaire (Pesudovs et al., 2006b), with separations and reliabilities aimed to remain at acceptable levels (i.e. >2 and > 0.8 respectively for both person and item). Statistically, it is essential to maintain the recommended values of separation ratio during item reduction to retain the final test quality (Velozo et al., 2000; Mallinson, Stelmack and Velozo, 2004), (Bond and Fox, 2007; Court et al., 2007). For this reason it was necessary to stop the removal of items before reaching the unacceptable value of separation ratio (i.e. <2).

It is interesting to note that items related to reading errors and visual short term memory problems typically associated with dyslexia, or questions that do not ask definitively about actual visual stress symptoms (i.e. visual distortion and asthenpia) were also removed from the construct during this process. This indicates that these symptoms are not measuring the visual stress, for example;

Do you Re-read words or lines?

Confuse letters or words, e.g. orientation or progression of written material?

Reverse letters (b-d, p-q) or words (saw-was)? Do you misread numbers or copying them incorrectly?

Do you have problems tracking print as you read or copy?

Do you have any difficulties remembering what words look like, e.g. when you are copying information from the board or screen?

Exclusion of such items from visual stress questionnaire and deciding which items should be used or are worthy to be used helps to develop a questionnaire to measure visual stress in the given population. Questions 39 to 43 (using coloured overlay, lenses or papers to help in reading and writing and in improving symptoms) are more likely to be diagnostic criteria for Meares Irlen Syndrome (Irlen, 1991), and perhaps the stringent response (i.e. yes or no) is the proper role for answering such questions.

Content validity is "the extent to which the items in the instrument reflect the entirety of the concept being measured" (Pesudovs et al., 2007). Thus the present study demonstrated the potent final 16 items, based on both concept influences and goodness of fit statistics to the Rasch model, where the final person and item reliabilities were high (0.91 and 0.96 respectively), and this reflects the content validity of this construct for measuring visual stress that imply uni-dimensionality of the scale.

The final person item map showed that the means for item and persons are separated more widely after reducing the number of items from 40 to 16, and that the questionnaire is well targeted to the adult dyslexic population.

In conclusion, this study has produced a useful and properly constructed tool to provide a quantitative measure of visual stress in the adult dyslexic population.

Chapter 3

Validation of Cardiff Visual Stress Questionnaire for Adults with Dyslexia (CVSQAD)

3.1 Introduction

As reported in chapter 1 (section 1.6), dyslexic people are more susceptible to visual stress symptoms attributed to pattern glare and perceptual visual distortion, such as blurring and movement of the lines of the text when engaged in reading, compared to those without dyslexia (Irlen, 1991; Wilkins, 1995; Singleton and Trotter, 2005) Dyslexic people with Meares Irlen Syndrome, identified with significant increasing of reading rate with prescribed colour filters as a diagnostic criteria of MIS (Irlen, 1991; Evans and Joseph, 2002), have been shown to have higher levels of visual stress (in terms of reported symptoms) compared to non-dyslexics adults (Singleton and Trotter, 2005), non dyslexic children or to dyslexic children without MIS (i.e. those who did not show significant improvement in reading rate with coloured filters) (Singleton and Henderson, 2007a).

From the above it is hypothesised that dyslexic adults without MIS have less visual stress compared to dyslexic adults with MIS.

In chapter 2 a short 16-item questionnaire was developed to measure visual stress. Results of person-item mapping showed which items/questions were targeted at a dyslexic population.

In this chapter the visual stress will be evaluated by administering the short version questionnaire to a dyslexic group, assessing its reliability.

3.1.2 Aim and objectives

In this study the primary aim was to validate (i.e. assess reliability of) the 16-item CVSQAD (Cardiff Visual Stress Questionnaire for Adults with Dyslexia) by investigating five targeted objectives:

1. Evaluation of the functioning of the 4 response categories
2. Evaluation of the targeting of the 16-item to the subject population.
3. Assessment of content validity of the instrument.
4. Evaluation of instrument performances by assessing construct validity of the instrument.
5. Providing reference scoring scale representing the validated CVSQAD.

Content validity of instrument describes the scope of included items perfected to measure an underlying concept, and it can be demonstrated by the Rasch model fit statistics and methods used in instrument development such as item reduction (Pesudovs et al., 2007). Construct validity examines the extent to which the instrument measures what it purports to measure (i.e. the latent trait of visual stress) (Pesudovs et al., 2007).

Reliability evaluates the consistency of instrument by examining the use of the same questionnaire over a different group of subjects, or via different administration, e.g. to assess test re-test reliability over two visits, where item difficulty estimate would have the same level of difficulty each time (Bond and Fox, 2007). However, reliability assessed in this latter way doesn't express the true validity, as there is no assurance that the questionnaire is valid each time, just that it is behaving the same way (Pesudovs et al., 2007). Evaluation of reliability of a questionnaire in a single session (validity) can be assessed by using internal consistency tests that reflect how well every item in the questionnaire correlates with every other items in the construct – the uni-dimensional nature of the questionnaire which should fundamentally mean that all included items measure the same feature (Hays and Revicki, 2005; Pesudovs et al., 2007). The uni-dimensionality of an instrument can be conventionally assessed by Cronbach's alpha value, which explains the correlation of each item with every other item in the instrument: when this value is near to 1 this reflects consistency of the scale (Pesudovs et al 2007).

After evidential validation of CVSQAD as a reliable tool for assessing visual stress in the targeted population, i.e. the adult dyslexic population, by means of content and construct validities, the next step is assessment of the single administration reliability or validity of the test. Rasch analysis estimated measures (i.e. item and category measures) enabled the production of scores along an interval scale (Massof, 2007), and this accurate computed scoring (representing all items and the 4 response categories used in the present study) is beneficial as it can be used as a referential source when the same questionnaire is applied to a similar population without need for the re-evaluation using Rasch analysis (Massof, 2007).

The *secondary* aim for the present study is to examine the factors that may influence the visual stress in the tested population including age, gender, handedness, refractive error, sensitivity to light and sensitivity to pattern glare. This was by done quantifying the relationship between the final validated visual stress scorings and between each factor reported above. This is the first time these associations have been examined in the adult dyslexic population using a validated VS score.

3.2 Methods

3.2.1 Participants and recruitment

Students with dyslexia and/or MIS were recruited initially by flyers and posters that were distributed in different areas in Cardiff University: interested volunteers made contact via email and were invited to participate.

Inclusion criteria were an official diagnosis (statement) of dyslexia and/or MIS (defined by use of colour filter to help in reading), and age between 18 and 38 years.

Exclusion criteria were having a history of migraine or severe headache or photosensitive epilepsy. Subjects were also excluded if they presented with strabismus, or unequal visual acuity between eyes of more than two lines, at their assessment visit.

Ethical approval was obtained from Cardiff School of Optometry and Vision Science Ethical Committee and all procedures follow the tenets of the Declaration of Helsinki.

3.2.2 Questionnaire administration

On an appointment basis dyslexic students required to attend the optometry clinic for a single session and the 16-items questionnaire (Appendix 2.1) was administered by the researcher in face to face interview last for a maximum time of 10 minutes. Visual acuity, refractive error and results from cover testing were recorded for screening purposes before completion of the questionnaire.

3.2.3 Demographic data

Demographic date such as age, gender, handedness, refractive error correction, and dyslexic condition were recorded from all subjects.

Subjects who reported using the coloured filters (overlays or spectacle lenses) were requested to bring their filters with them on the examination day in order to identify their case condition accurately. Those who used the colour filters were identified as 'dyslexic with MIS' cases.

3.2.4 Data analysis

3.2.4.1 Rasch analysis

Rasch analysis is described in detail in chapter 2 in developing the CVSQAD (section 2.2). Rasch analysis was applied to the results in this study in order to:

1. Evaluate the structure, functioning and diagnostic statistics of the four response categories.

2. Confirm the ability of the CVSQAD to target the adult dyslexic population, by describing the distribution of item difficulties compared with the range of person ability estimates.

3. Assess the content validity of the CVSQAD by examining item and person separation indices that describe the distribution manner of items and persons along the continuum (Hymes, Johnston and Hays, 2001b; Bond and Fox, 2007; Pesudovs et al., 2007). Item and person separation value of 2 is the required considered separation value that providing the good separation competence (capacity) for the instrument and indicating that the scale is measuring 3 levels of item difficulty and person ability (Itzkovich et al., 2002; Bond and Fox, 2007), and therefore the instrument demonstrates good content validity. Content validity also can be evaluated by examining Rasch item fit statistics. For the good content validity value of the item fit statistics should be in range 0.7 to 1.5 (Linacre, 2005).

4. Assess internal consistency of the questionnaire by calculating person and item separation reliability coefficients that reflect the construct precision. The reliability index (of item and person separation) is similar to Cronbach's alpha (Andrich, 1982; Bond and Fox, 2007), and both are assigned on a 0 to 1 scale; therefore they have similar understanding value, ie, above 0.8 is very good (Bond and Fox, 2007), or above 0.7 (Bland and Altman, 1997; Mllison, 2007) is good for the scale (see section 2.3.4 separation and reliability-introduction to Rasch analysis, chapter 4).

5. Produce referential scoring for CVSQAD using Rasch estimated item measure and estimated category measure (Massof, 2007). Reference score for

each item and the 4 response categories were calculated by adding estimated item measure to the category measure (the equation). The equation used was:

Reference score = estimated item measure + category measure (Linacre, 2005),

and thereafter all the raw scores collected from information of subject responses were converted to the meaningful scores by calculating the reference scores.

3.2.4.2 Statistical Package for the Social Sciences

SPSS (version 16, SPSS Inc Chicago, Illinois, USA) statistical program was specifically used to:

1. Asses the construct validity by studying the correlation between the final subject' questionnaire scoring with the case condition for all subjects using independent t-test.

2. Evaluate the correlation between subjects final scoring and independent categorical items age, gender, handedness, presence of refractive error, sensitivity to the light and sensitivity to pattern glare using multiple linear regression analysis.

3. Statistical description of the studied population and distribution of collected data and the final subject scores.

3.3 Results

3.3.1 Description of sample population

Fifty eight subjects took part in the study and two subjects were excluded as they were outside the age range for inclusion. For the 56 included questionnaires, 55.4% (n=31) were from female respondents, and 44.6 % (n=25) from males. The mean age for the entire cohort was 23.6±5.3 years, median age 22 years, range 18-38 years). Age was not normally distributed and Kolmogrov-Smirnov (K-S) test was significant (p=0.000). There was only one subject with missing data, but it was only 6.25% of missing data, i.e. only one question. The responses from this subject were still included as it is only becomes unreliable when more than 33% of data is missing (Pesudovs et al., 2004; Court et al., 2007).

All subject were confirmed to be dyslexic by presenting a statement (a psychological assessment report) describing their condition and the recommended supports, i.e. using coloured filters, extra time in examination, etc. twenty-seven of the sample were using colour filters to improve their reading performance; subsequently they were identified for analysis as 'dyslexics plus MIS' group.
Our sample consisted 55.4 % (n=31) females and 44.6 % (n=25) males.
The majority of the subjects in the present study were right handed (n=47, 84%).
41% (n=23) of the total sample used a form of optical correction; 12 were using contact lenses.
Few subjects (n=5) reported to a lazy eye in their childhood that was treated successfully; three of them received eye patch treatment. Of the entire cohort, 9 subjects had received orthoptic (eye exercise) treatment in their history. Generally, 6 subjects reported sensitivity to light and 6 subjects reported pattern glare problems.

Rasch statistics showed that 10 people (numbers 20, 53, 33, 9,24, 57, 5, 45, 11 and 7) misfit the Rasch model, i.e. fit statistics >1.40 (Bond & Fox 2007, Court et al 2007. So, their questionnaire were inspected to check for odd response patterns (such as ticking all the sever categories) but all subjects appeared to have randomly chosen the response options. So, all the subjects were included for the final analysis.

3.3.2 Response scale analysis

The category probability curves for the four categories were distinct (peaks are not overlapped). The category diagnostic statistics, i.e. category measure and pattern of category threshold, i.e. step calibration, showed that all four categories were ordered; meaning that the categories are distinguishable among the different persons difficulties, and have a realistic probability of being selected (Bond and Fox, 2007; Court et al., 2007). Category measures demonstrated that the categories are separated by the recommended value of 1.4-5 Logits (Bond and Fox, 2007). Category utilization was also good, and infit and outfit measures were < 2 (Bond and Fox, 2007). In conclusion, all these criteria verified the validity of 4 response categories for the 16-item CVSQAD (Table 3.1 & Figure 3.1).

Category label	Category utilization (%)	Step calibration (logits)	Category measure (logits)
0	30	None	-2.47
1	26	-1.17	-0.74
2	24	-0.07	0.72
3	19	1.24	2.51

Table 3.1: Category diagnostic statistics for 4 response categories for the 16-item questionnaire.

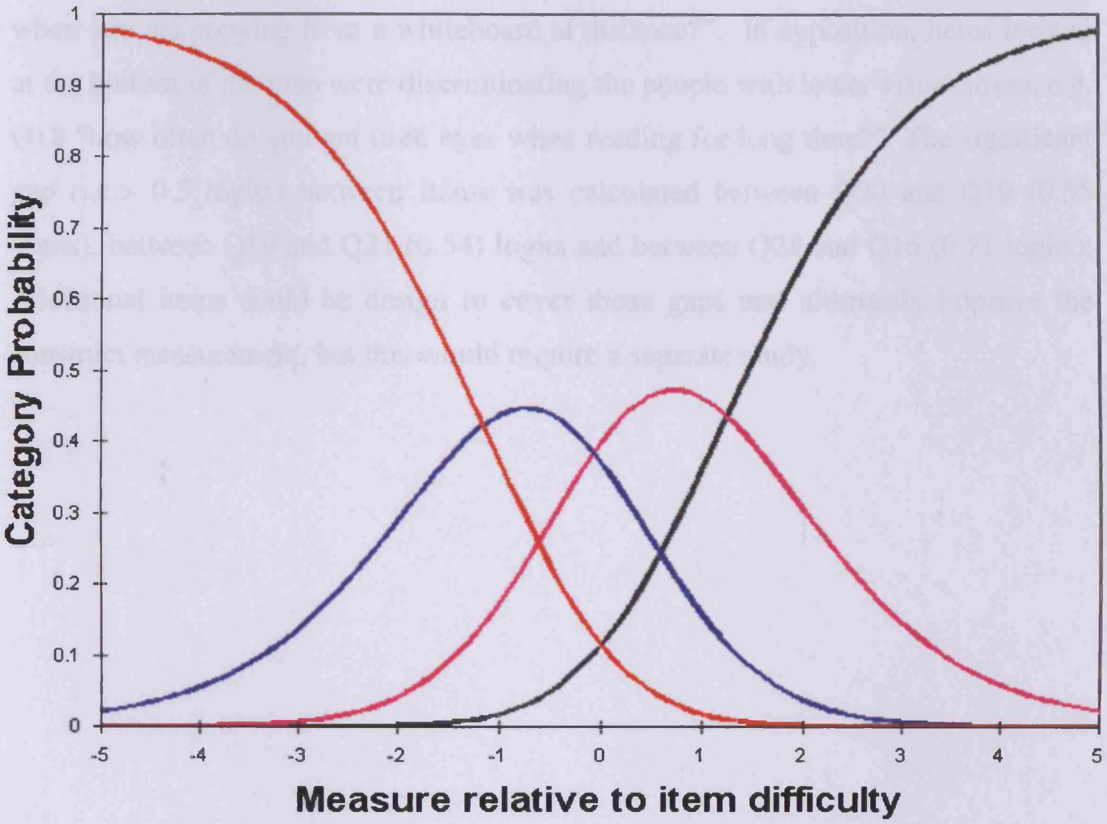

Figure 3.1: Category probability curves for the four response categories (0, 1, 2, 3) for the16-item questionnaire.

3.3.3 Person and item estimates for the 16-items questionnaire

The sequenced distribution of items (item difficulty) compared to persons (person ability) is illustrated in person-item map (Figure 3.2). The means for the two distributions (person and item) were very close, separated by the mean difference of -0.35 Logits; the mean person ability was -0.35 logits and mean item difficulty was 0 Logits (range -2.07 to 1.65). Items located at the top of the map discriminating people with high visual stress, e.g. Q26 "do the words ever get smaller or bigger when you are copying from a whiteboard at distance?". In opposition, items located at the bottom of the map were discriminating the people with lower visual stress, e.g. Q18 "how often do you get tired eyes when reading for long time?". The significant gap (i.e.> 0.5 logits) between items was calculated between Q20 and Q19 (0.55 logits), between Q19 and Q21 (0.54) logits and between Q28 and Q16 (0.71 logits). Additional items could be design to cover those gaps and ultimately improve the construct measurement, but this would require a separate study.

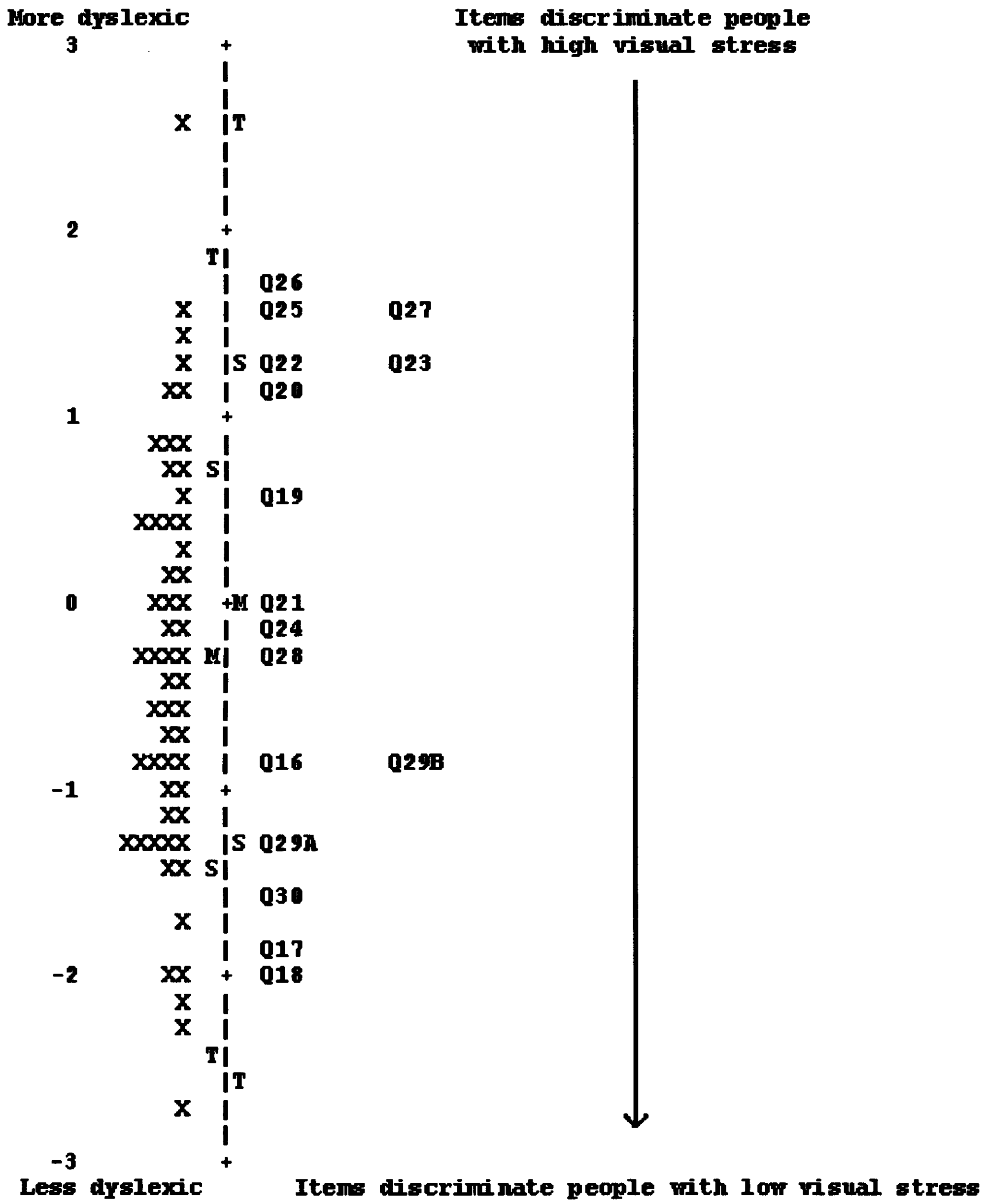

Figure 3.2: Person-item map for 16-items, Person visual ability (with different levels of visual stress)/ item difficulty (items discriminating different levels of visual stress) map. On the left of the continuum, each subject is represented by "x" and on the right of the continuum items are represented as Q and number of the questions (i.e.Q20).M=means, S=1 standard deviation from the mean, T= 2 standard deviation from the mean. The more dyslexic persons and items discriminating high levels of visual stress are located at the top of the map.

3.3.4 Item fit statistics

For the 16 items the MNSQ (mean square infit) ranged from 0.58 to 1.55 logits and the MNSQ outfit ranged from 0.52 to 1.9 logits (see the Appendix 2.2). It is apparent that the values of higher infit 1.55 and outfit 1.9 (>1.3) (Pesudovs et al., 2003; Pesudovs et al., 2007) are for an item misfitting the Rasch model expectation; i.e. under fitted, these values belonged to question 30 ("do you do lots of crossing out in writing?") and indicate this item is not measuring the underlying variable (visual stress), and hence this item should be removed from the scale.

After removing item Q30, Rasch analysis was repeated over the remaining 15 items. This time item 25 showed over fitted values, infit MNSQ 0.58 and outfit MNSQ 0.52. However this item is still measuring the visual stress and the decision was to keep this item to avoid losing significant information (Stelmack et al., 2004).

Although item 27 has infit MNSQ of 1.23 and outfit MNSQ of 1.36 which are slightly higher than the strict criteria proposed by Pesudovs (Pesudovs et al., 2003; Pesudovs et al., 2007), Linacre suggested that items with values 1.5 infit and outfit are still acceptable for the measurement (Linacre, 2005). So, Q 27 remained.

Table 3.2 shows the Rasch statistics for the 15-item illustrating that all 15 items are measuring the underlying construct with missing data of 6.25% from question 18.The range of item measure was between 1.62 to -2.28 Logits. All values have normal skew and kurtosis values indicating normally distribution of item measures.

Removal of misfit item (Q 30) in the questionnaire revealed response category curves a similar to those for the 16-item construction. Categories remained separated by the recommended value >1.4 logits, infit and outfit < 2, and the utilization was good, indicating the validity of the 4 category response structure for the selected population (dyslexic adults).

Category label	Category utilization (%)	Step calibration (logits)	Category measure (logits)
0	32	None	-2.55
1	27	-1.26	-0.79
2	24	-.11	0.75
3	17	1.37	2.61

Table 3.2: Category diagnostic statistics for 4 response categories for 15-item questionnaire.

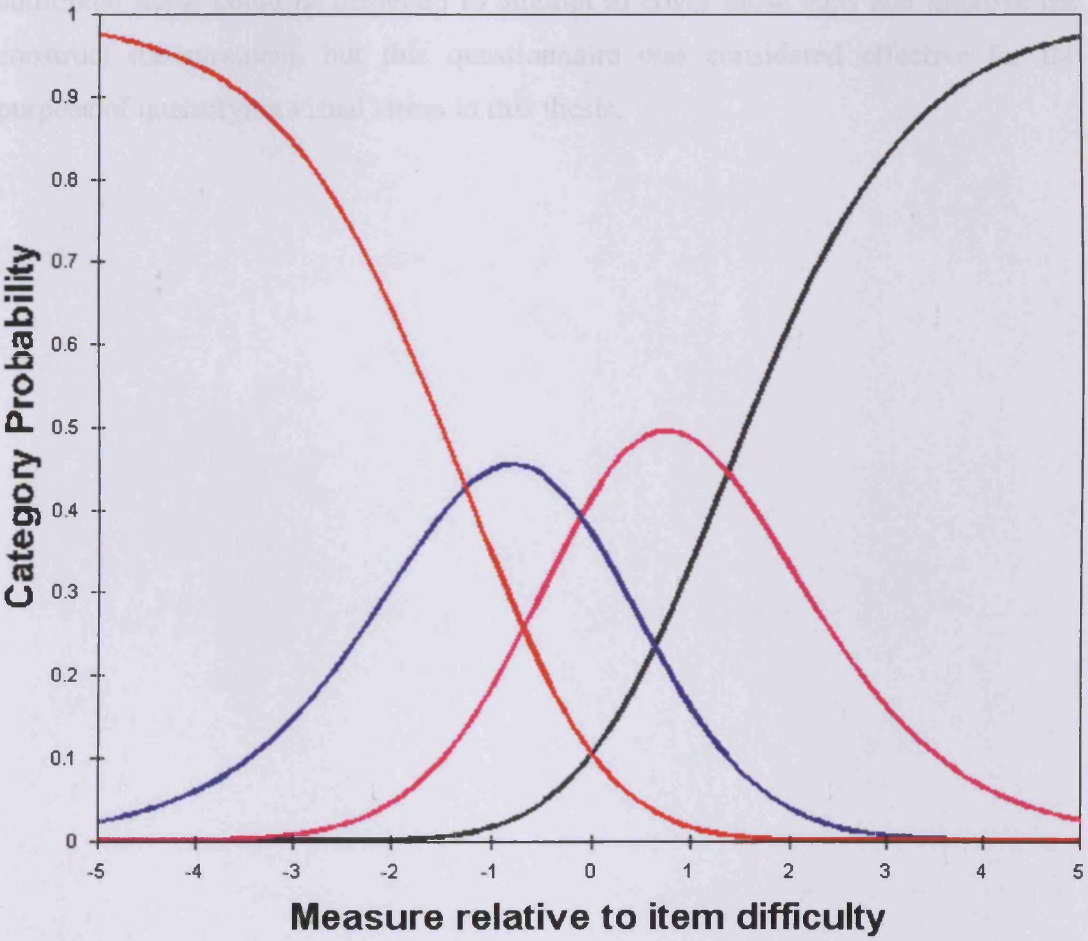

Figure 3.3: Category probability curves for the four response categories (0, 1, 2, 3) for the 15-item questionnaire.

3.3.5 Person and item estimates for the 15-items questionnaire

The distribution of items (item difficulty) compared to persons (person ability) is illustrated in the person-item map (Figure 3.4). Good targeting was indicated by aagreement of items to the subjects, where the means for the two distributions (person and item) were very close, separated only by the mean difference of -0.48 Logits (the mean person ability was -0.48 logits (range from -3.10 to 2.52 on the scale) and mean item difficulty is 0 Logits (range from-2.28 to 1.62 on the scale)). The significant gaps between items were calculated between Q20 and Q19 (0.56 logits), between Q19 and 21 (0.58) logits as before), but also between Q28 and Q29B (0.61 logits) and between Q29A and Q17 (0.54) logits. As mentioned previously, additional items could be designed to attempt to cover those gaps and improve the construct measurement, but this questionnaire was considered effective for the purpose of quantifying visual stress in this thesis.

```
PERSONS MAP OF ITEMS                         Items discriminate people
        <more>|<rare>                         with high visual stress
 3            +
              |
              |
          X   |T
              |
              |
 2            +
             T|
              |  Q26
        XXX   |  Q25       Q27
          X   |S
              |  Q22       Q23
 1        X   +  Q20
        XXX   |
        XXX  S|
              |  Q19
          X   |
     XXXXXX   |
 0       XX   +M
          X   |  Q21       Q24
        XXX   |  Q28
     XXXXXX  M|
       XXXX   |
              |
-1        X   +  Q29B
       XXXX   |  Q16
         XX   |S
     XXXXXX   |  Q29A
             S|
         XX   |
-2       XX   +  Q17
              |
         XX   |  Q18
          X   |T
              |
             T|
-3            +
          X   |
              |
              |
              |
              |
-4            +
        <less>|<frequ>   Items discriminate people with low visual stress
```

Figure 3.4: Person-item map for 15-items shows good targeting of items to subjects

3.3.6.1 Assessment validity of the 15-items CVSQAD

3.3.6.1.1 Content validity

Content validity (Pesudovs et al., 2007), that describes the perfection of included items to measure an underlying concept (in this case, visual stress) in a given population (in this case, dyslexic adults), was evidentially demonstrated by item fit statistics, which were acceptable for the all 15 items (Table 3.3) and by person and item separation indices which were high (>2 logits, Table 3.4). Hence, the content validity for 15-item CVSQAD was judged to be good.

Items	Skew	Kurtosis	Missing data (%)	MnSq Infit (ZSTD)	MnSq Outfit (ZSTD)	Item measure (SE)
16. particular difficulties with reading	-0.37	-0.69	0	0.87 (-0.7)	0.94 (-0.2)	-1.09 (0.18)
17. any difficulties with spelling	-0.79	0.38	0	1.08 (0.5)	1.25 (1.1)	-2.01 (0.21)
18. tired eyes when reading for a long time	-1.41	1.21	6.25	1.18 (0.9)	0.98 (0.0)	-2.28 (.22)
19. double vision when reading for a short time	0.47	-0.64	0	1.12 (.7)	1.20 (1.0)	0.46 (0.19)
20. words fade or disappear when reading	0.99	-0.08	0	1.20 (1.0)	1.10 (0.5)	1.02 (0.20)
21. words jump around or move when reading	0.16	-1.00	0	0.95 (-0.2)	0.94 (-0.3)	-0.12 (0.18)
22. words get smaller or bigger when reading	1.31	1.06	0	0.78 (-1.1)	0.64 (-1.6)	1.24 (0.21)
23. words get faint colour around when reading	1.15	0.09	0	1.22 (1.1)	1.18 (0.8)	1.19 (0.21)
24.words go blurred when copying from a white board	0.19	-0.45	0	0.69 (-1.19)	0.75 (-1.4)	-0.21 (0.18)
25. words fade or disappear when copying from a white board	0.69	-0.45	0	0.58 (-2.3)	0.50 (-2.1)	1.47 (0.22)
26. words get smaller or bigger when copying from a white board	1.40	1.72	0	1.01 (0.1)	0.93 (-0.1)	1.26 (0.23)
27. words get faint colour around when copying from a white board	1.39	0.93	0	1.23 (1.1)	1.36 (1.3)	1.47 (0.22)
28. difficulty in changing focus from near to distance and vice versa	0.15	-1.02	0	1.18 (1.1)	1.15 (0.9)	-0.34 (0.18)
29 A. skip or omit words or lines during reading or studing	-0.44	-0.64	0	1.04 (0.3)	0.98 (-0.1)	-1.47 (0.19)
29 B. use finger as a marker during reading or studing	-1.41	-0.98	0	0.94 (-0.3)	0.89 (-0.6)	-0.78 (0.20)

Table 3.3: Construct Descriptive statistics, Rasch fit statistics and item measures for the final 15 items of visual stress questionnaire. (Items with higher positive values measure discriminating higher levels of visual stress).

Parameter	Separation index	Reliability	Average infit	Average outfit	Model measurement error	SD
Person ability	2.53	0.87	1.00	0.99	0.24	0.07
Item difficulty	6.06	0.97	1.00	0.99	0.21	0.02

Table 3.4: Fit statistics for person ability and item difficulty for the final 15-item CVSQAD

3.3.6.2 Assessment of internal reliability of the 15-item CVSQAD

Internal reliability was demonstrated by relatively high values of person and item separation reliability coefficients, which were 0.87 and 0.97 (Table 3.4) respectively that indicated consistency of the questionnaire (table 3.4).
The root mean square error over all items was 0.21, indicating high construct reliability, i.e. the closer the value to zero the higher the internal construct reliability (Wright and Linacre, 1994; Bond and Fox, 2007).

3.3.6.3 Construct validity

Construct validity examines whether the instrument measures what it purports to measure (i.e. the latent trait of visual stress) (Pesudovs et al., 2007). One way is to examine the original hypothesis, i.e. *dyslexic people have significantly less visual stress compared to dyslexics plus MIS condition.* Independent sample t-test revealed a highly significant difference $P<0.001$ ($P=0.000$) between the two groups (Figure 3.5). Subjects with dyslexia only (n=29) showed lower visual stress scores (mean = -0.97, SD=0.57) compared with those who have dyslexia with MIS, (n=27, mean = 0.23, SD= 0.81). This result implied a strong correlation between the self reported final visual stress scores and subject conditions, i.e. a strongly supported the hypothesis inferring very good construct validity.

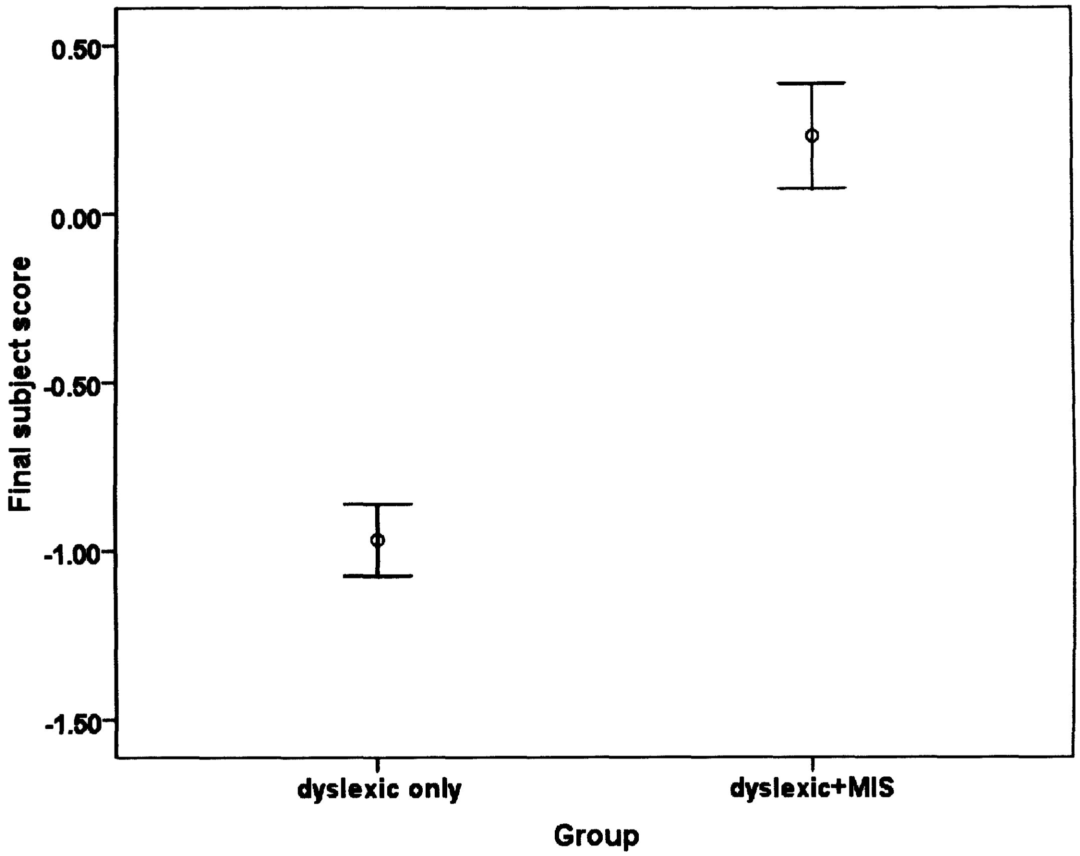

Figure 3.5: The final subject score (mean ± 1 SE) in dyslexia and dyslexia with MIS groups.

3.3.7 The relationships between the visual stress scores (VSS) and potential influencing factors

Factors that may influence the visual stress in the tested population, i.e. independent variables, including case, age, gender, handedness, binocular visual history, existing refractive error, sensitivity to light and sensitivity to pattern glare were examined.

The final visual stress score are normally distributed (Figure 3.6): the mean is -0.39 and SD 0.92.

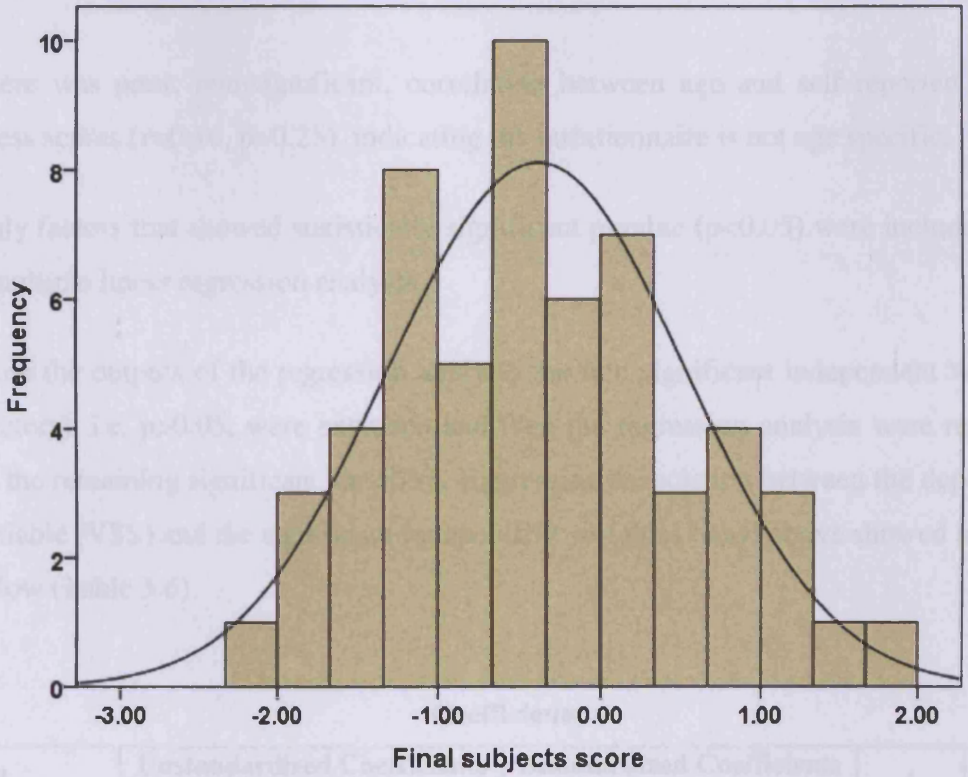

Figure 3.6: normality histogram for final visual stress scores

To examine the differences in VSS for subjects grouped according to independent variables (factors), independent t-testing was applied between groups (Table 3.5).

Independent variable	Response	N	VSS Mean (SD)	t	p-value 2-tailed
Case	Dyslexia only	29	-0.97 (0.57)	-6.43	0.000
	Dyslexia + MIS	27	0.23 (0.81)		
Gender	Male	25	-0.67 (0.75)	-2.02	0.039
	Female	31	-0.16 (0.99)		
Sensitivity to light	Yes	6	0.43 (1.11)	2.41	0.020
	No	50	-0.49 (0.85)		
Sensitivity to pattern glare	Yes	6	0.65 (0.92)	3.17	0.003
	No	50	-0.51 (0.84)		

Table 3.5: independent variables with significant differences.

There was poor, non-significant, correlation between age and self reported visual stress scores ($r=0.16$, $p=0.25$), indicating the questionnaire is not age specific.

Only factors that showed statistically significant p-value ($p<0.05$) were included into a multiple linear regression analysis.

From the outputs of the regression analysis the non significant independent variable (factors), i.e. $p>0.05$, were excluded and then the regression analysis were repeated on the remaining significant variables. Regression association between the dependent variable (VSS) and the significant independent variables listed above showed in table below (Table 3.6).

Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	P value
	B	Std. Error	Beta		
(Constant)	-0.68	0.85		-0.79	0.43
Case	1.02	0.18	0.56	5.69	0.000
Gender	0.43	0.17	0.24	2.53	0.015
Light	-0.28	0.29	-0.09	-0.96	0.34
Pattern glare	-0.72	0.29	-0.25	-2.49	0.016

Table 3.6: Regression association between the VSS and case, gender, sensitivity to light and sensitivity to patterns.

The beta coefficient is the slope of the regression line; the larger the beta the steeper the slop, the more the dependent variable changes for each unit in the independent variable. The independent variable with non significant beta coefficient (p>0.05) were removed and the analysis was repeated. Significant values for the independent variables analysed with multiple regression are shown in the table 3.7, R-Square was 0.551 indicating that the association correlation between the VS and the independent factors all together is high (strong) (i.e. VS is 55% influenced by the case, gender and the sensitivity to pattern glare as a whole, all together).

Model	Unstandardized Coefficients		Standardized Coefficients	t	P value
	B	Std. Error	Beta		
(Constant)	-1.16	0.69		-1.69	0.097
Case	1.05	0.18	0.58	5.99	0.000
Gender	0.45	0.17	0.24	2.61	0.012
pattern glare	-0.78	0.28	-0.27	-2.76	0.008

Table 3.7: Regression association between the VSS and case, gender, and sensitivity to patterns.

3.3.8 Referential scoring of the 15-item CVSQAD

Reference scores for each item and the 4 response categories were calculated by adding estimated item measure to the category measure;

Reference score = estimated item measure + category measure (Linacre 2005).

Table 3.8 shows the referential scoring representing the 15-item CVSQAD.

Items	Response category score (Logits)			
	Never 0	1	2	always 3
16. particular difficulties with reading	-3.64	-1.88	-0.34	1.52
17. any difficulties with spelling	-4.56	-2.8	-1.26	0.6
18. tired eyes when reading for a long time	-4.83	-3.07	-1.53	0.33
19. double vision when reading for a short time	-2.09	-0.33	1.21	3.07
20. words fade or disappear when reading	-1.53	0.23	1.77	3.63
21. words jump around or move when reading	-2.67	-0.91	0.63	2.49
22. words get smaller or bigger when reading	-1.31	0.45	1.99	3.85
23. words get faint colour around when reading	-1.36	0.4	1.94	3.8
24.words go blurred when copying from a white board	-2.76	-1.00	0.54	2.4
25. words fade or disappear when copying from a white board	-1.08	0.68	2.22	4.08
26. words get smaller or bigger when copying from a white board	-0.93	0.83	2.37	4.23
27. words get faint colour around when copying from a white board	-1.08	0.68	2.22	4.08
28. difficulty in changing focus from near to distance and vice versa	-2.89	-1.13	0.41	2.27
29 A. skip or omit words or lines during reading or studing	-4.02	-2.26	-0.72	1.14
29B.use finger as a marker during reading or studing	-3.5	-1.74	-0.2	1.66

Table 3.8: Referential scoring representing the 15-item CVSQAD.

This accurate computed scoring is beneficial as it can be used as a reference source when the same questionnaire is applied to a similar population without need for the re-evaluation using Rasch analysis (Massof , 2007).

3.4 Discussion

The present study concluded that the 15-item CVSQAD is a valid and reliable tool for assessing visual stress in the dyslexic adult population, by means of content and construct validities and the single administration reliability of the test. Rasch findings revealed uni-dimensionality of the 15-items CVSQAD which was evidenced by item fits statistics that were considered acceptable for the all 15 items. This indicated the appropriateness of the included items to measure visual stress in a dyslexic adult population (Pesudovs et al., 2007). Consistency of the construct has been explained by the internal reliability and demonstrated by relatively high values of person and item separation reliability coefficients, which were 0.87 and 0.97 respectively. The low root mean square error over all items (0.21) indicated high construct reliability (Bond and Fox, 2007). High separation index of person ability (2.53) indicated the ability of the instrument to discriminate between dyslexic people with different levels of visual stress. So the content validity for 15-item CVSQD was good.
The person item map for the final 15 item CVSQAD illustrated four considerable gaps between seven items where the difference was >0.5 logits (the acceptable gap is between 0.15 to 0.3 logits) (Wolfe and Kong, 1999; Bond and Fox, 2007), and perhaps future development of this questionnaire could include designing additional items to cover those gaps and ultimately further improve the construct measurement, i.e. improves the precision of item discriminating different person abilities (scores or levels of visual stress in this study).

The present study established the stability and reliability of the four response category as assessment tool for subject responses in evaluating visual stress in dyslexic population. This is in agreement with previous work where four response categories have been proposed to measure different levels of visual discomfort in university students' population (Conlon et al., 1999; Borsting et al., 2007).

Another significant finding of the present study has been to demonstrate that the 15-item CVSQAD measures what it purports to measure. The hypothesis that higher stress scors would be found in dyslexic adults who also have MIS was supported by the results. This hypothesis was developed on the basis of the current knowledge (Singleton and Trotter, 2005, Singleton and Henderson 2007a). Findings on this issue revealed a highly significant difference (P= 0.000) between the two group conditions.

This result implied a strong correlation between the self reported final visual stress scores and subject conditions, i.e. dyslexic only versus dyslexic with MIS and that strongly supports the hypothesis we have proposed reflecting very good construct validity.

To the best of the author's knowledge the present study is the first to explore a validated visual stress questionnaire in a dyslexic university student population, and the first to investigate the relationships between quantitative, weighted self-report visual stress scores and the presence or absence of MIS in these dyslexic university students.

Studies in visually stressed, non-dyslexic adult reported a highly skewed distribution of visual stress scores (Conlon et al., 1999; Borsting et al., 2007) toward low level of visual stress scores. This study found normally distributed visual stress scores in the dyslexic sample indicating the accurate reflection of this questionnaire in obtaining 'normal' data from this specific population.

Borsting and colleagues went on to apply Rasch analysis to validate the questionnaire adopted by Conlon et al (1999) in term of uni-dimensionality and to evaluate to evaluate the distribution of visual stress levels in university students generally, and found three levels of visual discomforts; low (score of 0-35%), moderate (score 35%- 69.5%) and high (score of 70% or greater) (Borsting et al., 2008)

This investigation revealed a strong correlation between self-reported visual stress scores and factors were predicted to influence visual stress, i.e. case (dyslexia with or without MIS condition), gender and sensitivity to pattern glare. Regression analysis revealed to r-square of 0.551 indicating that the association between the VS and the reported factors all together is high, i.e. that VS scores were influenced by the case, gender and the sensitivity to pattern glare.

Females in the present sample reported higher visual stress scores (mean=-0.16) compared to males (m=-0.67). Although the females represented 55.4% of the studied sample however regression analysis findings indicated that this higher visual stress scores in females were not influenced by other factors. A preponderance of higher visual stress symptom scores in females has also been reported by other authors (Borsting et al., 2007) taking into account any gender response bias. This higher incidence of visual stress in women may be attributed to the psychological

nature of women in describing severity of symptoms.
There were only weak correlation between age and self report visual stress scores, indicating the questionnaire is not considering the age implication visual factors across university age, i.e.18-38 years. The age range of respondents would need to expand to fully explore this factor.

From a theory point of view it is important to understand the different visual factors that are correlated to visual stress and that may influence the higher degree of self-reported visual stress scores. Pattern glare is one of the most commonly considered factor when describing condition of MIS (Wilkins, 1995; Evans et al., 1996b), and it represents symptoms of visual stress that may handicap reading performance (Wilkins and Noimmo-Smith, 1984), such as coloured halos, change spacing between letters and motion of the reading material (words jump around or move) and hence this can cause one of the typical reading errors, i.e skip or omit words or lines making the subject to use finger to help in limiting this reading error. In the present study there was a highly statistically significant association between high visual stress scores and pattern glare (regression model; $p=0.008$). Conlon et al (1999) reported that university students (non-dyslexic) who reported higher scores in visual discomfort scale reported higher sensitivity to patterns, i.e. experienced greater ratings of unpleasant of somatic and visual distortion symptoms when viewing patterns (spatial frequency 2.5c/d square waves).

In conclusion, the present 15-item questionnaire is a valid and reliable measure of visual stress in dyslexic across the age range of university students and representing wide range of visual stress levels. The present results established the possible factors that influenced scores of visual stress such as case condition, gender and pattern glare. In addition, this short construct has advantages of saving time and burden in examination of the dyslexic population.

Chapter 4

Differences in visual performance between adults with dyslexia and control subjects

This part of the thesis now presents the work conducted to address one of the principle aims – how fatigue affects visual performance in adults with dyslexia, with and without MIS. Chapter 6 examines the baseline status of any differences between adults with and without dyslexia compared to controls.

4.1 Introduction

Reading is a complex, usually binocular, activity which requires accurate eye saccades separated with brief fixations. Hence both static and dynamic binocular measures need to be investigated in order to evaluate visual correlates of the condition dyslexia. During reading the accommodative and vergence systems work together to allow comfortable reading. The vergence system acts to provide an accurate binocular localization and reduce retinal disparity whilst accommodation acts to maintain clear vision. However, the association between binocular vision functions, symptoms associated with MIS and reading performance remain uncertain in dyslexia.

Several studies have found that binocular vision instability is more common in the young (children) dyslexic population (see section 1.9.4 for details). Section 1.9.3 of this thesis highlighted specific binocular vision anomalies that may occur in dyslexic children, particularly a reduced amplitude of accommodation (Hung, 1989; Evans et al., 1992a; Evans et al., 1994a; Dusek et al., 2010) and fusional reserves (Eames, 1934; Stein et al., 1988; Hung, 1989; Evans et al., 1992a; Eden et al., 1994; Evans et al., 1994a; Bucci and Kapoula, 2008). Other studies have reported reduced amplitude of accommodation and fusional reserves (Evans et al., 1995; Lightstone and Evans, 1995; Evans et al., 1996b; Scott et al., 2002) in subjects with MIS. Dyslexia is a life long condition (see section 1.3.1) and many children will continue to struggle in

University educations. However it appears from the literature review, that no study has investigated the binocular vision status in dyslexic adults and with those who have MIS. Therefore this study was designed to investigate the binocular vision status in dyslexic adults with and without MIS compared to each other and to the control group.

4.1.1 Aims and hypothesis

This study had the principal aims to investigate the following hypotheses regarding binocular visual dysfunction in dyslexia with and without Meares Irlen syndrome, in adult population.

1. Reduced vergence reserves and amplitudes and poor convergence are more common in dyslexic subjects with and without MIS, compared to controls.
2. Accommodative dysfunctions (reduced amplitude of accommodation and accommodation lag) are more common in dyslexic subjects with and without MIS.
3. Vergence instability is present more often in dyslexic group with and without MIS.
4. Dynamic visual functions (accommodative and vergence facility) are reduced in dyslexic subjects with and without MIS.

The secondary aims in the present study were:

1. To assess the link between accommodation and vergence system by investigating the relationship between amplitude of accommodation with the near point of convergence and vergence amplitudes.
2. To assess the relationship between visual stress scores with binocular vision functions that are expected to be correlated to visual stress, i.e. associated phoria at near, dissociated phoria at near, vergence amplitudes, binocular amplitude of accommodation and vergence stability.

4.2 Methods

4.2.1 Participants and recruitment

Three groups of volunteers were recruited – one group of controls, one group of adults with dyslexia, and a final group with dyslexia plus MIS.

1. *Students with dyslexia* were recruited initially by flyers or posters that were distributed in Cardiff University and via Student Support Centre at Cardiff University.

2. *Control subjects* were selected from the general student population at School of Optometry and Vision Sciences in Cardiff University who:

a) Had not reported, in the questionnaire of the previous study (Chapter 4), reading or spelling problems, or
b) Use coloured overlays or tinted lenses to help in reading or writing, or
c) Had not officially diagnosed with dyslexia and/or MIS.

4.2.2 Inclusion and exclusion criteria

Inclusion criteria for dyslexic subjects were being officially diagnosed with dyslexia (use colour filter to help in reading) and age between 18 and 38 years.
Exclusion criteria for all subjects (dyslexic and control) were having a history of migraine or severe headaches or photosensitive epilepsy. Subjects were also excluded if their monocular VA was worse than 6/7.5 or had unequal visual acuity between eyes (more than two lines), or strabismus.
Ethical approval was obtained from Cardiff School of Optometry and Vision Science Ethical Committee and all procedures follow the tenets of the Declaration of Helsinki.

Prior to the experiments, written informed consent was provided by all subjects after the methodology had been explained to them and the opportunity was given to the subjects to ask further questions.

4.2.3 Procedures

All tests were performed with the subject's habitual refractive correction in place and the room illumination was maintained at 500 lux, as measured using a Minolta illuminamce meter.

Screening tests included visual acuity and cover test assessment. Binocular vision tests formed the main investigations in this study.

4.2.3.1 Visual Acuity

This is the ability to resolve the smallest/critical detail with the appropriate refractive correction. Minimum angle of resolution at which a person's eye can discriminate the details and, therefore, identify a visual acuity test letter subtends 1 minute of arc (this is 6/6) at the nodal point of the eye (Davidson, 1991). The inverse amount of this angle is equivalent to VA measurement. For example, if angle of resolution of a letter is 2 minutes of arc equates to a VA of 6/12 or 0.50 decimal.

Visual acuity at distance is conventionally measured using a letter chart such as Snellen or LogMAR. Table 4.1 shows three different notation (Snellen (metric), Decimal, Log MAR) of visual acuity.

Snellen (metric)	Decimal	Log MAR
6/1.9	3.15	-0.5
6/2.4	2.50	-0.4
6/3	2.0	-0.3
6/3.8	1.6	-0.2
6/4.8	1.25	-0.1
6/6	1.00	0.0
6/7.5	0.80	0.1
6/9.5	0.63	0.2
6/12	0.50	0.3
6/15	0.40	0.4
6/19	0.32	0.5
6/24	0.25	0.6
6/30	0.20	0.7
6/38	0.16	0.8

Table 4.1: Distance visual acuity conversion table

In this study, the monocular visual acuity, with the subject's habitual correction was measured at distance of 6m and recorded using Log MAR chart notation. A LogMAR (National Vision Research Institute, Australia) chart was used in this study which is similar to that designed by Bailey and Lovie (Baily and Lovie, 1976). The chart consists of 14 lines of 5 letters each. Size of letters in each line is progressively reduced in 0.1 logarithmic units from 0.8 to -0.5 Log Mar unit. The largest and smallest line recorded on the chart was equivalent to VA of 6/38 and 6/1.9 in meter respectively. The chart was externally illuminated (730 Lux), with room illumination at 500 Lux.

4.2.3.2 Cover test

A unilateral cover test was carried out at distance (6 meters) and near (30 cm), in order to exclude subjects with strabismus. Subjects were asked to fixate (binocularly) a single letter on the line of the worst monocular VA on the LogMAR chart while one eye was covered for 2 seconds, and the non-covered eye was investigated for deviation (squint). The cover was removed for few seconds then the other eye was covered and the non covered eye was examined for the deviation. The same procedure was repeated at near while subject was fixating a detailed target shown on a near fixation stick.

Monocular visual acuity and cover test were considered as screening tests to exclude subjects with VA that worse than 0.2 Log Mar (equated to 6/7.5) and/or unequal visual acuity and subjects with strabismus.

4.2.3.3 Binocular vision tests

These were performed in a randomised order throughout the study to avoid any order effects.

Horizontal dissociated/associated heterophoria and fixation disparity tests were performed for both distance and near. However, vertical heterophoria was not assessed. It is acknowledged that convergence/divergence is an active mechanism and accommodative vergence refers to a blur-driven change in the horizontal alignment of the two eyes (Toates, 1974; Schor and Ciuffreda, 1983).

4.2.3.3.1 Horizontal dissociated heterophoria

Dissociated heterophoria, a latent deviation in visual axis, is present when the eyes are dissociated by simultaneously a different image to each eye which prevents fusion (Daum, 1991d; Evans, 2002b).

Near dissociated heterophoria was measured using a *Maddox Wing* from Clement Clarke international Ltd and according to Barrett and Elliott (Barrett and Elliott, 2007). The eyes are dissociated by means of a septum that allows the subject to view an arrow with one eye and a tangent scale with the other eye. Each number of the tangent scale represents 1 prism dioptre (Δ). Test working distance for Maddox Wing was 30cm.
Subjects were asked to report the number that the arrow pointed to on the horizontal scale. The reading was taken when subjects report a stable position of the arrow. In cases of unstable phoria, i.e. reading indicated by unstable arrow position, average reading of the highest and lowest reported values of phorias for that subject was taken.

Distant horizontal dissociated heterophoria was assessed at 6 meter with a *Maddox Rod* (MR). In this test the eyes are dissociated by means of Maddox rod: the MR is placed in front of the right eye and the subject views a spot of light at 6m. A vertical streak is seen by the right eye and a spot light is seen by the left eye (Evans, 2002b; Barrett and Elliott, 2007). The subject is required to report the position (both separation and direction) of the streak in relation to the spot light. The amount of the prism power required to align the streak and the spot light is equivalent to the size of distance heterophoria (Evans, 2002b; Barrett and Elliott, 2007).

4.2.3.3.2 Associated heterophoria at distance and near

In normal binocular vision when the image of an object in space is perceived simultaneously by the corresponding retinal points, it will be seen as a single perceptual image (Millodot, 1997). In fact, a single point on one (or either) retina, i.e. fovea, corresponds to a small retinal area in the other eye, i.e. centred on the fovea; this area is called Panum's area. Consequently a slight misalignment (over or under convergence) of one or both eyes within the Panum's area can occur whilst maintaining binocular single vision (Dowley, 1989; Goss, 1991; Evans, 2002b). Such a small misalignment is known as fixation disparity (FD). The prismatic power required to neutralize a fixation disparity is called the associated heterophoria (Mallett, 1974; Goss, 1991; Millodot, 1997). Therefore, associated heterophoria is an indicator of FD (Pickwell 1989). Fixation disparity is considered to be an indicator of a decompensated heterophoria that is most likely to occur when the binocular visual system is under stress (Mallett, 1974; Evans, 2002b).

A Mallet fixation disparity unit was used to assess the associated heterophoria at near and distance.
The Mallet unit consists of three adjacent marks (the letters OXO) that are seen binocularly (Goss, 1991; Evans, 2002b). The letters act as a central fusion lock, i.e. the central binocular fixation target (X) and para-foveal fixation lock (O's). In horizontal FD target and for assessment of horizontal associated heterophoria two vertical are viewed through Polaroid filters. The nonius lines are coloured green for near and red for distance, and each is seen with either eye through Polaroid filters; for horizontal measurements the bars are vertically in alignment with the central X, whereas in the vertical mallet unit the nonius bars are horizontally aligned (Goss, 1991; Evans, 2002b; Barrett and Elliott, 2007).

The subject was asked to fixate on the central X and to report if one of the nonius bars is not in alignment with X and the direction of the misalignment. If there is a misalignment present it will indicate of the existence of a FD and the magnitude of the associated heterophoria can be measured by placing the minimum amount of prism required to bring the nonius bars into alignment with X Prism measurement was in 0.5Δ or 1Δ steps, and remained on the deviated eye for subject judgment for less than 5 sec. to avoid prism adaptation (Schor, 1979; Evans, 2002b).
The working distance for the test was 40cm at near and 6 meter at distance, and the test was performed under normal room illumination (500 lux).

4.2.3.4 Near point of convergence

The near point of convergence (NPC) is the nearest point where the lines of sight intersect when the eyes converge (London, 1991a; Millodot, 1997), thus it give an indication of the subject's convergence ability (Barrett and Elliott, 2007).
The RAF Near point rule (Clement Clarke International) was used to measure the

NPC. The NPC target is a vertical line (25mm long by 0.5mm wide) with a central (2.0mm diameter black dot). The target was moved slowly along the rule at the midline towards the subject. The subject was asked to maintain a single image of the line as long as possible and the NPC was identified subjectively at the point where the subject report diplopia of the target. This point indicated that single binocular vision was broken down (the break point). The test was repeated three times and the average reading was recorded in (cm). Normal break point for our group population was taken to be equal to or better than 5 cm (Manny and Fern, 1997). In some subjects who did not report diplopia, the NPC was determined objectively as the point at which the observer saw an eye deviate (objective break point).

4.2.3.5 Prism vergence

Prism vergences are the magnitude of prism that can be placed before the eyes, while maintaining the fixation of a target located at a certain distance, without creating blurring or diplopia of the target (Evans, 2002b).

Fusional reserves is a term synonymous with prism vergence (Barrett and Elliott, 2007).

Fusional reserves can be positive or negative. Positive fusional reserves are measured using base out prisms placed in front of the eyes to induce convergence whereas the negative fusional reserves is measured using base in prisms placed in front of the eyes to induce divergence. Three measurements may be recorded as blur, break and recovery points. The prism before the eyes is gradually increased, initially, in order to maintain a clear single binocular vision, the vergence component which can be changed independently of accommodation will allow convergence or divergence to increase without causing blure of the target but when those components are exhausted, i.e. over-fatigued, then the accommodation will be induced, i.e. stimulated in forced convergence and relaxed in forced divergence, and the subject may notice blurred target image while single vision was still maintained, this is the blur point (Barrett and Elliott, 2007). As the prism is increased the subject will eventually report diplopia and this is known as the break point. At this point the vergence reserve are exhausted. As the prism power is gradually reduced the point when the subject regains single vision is known as the recovery point.

In this study, prism vergences at near were evaluated using prism bars (base in and then base out). Each subject was asked to fixate binocularly on a vertical line of 6/9 letters, shown on the near fixation stick, held by the subject at a distance of 40 cm. This detailed target was used so the blur, break and the recovery points could be more accurately reported by the subject.

While increasing the prism power of the prism bar, the subject was instructed to fixate on the vertical line and to report once the target was blurred and then the double image, then the amount of prism was reduced gradually until the subject report single vision again (the recovery point). Changing the prism amount was fast (every 2-3 seconds) to avoid prism adaptation (Sethi and North, 1987; Griffin and Grisham, 1995; Evans, 2002b). The expected normal values for near negative fusional reserves are at least 12/20/11 and for near positive fusional reserves are at least 15/19/8 for blur, break and recovery points respectively (Griffin and Grisham, 1995). Negative prism vergence was measured before the positive prism vergence to avoid the influence of exercising convergence component on the divergence ability (Pickwell, 1989).

4.2.3.6 Stereopsis

Stereopsis is referred to the ability to perceive the relative distance between the target and the observer (awareness of depth of perception) and it is a result of the lateral disparity of right and left retinal images (Cooper, 1991; Millodot, 1997). Thus, stereo acuity is the measurement of the minimum retinal image disparity the subject can perceive. It was reported that 96% of normal adult population have a stereoacuity of 40 seconds of arc (Cooper, 1991).

To measure stereo acuity, the Titmus stereo test was used (Rosner and Rosner, 1990; Cooper, 1991). The test consists of nine numbered diamonds, each of which contains four circles. One of the circles in each diamond should to stand forward from the other circles in its diamond when viewed through crossed polarized filters (at 45 and 135 degrees). Each consecutive higher number of diamonds required a higher level of stereo-acuity.

Subjects were instructed to wear the polarized filters over their usual refractive correction and hold the stereo test at 40cm as subject and report which circle appeared stand forward compared to the other circles. Stereo-acuity was recorded as the last correctly identified set of circles.

4.2.3.7 Accommodation Tests

Accommodation is the mechanism within the eye that results in a change of the refractive power. The refractive power of the eye is changed in order to attain a focused retinal image of an object at different distances. During accommodation the ciliary muscles attached to the crystalline lens contract. Accordingly, the shape of the crystalline lens would change, i.e. the anterior surface of the lens will move forward and give rise to a steep surface, i.e. increase the thickness of the lens centre and a steep curve of the lens surface, this equilibrium shape occurred when the lens has less stress from the ciliary muscles (Bennett and Rabbetts, 1989; Kaufman, 1992).

4.2.3.7.1 Amplitude of accommodation

Amplitude of accommodation (AA) is the maximum amount of accommodation that can be exerted by the eye (London, 1991b; Millodot, 1997; Barrett and Elliott, 2007).

This test can be measured subjectively by moving a small detailed target slowly and steadily toward subject's eye until the subject report blurring of the target. As the distance reduces, the angular size that the object subtends as a retinal image will increase, and hence increase the clarity of the target, even beyond where the accommodation mechanism of the crystalline lens and ciliary muscles has become saturated (the true amplitude of accommodation), therefore the measure of amplitude of accommodation is artifactually. This overestimating of AA, resulting from this 'push up' technique, can be limited by taking the average of the push-up and push-down techniques (where clarity is reported as the target is moved away) as the push down technique usually slightly under-estimates the value of AA (London, 1991b; Barrett and Elliott, 2007). The average between blur point and clear point (Evans, 2002b) can be calculated in cm (near point of accommodation) and then converted into dioptric power to give the total amount of accommodation available.

In this study AA was measured monocularly (right eye then left eye) and then binocularly using a RAF rule.

4.2.3.7.2 Accommodation response

The *Accommodation response* is the actual amount of accommodation exerted by subject's eye (Daum, 1991a) for a particular target at a given distance (Daum, 1991a; Barrett and Elliott, 2007).

Accommodation lag or lead is the amount of the under-action or overaction, respectively, of the accommodation response that is required for a particular near point target, i.e. it can be calculated as the different between the actual amount of accommodation and accommodation required for a dioptric stimulus of a particular near point (Cooper, 1987; Bennett and Rabbetts, 1989; Daum, 1991a; Barrett and Elliott, 2007). Hence it can be considered as an accommodative in-accuracy (Evans 2002). Accommodative lag indicates an under action of the accommodation required to focus a target of regard. Assessment of accommodative lag is useful in cases of subjects with a low amplitude accommodation (Evans, 2002b).

In the present study, accommodative lag was measured objectively by using the dynamic retinoscopy technique and monocular estimate method (MEM technique) (Evans, 2002b), carried out in a dim room with an additional overhead light to illuminate the near point target (N5) fixed at 40 cm on the RAF rule drum (Cooper, 1987; Barrett and Elliott, 2007).

While the subject wears their habitual distance correction, they were asked to view binocularly and try to maintain a clear image of target of regard. The amount of accommodation required to focus a target at 40cm is 2.5diopters; streak retinoscopy was carried out along the horizontal meridian as spherical lenses were briefly introduced in front of the eye to avoid the interruption of subject binocular accommodative response (Evans, 2002b; Barrett and Elliott, 2007).

During the procedure the subject was instructed to read out the printed line text to ensure accurate focus. If a 'with retinoscopy movement is seen the positive spherical lens that gives a neutral reflex represents the amount of accommodative lag. An accommodative lag of 0.50 D to 0.75D is considered normal for a test distance of 40 cm and ≥ 1.00D of lag indicates accommodative insufficiency (Daum, 1991a; Evans and Joseph, 2002).

A negative lens represents accommodative lead and indicates accommodation spasm (Daum, 1991a; Evans, 2002b) or significant exophoria (Daum, 1991a).

4.2.3.7.3 Accommodative facility

This test assesses the speed and ability to change accommodation and is also known as jump accommodation (Evans, 2002b) which reflects the quality of accommodation (Daum, 1991b; Barrett and Elliott, 2007). The inability of subject to change focus rapidly from near to distance (e.g. from book to the board) would indicate poor accommodative facility and this may cause visual discomfort and reduce vision efficiency, i.e. poor near/distance visual performance (Griffin and Grisham, 1995). Poor Accommodative facility can be present even when the other accommodation measures, i.e. amplitude of accommodation, are normal (Barrett and Elliott, 2007) and is considered a significant clinical factor in symptomatic subjects (Daum, 1991b; Gall and Wick, 2003; Barrett and Elliott, 2007).

The standard procedure used for this test is using a lens flipper method: +/-2.00 flipper lenses being the most commonly used (Daum, 1991b). The test can be carried out monocularly and binocularly. In this study, the binocular test was carried out as reading is normally a binocular task.

A near fixation stick was held by the subject at a distance of 40 cm at the same level as the eye, and the subject was asked to view a horizontal line of letters (one line larger than the best line he can see at near distance of 40 cm) through the habitual distance correction. The binocular +/2.00 DS flipper was introduced before the subject's eyes, +2.00 lenses was introduced first, and the subject was asked to indicate when the target appears clear by stating "yes" or "clear". The flipper is then flipped quickly to the minus lenses and again the subject was instructed to report once the letters appear clear again. This procedure was repeated for one minute. The change in the visual response from +2.00 to - 2.00 and back to +2.00 was counted as one cycle and the number of cycles per minute (cpm) was calculated. For a test method using a ±2.00 lens flipper with 40cm working distance, a cut-off criterion of 7.7 cpm (± 5cpm) is considered normal (Evans 2002b). This test procedure is considered to be significant in detecting accommodative facility anomalies (Daum, 1991b).

4.2.3.7.4 Vergence facility at near

This test evaluates the dynamics of fusional vergence system and its ability to respond rapidly and smoothly to a prismatic stimulus over a specific period of time without changing the accommodation (Daum, 1991c; Barrett and Elliott, 2007). Flexibility of the vergence system is important for comfortable binocular vision. The larger the value of vergence facility the more flexible the binocular visual system (Daum, 1991c).

It has been suggested that vergence facility should be evaluated in symptomatic subjects with binocular vision disorders (Gall, Wick and Bedell, 1998; Gall and Wick, 2003; Barrett and Elliott, 2007). Although such subjects may have normal fusional vergence amplitude, they can still have reduced vergence facility (Barrett and Elliott, 2007).

The recommended binocular prism flipper powers at near (40cm) are 3ΔBI/12ΔBO, as it has been found to have repeatable results and able to distinguish between symptomatic and a symptomatic groups with failure criterion of 15 cpm at near, (Gall et al., 1998; Barrett and Elliott, 2007). The test procedure was performed in a similar manner to measuring accommodative facility at 40cm. The subject was asked to view letters one line larger than the best line that he can see at 40 cm through the habitual distance correction. The subject was asked to indicate when the letters appear clear and single when 12 BO prism was introduced and then to report immediately once the letters are single and clear through the 3 BI prism. The change in vergence response from the positive fusional vergence (induced with BO prism) to negative fusional vergence (induced with BI prism) counted as one cycle. The number of cycles per minute were computed and recorded in cpm.

4.2.4 Statistical analysis

SPSS (version 16, SPSS inc Chicago, Illinois, USA) statistical computer program was used to;

1- Provide a statistical description of the studied subjects (age and gender).

2- Evaluate binocular visual function amongst the three subject groups (dyslexics without MIS, dyslexics with MIS and control group) using analysis of variance (ANOVA) and Post Hoc test.

3- Evaluate the relationship between binocular visual function variables using Pearson correlation.

Kolmogorov-Smirnov tests were used to evaluate the normality of the data. Data is considered not normally distributed when $p<0.05$.

In the present study both parametric (ANOVA-between groups) and non-parametric (Kruskal-Wallis) tests were employed. However the preferred method of analysis here was to use ANOVA in order to utilise the advantages of the one step Post Hoc testing and to avoid time consuming and potential test bias by using manual multiple comparisons i.e. using three tests of Mann-Whitney U-test, in each of which 5% chance of failed result is usually accepted ($p<0.05$) and that indicating that the test is facing probability of false result of 15%. This problem can be reconciled by using ANOVA which enable to detect significant differences between means of the three groups as a whole and provide an automatic single test of multiple comparison, using the post-hoc 'Tukey' multiple comparison technique to identify between which groups the significant difference is taking place by employing a single chosen probability value ($p<0.05$), whereas there is no post-hoc option available for Kruskal-Wallis test (Chan, 2003). In addition the non-parametric test is considered to be less sensitive than the corresponding parametric tests and hence they may not detect the same differences between groups as parametric tests do (Vickers, 2005) implying that ANOVA is more robust in specifying data outcomes. Furthermore, using means in the results of health clinical data reflects a clear relevant figure compared to medians (Thompson and Barber, 2000; Vickers, 2005; Altman and Bland, 2009) and therefore a better guideline for the right conclusion (Thompson and Barber, 2000).

4.3 Results

The dyslexic subject group compromised 56 students who were then divided into two groups according to the presence or absence of MIS. Dyslexic subjects without MIS consisted of 29 students, 15 (52%) of whom where female. Dyslexic subjects with MIS comprised 27 students, 16 (59%) of whom were female and in the control group there were 33 students, 22 (67%) of whom were female. Table 4.2 shows the three groups' distributions.

Group	N	Male/Female	Age (SD)
Dyslexia	29	14/15	23.0(5.1)
Deslexia with MIS	27	11/16	24.3(5.6)
Control	33	11/22	23.7(5.0)

Table 4.2: Three subjects groups' distributions.

4.3.1 Results from screening tests

4.3.1.1 Visual acuity

Results showed no significant difference between right and left eye visual acuities using independent samples t-test (p>0.05) within each group. Amongst the three groups, ANOVA between groups test showed no significant differences of the visual acuities of the right and/or the left eye between the three groups. Descriptive and comparative statistical analysis of monocular visual acuity within and between groups is shown in tables 4.3 and 4.4 respectively.

	N	Right eye Mean (SD)	Left eye Mean (SD)	Mean Difference	P value (2-tailed)
Dyslexic	29	-0.032 (0.08)	-0.015 (0.07)	-0.016	0.403
Dyslexic+MIS	27	-0.033 (0.07)	-0.026 (0.05)	-0.006	0.690
Control	33	-0.027 (0.08)	-0.013 (0.08)	-0.013	0.490

Table 4.3: Descriptive and comparative statistics of monocular visual acuity within each group.

	Group	N	Mean (SD)	P value ANOVA
VA (RE)	**1. Dyslexic**	29	-0.032 (0.08)	0.95
	2.Dyslexic+MIS	27	-0.033 (0.07)	
	3.Control	33	-0.027 (0.08)	
VA (LE)	**1. Dyslexic**	29	-0.015 (0.07)	0.71
	2.Dyslexic+MIS	27	-0.026 (0.05)	
	3.Control	33	-0.013 (0.08)	

Table 4.4: Descriptive and comparative statistics of monocular visual acuity (in logMAR notation) between the three groups.

4.3.1.2 Cover test

Cover test confirmed that none of the subjects recruited presented with strabismus.

4.3.2 Results from binocular vision function tests

4.3.2.1 Stereo-acuity

Analysis with ANOVA test showed that there was no significant difference between the three groups (P =0.517). Descriptive and comparative statistics are shown in table 4.5.

	Group	N	Mean (SD)	P value ANOVA
Stereo-acuity	**1. Dyslexic**	29	41.72 (5.39)	0.52
	2.Dyslexic+MIS	27	43.70 (8.84)	
	3.Control	33	41.81 (7.27)	

Table 4.5: Descriptive and comparative statistics of stereo acuity between the three groups.

4.3.2.2 Associated heterophoria

Associated heterophoria measurements at near and distance were investigated and analysed in the three groups in two ways; firstly, comparing the actual measured values between the three groups by considering the relative incidence of esophoria (recorded as a positive signs) and exophoria (recorded as a negative signs) and secondly, the magnitude of deviation (regardless the direction of heterophoria) was investigated by evaluating the absolute value of heterophoria measurements. The descriptive and comparative statistics of the associated heterophoria at distant and near are summarised in table 4.6.

	Group	N	Mean (SD)	P value ANOVA	Mean difference	P value Post-Hoc
AP (near) Actual value	**1. Dyslexic**	29	-0.88 (1.10)	0.028	1-2= -1.21	0.022
	2.Dyslexic+MIS	27	0.33 (2.37)		1-3= -0.68	0.249
	3.Control	33	-0.20 (1.37)		2-3= 0.53	0.442
AP (near) Absolute value	**1. Dyslexic**	29	0.88 (1.09)	0.074	1-2= -0.57	0.307
	2.Dyslexic+MIS	27	1.44 (1.88)		1-3= 0.29	0.709
	3.Control	33	0.59 (1.25)		2-3= 0.85	0.061
AP (distance) Actual value	**1. Dyslexic**	29	-0.12 (1.11)	0.114	1-2= -0.66	0.192
	2.Dyslexic+MIS	27	0.54 (1.88)		1-3= 0.05	0.991
	3.Control	33	-0.17 (1.16)		2-3= 0.70	0.136
AP (distance) Absolute value	**1. Dyslexic**	29	0.67 (0.88)	0.162	1-2= -0.46	0.324
	2.Dyslexic+MIS	27	1.13 (1.59)		1-3= 0.11	0.927
	3.Control	33	0.56 (1.02)		2-3= 0.57	0.160

Table 4.6: Descriptive and comparative statistics of associated heterophoria at near and distance (in Δ) between the three groups.

The result shows that there was a significant difference between the means of the actual values for AP at near between the three groups (P=0.028). The Dyslexia with MIS group tended to exhibit higher esophoria at both distance and near while dyslexia group without MIS exhibited a higher value of exo-deviation at distance and near. The Dyslexia with MIS group exhibited the larger absolute value of the measurement, at distance and near, followed by the dyslexic group. However there was no significant difference between the absolute value in the three groups (although a borderline significance p=0.061 is shown between dyslexia with MIS and the control group).

4.3.2.3 Dissociated heterophoria

Similar to the associated heterophoria analysis, dissociated heterophoria measurements at near and distance were investigated and analysed in the three groups in two ways; firstly, comparing the actual measured values between the three groups by considering the relative incidence of esophoria (recorded as a positive signs) and exophoria (recorded as a negative signs) and secondly, the magnitude of deviation (regardless the direction of heterophoria) was investigated by evaluating the absolute value of heterophoria measurements. The descriptive and comparative statistics of the dissociated heterophoria at distant and near are shown in table 4.7.

	Group	N	Mean (SD)	P value ANOVA
DP (near) Actual value	1. Dyslexic	29	-2.53 (4.42)	0.140
	2.Dyslexic+MIS	27	-0.52 (2.97)	
	3.Control	33	-1.52 (3.53)	
DP (near) Absolute value	1. Dyslexic	29	2.81 (4.11)	0.514
	2.Dyslexic+MIS	27	1.81 (2.39)	
	3.Control	33	2.06 (3.23)	
DP (distance) Actual value	1. Dyslexic	29	-0.26 (2.94)	0.512
	2.Dyslexic+MIS	27	0.56 (2.35)	
	3.Control	33	0.42 (2.94)	
DP (distance) Absolute value	1. Dyslexic	29	2.02 (2.12)	0.679
	2.Dyslexic+MIS	27	1.59 (1.79)	
	3.Control	33	2.00 (2.17)	

Table 4.7: Descriptive and comparative statistics of dissociated heterophoria at near and distance (in Δ) between the three groups.

The results show that the dyslexia without MIS group exhibited larger exophoria at near and distance, as postulated by means in actual value, but there was no significant difference between the measurements in the three groups. Dyslexia without MIS group exhibited the larger absolute value of the measurement, at distance and near, followed by the control group, but similarly there was no significant difference between the absolute value in the three groups.

4.3.2.4 Stability of associated and dissociated heterophoria

4.3.2.4.1 *Stability of associated heterophoria*

Stability of associated heterophoria at near was investigated by using Chi-Square test for independence by applying a Cross-tabulation test that evaluates the association between two categorical variables with two or more categories in each i.e. stability of Nonius lines in the Mallet unit, stable (equivalent to zero score) or unstable (equivalent to 1 score) at near and the population case (dyslexia, dyslexia with MIS, control). An associated heterophoria was considered to be unstable if the subject reported flickering and/or constant movement of one or both Nonius lines.
Table 4.8 shows the incidence of instability of AP and Chi-Square p-value.

	N	Count	%	Chi-Square value	P-value (2-sided)
Dyslexic	29	7	24.1	13.889	0.001
Dyslexic+MIS	27	10	37.0		
Control	33	0	0		

Table 4.8: Incidence of the presence of AP instability Chi-Square correlation.

ANOVA testing indicated a significant difference between the stability of associated heterophoria at near between the three groups. This means, there was significant association between the stability of associated heterophoria at near and the group case identified as dyslexia, dyslexia with MIS and control.

In terms of stability of the AP, the Chi-Square test with continuity correction found no significant difference between the dyslexic with/without MIS groups, while there was a significant difference between the whole dyslexic group (dyslexic + dyslexics with MIS, N=56) and control group (Table 4.9), thus indicating there was association between the stability of AP (instability of Nonius lines in Mallet unit) and dyslexia.

	Chi-Square value	Continuity correction	P value (2-sided)
(Dyslexic) VS (Dyslexia + MIS)	1.10	0.58	0.45
(Dyslexic) & (Dyslexia + MIS) VS (Control)	12.38	10.49	0.001

Table 4.9: Association between instability of Nonius lines and group population

4.3.2.4.2 *Stability of dissociated heterophoria*

Stability of dissociated heterophoria at near was investigated in the same way using stability of arrow in Maddox Wing (stable=0 or unstable=1) at near and the population case (dyslexia, dyslexia with MIS, control) in the Chi-Square test. Table 4.10 shows the incidence of instability of arrow and Chi-Square p-value.

	N	Count	%	Chi-Square value	P value (2-sided)
Dyslexic	29	6	20.7	16.02	0.000
Dyslexic+MIS	27	11	40.7		
Control	33	0	0.00		

Table 4.10: Incidence of instability of arrow and Chi-Square correlation

The significant p-value indicates there was significant difference between stability of associated heterophoria at near in the three group population. This means there was a significant association between stability of dissociated heterophoria at near and the group case. In terms of stability of arrow of Maddox Wing, Chi-Square value with continuity correction found no significant difference between the dyslexic with/without MIS groups. However there was a significant difference between the incidence of instability in whole dyslexic group (dyslexic + dyslexics with MIS, N=56) compared with controls n=33 (Table 4.11).

	Chi-Square value	Continuity correction	P value (2-sided)
(Dyslexic) VS (Dyslexia + MIS)	2.66	1.79	0.180
(Dyslexic) & (Dyslexia + MIS) VS (Control)	12.38	10.49	0.001

Table 4.11: Association between instability arrow and group population.

4.3.2.5 Prism vergences at near

Almost all subjects were unable to detect a blur point so the analysis uses values for break and recovery points only.

4.3.2.5.1 Positive and negative prism vergences

Descriptive and comparative statistics for the positive and negative prism vergences in the three groups are illustrated in table 4.12. ANOVA testing revealed significant differences amongst the three groups for the positive vergences (break and recovery points). These differences were clearly between dyslexic and control groups where both dyslexia and dyslexia with MIS group exhibited significantly reduced mean values for break and recovery point of positive vergence reserves, compared to the control group. There was no significant difference for the negative prism vergence between the three groups.

	Group	N	Mean (SD)	P value ANOVA	Mean difference	P value Post-Hoc
BO (break)	1. Dyslexic	29	26.41 (13.28)	0.02	1-2= -0.18	0.99
	2.Dyslexic+MIS	27	26.41 (14.04)		1-3= -9.46	0.04
	3.Control	33	35.88 (17.29		2-3= -9.29	0.05
BO (recovery)	1. Dyslexic	29	17.41 (10.54)	0.002	1-2= -0.48	0.99
	2.Dyslexic+MIS	27	17.89 (9.81)		1-3= -9.79	0.01
	3.Control	33	27.21 (14.66)		2-3= -9.32	0.01
BI (break)	1. Dyslexic	29	17.97 (5.99)	0.42	1-2= 1.15	0.77
	2.Dyslexic+MIS	27	16.81 (6.59)		1-3= 2.12	0.39
	3.Control	33	15.85 (6.29)		2-3= 0.97	0.83
BI (recovery)	1. Dyslexic	29	12.86 (5.33)	0.22	1-2= 0.53	0.93
	2.Dyslexic+MIS	27	12.33 (5.37)		1-3= 2.26	0.23
	3.Control	33	10.61 (5.34)		2-3= 1.73	0.43

Table 4.12: Descriptive and comparative statistics for positive and negative prism vergences (in Δ) in the three groups.

4.3.2.5.2 Prism vergence amplitudes

Differences between base out and base in, for break and recovery points, were computed as vergence amplitudes. Descriptive and comparative statistics for break and recovery point vergence amplitudes in the three group population are illustrated in table 4.13. Control tended to have larger amplitudes of prism vergence (break and recovery).

The ANOVA test found significant differences between the vergence recovery points in the three groups (p=0.04). Dyslexic and dyslexia with MIS groups tends to have clearly reduced recovery values compared to the control group. The mean break point vergence amplitude was greater in the control group than in the dyslexic and dyslexic with MIS group. However ANOVA test found no significant difference between the break point vergence amplitude in the three groups.

	Group	N	Mean (SD)	P value ANOVA	Mean difference	P value Post-Hoc
Break Amplitude (Δ)	**1. Dyslexic**	29	44.38 (16.51)	0.13	1-2= 0.97	0.98
	2.Dyslexic+MIS	27	43.22 (16.76)		1-3= -7.35	0.23
	3.Control	33	51.73 (18.61)		2-3= -8.32	0.16
Recovery Amplitude (Δ)	**1. Dyslexic**	29	30.28 (13.24)	0.04	1-2= 0.05	1.00
	2.Dyslexic+MIS	27	30.22 (12.06)		1-3= -7.54	0.07
	3.Control	33	37.82 (14.49)		2-3= -7.59	0.08

Table 4.13: Descriptive and comparative statistics for break and recovery point vergence amplitudes (in Δ) in the three groups.

4.3.2.6 Near point of convergence

Descriptive and comparative statistics (Table 4.14) showed that dyslexia with MIS group exhibited a more distal NPC followed by dyslexia without MIS group. ANOVA found significant differences between the NPC in thee groups (p= .047) with the dyslexia with MIS and the control group being significantly different between dyslexia with MIS and control groups.

	Group	N	Mean (SD)	P value ANOVA	Mean difference	P value Post-Hoc
NPC (cm)	**1. Dyslexic**	29	7.00 (3.64)	0.047	1-2= -2.04	0.12
	2.Dyslexic+MIS	27	9.02 (4.77)		1-3= 0.29	0.95
	3.Control	33	6.71 (2.93)		2-3= 2.32	0.05

Table 4.14: Descriptive and comparative statistics for NPC (in cm) in the three group population

4.3.2.7 Accommodation Test

4.3. 2.7.1 Monocular and binocular amplitude of accommodation

Descriptive and comparative statistics (Table 4.15) showed that subjects with dyslexia and MIS exhibited significantly worse monocular amplitudes of accommodation, than both the dyslexia without MIS and control groups, and worse binocular amplitudes than the control group. There was no significant difference between the binocular amplitude of the dyslexic groups.

	Group	N	Mean (SD)	P value ANOVA	Mean difference	P value Post-Hoc
A/A (RE) (D)	1. Dyslexic	29	8.53 (2.38)	0.005	1-2= 1.68	0.008
	2.Dyslexic+MIS	27	6.84 (1.71)		1-3= 0.20	0.92
	3.Control	33	8.33 (2.01)		2-3= -1.48	0.018
A/A (LE) (D)	1. Dyslexic	29	8.52 (2.41)	0.004	1-2= 1.65	0.012
	2.Dyslexic+MIS	27	6.87 (1.79)		1-3= -0.05	0.99
	3.Control	33	8.57 (2.08)		2-3= -1.69	0.007
A/A (BE) (D)	1. Dyslexic	29	8.46 (2.30)	0.005	1-2= 1.11	0.11
	2.Dyslexic+MIS	27	7.34 (1.61)		1-3= -0.63	0.44
	3.Control	33	9.09 (2.07)		2-3= -1.75	0.004

Table 4.15: Descriptive and comparative statistics for amplitude of accommodation of right eye (RE), left eye (LE) and both eyes (BE) (in dioptres) in the three group population.

4.3.2.7.2 Accommodation lag

Result shows no significant under or over accommodation in the three groups. Statistical analysis found no significant difference between the measures in the three groups. Descriptive and comparative statistics are shown in table 4.16.

	Group	N	Mean (SD)	P value ANOVA
Accommodation Lag (D)	1. Dyslexic	29	0.17 (0.26)	0.83
	2.Dyslexic+MIS	27	0.17 (0.53)	
	3.Control	33	0.23 (0.47)	

Table 4.16: Descriptive and comparative statistics for accommodation lag (in spherical lens power) in the three groups.

4.3.2.8 Dynamic binocular visual functions

4.3.2.8.1 *Accommodative facility*

The descriptive and comparative statistics (Table 4.17) show that control group performed faster in dynamic accommodation than dyslexic population with and without MIS who exhibited equal number of cycles/minute. ANOVA found no significant difference between number of cycles per minute in the three groups (p= 0.23).

	Group	N	Mean (SD)	P value ANOVA
Accommodation Facility (cpm)	**1. Dyslexic**	29	7.95 (5.70)	0.23
	2.Dyslexic+MIS	27	7.17 (4.83)	
	3.Control	33	9.48 (4.49)	

Table 4.17: Descriptive and comparative statistics accommodation facility (cycle/min) in the three group population

4.3.2.8.2 Vergence facility

Results show that the three groups demonstrated similar dynamic vergence facility. ANOVA found no significant difference in number of cycles per minute between the three groups (p= 0.63). The descriptive and comparative statistics are shown in table 4.18.

	Group	N	Mean (SD)	P value ANOVA
Vergence Facility (cpm)	**1. Dyslexic**	29	13.71 (4.19)	0.63
	2.Dyslexic+MIS	27	13.91 (4.08)	
	3.Control	33	14.67 (4.11)	

Table 4.18: Descriptive and comparative statistics vergence facility (cycle/min) in the three group population

The significant findings of BV measure(s) between groups are summarised in table 4.19.

BV measure	Group	P value ANOVA	P value Post-Hoc
Associated phoria at near actual value (Δ)	**1. Dyslexic**	0.028	0.022
	2.Dyslexic+MIS		0.249
	3.Control		0.442
Base out Prism vergence to break point (Δ)	**1. Dyslexic**	0.02	0.99
	2.Dyslexic+MIS		0.04
	3.Control		0.05
Base out Prism vergence to recovery point (Δ)	**1. Dyslexic**	0.002	0.99
	2.Dyslexic+MIS		0.01
	3.Control		0.01
Prism vergence amplitude (measured to both recovery points) (Δ)	**1. Dyslexic**	0.041	1.00
	2.Dyslexic+MIS		0.07
	3.Control		0.08
Near points of convergence (cm)	**1. Dyslexic**	0.047	0.12
	2.Dyslexic+MIS		0.95
	3.Control		0.05
Amplitude of accommodation (RE) (D)	**1. Dyslexic**	0.005	0.008
	2.Dyslexic+MIS		0.92
	3.Control		0.018
Amplitude of accommodation (LE) (D)	**1. Dyslexic**	0.004	0.012
	2.Dyslexic+MIS		0.99
	3.Control		0.007
Amplitude of accommodation (BE) (D)	**1. Dyslexic**	0.005	0.11
	2.Dyslexic+MIS		0.44
	3.Control		0.004

Table 4.19: Summary table of significant BV findings.

4.3.3 Secondary analysis (correlations)

4.3.3.1 Amplitude of accommodation

Due to the close link between accommodation and vergence (Bennett and Rabbetts, 1989) and due to the reduced binocular amplitude of accommodation found in dyslexia with MIS group, correlations between binocular amplitude of accommodation and two binocular vision variables; near point of convergence and vergence amplitudes (break and recovery points) were investigated (Table 4.20). These correlations were calculated for each subject group separately and for combined of dyslexic groups and for all subjects.

Correlation	Group	N	Correlation	
			r	p
A/A(BE) & NPC	All dyslexic	56	-0.44	0.001
	Dyslexia only	29	-0.38	0.041
	Dyslexia with MIS	27	-0.47	0.013
	Control	33	-0.25	0.166
A/A (BE) & Vergence Amplitude (Break/Recovery)	All dyslexic	56	0.27/0.36	0.041/ 0.007
	Dyslexia only	29	0.56/0.59	0.002/ 0.001
	Dyslexia with MIS	27	-0.14/ -0.002	0.474/ 0.992
	Control	33	0.03/ 0.03	0.890/ 0.892

Table 4.20: Correlations between A/A (amplitude of accommodation), and NPC and vergence amplitudes (measured to recovery points). "r" represents Person correlation coefficient, the significance of which is given by the adjacent "p" value.

Table 4.20 shows a significant negative correlation between amplitude of accommodation and near point of convergence in the dyslexic groups, but not in the control groups. As amplitude of accommodation increases in dyslexic individuals, the NPC appears to decrease. A significant positive correlation was observed between the amplitude of accommodation and vergence amplitude (measured between both recovery points) in the dyslexic group, but not in controls or in subjects with dyslexia and MIS.

4.3.3.2 Vergence stability in principle

The correlation (Spearman correlation coefficients) between vergence stability and dissociated phoria at near, near point of convergence, vergence amplitudes, and amplitude of accommodation is shown in table 4.21. The correlation was not possible for control group as the incidence of instability reported by the controls was zero.

Correlations	Group	N	Correlation	
			r	p
Vergence stability & DP (near)	All dyslexic	56	-0.37	0.005
	Dyslexia only	29	-0.66	0.00
	Dyslexia with MIS	27	0.23	0.24
Vergence stability & NPC	All dyslexic	56	0.01	0.92
	Dyslexia only	29	0.16	0.41
	Dyslexia with MIS	27	-0.13	0.53
Vergence stability & Vergence Amplitude Break/ Recovery	All dyslexic	56	-0.21/ -0.26	0.13/ 0.06
	Dyslexia only	29	-0.31/ -0.24	0.11/0.21
	Dyslexia with MIS	27	-0.09/ -0.31	0.65/0.12
Vergence stability & A/A(BE)	All dyslexic	56	-0.29	0.03
	Dyslexia only	29	-0.22	0.25
	Dyslexia with MIS	27	-0.28	0.16

Table 4.21: Correlation between presence/absence of vergence stability and (DP) dissociated phoria at near, NPC (near point of convergence) Ver. Amp. (Vergence amplitudes) break and recovery points and A/A (amplitude of accommodation).
"r" represents Spearman correlation coefficient, the significant of which is given by the adjacent "p" value.

Results from table 4.21 showed highly significant correlations between vergence instability and dissociated phoria at near in the dyslexic group. The correlation reflects increase in vergence instability with increased of exophoric deviation at near. Dyslexic with MIS group showed positive association between vergence instability and increased esophoria at near, but this correlation did not reach statistical significance.

There was no significant correlation between vergence stability and NPC or vergence amplitudes in any group. There was a tendency of reduced amplitude of accommodation with increased vergence instability; this correlation reached significance only in the combined dyslexic group but not for each group separately.

4.3.3.3 Visual stress scores (VSS)

Visual stress scores (VSS) calculated according to the method described in chapter 3 and used in further investigation to calculate the Pearson correlation coefficient between VSS and the binocular vision variables that might be expected to be associated with visual stress: associated phoria (AP) at near, dissociated phoria (DP) at near, vergence amplitudes (break and recovery points), amplitude of accommodation (A/A), near point of convergence (NPC), and finally the correlation between VSS and vergence stability was calculated by Spearman correlation coefficient (Table 4.22). VSS are not available for the control group as the CASQAD is not valid for this group.

Correlations	Group	N	Correlation	
			r	p
VSS. & AP (near)	All dyslexic	56	0.20	0.14
	Dyslexia only	29	-0.055	0.78
	Dyslexia with MIS	27	-0.03	0.89
VSS. & DP (near)	All dyslexic	56	0.04	0.75
	Dyslexia only	29	-0.34	0.07
	Dyslexia with MIS	27	-0.05	0.80
VSS. & Vergence Amplitude Break/Recovery	All dyslexic	56	-0.08/ -0.08	0.56/0.56
	Dyslexia only	29	-0.12/ -0.06	0.53/0.76
	Dyslexia with MIS	27	-0.06/ -0.16	0.78/0.44
VSS. & A/A(BE)	All dyslexic	56	-0.28	0.04
	Dyslexia only	29	-0.23	0.23
	Dyslexia with MIS	27	-0.02	0.92
VSS. & NPC	All dyslexic	56	0.17	0.22
	Dyslexia only	29	0.06	0.77
	Dyslexia with MIS	27	-0.03	0.87
VSS. & Vergence stability	All dyslexic	56	0.25	0.06¥
	Dyslexia only	29	0.20	0.29¥
	Dyslexia with MIS	27	0.15	0.47¥

Table 4.22: Correlations between VSS (visual stress scores) and AP (associated phoria at near), DP (dissociated phoria at near) Ver. Amp. (Vergence amplitudes) break and recovery points, A/A (amplitude of accommodation), NPC (near point of convergence) and vergence stability. ("r" represents Pearson correlation coefficient, the significant of which is given by the adjacent "p" value), ¥ indicates Spearman correlation.

Table 4.22 shows that VSS did not significantly correlate with any of the binocular vision variables, apart from binocular amplitude of accommodation. Lower amplitudes of accommodation were associated with higher visual stress scores (p=0.04). Similarly, findings show that there might be a tendency of higher visual stress scores to be correlated positively with unstable response in Maddox Wing test; this correlation approached a borderline significance in combined group only.

4.4 Discussion

The proportion of male and females with dyslexia in this study is approximately equal (45% and 55% respectively) which agrees with several studies on the incidence of dyslexia who found that boys and girls are affected almost equally (Shaywitz et al., 1990; Flynn and Rahbar, 1994; Feldman et al., 1995; Waring et al., 1996; Moores et al., 1998). These findings conflict with those reports that dyslexia is more common in boys than girls (Critchley, 1970; Rutter and Yule, 1975; Bishop et al., 1979; Finucc and Childs, 1981; Ygge et al., 1993a; Evans, 2002a). However, the gender proportion in this study may not be representative of the adult students with dyslexia given the relatively small sample size.

In the statistical data analysis of binocular visual functions the aim was to determine whether the involvement of MIS would complicate the dyslexic condition and therefore increase the difficulties with tasks related to academic study. There was no statistically significant difference in stereo-acuity level between the three groups. This result did not support the present hypothesis and the previous studies where findings suggested that dyslexic population with (Evans et al., 1995; Evans et al., 1996b) or without MIS (Dunlop et al., 1973; Bedwell, Grant and McKeown, 1980; Riddle et al., 1987) may exhibit reduced stereopsis compared to controls. Although, several other studies have reported no relationship between reading performance and stereo acuity, and there was no significant difference between the dyslexic and control group at the level of stereo acuity (Buzzelli, 1991; Ygge et al., 1993a; Latvala et al., 1994; Evans et al., 1994a).

Data on associated heterophoria suggested that when MIS is not involved in dyslexia, the measure shows more exophoria at near while, in contrary to which was expected, dyslexic cases with MIS showed more esophoria at near which was significantly different from subjects without MIS. It is well established that MIS is the condition characterised with visual distortion and visual stress symptoms that can be alleviated with the use of individually prescribed coloured filters (Evans et al., 1995; Evans et al., 1996b; Jeans et al., 1997; Wilkins, 2001; Evans and Joseph, 2002; Evans, 2002a). The results are contrary to the commonly held belief that greater degrees of exo-fixation disparity (associated heterophoria) are usually associated with higher degrees of visual stress symptoms (Mallett, 1974; Jenkins, Pickwell and Yekta, 1989;

Jaschinski and Dr-Ing, 2002; Evans, 2002b; Karania and Evans, 2006). However, in a study of university students, it was suggested that a relationship between higher levels of exo fixation disparity and the good reading performance and academic success, while eso-fixation disparity was associated with poor reading skills (Silbiger and Woolf, 1968). It is of interest to note that with the larger absolute value of associated phoria at near and distance, this value reached to borderline significance when compared to controls at near and this may explain in somehow the severity of symptoms in dyslexia with MIS. Comparing dyslexic with control group, Holland (1987) also found differences in the type and degree of associated heterophoria (Holland, 1987). In the present study, there was no significant differences between the two groups, in agreement with Evans who studied dyslexic children (Evans et al., 1994a). The proposed hypothesis in the present study that dyslexic subjects are more likely to show exo-associated phoria at near than control subject was not supported in dyslexic subject who also had MIS.

The results regarding dissociated heterophoria, at near and at distance, revealed no significant differences between the three groups. These results did not support the hypothesis that dyslexic subjects with or without MIS would exhibit more exophoria at near compared to controls. In studies comparing dyslexic children with control groups using similar test at near (Maddox Wing) and cover test at distance, similar results were reported (Latvala et al., 1994; Evans et al., 1994a; Evans et al., 1996a; Bucci and Kapoula, 2008). However, using a different test (cover test), it has been previously reported that dyslexia is associated with exophoria at near (Anapolle, 1971; Evans et al., 1992a), which was categorized as a convergence insufficiency type of exo-deviation (Latvala et al., 1994). However, Ygge, using a cover test at near, found no statistically significant difference between dyslexic and control children (Ygge et al., 1993a).

Weakness in the binocular control vergence system would lead the subject to require extra effort for near tasks (e.g. reading) in order to maintain comfortable single binocular vision which may result in visual stress symptoms that contribute to reading difficulties. Results regarding heterophoria stability at near showed that the dyslexic subjects exhibited significantly reduced stability of arrow in the Maddox Wing test while all controls reported a stable measure. Twice as many the dyslexic subjects with MIS reported instability compared to those without MIS. This is perhaps attributed to the perceptual distortion symptoms that are usually associated with subjects with MIS. As has been described in detail in section 1.9.4 of this thesis, binocular instability (represented by an unstable heterophoria at near demonstrated by an excessive movement of arrow in the Maddox Wing test) (Giles, 1960) has been widely reported in dyslexic subjects (Evans et al., 1994a; Evans et al., 1996a; Evans, 1998, 1999; Evans et al., 1999; Evans, 2002a, 2004b).

Instability of the nonius lines in the Mallet unit test (a combined indicator of sensory and motor instability) was reported in dyslexic subjects (more in dyslexia with MIS) whilst in none of the controls. These results support the hypothesis that vergence instability is present more often in dyslexia subject with or without MIS. Evans and colleagues, using a similar procedure, found no significant difference of nonius line stability between a dyslexic and control groups but this was in children (Evans et al., 1994a). Poor vergence control and poor stability of fixation during reading may contribute to reading difficulty by interfering with the precise visual localization process required during reading (Stein and Fowler, 1985; Stein et al., 1988; Stein, 1989 a; Stein and Fowler, 1993; Eden et al., 1994; Bucci and Kapoula, 2008), and therefore creating reading errors and visual confusion such as blurring and moving letters (Cornelissen et al., 1991; Stein et al., 2000a). Stein suggested that poor binocular control and visual perceptual instability when the eyes converge at near i.e. at 30 cm, is attributed to the deficit of magnocellular system in dyslexia which is responsible for timing visual events during reading (Stein, 2001).

Commonly, binocular instability can be described by the presence of unstable heterophoria combined with reduced vergence reserves (Eden et al., 1994; Evans et al., 1994a; Evans et al., 1996a; Evans, 1998, 1999; Evans, 2002a). Data on vergence reserves in the present study supported these clinical findings with significantly reduced positive vergence reserves in dyslexia groups with and without MIS, but there was no significant difference in the negative vergence reserves. This implies that convergent ability, which is primarily required during reading, is reduced in dyslexic subjects with or without MIS. Reduced fusional convergence is found to be significant particularly for small targets (Eames, 1934; Stein et al., 1988). The presented results showed reduced vergence amplitudes for break and recovery points in both dyslexic groups compared to the control group. Although the significant value was only in the recovery amplitude, both motor vergence stability of dissociated heterophoria at near (not reported by any of controls) and vergence amplitude were significantly worse in the dyslexic group. However, the Spearman correlation coefficient did not demonstrate any significant correlation between these two variables (stability of arrow and vergence amplitudes in dyslexia with or without MIS). Evans and colleagues found a significant negative correlation between stability of arrow and vergence amplitude (break point) (Evans et al., 1994a).

Whilst dyslexic subjects without MIS, in the present study, demonstrated a significant positive correlation between instability of arrow in the Maddox Wing and exophoria at near, this may indicate that exophoria at near may contribute in weakening of the vergence control at near in dyslexic subjects without MIS. Those with MIS did not demonstrate any significant correlation between the two variables which may reflect that reduced vergence amplitude in this group is not a contributory causative factor in their reading difficulties or visual stress. This finding is supported by previous studies on dyslexic children who also were diagnosed with MIS (Evans et al., 1995; Evans et al., 1996b).

It has been previously reported that poor convergence, lack of accurate convergence (Anapolle, 1971; Stein et al., 1988) and /or poor binocular localization based on the Dunlop test (Stein and Fowler, 1981; Stein and Fowler, 1982; Stein et al., 2000a) in dyslexic children may be attributed to some reading symptoms suffered. In this study the NPC was significantly more distal in the dyslexia with MIS group when compared to the control group. Earlier work suggests similar findings in dyslexic children (Bishop et al., 1979; Latvala et al., 1994; Evans et al., 1994a). However it was not specified whether such dyslexia subjects were diagnosed with MIS condition per se. The present result did not demonstrate a correlation between vergence stability and NPC, although, the more distal NPC, i.e. convergence insufficiency, may contribute to visual stress symptoms at near (Evans, 2002a; Evans, 2002b). However, it appears that NPC does not contribute to the visual stress in the present dyslexic group. This is indicated by the lack of correlation between VSS scores and NPC measure of the same dyslexic population.

The results on amplitude of accommodation suggest that monocular and binocular responses were significantly reduced in dyslexia with MIS indicating that both blur-driven and convergence accommodative responses are reduced compared to controls. The dyslexic group without MIS demonstrated a reduction in amplitude of accommodation but the difference was significant compared to control group. These findings are in agreement with several studies who reported a reduction of the accommodation amplitude in dyslexic children (Hung, 1989; Evans et al., 1992a; Evans et al., 1994a; Evans et al., 1996b; Evans, 2002a) and in dyslexia with MIS (Evans et al., 1995; Evans et al., 1996b). Reduction in amplitude of accommodation and low fusional reserves may contribute to reading difficulties by causing blurred vision, diplopia, confusion, headache and visual discomfort (Evans et al., 1992a; Evans et al., 1994a; Evans et al., 1996b; Evans, 1998, 1999; Evans, 2002a). The present findings indicated a weak but significant correlation between reduced amplitude of accommodation and visual stress scores in the combined dyslexic group but not in the individual groups.

Accommodation is closely linked with convergence (Bennett and Rabbetts, 1989), and reduction of binocular amplitude of accommodation, in the present study, appeared to be significantly correlated with distal NPC in dyslexia with MIS and dyslexia without MIS individually and/or combined group where there was no significant correlation between the two variables in control group. Evans et al (1994) found similar results in dyslexic children (Evans et al., 1994a). Reduction of the binocular amplitude of accommodation in dyslexic subjects without MIS was significantly correlated with reduced vergence amplitude. However, as those with MIS did not demonstrate a significant correlation between the two variables this may indicate that poor monocular and binocular amplitude of accommodation is relatively attributed to higher level visual imbalance. Reduction in amplitude of accommodation in the dyslexic subjects in the present study may be a contributory factor in vergence instability (unstable response in Maddox Wing test) where it appeared that reduced amplitude of accommodation associated significantly with vergence instability.

Despite reduced amplitude of accommodation in dyslexic subjects, it did not appear to influence accommodation lag and accommodation facility. Results showed that there was no under or over accommodation in the three groups. Similar results were found by Evans (Evans et al., 1994a; Evans et al., 1996b). Results from this study on dynamic visual function also suggested no significant difference in accommodation facility between groups. Although the number of cycles per minute was slightly reduced in dyslexic group compared to control group. Using the similar technique (the flipper) Buzzelli found a similar finding when comparing dyslexic and control children (Buzzelli, 1991). Using a distance/near fixation or natural technique, Evans et al (1994) reported that dyslexic children preformed a little slower (but not significantly) in accommodation facility compared to controls. Buzzeli also found vergence facility significantly reduced in dyslexic group compared to control, whereas the present study found the similar performance in vergence facility across the three groups (Buzzelli, 1991).

The above findings from the present study agreed with previous works which suggested that although several optometric and/or binocular visual dysfunctions may contribute in reading difficulty. However, they may be unlikely to be the major cause of dyslexia (Evans et al., 1992a; Evans et al., 1994a; Evans et al., 1995; Evans et al., 1996a; Evans et al., 1996b; Evans, 2002a). This is apparently strongly relevant to the dyslexic sample with MIS condition which often reports the visual distortion symptoms that highly influenced by pattern glare effect which attributed to the hyper-excitability of the visual cortex (Wilkins, 1995; Evans et al., 1996b).

A summary of the hypothesis and the implications from the results are shown in table 4.23.

	Hypothesis	**Implication**	
		Dyslexia	**Dyslexia with MIS**
1	Exo-deviation at near (associated or dissociated heterophoria) is present more often in dyslexic subjects with and without MIS	Supported	Not supported
2	Vergence instability is present more often in dyslexic group with and without MIS.	Supported	Supported
3	Reduced vergence reserves and amplitudes are more common in dyslexic subjects with and without MIS.	Supported	Supported
4	The poor convergence is more common in dyslexic subjects with and without MIS.	May be supported	Supported
5	Reduced amplitude of accommodation and accommodation lag) are more common in dyslexic subjects with and without MIS.	Supported	Supported
6	Dynamic visual functions (accommodative and vergence facility) are reduced in dyslexic subjects with and without MIS	Not supported	Not supported

Table 4.23: Summary of the hypothesis and the implications from the results.

Chapter 5

The effect of induced visual fatigue on binocular vision functions in adults with dyslexia

5.1 Introduction

The previous chapter established certain differences in visual function between adults with dyslexia and those without. One of the principal goals for this thesis was to investigate how visual fatigue may affect these different populations. This was in response to a fundamental questions about the allocation of extra time in written examinations for university students with dyslexia; does having extra time to read and digest written information have the potential to help or hinder visual performance.

5.1.1 Binocular vision performance and visual stress

When the binocular visual system (vergence and accommodation) is stressed due to a sustained and/or repeated visual task (Hasebe, Graf and Scor, 2001) it can give rise to transient changes in binocular vision functions due to decompensation and binocular imbalance. Wilkins (1995) defined visual stress as "the inability to see comfortably without distortion and discomfort" during reading and other visual tasks (Wilkins, 1995), and it affects both dyslexics and non dyslexic individuals (Singleton and Henderson, 2007a , 2007b).
Indications of visual fatigue can be assigned subjectively and/or objectively. Visual discomfort symptoms that may be reported by subjects with visual fatigue include eyestrain, headache, diplopia, blur, difficulty to focus from near to far and opposite, sensitivity to the light in addition to visual distortion symptoms that are commonly reported in subjects with dyslexia and/or MIS (shape, motion and illusion of colour) (Wilkins and Noimmo-Smith, 1984; Wilkins, 1995; Evans and Joseph, 2002).

Binocular vision measures, for example decompensated heterophoria, can be indicators of visual stress or fatigue. When the fusional reserves are not sufficient to compensate for a deviation, the resultant latent squint or squint may induce visual discomfort or visual stress (Pickwell et al., 1987b; Yekta, Pickwell and Jenkins, 1989a). Fixation disparity at near is frequently considered as a sign of binocular vision decompensation and therefore of visual stress (Ogle and Prangen, 1953; Mallett, 1974; Pickwell, Yekta and Jenkins, 1987a; Pickwell et al., 1987b; Pickwell et al., 1987c; Yekta, Pickwell and Jenkins, 1989b; Pickwell, Kaye and Jenkins, 1991; Karania and Evans, 2006). An exo shift has been reported when the binocular vision system is fatigued: exophoric shift at near was reported when stress was visually induced in subjects (Choy et al., 2000).

A close correlation between near work, fatigue-related visual discomfort symptoms and accommodative dysfunctions has been reported (Iwasaki, 1993; Hasebe et al., 2001; Iribarren et al., 2002; Chase et al., 2009). Reduced monocular (Levine et al., 1985) and binocular accommodative and vergence functions have been suggested as possible diagnostic criteria for symptomatic subjects (Hennessey, Iosue and Rouse, 1984; Levine et al., 1985; Iribarren, Fornaciari and Hung, 2001), even with normal phoria (Gall and Wick, 2003). Iribarren et al (2002) found a correlation between cumulative near work, asthenopia and reduced accommodative facility.

Convergence insufficiency has been associated with a variety of visual discomfort symptoms associated with reading in school children (Borsting, Rouse and De Land, 1999). Owens and Wolf-Kelly concluded that one hour of near reading work (from hard copy or a video display terminal) regress the near point of vergence and accommodation, and that was associated with eye strain (Owens and Wolf-Kelly, 1987). Barkowsky & Le Callet (2010) found that 20 minutes of near work at 33cm, which consisted of reading and searching tasks, revealed faster vergence facility performance due to the learning process of how to control vergence during the near task (Barkowsky and Le Callet, 2010). Moreover, over a longer period of near work, Borsting and colleagues found an increase of accommodative and vergence facility in college students after one academic year (Borsting et al., 2008). They suggested that accommodation and vergence systems might approach to an "equilibrium point" due to the adaptation to the cumulative near work. However, Gur et al (1994) found cumulative near VDU work (over the working week) is associated with decreased convergence and accommodation amplitude with higher reductions in those with more efficient initial measures (Gur, Ron and Heicklen-Klein, 1994). Furthermore, refractive error (Wiggins and Daum, 1991), blurred distance vision (Iribarren et al., 2001) and transient myopia (Ehrlich, 1987) have also been reported to be associated with symptoms of visual discomfort or stress.

5.1.2 Factors affecting visual stress

See earlier discussion in section 2.1.2

5.1.3 Aims and hypothesis

To compare the pre- and post-visual fatigue binocular status results for the three groups (dyslexics without MIS, dyslexics with MIS and control group).
Features of interest were binocular visual function and reported visual discomfort.
The hypothesis was that control subjects would be less affected by visual fatigue than subjects with dyslexia, i.e. show less variation in their binocular stability, fusional reserves, etc. from the review of the literature, it was also hypothesised that dyslexics with MIS would be less susceptible to change in their oculomotor function post-fatigue.

5.2 Methods

5.2.1 Participants

Dyslexic and control subjects in this study were the same subjects who participated in chapter 4 (Investigating binocular vision functions in dyslexic adult population). Dyslexic subjects consisted of 56 university students: 27 of who were dyslexics with MIS and controls were 33 students (see section 4.2.1).

Ethical approval was obtained from Cardiff School of Optometry and Vision Science Ethical Committee and all procedures follow the tenets of the Declaration of Helsinki.

Prior to the experiments, written informed consent was provided by all subjects after the methodology had been explained to them and the opportunity was given to the subjects to ask further questions and they can feel free to withdraw at any time without penalty.

5.2.2 Experimental protocol

All subjects were required to attend for a single visit at the School of Optometry and Vision Sciences. The investigation lasted approximately 1.5 to 2 hours. The sequence of the experimental procedures was as follows:

1. Dyslexic subjects were asked to fill forming the CVSQAD developed in chapter 3.

2. A new visual discomfort score (VDCS) was assessed in all subjects. This new measure was necessary as the CVSQAD can not be applied to control subjects.

3. Binocular rivalry was assessed (see section 7.2).

4. Binocular vision (BV) functions were investigated as described in Chapter 4 (section 4.3).

5. VDCS was assessed again – this was to examine the possibility that purely carrying out optometric investigations may induce visual discomfort in some subjects, even before the deliberate fatigue process. This was described as pre-induced fatigue VDCS.

6. Visual fatigue was induced with the proposed method described below (section 5.2.3.1)

7. Post-fatigue VDCS was assessed after the fatigue procedure.

8. Finally, post-fatigue BV function assessment was carried out immediately.

5.2.3 Inducing visual fatigue

5.2.3.1 Materials, design, and method

Induced visual fatigue during a 30 minutes session compromised of reading, copying, and searching tasks from a hard copy, without breaks between the tasks. All tasks were performed under the following demanding visual conditions:

- Unusual close working distance (20 cm).

- Low room illumination (40 lux) that was controlled with room rheostat.

- Small (10 point print size) bolded print superimposed on stressful horizontally striped pattern background (see Appendix 3.1).

Each of the visual tasks for the fatigue session is described separately. The habitual spectacle corrections for reading (near vision) were worn during tasks.
The reading text comprised of 4 interesting French short stories. Stories were written in English language and have been selected from Google website; these stories were chosen as their words were simple and familiar. The print material was amended so words were closely spaced and letters were in bold and Arial font of 10 point. Lines of the text were superimposed on a visually stressful stimulus which was made up of equally wide black and white horizontally striped alternating pattern (Singleton and Henderson, 2007a, 2007b). These strips were created by using Draw plus 7 computer programs.

The reading material was mounted on a standing clipboard which was tilted about 35° from the working table to facilitate almost equal distribution of the light. Reading material was situated at distance of 20 cm from the subject's eyes and care was taken to maintain constant reading working distance. Subjects were asked to spend 10 minutes reading as much as they could from the short stories. Reading performance was not monitored and participants were allowed to point to the lines of text in order to avoid losing their place or jumping lines.

5.2.3.1.2 Copying task session

In this task, participants were required to spend 10 minutes copying (with hand writing) a text passage typed in a foreign language (French) into a blank sheet of paper. Words of the text were closely spaced and printed with bold Arial font and 10 point letter size. As in the reading task the text was placed over a horizontal striped black and white repetitive pattern background. The test material was mounted at distance of 20 cm and the paper was placed on a table or on a clipboard at distance of 35 cm to provide accessible hand writing. This fatigue task was carried out at low room illumination (40 lux).

5.2.3.1.3 Searching task session

In this task subjects were asked to spend 10 minutes searching through the text for 4 or 5 different selected letters (e.g. s, v, x, z and o) and record how many time each letter was displayed and repeated among the text ,e.g. letter 's' was repeated 123 Times, 'v' 13 times, 'x' 4 times, 'z' 3 times and 'o' was repeated 113 times among the text which comprised 25 lines of 340 closely spaced words written in a foreign language (Spanish) and printed in bold Arial font and 10 point letter size. Working distance was 20 cm and room illumination was dim (40 Lux.)

Visual discomfort was evaluated before and after the aforementioned visual fatigue tasks by using visual discomfort scale from 0 to 4.

Comfortable				Un-comfortable
0	1	2	3	4

5.2.3 Assessment of post-fatigue binocular vision functions

The following binocular vision functions were evaluated after 30 minutes of visually induced fatigue.

Horizontal dissociated and associated heterophoria at near and distance, near point of convergence, vergence reserves at near, stereopsis, amplitude of accommodation and dynamic visual functions ; accommodative facility and vergence facility at near.

The methodology used to evaluate post-fatigue BV functions were the same of those used in pre-fatigue investigations (see section 4.3)

Binocular vision tests were performed in a randomised order and all were performed with the subject's habitual refractive error correction (spectacles or contact lens) in place.

5.2.4 Statistical analysis

SPSS (version 16, SPSS Inc Chicago, Illinois, USA) statistical computer program was used to:

1. Evaluate the effect of visual induced fatigue method on visual discomfort scores (VDCS) for each individual group using Friedman test.

2. Compare the three groups (dyslexics without MIS, dyslexics with MIS and control group) in terms of pre- and post induced fatigue scores by using Kruskal-Wallis between groups comparison test.

3. Evaluate the effect of pre and post visual induced fatigue on binocular visual functions in each group using paired t-test.

4. To assess the effect of visually induced fatigue upon BV variables. This step was applied by using analysis of variance in order to use the advantages of the one step Post Hoc test.

A normality test showed that all data from visual discomfort scores (VDCS) were not normally distributed ($P<0.05$) therefore non-parametric tests were used in the analysis. Parametric tests were used in the analysis of post fatigue BV data for the similar reasons reported in Chapter 4 (section 4.2.4) and for the sake of consistency with the pre fatigue BV data results.

5.3 Results

5.3.1 Effect of visually induced fatigue on visual discomfort scores (VDCS)

Descriptive and comparative statistical analysis of the VDCS assessed in the three different occasions for the three groups is shown in Tables 5.1.a (see table 5.1b for parametric test results). Tables show an agreement between the two statistical analysis tests, however it was decided to consider the non-parametric (Friedman) test results shown in table 5.1.a. Results showed that all three groups demonstrated a significant increase in VDCS at each stage during the experiment.

Group	Occasion	Median	Chi-Square	P value
Dyslexia	1. Pre-BV tests	0.00	50.53	0.000
	2. Pre-fatigue	1.00		
	3. Post-fatigue	3.00		
Dyslexia+MIS	1. Pre-BV tests	0.00	43.37	0.000
	2. Pre-fatigue	2.00		
	3. Post-fatigue	3.00		
Control	1. Pre-BV tests	0.00	44.56	0.000
	2. Pre-fatigue	1.00		
	3. Post-fatigue	2.00		

Table 5.1a: Descriptive and comparative statistics of VCS (in score) amongst the three groups (Friedman test).

Group	Occasion	Mean (SD)	P value	Mean difference	Post-Hoc test
Dyslexia	1. Pre-BV tests	0.345 (.614)	0.000	1-2= -1.172	0.000
	2. Pre- fatigue	1.517 (.871)		1-3= -2.276	0.000
	3. Post- fatigue	2.621 (1.015)		2-3= -1.103	0.000
Dyslexia+MIS	1. Pre-BV tests	0.741 (.944)	0.000	1-2= -1.111	0.000
	2. Pre- fatigue	1.852 (.718)		1-3= -2.111	0.000
	3. Post- fatigue	2.852 (.662)		2-3= -1.000	0.000
Control	1. Pre-BV tests	0.242 (.502)	0.000	1-2= -0.818	0.000
	2. Pre- fatigue	1.061 (.747)		1-3= -1.727	0.000
	3. Post- fatigue	1.970 (.951)		2-3= -0.909	0.000

Table 5.1b: Descriptive and comparative statistics of VCS (in score) amongst and between the three groups. (ANOVA repeated measure).

5.3.2 Comparison of the three groups in terms of pre- and post induced fatigue VDCS

Descriptive and comparative statistics are shown in table 5.2a. Results showed that the VDCS were significantly different between the three groups before any clinical or reading task interventions. Post hoc test indicated that the significant difference was mainly between dyslexia with MIS and control groups (Table 5.2b).

Pre-fatigue tasks (post BV assessment) VDCS continued to be significantly different amongst the groups. Post hoc result indicated that the BV tests in dyslexic with MIS group was significantly different compared to control group and the group of dyslexia without MIS exhibited a border line significance compared to control group. The results suggest that dyslexics with MIS seem more susceptible to discomfort after optometric assessment. Finally, after the fatigue session, results showed that VDCS of both dyslexics and dyslexics with MIS were significantly higher compared to control subjects.

Occasion	Group	N	Median	Min.	Max.	Chi-Square	P value (K-W test)
Pre-BV test	1.Dyslexia	29	0.00	0	2	6.194	0.045
	2.Dyslexia+MIS	27	0.00	0	3		
	3.Control	33	0.00	0	2		
Pre-fatigue	1.Dyslexia	29	1.00	0	3	14.081	0.001
	2.Dyslexia+MIS	27	2.00	1	4		
	3.Control	33	1.00	0	3		
Post- fatigue	1.Dyslexia	29	3.00	0	4	16.030	0.000
	2.Dyslexia+MIS	27	3.00	1	4		
	3.Control	33	2.00	0	4		

Table 5.2a: Descriptive and comparative statistics of VDCS (in score) amongst and between the three groups in the three different occasions (pre-binocular vision (BV) tests, pre reading and post reading induced fatigue task)

Results are graphically presented in figure 5.1

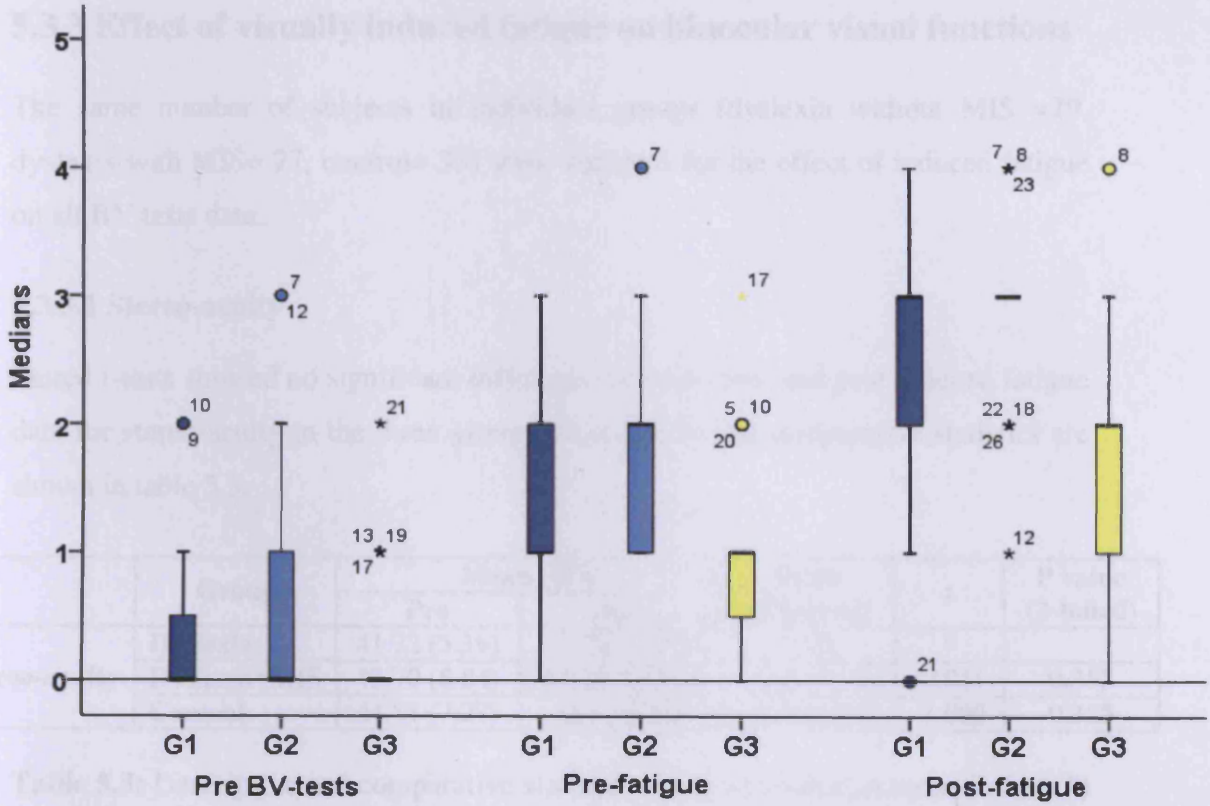

Figure 5.1: Box plot of VDCS for the three groups (G1=Dyslexia, G2=Dyslexia with MIS, G3=control) in the three test occasions (Pre-tests, Post-tests and Post-reading tasks). The medians of VDCS are represented by the thick black lines. The whiskers represent the highest and lowest values that are not outliers or extreme values. The circles represent the outlying data points and the asterisk marks represent the extreme cases.

Table 5.2b shows descriptive and comparative statistics of VCS amongst the three groups in the three different occasions using parametric findings of ANOVA test. Agreement results with non-parametric findings were postulated.

Occasion	Group	N	Mean (SD)	P value ANOVA	Mean difference	Post-Hoc test
Pre-BV test	1.Dyslexia	29	0.345 (0.61)	0.020	1-2= -0.396	0.09
	2.Dyslexia+MIS	27	0.741 (0.94)		1-3= 0.102	0.83
	3.Control	33	0.242 (0.50)		2-3= 0.498	0.019
Pre- fatigue	1.Dyslexia	29	1.517 (0.87)	0.001	1-2= -0.335	0.25
	2.Dyslexia+MIS	27	1.852 (0.72)		1-3= 0.457	0.06
	3.Control	33	1.061 (0.75)		2-3= 0.791	0.001
Post- fatigue	1.Dyslexia	29	2.621 (1.02)	0.000	1-2= -0.268	0.50
	2.Dyslexia+MIS	27	2.852 (0.66)		1-3= 0.651	0.01
	3.Control	33	1.970 (0.95)		2-3= 0.919	0.000

Table 5.2b: Descriptive and comparative statistics of VCS (in score) amongst and between the three groups in the three different occasions (pre-binocular vision (BV) tests, pre fatigue and post fatigue).

5.3.3 Effect of visually induced fatigue on binocular visual functions

The same number of subjects in individual groups (dyslexia without MIS =29, dyslexia with MIS= 27, control= 33) were analysed for the effect of induced fatigue on all BV tests data.

5.3.3.1 Stereo-acuity

Paired t-tests showed no significant difference between pre- and post induced fatigue data for stereo-acuity in the three groups. Descriptive and comparative statistics are shown in table 5.3.

	Group	Mean (SD)		Mean difference	t	P value (2-tailed)
		Pre	Post			
Stereo-acuity	Dyslexia	41.72 (5.39)	41.72 (5.39)	0.00	*	
	Dyslexia+MIS	43.70 (8.84)	45.19 (13.97)	-1.48 (8.18)	-0.941	0.355
	Control	41.81 (7.27)	42.12 (7.81)	-0.30 (1.74)	-1.000	0.325

Table 5.3: Descriptive and comparative statistics of stereo-acuity (in second of arc,") pre- and post induced fatigue in the three group population. P value in the right hand column is calculated from paired t-test. * t can not be computed because the standard error of difference is 0

5.3.3.2 Associated heterophoria

Descriptive and comparative statistics for pre- and post induced fatigue data for associated phoria at near and distance are given in table 5.4. Findings reflect a post fatigue exo-phoric shift of associated phoria (at near more than at distance) in both dyslexic groups, but this did not reach statistical significance. Results from paired testing showed that only dyslexia with MIS group showed a significant difference at near.

	Group	Mean (SD)		Mean difference	t	P value (2-tailed)
		Pre	post			
AP (near)	Dyslexia	-0.88 (1.10)	-1.26 (2.12)	0.38 (1.51)	1.353	0.187
	Dyslexia+MIS	0.33 (2.37)	-0.59 (1.72)	0.93 (2.18)	2.204	0.037
	Control	-0.20 (1.37)	-0.24 (2.00)	0.05 (0.77)	0.337	0.738
AP (distance)	Dyslexia	-0.12 (1.11)	-0.16 (1.17)	0.03 (0.64)	0.290	0.774
	Dyslexia+MIS	0.54 (1.88)	0.43 (1.94)	0.11 (0.97)	0.593	0.558
	Control	-0.17 (1.16)	0.14 (2.07)	-0.30 (1.33)	-1.305	0.201

Table 5.4 Descriptive and comparative statistics of associated phoria AP, at near and distance (Δ) pre- and post induced fatigue in the three groups. P value in the right hand column is calculated from paired t-test.

Results for near are graphically presented in figure 5.2

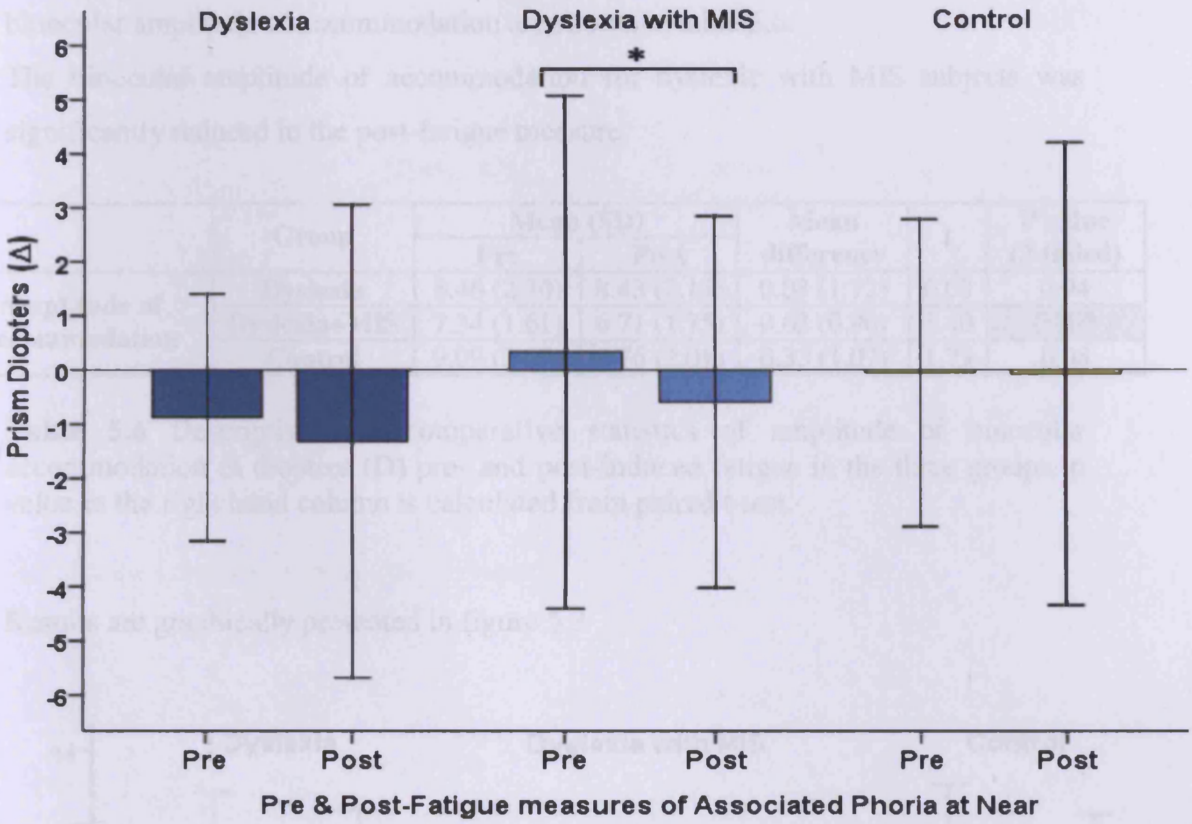

Figure 5.2: Pre and post fatigue measures of associated phoria at near for the three groups. * Significantly different $p<0.05$. Error bars indicates standared deviation.

5.3.3.3 Dissociated heterophoria

Descriptive and comparative statistics for pre- and post induced fatigue data of dissociated phoria at near and distance are given in table 5.5. There were no significant differences between pre- and post- fatigue measures in any group.

	Group	Mean (SD)		Mean difference	t	P value (2-tailed)
		Pre	Post			
DP (near)	Dyslexia	-2.53 (4.42)	-2.66 (4.11)	0.12 (1.92)	0.338	0.738
	Dyslexia+MIS	-0.52 (2.97)	-0.78 (1.70)	0.26 (1.96)	0.688	0.498
	Control	-1.52 (3.53)	-1.30 (2.98)	-0.21 (1.39)	-0.879	0.386
DP (distance)	Dyslexia	-0.26 (2.94)	-0.19 (2.84)	-0.07 (0.86)	-0.430	0.670
	Dyslexia+MIS	0.59 (2.35)	0.65 (2.50)	-0.06 (1.07)	-0.270	0.789
	Control	0.42 (2.94)	0.61 (3.99)	-0.18 (1.65)	-0.634	0.531

Table 5.5 Descriptive and comparative statistics of dissociated phoria DP, at near and distance (Δ) pre- and post induced fatigue in the three groups. P value in the right hand column is calculated from paired t-test.

5.3.3.4 Amplitude of accommodation

Descriptive and comparative statistics for pre- and post induced fatigue data of binocular amplitude of accommodation are shown in table 5.6.

The binocular amplitude of accommodation for dyslexic with MIS subjects was significantly reduced in the post-fatigue measure.

	Group	Mean (SD)		Mean difference	t	P value (2-tailed)
		Pre	Post			
Amplitude of accommodation	Dyslexia	8.46 (2.30)	8.43 (2.15)	0.03 (1.72)	0.08	0.94
	Dyslexia+MIS	7.34 (1.61)	6.71 (1.75)	0.63 (0.96)	3.40	0.002
	Control	9.09 (2.07)	8.76 (2.01)	0.33 (1.07)	1.79	0.08

Table 5.6 Descriptive and comparative statistics of amplitude of binocular accommodation in dioptres (D) pre- and post-induced fatigue in the three groups. p value in the right hand column is calculated from paired t-test.

Results are graphically presented in figure 5.3

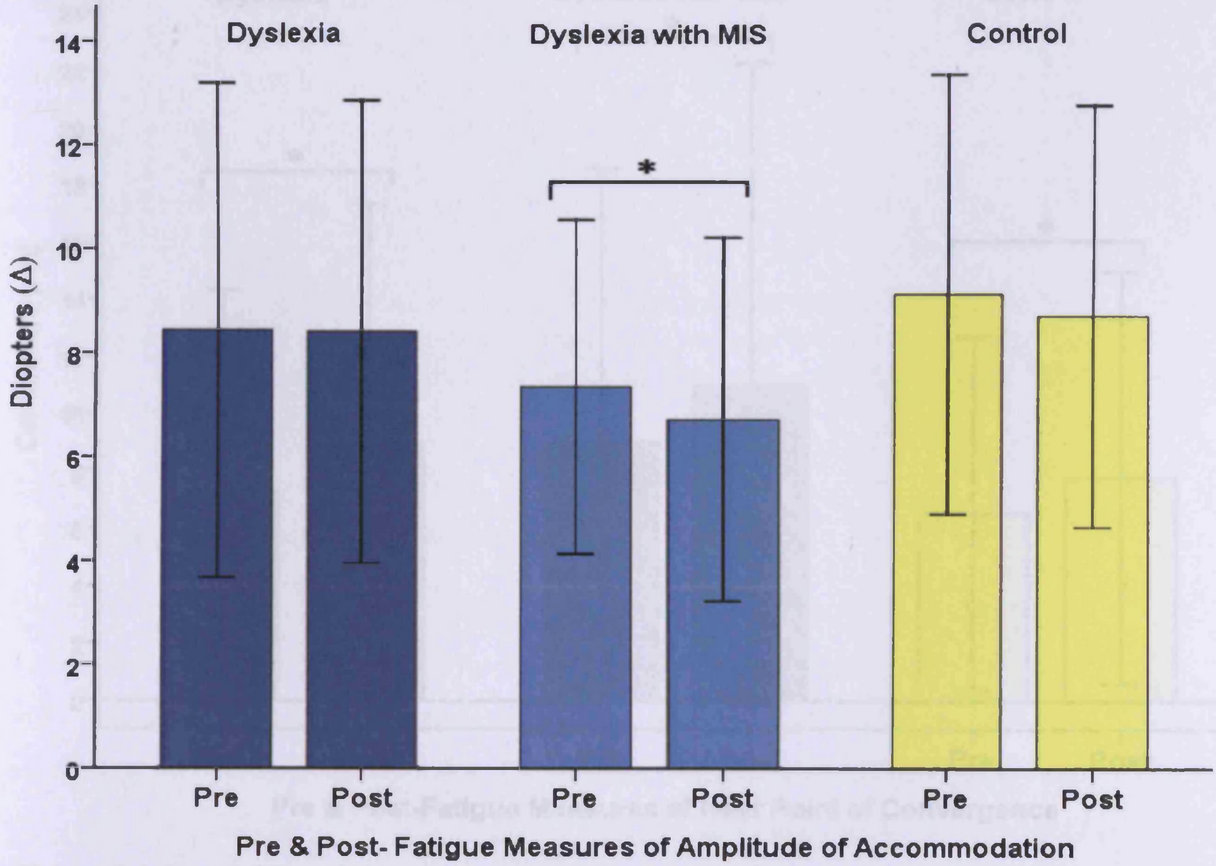

Figure 5.3: Pre and Post-fatigue measures of amplitude of accommodation for the three groups.* Significantly different $p<0.05$. Error bars indicates standared deviation.

5.3.3.5 Near point of convergence (NPC)

The data in table 5.7 show that NPC was increased significantly in all groups. Descriptive and comparative statistics for pre- and post induced fatigue data of NPC is given in table 5.7.

	Group	Mean (SD)		Mean difference	t	P value (2-tailed)
		Pre	Post			
NPC	Dyslexia	7.00 (3.64)	8.55 (4.39)	-1.55 (2.94)	-2.84	0.008
	Dyslexia+MIS	9.02 (4.77)	11.02 (5.61)	-2.00 (2.98)	-3.48	0.002
	Control	6.71 (2.93)	8.09 (3.42)	-1.38 (1.24)	-6.37	0.000

Table 5.7: Descriptive and comparative statistics of near point of convergence (NPC) (cm) for pre- and post induced fatigue in the three groups. P value in the right hand column is calculated from paired t-test.

Results are graphically presented in figure 5.4

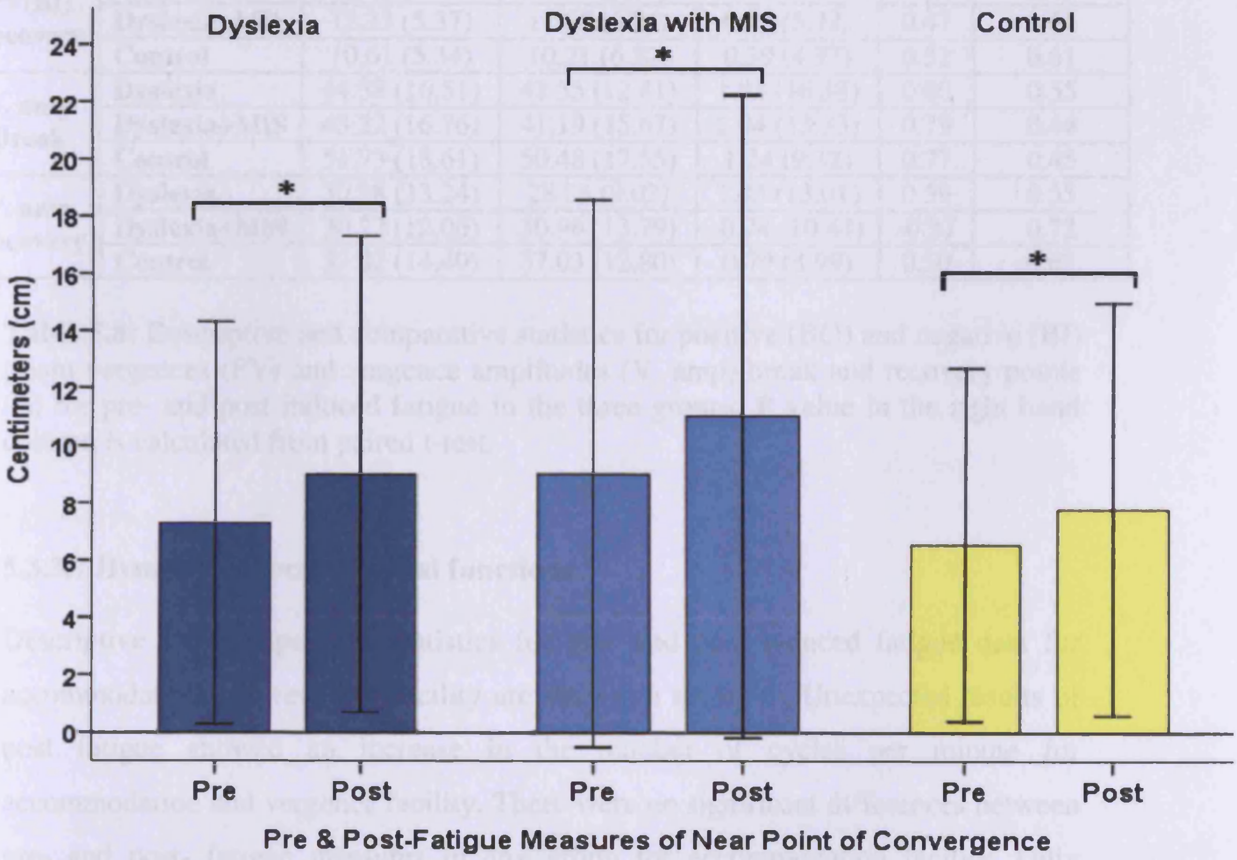

Figure 5.4: Pre and Post fatigue measures of near point of convergence for the three groups. .* Significantly different $p<0.05$. Error bars indicates standard deviation.

5.3.3.6 Prism vergence and Vergence amplitudes

Descriptive and comparative statistics for pre and post induced fatigue data for positive (BO) and negative (BI) prism vergences and vergence amplitudes (break and recovery points) are summarised in table 5.8. Results showed no significant effect of induced fatigue on post fatigue measure for any of the listed variables for the three groups.

	Group	Mean (SD)		Mean difference	t	P value (2-tailed)
		Pre	Post			
PV(BO) Break	Dyslexia	26.41 (13.28)	23.72 (8.94)	2.69 (15.54)	0.93	0.36
	Dyslexia+MIS	26.41 (14.04)	25.48 (12.56)	0.93 (10.97)	0.44	0.66
	Control	35.88 (17.29)	35.45 (17.47)	0.42 (8.74)	0.28	0.78
PV(BO) Recovery	Dyslexia	17.41 (10.54)	15.69 (6.81)	1.72 (12.10)	0.77	0.45
	Dyslexia+MIS	17.89 (9.81)	19.11 (11.83)	-1.22 (8.16)	-0.78	0.44
	Control	27.21 (14.66)	26.82 (13.53)	0.39 (8.06)	0.28	0.78
PV(BI) Break	Dyslexia	17.97 (5.99)	18.83 (6.60)	-0.86 (5.38)	-0.86	0.39
	Dyslexia+MIS	16.81 (6.59)	15.70 (8.05)	1.11 (7.45)	0.78	0.45
	Control	15.85 (6.29)	15.03 (6.18)	0.82 (3.97)	1.18	0.25
PV(BI) Recovery	Dyslexia	12.86 (5.33)	13.14 (5.19)	-0.28 (4.17)	-0.36	0.73
	Dyslexia+MIS	12.33 (5.37)	11.85 (6.24)	0.48 (5.32)	0.47	0.64
	Control	10.61 (5.34)	10.21 (6.32)	0.39 (4.37)	0.52	0.61
V. amp Break	Dyslexia	44.38 (16.51)	42.55 (12.41)	1.83 (16.38)	0.60	0.55
	Dyslexia+MIS	43.22 (16.76)	41.19 (15.67)	2.04 (13.33)	0.79	0.44
	Control	51.73 (18.61)	50.48 (17.55)	1.24 (9.32)	0.77	0.45
V. amp Recovery	Dyslexia	30.28 (13.24)	28.83 (9.02)	1.45 (13.01)	0.59	0.55
	Dyslexia+MIS	30.22 (12.06)	30.96 (13.79)	-0.74 (10.44)	-0.37	0.72
	Control	37.82 (14.49)	37.03 (12.80)	0.79 (8.99)	0.50	0.62

Table 5.8: Descriptive and comparative statistics for positive (BO) and negative (BI) prism vergences (PV) and vergence amplitudes (V. amp) break and recovery points (Δ) for pre- and post induced fatigue in the three groups. P value in the right hand column is calculated from paired t-test.

5.3.3.7 Dynamic binocular visual functions

Descriptive and comparative statistics for pre- and post induced fatigue data for accommodation and vergence facility are shown in table 5.9. Unexpected results of post fatigue showed an increase in the number of cycles per minute for accommodation and vergence facility. There were no significant differences between pre- and post- fatigue measures in any group for accommodation facility. Only dyslexia without MIS group exhibited a significant improvement of vergence facility post induced fatigue.

	Group	Mean (SD)		Mean difference	t	P value (2-tailed)
		Pre	Post			
Accommodation Facility	Dyslexia	7.95(5.70)	8.84(5.12)	-0.91 (3.08)	-1.57	0.13
	Dyslexia+MIS	7.17(4.83)	7.72(5.62)	-0.56 (3.19)	-0.90	0.37
	Control	9.48(4.49)	9.95(4.32)	-0.47 (2.36)	-1.14	0.26
Vergence Facility	Dyslexia	13.71(4.19)	14.91(4.33)	-1.21 (2.51)	-2.59	0.015
	Dyslexia+MIS	13.91(4.08)	14.91(3.81)	-1.00 (4.13)	-1.26	0.22
	Control	14.67(4.11)	15.59(4.82)	-0.92 (3.10)	-1.71	0.09

Table 5.9 Descriptive and comparative statistics for accommodation and vergence facility (cycle/min) for pre- and post induced fatigue in the three groups. P value in the right hand column is calculated from paired t-test.

5.3.3.7 Summary of the significant trends in post-fatigue BV measure(s)

The significant trends in post-fatigue BV measure(s) for the three group samples are summarised in table 5.10

Group	Variables	P value (2-tailed)
Dyslexia	Near Point of Convergence	0.008
	Accommodation facility	0.015
Dyslexia+MIS	Associated phoria at near	0.037
	Amplitude of accommodation (BE)	0.002
	Near Point of Convergence	0.002
Control	Near Point of Convergence	0.000

Table 5.10 The significant trends in post-fatigue BV measure(s) in the three groups.

5.3.4 Comparing the three groups in terms of pre-post induced fatigue difference of BV variable data

The pre-post differences in BV variables were computed in each individual and an ANOVA between groups was applied for each measure in order to calculate differences between the three groups. ANOVA found none of the variables reached significance by considering differences between the three group populations.
Descriptive and comparative statistics for pre-post induced fatigue data differences within and between the three group populations are listed in (Appendix 3.2).

5.4 Discussion

The present study explored the effect of clinically induced visual fatigue on binocular vision functions in dyslexic adults as identified in CVSQAD in chapter 3. To the best of this researcher's knowledge this study is the first to apply clinical but natural tasks including academic tasks (reading, copying, and searching) that are performed under demanding conditions; close viewing distance, poor room illumination and exacting print characteristics, to evaluate the effect of induced visual fatigue on binocular vision performance in dyslexic adults with or without MIS compared to a control group. Although reading performance was not monitored, copying and searching were challenging tasks. Studies in visual stress have demonstrated the effect of working under similar visual conditions of unusual close distance and poor room illumination on visual comfort status and on some binocular visual functions in non dyslexic populations (Pickwell, 1984; Owens and Wolf-Kelly, 1987; Yekta, Jenkins and Pickwell, 1987; Pickwell et al., 1987b; Pickwell et al., 1987c; Pickwell et al., 1987d; Yekta et al., 1989a; Jaschinski-Kruza, 1994; Jaschinski and Dr-Ing, 2002).
It appears that there is only one study that has evaluated visual stress level in dyslexic subjects (Singleton and Henderson, 2007a). They applied visually stressful searching task with print characteristics similar to those used in the present study (10pt and bolded letter size with stressful background of horizontal striped pattern). However, they did not evaluate the binocular visual functions before or after excitation with such effort.

Another novel aspect of the present study is the evaluation of visual comfort status after clinical tests measuring binocular vision functions. From the literature review it appears that there are no previous reports that have evaluated visual comfort after a clinical course of binocular vision function tests in dyslexic or non dyslexic subjects. It is clear from the results on the effect of BV tests on visual comfort status that there was a significant increase in visual discomfort (VDCS) in all three groups, but it was most apparent in the group with dyslexia and MIS. This result suggests that binocular visual system effort increases during BV testing to maintain single and clear binocular vision. It is well established that dyslexic subjects are more susceptible to the visual stress and those with MIS (as identified by improving of reading performance with colour filter) showed higher scores of visual stress (Singleton and Trotter, 2005; Singleton and Henderson, 2007a, 2007b). Therefore, it was expected that dyslexic with MIS subjects would be visually distressed most easily. Two possible explanations for this result are that the initial scores of VDCS were higher in this group that may be attributed to a neural context. Singleton and Henderson (2007a) suggested that dyslexia with high visual stress (MIS) may have a magnocellular deficit along with cortical hyper-excitability. The other explanation is that it may be due to poor stability of the vergence system which was shown to be double the incidence of vergence system instability demonstrated in dyslexic without MIS in the previous chapter.

Inducing fatigue in the three groups produced significantly increased VDCS for all, but there was a significant difference in VDCS between controls and the two dyslexic cohorts. This indicates that dyslexic subjects are more susceptible to discomfort associated with these tasks. This supports the view that dyslexic subjects are more susceptible to visual stress than non dyslexic subjects (Meares, 1980; Cornelissen et al., 1991; O'Brien et al., 2000; Skottun, 2001; Chung, 2002; Spinelli et al., 2002; Tripathy and Cavanagh, 2002; O'Brien et al., 2005; Singleton and Trotter, 2005; Singleton and Henderson, 2007a, 2007b). This finding confirms a relationship between the dyslexic condition and visual stress.

Stein (2001) suggested that visual stress is attributed to magnocellular deficit in dyslexia. However, the aetiological linkage mechanism is inconclusive (Stein, 2001; Singleton and Trotter, 2005). Magnocellular deficit in dyslexia has an impact on letter localisation (Cornelissen et al., 1998) and therefore dyslexic subjects may need to exert more visual effort during reading in order to perform a proper coding and comprehension of the reading material and this will be harder with stressful reading material. Importantly, as visual stress is usually manifested when both eyes are involved during reading only binocular measures were assessed in the present study. Literature states that monocular occlusion can reduce visual confusion and improve reading performance in children with dyslexia; hence occlusion prevents binocular stress (Stein and Fowler, 1981; Stein and Fowler, 1985; Cornelissen et al., 1992; Stein et al., 2000a).

As clinicians, we must be aware that optometric procedures have the potential to induce discomfort in most individuals, but particularly those with MIS, and that challenging visual tasks have the potential to induce discomfort in dyslexic individuals much more than in people without this condition.

The two groups of dyslexic subjects in the present study showed a similar VDCS post induced visual fatigue, but their average responses in their binocular vision measures were quite different after the fatigue procedure.

Analysis of pre/post binocular functions revealed that dyslexia with MIS subjects showed the significant change in three measures; associated phoria at near, NPC, and binocular amplitude of accommodation. While dyslexic without MIS showed the significant shift only in the near point of convergence and vergence facility. The only variable in the control group that was significantly influenced by induced fatigue was NPC.

The fact that all groups demonstrated significant worsening in their mean NPC suggests that NPC always tends to increase when people are visually tired. This may suggest that NPC is the most sensitive BV measure that may reflect the visual fatigue. Previously, Owens and Wolf-Kelly (1987) found that one hour of near reading work (from hard copy or a video display terminal (VDT) regress near point of vergence and that was associated with eye strain (Owens and Wolf-Kelly, 1987). Borsting et al (1999) found a variety of visual discomfort symptoms associated with reading in convergence insufficiency school children (Borsting et al., 1999). The findings here indicate an important message for clinicians: a patient may have symptoms that indicate problems with convergence but your measurement at 10am may not truly indicate the NPC at the end of the working day in someone with a visually demanding job.

It is also clear from the results that all groups demonstrated an exo shift in associated phoria at near, but this was only significant in those individuals that had dyslexia with MIS. This was not surprising as it has been extensively reported that fixation disparity and/or associated heterophoria is a common sign of visual stress (Ogle and Prangen, 1953; Mallett, 1974; Pickwell et al., 1987a; Pickwell et al., 1987b; Pickwell et al., 1987c; Yekta et al., 1989b; Pickwell et al., 1991; Karania and Evans, 2006), and these subjects tended to demonstrate greater levels of visual stress compared to

other groups. This is most likely due to weakness and instability of vergence system in such population with high level of visual stress.
During binocular fixation at near, convergence and accommodation are closely correlated where they interact through crossed-links mechanisms that termed as accommodation convergence (AC) and convergence accommodation (CA) (Bennett and Rabbetts, 1989; Barrett and Elliott, 2007). A close correlation between near work, fatigue-related visual discomfort symptoms and accommodative dysfunction has been reported (Iwasaki, 1993; Hasebe et al., 2001; Iribarren et al., 2002; Chase et al., 2009). The binocular amplitude of accommodation significantly decreased in dyslexic group with MIS - this may be due to an inherent difficulty associated with the initial weakness of amplitude of accommodation in this group, or because of binocular instability which Chapter 4 showed to be as twice that in dyslexics without MIS.

This study also assessed the dynamic visual functions. It was suggested that reduced performance of accommodative and vergence facilities may be a diagnostic criteria for clinical symptomatic non-dyslexic subjects (Hennessey et al., 1984; Levine et al., 1985; Iribarren et al., 2001) with normal phoria (Gall and Wick, 2003). However, results in the present study showed a slight (but clinically insignificant) improvement in number of cycles per minute for both accommodative and vergence facilities but the only significant change was exhibited by dyslexia without MIS subjects who showed significant improvement in only vergence facility. It is difficult to explain these results other than via a learning effect.

Similar conclusion were suggested by Barkowsky and Le Callet (2010) who used 20 minutes near work (reading and searching tasks) to induce fatigue (Barkowsky and Le Callet, 2010). Over a longer period of near work, Borsting et al (2008) found increase of accommodative and vergence facility in college students after one academic year (Borsting et al., 2008). They suggested that accommodation and vergence systems might approach to an "equilibrium point" due to the adaptation to the cumulative near work. Based on the suggested effect factor of learning process, the present results showed that dyslexic subjects with MIS exhibited the least positive shift in vergence facility. This can be possibly explained by poor visual attention in subject with high visual stress (Conolon et al., 1998; Conlon and Humphreys, 2001; Singleton and Henderson, 2007a).

The three groups in the present study did not demonstrate any significant post fatigue change in variables of stereoacuity, dissociated heterophoria at distance and near, and vergence reserves. This may suggest that these BV measures are more stable and least likely to be influenced by the induced fatigue method used in the present study. Another possible reason is that the measures used were not sensitive enough to detect change or the sample size was too small.

In conclusion, this study has shown that fatigue has a different effect on certain aspect of binocular vision functions depending on whether subjects have dyslexia or dyslexia with MIS. Increasing near point of convergence appears to be an indicator of visual stress in all subjects, whilst dyslexic subjects with MIS showed decreases in their amplitudes of accommodation and associated phorias at near – all important features for clinicians to be aware of when managing such patients.

Chapter 6

Binocular Rivalry in the Normal Population

In section 1.9.5 the significance of instability of ocular dominance in relation to dyslexia was reviewed, and its significance remains under debate. Whilst recent findings using tests of motor dominance seem to find no particular preference for right or left relates to reading ability in children (Castro et al., 2008; Fagard et al., 2008), the results from studies employing tests using sensory dominance techniques are less clear. The Dunlop test appears to suggest unstable ocular dominance is associated with dyslexia although its reliability as a measurement tool has been questioned (Bishop, 1989). This chapter describes the experimental work to develop a quantitative method for assessing sensory dominance that can be applied to the adult population.

6.1 Introduction

Several studies have investigated the correlation between dyslexia and instability of ocular dominance as identified with Dunlop test (Stein and Fowler, 1980; Stein and Fowler, 1982; Bigelow and McKenzie, 1985; Evans et al., 1994a). Using the Dunlop test, it has been found that a majority of dyslexic children (65%) exhibited unstable ocular dominance, i.e. inconsistence response in the Dunlop test (Fowler and Stein, 1980; Stein and Fowler, 1981; Stein and Fowler, 1982). In contrast, only 20% dyslexic subjects from the unselected school children exhibited unstable responses in the Dunlop test (Stein et al., 1986). This led the authors to suggest a causal relationship between dyslexia and instability of ocular dominance (Fowler and Stein, 1980; Stein and Fowler, 1981; Stein and Fowler, 1982; Stein and Fowler, 1985; Stein et al., 1986). The authors believed that the Dunlop test is of a sensory motor variety and they hypothesized that failure of exact coordination between retinal (foveal) signals of an image (of binocularly viewed small target) and ocular motor control may result in confusion and therefore instability of motor ocular dominance which can cause visual confusion in reading and non-reading tasks (Stein and Fowler, 1981; Stein and Fowler, 1982; Stein and Fowler, 1985). Further authors have found the test to be less useful (Bishop et al., 1979; Newman et al., 1985; Aasved, 1987; Ygge et al., 1993a; Evans et al., 1994a), where they failed to attain to the similar results or the conclusion of Stein and Fowler. Similarly, Bigelow and McKenzie (1985) did not find a correlation between reading disability and reversal error, nor any increase time taken to discriminate left-right mirror figures in dyslexic children with unstable motor ocular dominance (Bigelow and McKenzie, 1985). Conflicting results from the Dunlop test suggest that the test to be "unreliable" (Evans et al., 1994a), and may relate to a person's understanding of the test (Bishop, 1989). Furthermore, if the Dunlop test is considered as a method to detect binocular instability (Stein et al., 1986), other methods can be more easily used such as reduced vergence reserves and unstable heterophoria (Evans, 1993b; Evans et al., 1994a).

It has been suggested that the visual confusion experienced by people with dyslexia may be more complicated by binocular retinal rivalry that arises when different images from either eye are alternately suppressed (Cornelissen et al., 1991). Since confusion of orientation or progression of written material in dyslexia appears to mainly be caused by incomplete sensory dominance or "confused cerebral dominance" (Orton, 1925), it is a logical step to investigate the sensory dominance in terms of binocular rivalry. Although sensory visual input obviously plays a substantial part in reading, there appears to be no consensus in the published literature concerning the assessment of sensory ocular dominance in the dyslexic population and its relation to reading performance. This experiment was designed to devise a method of assessing sensory ocular dominance using retinal rivalry in adults.

Here follows a review of the origins of retinal rivalry.

6.1.1 Definition of binocular rivalry

Binocular rivalry was first discovered by Porta in 1593, who gave a description of one eye dominancy while viewing 2 different pages from 2 books separately at the same time.

The first methodical description of rivalry was introduced by Sir Charles Wheatstone in 1838 (Wheatstone, 1838), who invented a mirror stereoscope and used different alphabetic letters as rival targets. He described three conditions during rivalry:

a) Complete suppression of one of the rival stimuli.

b) Equal alternation of dominance duration between the two eyes,

c) Piece portions of the rival stimuli that were related to transition duration.

Wheatstone reported that "the mind is inattentive to an impression made on one retina when it cannot combine the impression on the two retinas together so as to resemble the perception of some external objects".

When a person views a particular visual scene he/she actually is inattentive of which eye is used more frequently in viewing targets of regard (Von Helmholtz, 1909). Further, when two images of dissimilar objects are presented to each eye and the visual system cannot reconcile them, it gives way to alternation of perceptual images between the two eyes. This is the phenomenon known as binocular rivalry (Von Helmholtz, 1910), in which unstable monocular images predominate in the visual system (Blake and Camisa, 1978).

Binocular rivalry is often defined as a phenomenon of alternating periods of perceptual dominance during which one visual stimulus or the other is exclusively seen at a time, and it occurs when dissimilar monocular visual stimuli are presented simultaneously at the same spatial region, and occupy corresponding retinal regions of both eyes (Blake, 19892001). However, binocular fusion doesn't take place as the monocular images are not matched (Blake and Camisa, 1978).

Binocular rivalry is considered to be a targeted method to investigate the neural correlates of visual perception (Blake and Logothetis, 2002), and it is also used as a quantitative measure for sensory ocular dominance (Walls, 1951; Coren and Kaplan, 1973; Blake and Logothetis, 2002; Handa et al., 2004 a; Handa et al., 2006).

During such rivalry, two perceptual phases are usually encountered for each monocular stimulus – either being visible (dominance phase) or invisible (suppression phase). This may imply that the perceptual alternation occurs corresponding to the activity of the monocular channels in the visual system between dominancy and suppression (Fox and Rasche, 1969). The fluctuation between dominance and suppression periods in binocular rivalry is unpredictable and some non-overlapping patches from each image may be perceived (Blake and Camisa, 1978).

6.1.2 Anatomical background to retinal (binocular) rivalry

Signals of visual information flow through to the neural visual system along visual pathways, starting with the retina and ending with the primary visual cortex. The retina is the only part of the brain that can be viewed directly through the eye. In the retina the visual inputs are received by the visual receptors, Cones and Rods. Cones are concentrated at the central retina of the eye, the macula, where detailed vision occurs. Cones are sensitive to red, blue, and green wavelengths and provide detection of colours, whereas rods concentrate more outside the macula and provide motion and shape detection for objects in the periphery. Cones needs higher light levels to be activated but rods are very sensitive to light, and responsible for night vision, i.e. active in the dark.

Inputs from cones and rods transfer to the ganglion cells through horizontal and bipolar cells (Figure 6.1). Ganglion cells are made up of M-Magno (large) cells and P-Parvo (small) cells.

Through the optic nerves axons from Magno-cells project to make up the Magno cellular layers in Lateral Geniculate body or nucleus (LGN), (the inner 2 layers), and axons from Parvo cells project to make-up the upper (outer) 4 layers of the LGN, the parvo-cellular layers.

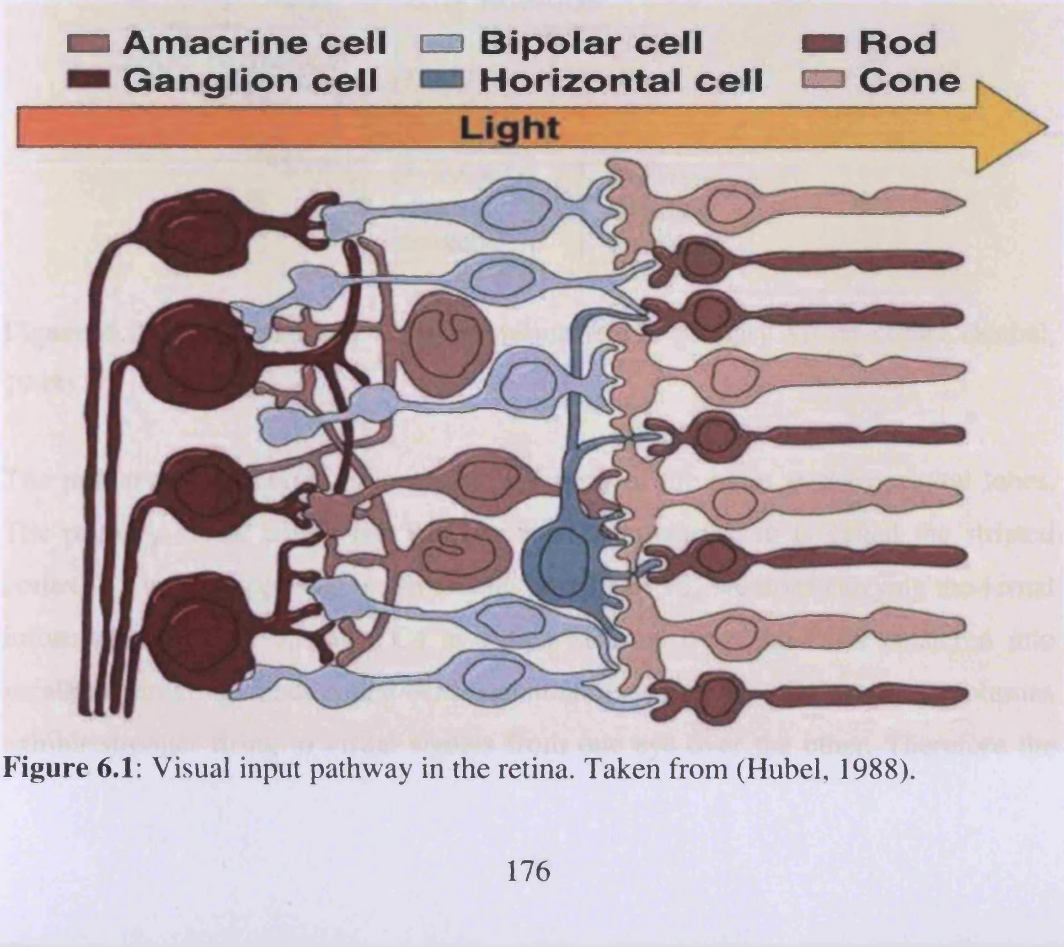

Figure 6.1: Visual input pathway in the retina. Taken from (Hubel, 1988).

Optical nerve fibers carry the visual signals from the retina through the optic nerve. Half of the fibers of the optic nerve cross at the optic chiasm to the opposite LGN (the opposite side of the brain) so the visual images on the left sides of each retina send signals to the left LGN and visual cortex and the images from right half of each retina send signals to the right visual cortex through the right LGN i.e. the visual information from one half of the visual field travel to the opposite hemisphere of the brain. In other words, each hemisphere receives visual information from both eyes (Figure 6.2).

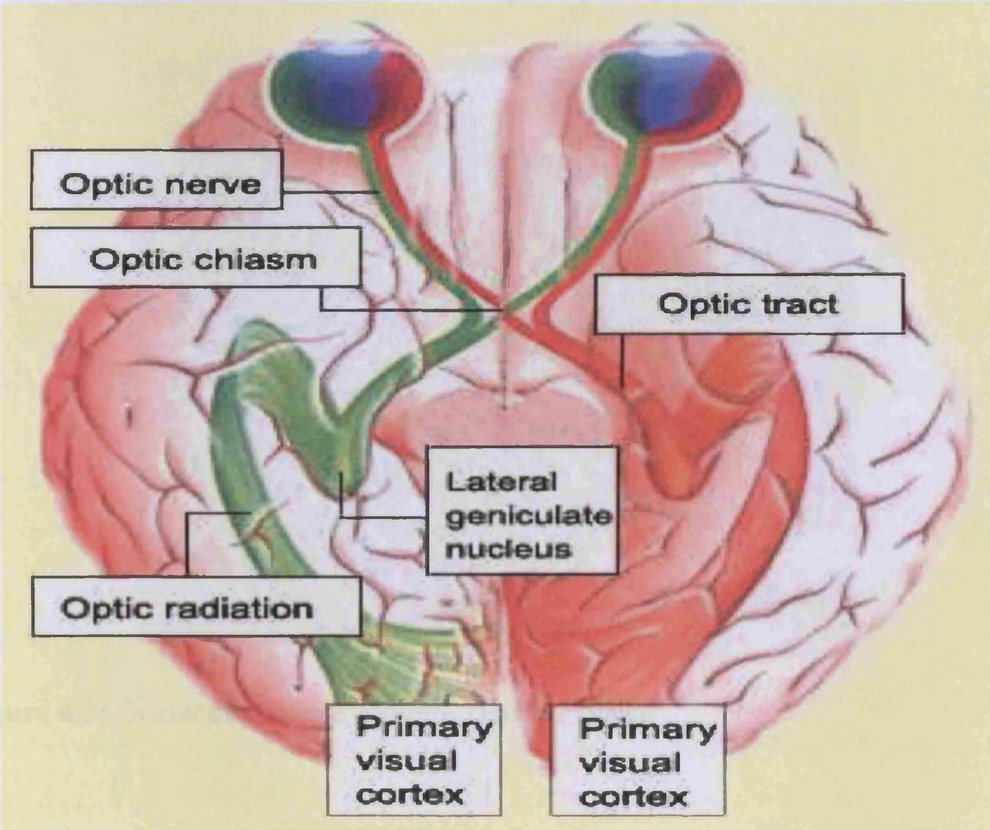

Figure 6.2: Visual bathway from the retina to the primary visual cortex (Hubel, 1988).

The primary visual cortex is located at the back of the brain in the occipital lobes. The primary visual cortex (or V1) has a striped pattern, so is called the striated cortex. V1 is corresponding to Brodmann area 17 at V1. Neurons carrying the visual information synapse on layer C4 at which neurons from the LGN clustered into parallel alternating bands called *ocular dominance columns* (ODCs) - these columns exhibit stronger firing to visual signals from one eye over the other. Therefore the neurons at this layer, are monocular (i.e. receive visual inputs predominantly from one eye), whereas the neurons in the contiguous column receive inputs from the opposite (fellow) eye. This can explain the perceptual fluctuating of the different steady monocular stimuli images during binocular rivalry.

Appearance of the ODCs has the shape of finger print (Figure 6.3), where dark areas correspond to regions of one eye retina (ocular dominant) and white areas correspond to regions of the other eye retina.

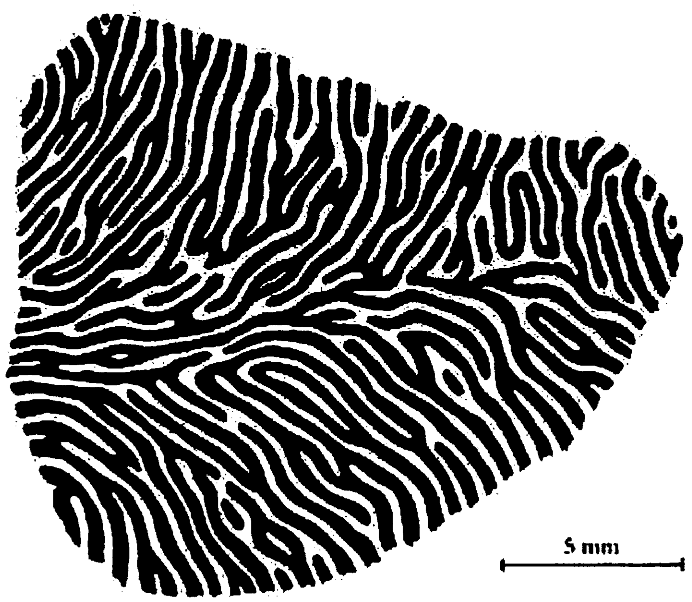

Figure 6.3: Ocular dominance columns (Hubel, 1988).

Sub-column neurons can be found within the ocular dominance column (Figure 6.4). These neurons are sensitive specifically to a particular orientation of a target in the space - termed orientation columns.

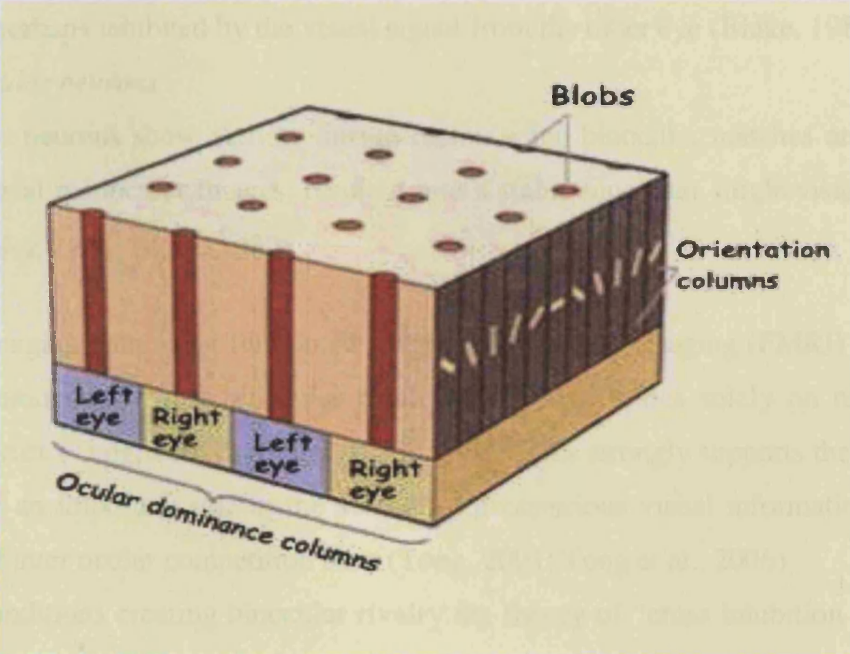

Figure 6.4: Sub-column neurons in ocular dominance columns (Hubel, 1988).

The presence of ocular dominance columns within the primary visual cortex was first established by Hubel and Wiesel (1962). Hubel and Wiesel studied the functional architecture of the striated visual cortex in cat (Hubel and Wiesel, 1962) and monkey (Hubel and Wiesel, 1968, 1977). They used electrodes in cat visual cortex measuring visual innervations (neuron activity). They reported that most of V1 neurons are binocular, however they emphasized that neurons in layer (4) (the ocular dominance, ODC) are purely monocular, i.e. are exclusively receiving innervations from only one eye (Hubel and Wiesel, 1962, 1968, 1977).

Binocular rivalry is considered to be a complex and multilevelled process (Blake and Logothetis, 2002; Tong, Meng and Blake, 2006).

It has been assumed that two types of cortical neurons may be demonstrated during visual processing and they are different in their activity (Blake, 1989).

A- Monocular neurons

During binocular rivalry, monocular neurons are activated by visual signals from one eye and perhaps inhibited by the visual signal from the other eye (Blake, 1989).

B- Binocular neurons

Binocular neurons show activity during fusion when binocular matches are present i.e. identical monocular images, resulted into a stable binocular single vision (Blake and Camisa, 1978; Blake, 1989).

Neuro imaging data using functional magnetic resonance imaging (FMRI) of visual cortex demonstrated that binocular rivalry mechanism relies solely on monocular visual cortex (Tong, 2001; Lee and Blake, 2002). This strongly supports the idea that V1 plays an important role in the selection of conscious visual information during rivalry of inter ocular competition base (Tong, 2001; Tong et al., 2006).

Under conditions creating binocular rivalry the theory of "cross inhibition and slow self adaptation" (Wilson, 2005) can explain neural correlates of the perceptual alternation of competing images in the neural system. During rivalry, a monocular image, in terms of a neural representation, becomes superior and evokes inhibitory factors over the other image (neural) representation. This process promotes itself to reach the maximum neural activity of one image presentation and the minimal neural activity of the other's, and this is manifested in dominant and suppression phase respectively. A reciprocal situation of stimuli neural representation starts with reduction of the dominant image activity due to slow self-adaptation to reach the counterbalance and ends up with the counter phase, and so on. This infers that durations of suppression and dominance in binocular rivalry are inversely related (Fox and Rasche, 1969; Blake, 1977).

6.1.3 Factors affecting binocular rivalry

- **Rivalry period**

For binocular rivalry to take place the dissimilar monocular stimuli (rival stimuli) are required to be viewed without disruption for at least several hundred milliseconds. Too brief a presentation of rival targets would result in a combined image of binocular stimuli (Anderson, Bechtoldt and Gregory, 1978; Wolfe, 1983; Blake, Westendorf and Yang, 1991). For example, a crossed pattern would result from brief flashes of orthogonal gratings in a rival pattern. Therefore, rapid flickering of rival stimuli will disrupt binocular rivalry (O'Shea and Crassini, 1984).

Many studies on binocular rivalry rely on 1 min (60 sec) duration of rivalry test to ensure quantitative measurement of sensory ocular dominance (Wade, 1975; Wiesenfelder and Blake, 1990; O'Shea, Sims and Govan, 1997; Handa et al., 2004 a; Handa et al., 2006). The binocular rivalry duration in one of Blake's experiment was extended for 70 sec (Blake, 1977). Ooi et al (2001) presented the rival stimuli for 333 miliseconds (Ooi et al., 2001), while the total rivalry time was extended to 2 minutes in one study of sensory ocular dominance in children (Fagard et al., 2008). A longer trial duration of 5 minutes was employed by Brascamp and colleagues in an attempt to show that subject visual fatigue has no effect on rivalry results (Brascamp et al., 2006a).

- **Dynamic and Physical factors**

Sudden swapping of the stimuli between eyes or sudden alterations in physical factors of the suppressed stimulus would cause release of suppression and cause interruption for rivalry situation (Grindley and Townsend, 1965). Examples of these physical factors are:

- sudden change in motion, from a static situation (Walker, 1975; Walker and Powell, 1979),
- Increased velocity of motion (Breese, 1899; Andrews and Blakemore, 1999).
- Waving a target (pencil) unexpectedly in front of the suppressed stimulus (Grindley and Townsend, 1965).

• **Contrast**

The dominance duration and the strength of contrast appear to be positively correlated (Breese, 1909; Blake, 1977). Increasing the contrast of the suppressed stimulus can release the suppression (Blake and Fox, 1974a; Hollins, 1980) (Blake, Westendorf and Fox, 1990). Neural activity in V1 was measured in the human visual cortex during rivalry of high and low contrast monocular patterns using FMRI (Menon et al., 1997; Polonsky et al., 2000), and demonstrated increases in neural activities when a high contrast pattern was perceived and decreased activity with a low contrast pattern (Polonsky et al., 2000).
Binocular rivalry is stronger when rival stimuli are equally strong (Breese, 18991909; Levelt, 1965; Liu, Tyler and Schor, 1992). Rival stimuli with equal contrast would demonstrate rapid alteration in dominance with unpredicted dominance and suppressing periods (Levelt, 1965). However, where there is a difference in contrast the stimulus with higher contrast would show dominance for longer duration than the compatible stimulus with lower contrast (Mueller and Blake, 1989; Bossink, Stalmeier and de Weert, 1993), and would be suppressed for shorter periods (Levelt, 1965; Fox and Rasche, 1969).

• **Intensity** (Kakizaki, 1960; Fox and Rasche, 1969)

It was assumed that when the physical strength i.e. intensity of rival stimuli (horizontal and vertical gratings) are equal the dominant eye, the stronger sensory dominance, (Walls, 1951) is the eye that perceive the image more frequent than the other eye (Ooi et al., 2001).

• **Spatial frequency** (Hollins, 1980; Andrews and Purves, 1997; O'Shea et al., 1997)

It has been presumed that binocular rivalry relies on the Magnocellular pathway of visual system, evidenced by the finding that no rivalry occurs when rival stimuli compromised of high spatial frequency grating or lines (Livingstone and Hubel, 1987).
The relationship between binocular rivalry i.e. exclusive visibility of rival gratings stimuli and spatial frequency have been studied by several authors (Hollins, 1980; O'Shea et al., 1997). In Hollins study, rival stimuli of sinusoidal gratings presented in a consistent field size of 2 degrees, were showed vertically to one eye and

horizontally to the other eye over a rivalry test period of 100 seconds. Hollins found a curvilinear relationship between the exclusive visibility period and spatial frequency with the highest period of exclusive visibility showing at 3c/d (cycle per degree) spatial frequency. O'Shea et al studied the effect of spatial frequency (0.5 to 16 c/d) over field sizes of (0.5 to 8 degrees) on the exclusive visibility - their results showed an inverse relationship between exclusive visibility and spatial frequency.

• The size (O'Shea et al., 1997) and retinal eccentricity (Fahle, 1987) of rival stimuli have been also found to have an effect in measuring sensory ocular dominance in the binocular rivalry process. When the retinal angular field of rival stimuli are small, the response will be alternated between eyes (rival targets) every few seconds with unpredicted dominant periods (Fox and Herrmann, 1967), as opposed to the mosaic pattern with larger targets. It was found that a small degree of eccentricity to the right or left of foveae (for a stimulus of circular field 1^{o}) is necessary for the identification of sensory ocular dominance (Leat and Woodhouse, 1984).

6.1.4 Attention and binocular rivalry

Although binocular rivalry mechanism appears to be uncontrolled which implies that the neural visual system is solely predominant in the process, this suggests that attention has no role in selecting the sensory visual inputs during rivalry. However, evidence demonstrates that visual attention has an effect on binocular rivalry and can end the suppression of a target and bring it into dominance (Ooi and He, 1999) by means of "conscious perception" of visual inputs (Crick and Koch, 1995). This can be achieved through 'cuing attention', and 'pop out' cues that influence the involuntary attention to the specific eye image during rivalry (Ooi and He, 1999). For example, introducing an image into a blank field of one eye will permit that image to be seen immediately and end the suppressed phase of this eye to become dominant, known as the Cheshire Cat effect (Duensing and Miller, 1979).

The role of attention in binocular rivalry has been established previously by Helmholtz (Helmholtz, 1910, 1962) in terms of the ability of the sensory visual system in recognizing and selecting the sensory visual inputs (Andrews and Purves, 1997; Leopold and Logothetis, 1999; Lightstone, Lightstone and Wilkins, 1999).

In contrast, other peripheral mechanisms like blinking and accommodation do not show a role in attention i.e. do not interrupt attention during binocular rivalry processing - suggesting that the condition does seem to be a completely neural mechanism (Lack, 1978).
Interestingly, non-visual factors such as meaningful stimuli are predominant during rivalry. For example, a recognizable picture (like a face) predominates over a pattern stimulus (Yu and Blake, 1992), and religious symbols like a star of David or a cross stimulating may dominate according to the observer's religion (Lo Sciuto and Hartley, 1963). This also supports the idea that non visual factors such as concentration and comprehension processes can play an important role on stimulus predominance (Yu and Blake, 1992).

6.1.5 Measuring sensory ocular dominance

Binocular rivalry is a quantitative measure of sensory ocular dominance (Walls, 1951; Coren and Kaplan, 1973) which can be evaluated by calculating the difference of the exclusive visibility of rival stimuli between right and left eye i.e. dominant and non dominant eye (Ooi et al., 2001; Handa et al., 2004 a; Handa et al., 2004 b). When both eyes are equally dominant, one will predict that exclusive visibility periods of rival stimuli images will be distributed equally (50%) between the two eyes. On other hand, when the exclusive visibility of a particular (a given) rival stimulus is longer (> 50% of rivalry time) than the other eye's perceived stimulus (the fellow eye's stimulus), the eye perceiving the target with longer duration is considered to be the sensory dominant eye, and the fellow eye is the non-dominant eye (Ooi et al., 2001; Handa et al., 2006).

During rivalry three classical perceptual states may be experienced.

1. Exclusive visibility of one or the other monocular stimulus
2. Suppression of one or the other monocular stimulus
3. Mixture of both monocular stimuli that the perceptual image consists of patches or pieces from right eye image and pieces from the left eye image. A perceptual condition known as *piecemeal* at which same area of visual field (of the perceived target field) consist parts of one of the monocular stimuli

and the other areas of visual field consist other parts of the compatible stimuli image (Blake, O'Shea and Mueller, 1992).

The aforementioned visual perceptual conditions, dominant, suppression, piecemeal, rely on internal neural visual process that can be described as uncontrolled (Livingstone and Hubel, 1987; Blake, 1989, 2001).

A BalancingTechnique (Ooi et al., 2001) has been used to measure sensory ocular dominance by measuring the amount of inter-ocular imbalance of sensory input. This can be achieved by controlling the contrast of rivalry targets of each eye image to reach the point of equal dominance (or a phase of no sensory ocular dominance); i.e. exclusive visibility periods are equally distributed between the two eyes. This is also known as inter-ocular balance. This technique is applied by reducing the physical intensity or contrast of the dominant eye target to reach the point of reversal where the exclusive visibility duration of non dominant eye becomes just longer than that of dominant eye (Handa et al., 2004 a; Handa et al., 2004 b). "Reversal point" may be referred to by the minimum amount of contrast required for a previously suppressed pattern grating to induce suppression for the dominant pattern presented to the other eye. This is termed usefully as the *rivalry threshold* and defined as "minimum contrast necessary for generating binocular rivalry" (Blake, 1977).

In other words, value of rivalry threshold may be corresponding to the strength of the contra-lateral pattern presented to the other eye. However, Blake found that contrast of the contra-lateral pattern has no effect on rivalry threshold (contrast sensitivity or threshold of visibility) of a given stimulus, and once that stimulus is visible, duration of visibility is independent on its contrast (Blake, 1977). However, the suppression duration of low contrast stimulus is longer than that of high contrast stimulus (Blake, 1977), and in fact, dominant and suppression durations are inversely related (Fox and Rasche, 1969).

6.1.6 Types of binocular rivalry

Binocular rivalry can be described based on the features of rival stimuli for example:

a. Binocular contour rivalry – when the difference between stimuli is only in their contour or form (Wheatstone, 1838) Binocular rivalry is strongest when rival stimuli differ in their countours i.e. using rectangular (diamond patches) orthogonal gratings (Wheatstone, 1838; Fox and Herrmann, 1967; Hayashi and Bryden, 1967; Kovacs et al., 1996; Logothetis, Leopold and Sheinberg, 1996; O'Shea et al., 1997; Tong et al., 1998; Freeman and Nguyen, 2001; Handa et al., 2004 a; Handa et al., 2006; Fagard et al., 2008).

b. Binocular colour rivalry – when the difference between stimuli is only in their colour (Hollins and Leung, 1980; Kovacs et al., 1996; Ooi et al., 2001).

c. Binocular luster rivalry – when the difference between stimuli is only in their lightness, luminance (Kakizaki, 1960; Fox and Rasche, 1969)

When one eye is presented to an object image (face on grating) and a blank field is presented to the other eye in this situation, no rivalry will be experienced as the observer usually observe the image continuously - a condition known as contour dominance, which will occur unless introducing different image of equal strength or a real motion i.e. a waving hand or moving a rod into the blank field at the time of rivalry. This technique is known as the Cheshire Cat effect (Duensing and Miller, 1979)

6.1.7 Types of stimuli may use in binocular rivalry

For binocular rivalry to be conventionally accomplished, bistable, static, rival stimuli are required (Freeman and Nguyen, 2001).

- **Simple** (Blake, 2001)

For example presentation of rival patterns of two orthogonal gratings of opposite orientations (Fox and Herrmann, 1967; Logothetis et al., 1996; O'Shea et al., 1997;

Freeman and Nguyen, 2001; Handa et al., 2004 a; Handa et al., 2006; Fagard et al., 2008).

• **Complex** (Tong et al., 1998; Blake, 2001; Tong, 2001)

For example; 1) Different pictures like ape & text (Kovacs et al., 1996), a face and a house (Tong et al., 1998). 2) Different alphabetic letters for letter detection in rivalry i.e "A" and "S" letters viewed separately and simultaneously to both eyes where "A" viewed by the right eye and S viewed by the left eye (Wheatstone, 1838; Hayashi and Bryden, 1967).

6.1.8 The piecemeal effect

This is demonstrated when patchwork rival images from both eyes are combined specifically for a period of time during rivalry during which binocular dominancy occurs., i.e. right and left eye dominate at the same time during rivalry of two different images (Kovacs et al., 1996; Alais and Blake, 1999). For example; presentation of patches of red and green patterns to one eye and the opposite pattern of green and red patches to the other eye, according to inter-ocular grouping the viewer would occasionally reports observation of all red or all green patches (Kovacs et al., 1996). In another words, piecemeal rivalry is the periods of binocular mixed dominance perception of patchwork image which consists mixed portions of right and left eye images (Meenes, 1930; Blake, 2001) i.e. dynamic mosaic of both eyes images (Blake, 1989). This suggests that rivalry occurs between spatial regions (local suppression and dominant regions), and not between entire eyes. The condition is usually brief and unstable and acts as one image "sweeps" the other for dominancy.

However, transition periods (Brascamp et al., 2006b), when both rival images are visible, are usually experienced and cause the piecemeal effect (Blake, 1989; Brascamp et al., 2006b). This condition is characterized by "return transitions" - periods that occur when the perceptual image of the dominant eye alter from the dominance phase to transition, and then return to dominancy without domination effect from the other eye image (Brascamp et al., 2006b).

6.1.9 Factors affecting the incidence of piecemeal conditions

• **Target size** – as the target size increase, the incidence of piecemeal periods increases (Blake, 1989). Small size rival stimuli have been used by many authors to avoid piecemeal rivalry as much as possible (Meenes, 1930; O'Shea et al., 1997; Freeman and Nguyen, 2001; Handa et al., 2004 a). Assuming target sizes of less that 1 degree retinal angle, complete periods of stimuli suppression and dominancy would be experienced for a specific period of rivalry time (Blake, 1989, 2001). It has been suggested that a visual angle of 0.1degree or less can only create exclusive rivalry of rival stimuli without any transient periods of piecemeals. In this condition the rivalry can be called unitary (Blake, 2001). Conversely, observers will report a perception of piecemeal phenomenon with pieces of images from the right eye combined with pieces of images of left eye of rival targets quite often when the rival stimuli have large retinal image size (Meenes, 1930; Blake et al., 1992).

• **Rivalry time** - longer rivalry period increase the incidence of patchworks condition (Hollins and Hudnell, 1980).

• **Luminance** - Presentation of rival stimuli at low light levels reduce the incidence of piecemeal condition during rivalry (O'Shea, Blake and Wlofe, 1994).

6.1.10 Aims for this study

- To develop a method of quantitative assessment of binocular rivalry.

- To compare measures of sensory ocular dominance in normal adult subjects using different rivalry stimuli patterns.

- To study the correlation between sighting ocular dominance, defined with Hole in the Card (HIC) test, and sensory ocular dominance, defined with different binocular rivalry stimuli patterns.

- To evaluate the effect of different rival patterns on the cumulative exclusive rivalry duration CERD (*duration during which one or the other rivalry stimulus was exclusively visible i.e. target dominancy*).

- To evaluate the effect of different rivalry stimulus sizes or spatial frequencies on the cumulative exclusive rivalry duration (CERD).

- To evaluate the effect of different rival patterns on the cumulative exclusive rivalry rate CERR *(defined by the number of switches during CERD*).

6.2 Methods

6.2.1 Subjects

Twenty two subjects were recruited from students and staff at School of Optometry and Vision Sciences in Cardiff University. The study design was approved by the School of Optometry & Vision Science Research Ethics Committee; subjects gave informed consent, and the experiment followed the tenets of the declaration of Helsinki. All subjects had to have normal binocular vision and the absence of amblyopia, asthenopic visual symptoms or history of migraine/epilepsy. Subjects were enrolled in this study according to inclusion/exclusion criteria shown in table 6.1.

Test	Criteria
Age	18-40
Sex	Either
General health	No history of migraine
Best corrected VA (LogMAR)	0.1 or better (both eyes)
Cover test	No squint or history of binocular vision anomaly
Stereoacuity (Titmus Fly test)	60 sec. of arc or better

Table 6.1: Inclusion criteria

6.2.2 Procedures

Subjects attended for a single session with one examiner. After giving informed consent the following preliminary procedures were carried out:

1. A brief questionnaire was administered verbally to each individual to determine whether there were any asthenopic symptoms at the time of the investigation and whether there was a history of migraine.

2. Monocular visual acuity measurement at distance (6 m) was checked using the VA Log MAR chart with the best correction in place.

3. Stereo-acuity and strabismus screening for subjects were performed using the Titmus fly stereo test and cover test respectively.

4. Sighting ocular dominance was defined with Hole in the Card test (Durand and Gould, 1910).

A computer disc (CD) with 1.5 cm diameter central hole was wrapped in white paper and utilized for this test. The subject was asked to hold the disc with both hands at arm's length until the hole coincided with the observer's nasal bridge. Then with both eyes open, the subject was asked to view a target (spot of light) at distance of 6 meters throgh the aperture. The subject was then asked to close each eye in turn and report which eye was viewing the target, this eye was reported to be the dominant one.

6.2.3 Stimuli and apparatus

Binocular rivalry was produced by presenting constant and continuous (static) test stimuli to the both eyes simultaneously. Test stimuli consisted of either:

a) Fixed high contrast (100%) square wave gratings presented in orthogonal directions, tilted to the right at 45°, seen by the right eye, and tilted to the left at 135°, seen by the left eye; or,

b) Fixed high contrast (100%) letter stimuli 'A' presented to the right eye and 'S' presented to the left eye. Word stimuli ('WAS' presented to the right eye and 'SAW' presented to the left eye.

Each stimuli subtended a circular retinal field sizes of 1° (foveal size image), 2.5° (macular size image) and larger 7° (Stein et al., 1988). This has been achieved by calculating the inverse tangent of the retinal image angular sizes.

Tan 1=x/d **Tan 2.5=x/d** **and** **Tan 7=x/d**

Where:

x =diameter of the target in cm, and

d=distance between eye pieces in synoptophore and slides (target) =15 cm.

The gratings were presented in circular apertures subtending 1°, 2.5° or 7° with diameters of 0.26 cm, 0.65 cm or 1.8 cm respectively. For circular aperture of field size 1°, gratings had spatial frequency of either 1 c/d, 2 c/d or letter rival patterns. For 2.5° and 7° field sizes, grating stimuli had spatial frequencies of either 2 c/d or 4 c/d. The 2.5° field size had also the word rival patterns. Therefore eight sets of stimulus patterns were presented for each subject. Table 6.2 shows stimuli field sizes and rival pattern types accordingly.

Each stimulus was centred in identical 3.0x3.0 cm (30% grey) square shaped fusion contour which had a black distinct border and the reminder of the field was transparent. The squares were to help facilitate fusion, stabilize and control vergence eye movements, i.e. maintain constant eye vergence and, hence, improve stable and accurate binocular alignment of the two rival targets (Wiesenfelder and Blake, 1990).

Field size	1°			2.5°			7°	
Target type	(A) 2c/d	(B) 1c/d	(G) letters	(D) 2c/d	(C) 4c/d	(H) words	(F) 2c/d	(E) 4c/d

Table 6.2: Target stimuli patterns occupied the field size

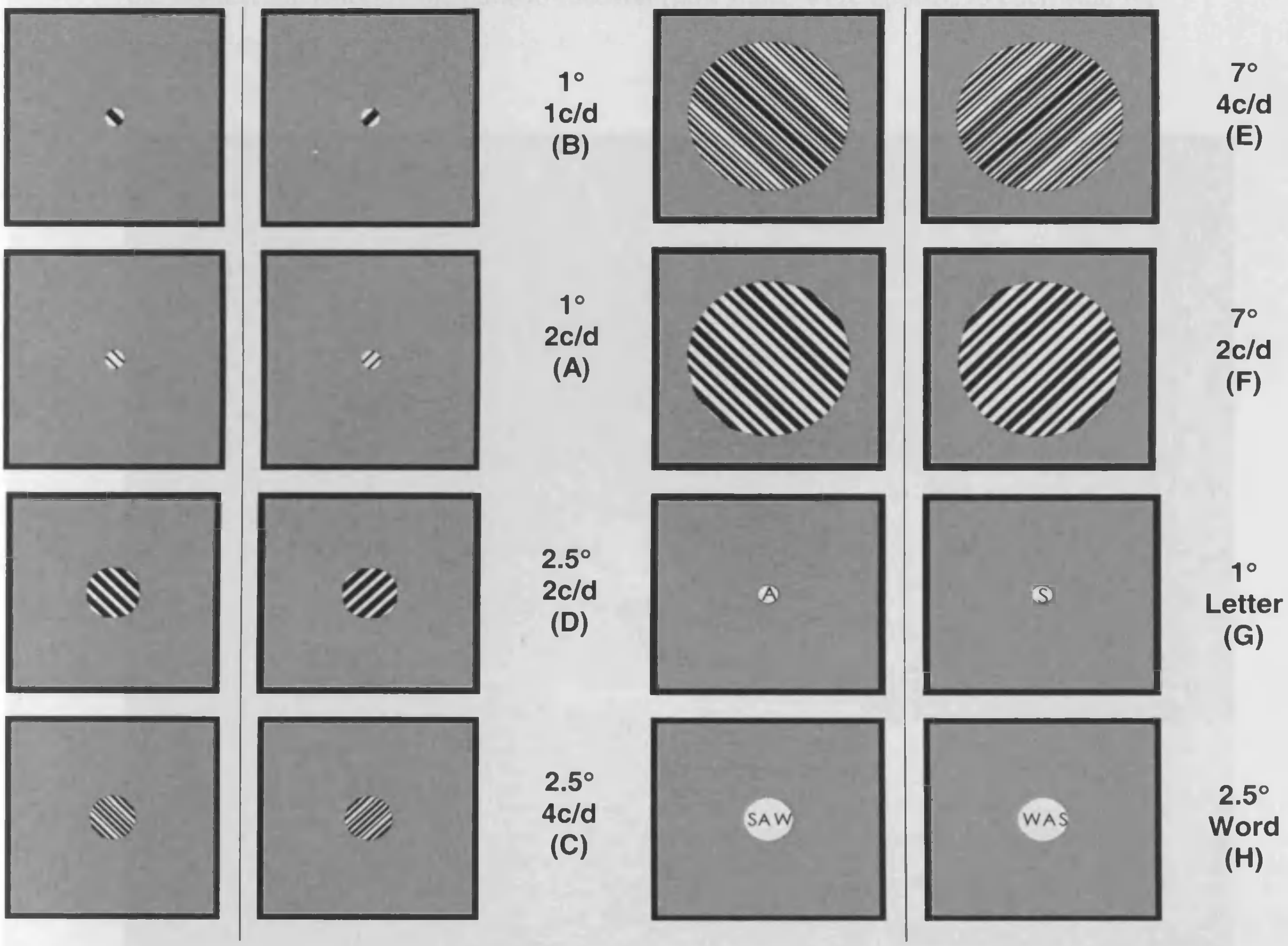

Figure 6.5: Rivalry stimuli used in the study

Small rivalry stimuli targets which subtended a small retinal image size were used in order to minimise the piecemeal effect (Blake, 1989; Freeman and Nguyen, 2001). These rivalry stimuli were created using a software computer program (Corel DRAWx3 Version 13). Rivalry stimuli patterns were drawn in black and printed on a transparent sheet. Each pattern was then adjusted to be located concentrically with a synoptophore slides with diameter of 8.2cm x 8.2cm. Background luminance of the slide was 26 lux (measured at the level of eyepieces of Synoptophore). In any one trial, participants were presented with a pair of gratings with opposite orientations but similar sizes and spatial frequency.

A synoptophore (Clement Clarke; Figure 6.6) was used to display the stimuli to ensure binocular fixation and fusion and to permit independent control of test stimuli to each eye. Background luminance of the two slides was equalized and adjusted to the highest intensity by the built-in rheostat (new bulbs were applied to each side for this experiment).

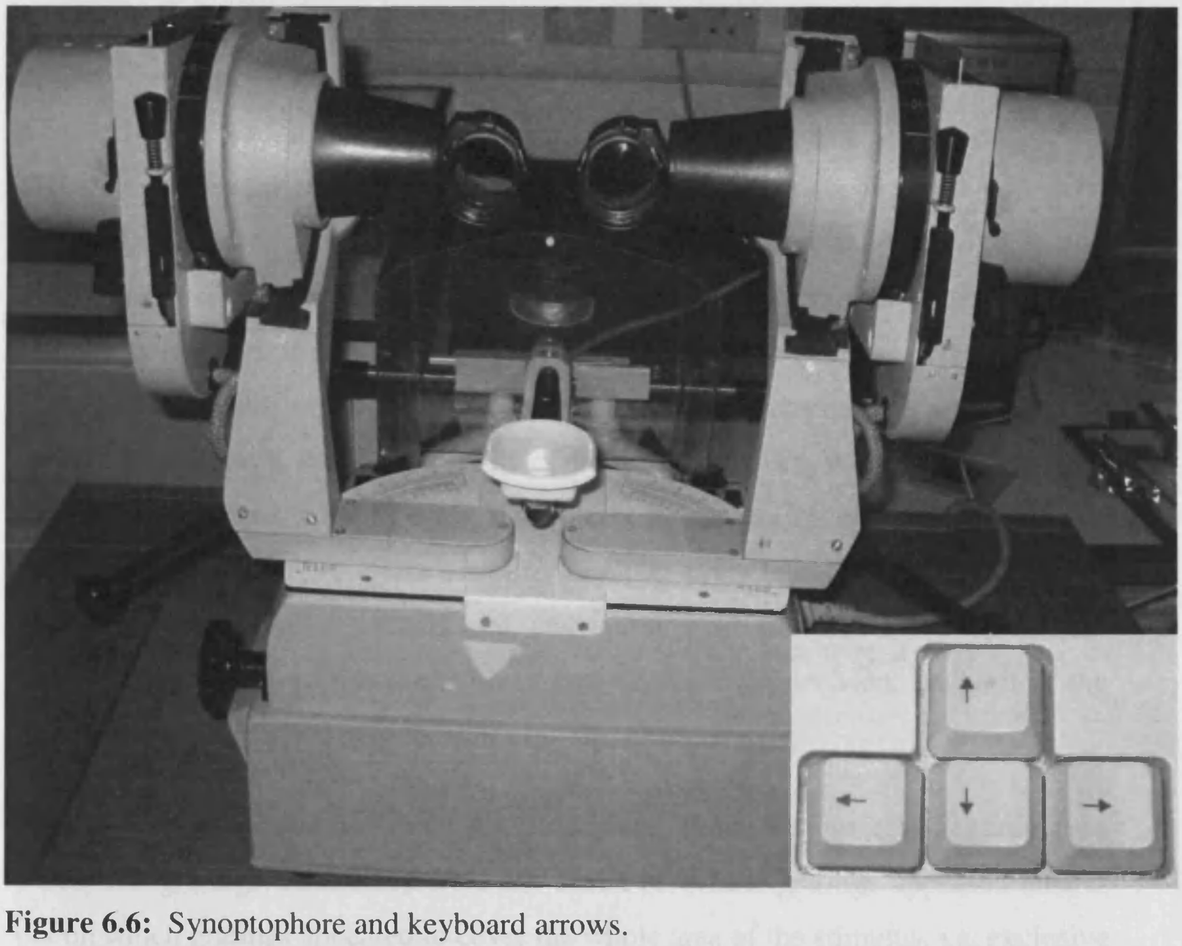

Figure 6.6: Synoptophore and keyboard arrows.

Subjects gave their responses for the right or the left image dominancy (exclusive visibility) by pressing rightward or leftward arrows of a computer keyboard and downward or upward arrows for mix responses. The keyboard was placed a table at the right side of the subject (Figure 6.6).

Quantitative assessment of time dominancy was calculated as total duration of exclusive target visibility viewed by a single eye and/or both eyes image during a trial and subject responses were stored by using a software computer program. The program was stopped manually and all data of subject responses files were stored into the Excel software computer program.

6.2.4 Binocular rivalry procedure

Prior to the rivalry tests the synoptophore was set up for each subject and the eye pieces were set at the individual's inter pupillary distance.

Participants were seated in a darkened room (luminance 5lux) as low levels of lighting are known to reduce the incidence of piecemeal effect (O'Shea et al 1994). The test stimuli were viewed through the eye pieces of the synoptophore and the subject' head was supported by a head and chin rest. Verbal instructions were provided to the participants before commencing the experiments.

The targets were aligned so that right and left stimuli could be fused and keep fixation in about the central area of the field. Participants rested their middle and index fingers of their right hands on the right and left arrow buttons on the keyboard to indicate the time of exclusive visibility of the rival target (for right eye or left eye response) and instructed to manually record fluctuations (changes) in dominance of the two rival targets through that pair of buttons on the keyboard ("R" OR "L"). Perceptual responses were reported by subjects by depressing and releasing one of two keys consistent to exclusive visibility of either eye's image, i.e. when the target was defined to be entirely dominance, and pressing the bottom (or the top button) when perceptual image was doubtful. In case of uncertain decision, i.e. both of the rival stimuli were visible may indicate equi-dominance.

During rivalry conditions, responses that were given by subjects regarding to perceptual gratings dominancy were not based on which gratings appeared clearer but on which gratings appeared to cover the whole area of the stimulus, i.e. exclusive visibility. For example, subjects pressed the right button when rightward tilted (at 45 deg.) gratings, letter 'A' or word 'WAS', were exclusively visible over the whole field and the left button was pressed when leftward tilted (at 135 deg.) gratings, letter 'S' or word 'SAW' were exclusively visible over the whole field, and the bottom button key was pressed when both gratings, letters or words were incompletely visible or overlapped (ambiguous perceptual response).

To summarise, the report of dominance state was represented and shown in one of three responses, right eye dominance, left eye dominance or mixed (when perceptual response represented pieces of either eye stimuli. i.e. both eyes images appeared to be overlapped).

Diagram below shows an example of subject responses during a trial (Figure 6.7).

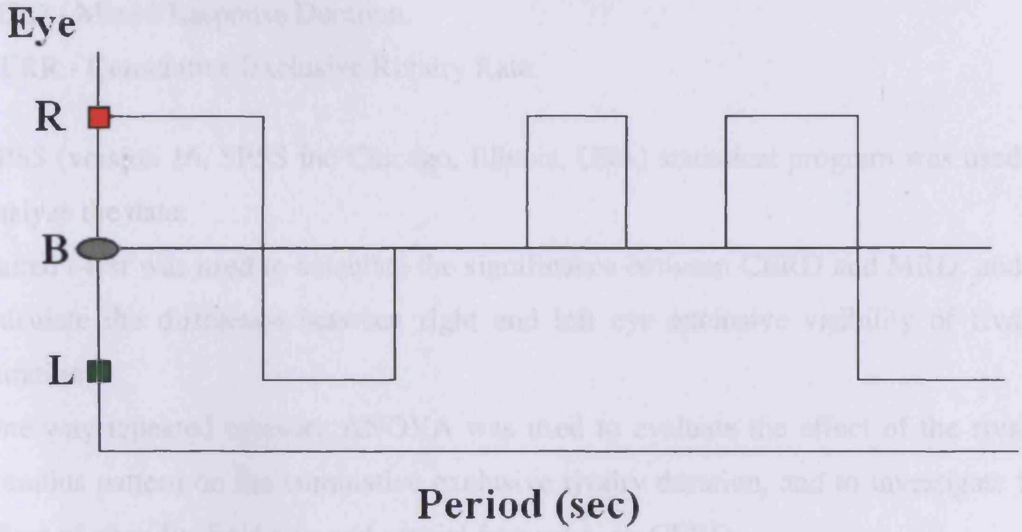

Figure 6.7: An example of subject responses during a trial of rivalry; R (right eye), L (left eye), B (both eyes).

Strength of the ocular dominance and stability could be indicated by the presence of the significant difference between duration, in terms of number of seconds, of exclusive visibility of a trial target of one eye compared with the other eye's target.

Eight presentations were carried out for each subject. Trial presentations were carried out in random order across subjects. Where the three sizes and stimuli patterns were randomly assigned to the two eyes. All trials were performed for subjects in the same day. Each trial was lasted for 70 seconds, this would guarantee that rivalry would take place and to allow adequate time for a subjective quantitative measurement of ocular dominance. Each trial was followed by an inter-trial interval of about 45-60 seconds.

All subjects were started with slide 'A' in order to familiarize them with the test. The same rivalry stimuli were repeated again during the experiment.

6.2.4 Data analysis

Trial duration for all observers (subjects) were revised into 60 seconds intervals for each stimuli (slide) used, i.e. 176 trials have been revised, using a Microsoft excel program (Office 2003). The following features were calculated from the data:

CERD - Cumulative Exclusive Rivalry Duration.
MRD - Mixed Response Duration.
CERR - Cumulative Exclusive Rivalry Rate.

SPSS (version 16, SPSS inc Chicago, Illinois, USA) statistical program was used to analyze the data.
Paired t-test was used to calculate the significance between CERD and MRD, and to calculate the difference between right and left eye exclusive visibility of rivalry duration.
One way repeated measure ANOVA was used to evaluate the effect of the rivalry stimulus pattern on the cumulative exclusive rivalry duration, and to investigate the effect of stimulus field size and special frequency on CERD.

6.3 Results

All 22 subjects participated in this study, 12 of whom were female; mean age was 27 years (range 20 to 39 years). Mean visual acuity in the right eye was 0.00 and in the left eye was 0.01 LogMAR. Paired T-test showed no significant difference between right and left eye visual acuity (p=0.126).

Figure 6.8 shows the incidence of sighting ocular dominance using HIC test. 91% of subjects reported right eye dominance.

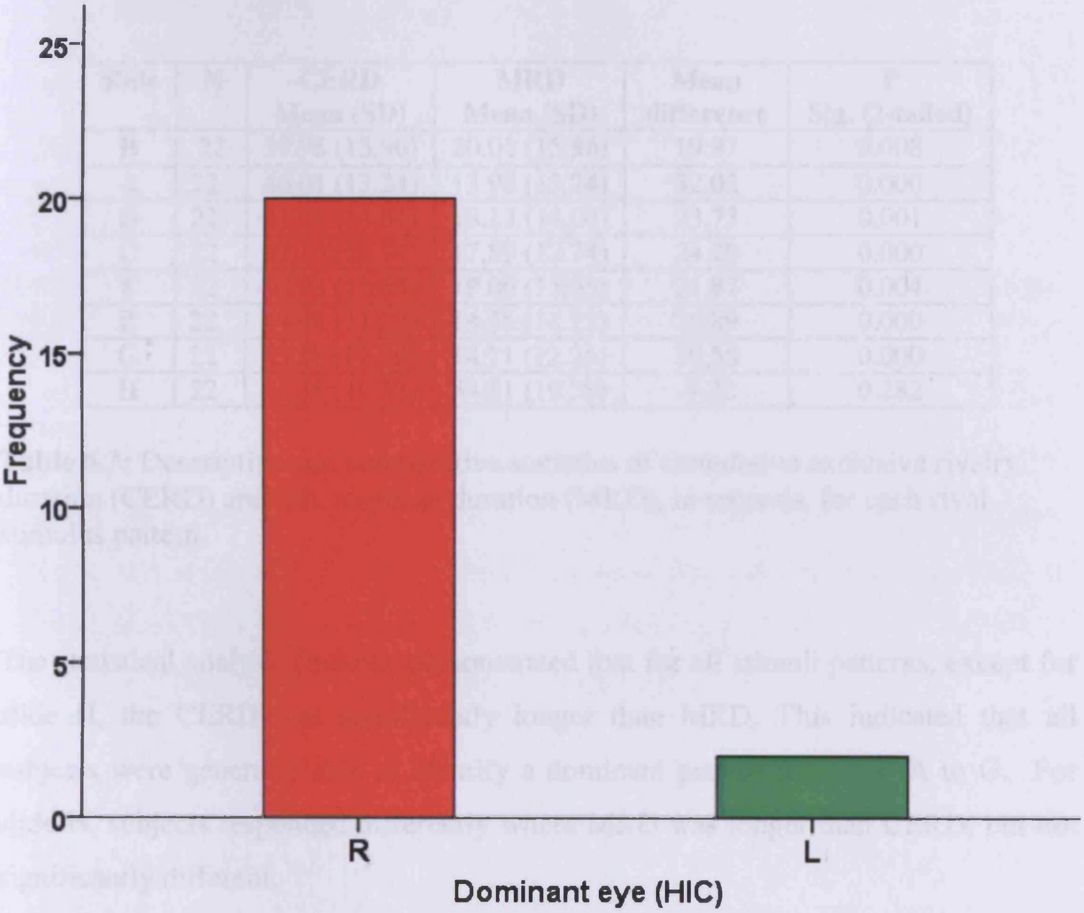

Figure 6.8: Incidence of sighting ocular dominance

6.3.1 Effect of the stimulus pattern on cumulative exclusive rivalry duration [CERD], and on mixed response duration [MRD]

Effect of the rivalry stimulus pattern on the cumulative exclusive rivalry duration (the duration of exclusive visibility of the right eye plus duration of exclusive visibility of the left eye), and on mixed response duration (when pieces of each images are visible) was examined by calculating the difference between the two durations for each slide separately using a paired t-test.

Descriptive and comparative statistics are illustrated in table 6.3.

Slide	N	CERD Mean (SD)	MRD Mean (SD)	Mean difference	P Sig. (2-tailed)
B	22	39.98 (15.96)	20.01 (15.96)	19.97	0.008
A	22	46.01 (13.24)	13.98 (13.24)	32.02	0.000
D	22	41.86 (14.04)	18.13 (14.04)	23.73	0.001
C	22	42.10 (12.74)	17.89 (12.74)	24.20	0.000
F	22	40.93 (15.63)	19.06 (15.63)	21.87	0.004
E	22	44.44 (11.22)	14.55 (11.22)	28.89	0.000
G	22	45.28 (12.26)	14.71 (12.26)	30.56	0.000
H	22	25.38 (19.58)	34.61 (19.58)	-9.22	0.282

Table 6.3: Descriptive and comparative statistics of cumulative exclusive rivalry duration (CERD) and mix response duration (MRD), in seconds, for each rival stimulus pattern.

The statistical analysis findings demonstrated that for all stimuli patterns, except for slide H, the CERD was significantly longer than MRD. This indicated that all subjects were generally able to identify a dominant pattern for slides A to G. For slide H, subjects responded differently where MRD was longer than CERD, but not significantly different.

Results are graphically presented in figure 6.9.

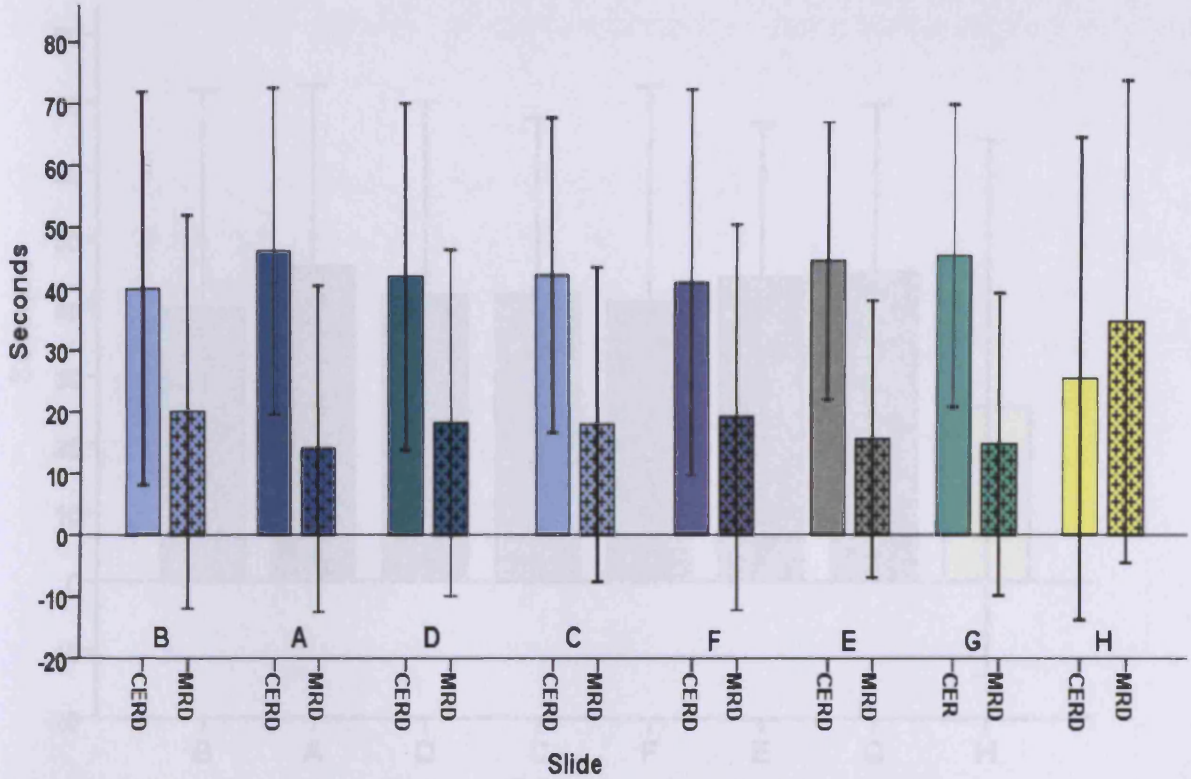

Figure 6.9: Mean cumulative exclusive rivalry duration (CERD) versus mean mixed response duration (MRD). Error bars indicate standard deviations.

One way repeated measure ANOVA revealed a significant difference in CERD amongst the slides used, where p value of Wilks' Lambda Multivariate tests was 0.017. Pairwise comparisons (Bonferroni) showed that slide H was the source of significance differences (see Table 6.4 for detail) whilst there were no significant differences between the rest of the slides (p=1.000 for all).

Slides	H-B	H-A	H-D	H-C	H-F	H-E	H-G
p value	0.009	0.004	0.002	0.001	0.070	0.010	0.007

Table 6.4: Significance differences between slides in terms of CERD.

This result is graphically presented in figure 6.10.

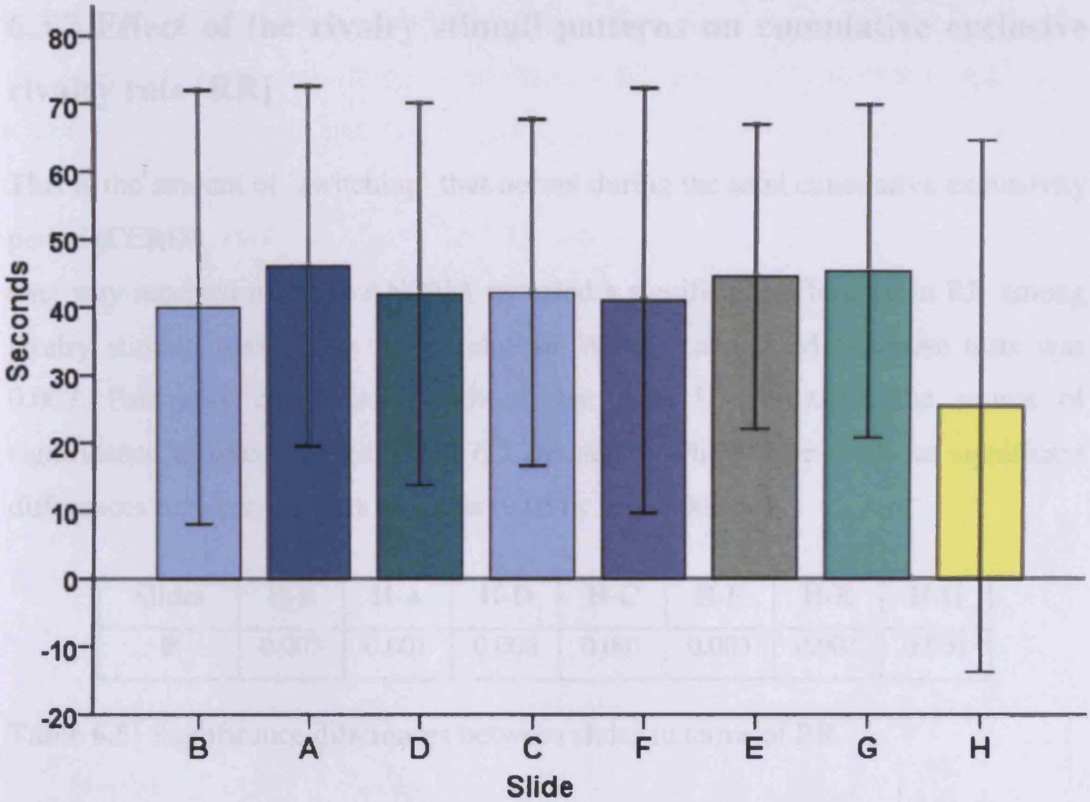

Figure 6.10: Effect of the slides (rivalry stimulus type) on cumulative exclusive rivalry duration [CERD]. Error bars indicate standard deviations.

It is obvious from the figure the small variations in CERD between the slides except for the slide H.

6.3.2 Effect of the rivalry stimuli patterns on cumulative exclusive rivalry rate [RR]

This is the amount of 'switching' that occurs during the total cumulative exclusivity period (CERD).

One way repeated measure ANOVA revealed a significant difference in RR among rivalry stimuli used where the p value of Wilks' Lambda Multivariate tests was 0.007. Pair wise comparisons showed that slide H was again the source of significance differences (see Table 6.5 for detail) while there were no significant differences between the rests of slides (0.051< P <1.000).

Slides	H-B	H-A	H-D	H-C	H-F	H-E	H-G
P	0.007	0.001	0.006	0.001	0.003	0.001	0.001

Table 6.5: Significance differences between slides in terms of RR.

6.3.3 Effect of slides rivalry stimuli on right or left eye dominancy duration

In order to measure the sensory ocular dominance quantitatively, the mixed response duration MRD was excluded from the total duration of each trial, and then the right versus left comparison was made. Descriptive and comparative statistics of the difference between right and left eye exclusive visibility of rivalry images duration (indicated by exclusive rivalry duration ERD) for the different stimuli type are summarized in table 6.6.

Slide	N	CERD	RED Mean (SD)	LED Mean (SD)	Mean difference	P (2-tailed)
B	22	39.98	23.05 (13.35)	16.93 (10.32)	6.11	0.121
A	22	46.01	26.63 (11.62)	19.38 (8.96)	7.25	0.046
D	22	41.86	24.06 (8.83)	17.80 (8.11)	6.26	0.006
C	22	42.10	23.14 (7.72)	18.95 (7.50)	4.18	0.028
E	22	44.44	23.47 (6.58)	20.97 (7.38)	2.50	0.174
F	22	40.93	23.76 (9.10)	17.17 (8.73)	6.58	0.002
G	22	45.28	25.16 (12.10)	20.12 (11.65)	5.04	0.258
H	22	25.38	18.88 (16.03)	6.50 (7.58)	12.37	0.001

Table 6.6: Descriptive and comparative statistics of the difference between right eye duration (RED) and left eye duration (LED), in seconds, for the different stimuli type.

Results showed that all subjects displayed evidence of sensory ocular dominance for all slides, i.e. there was always a dominant eye. Table 8.4 shows that right eye exclusive visibility duration for each slide is generally longer than that of the left eye. However this difference was not always statistically different. Differences were significant with slides A,C,D,F, and H, whilst slides B, E and G showed no significant difference between right and left exclusive visibility duration.
The result is graphically presented in figure 6.11.

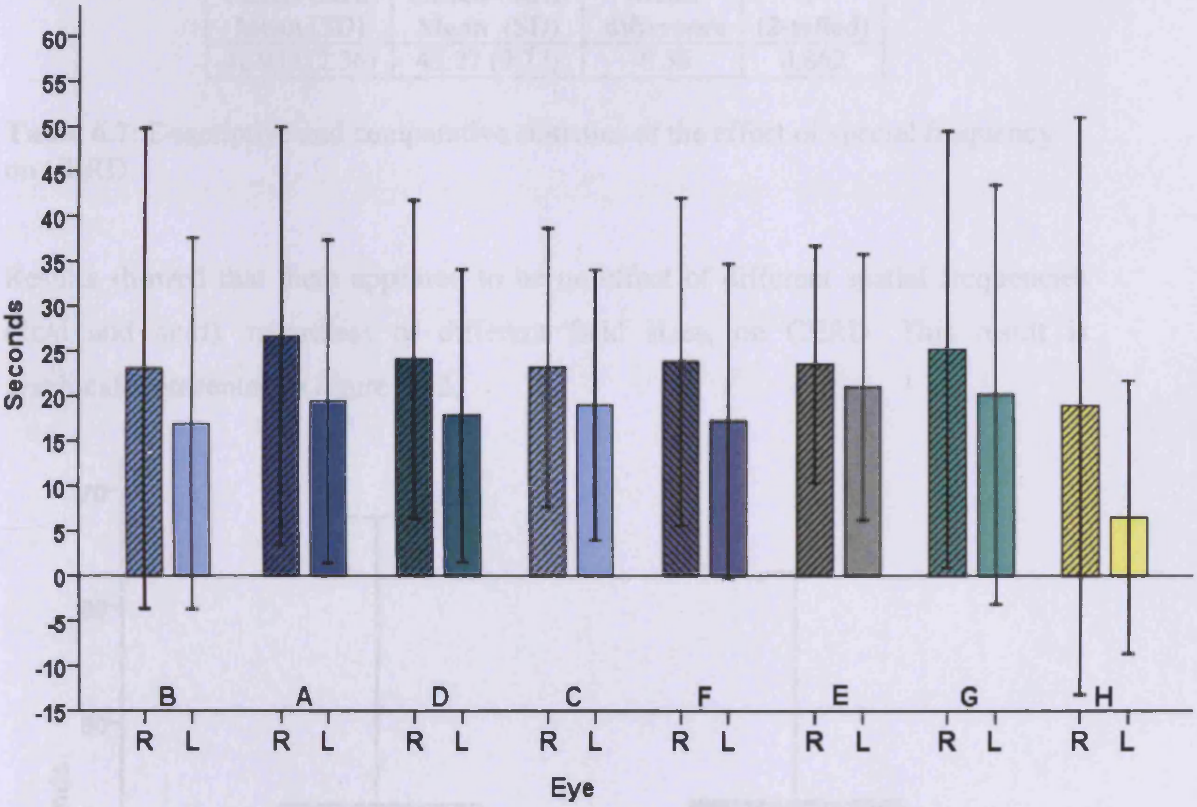

Figure 6.11: mean differences between right and left eye duration (in seconds) for the different stimuli type. Error bars indicate standard deviations.

To obtain a global indicator of right or left sensory dominance in this cohort, the means of right and left eye duration for all slides together was computed (averaged) and the difference between right and left eye durations was then examined by paired t-test. A significant difference indicated the presence of strong sensory ocular dominance ($p<0.0001$). This result showed, in general, an agreement between the sighting dominance results (predominantly right eyed in this cohort) and sensory ocular dominance results.

6.3.4 Effect of the spatial frequency on CERD

To investigate the effect of spatial frequency on CERD the average means of CERD for slides A, D and F (2c/d) and for slides C & E (4c/d) were collated and the difference of the average duration between the two different special frequency stimuli durations was then calculated by independent t-test.

Descriptive and comparative statistics are shown in table 6.7.

CERD (2c/d) Mean (SD)	CERD (4c/d) Mean (SD)	Mean difference	P (2-tailed)
42.93 (12.36)	43.27 (9.77)	-0.33	0.862

Table 6.7: Descriptive and comparative statistics of the effect of special frequency on CERD.

Results showed that there appeared to be no effect of different spatial frequencies (2c/d and 4c/d), regardless of different field sizes, on CERD. This result is graphically presented in figure 6.12.

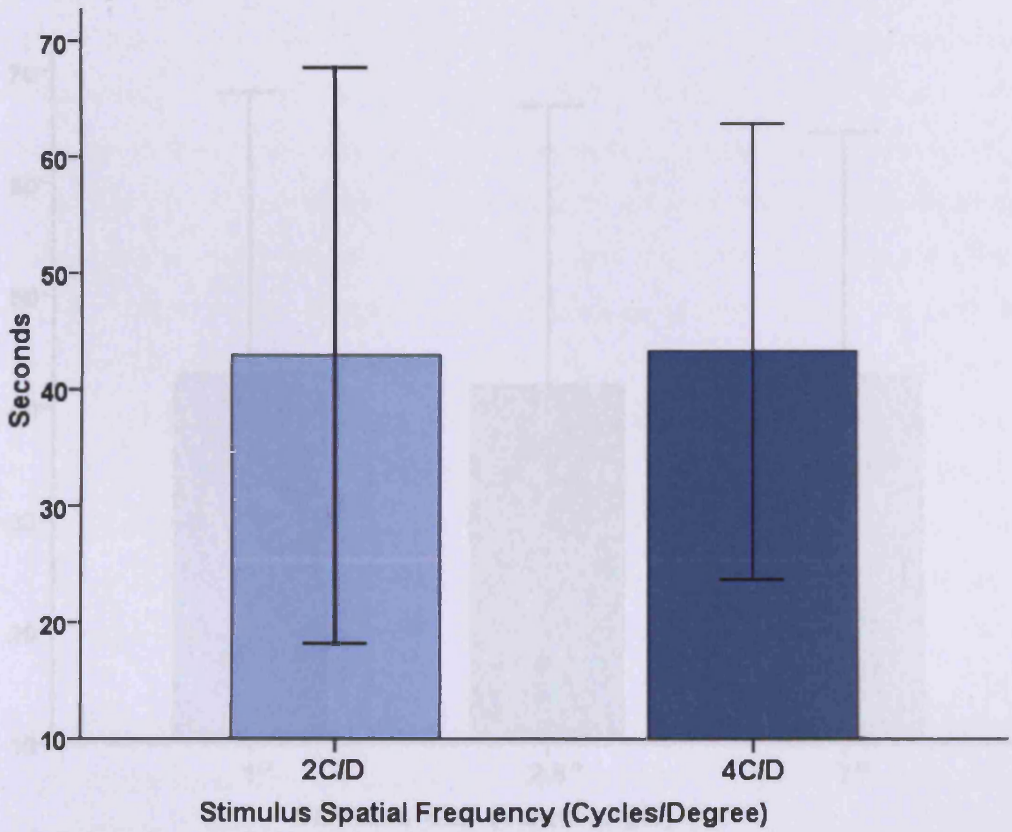

Figure 6.12: Effect of the spatial frequency on CERD. Error bars indicate standard deviations.

6.3.5 Effect of the field size on CERD

To investigate the effect of stimulus field size on CERD the average means of CERD for slides A & B (1 degree), for slides C & D (2.5 degree) and for slides E & F were collated and the difference of the average duration between (among) the three different sizes of rival stimuli durations were then calculated by Repeated Measure ANOVA.

Descriptive and comparative statistics are shown in table 6.8.

CERD (1°) Mean (SD)	CERD (2.5°) Mean (SD)	CERD (7°) Mean (SD)	ANOVA p value
43.00 (12.57)	41.98 (12.38)	42.69 (10.90)	0.827

Table 6.8: Descriptive and comparative statistics of the effect of stimulus field size on CERD.

Results showed that no effect of different field sizes, regardless the different spatial frequencies occupied the field areas, on CERD. This result is graphically presented in figure 6.13.

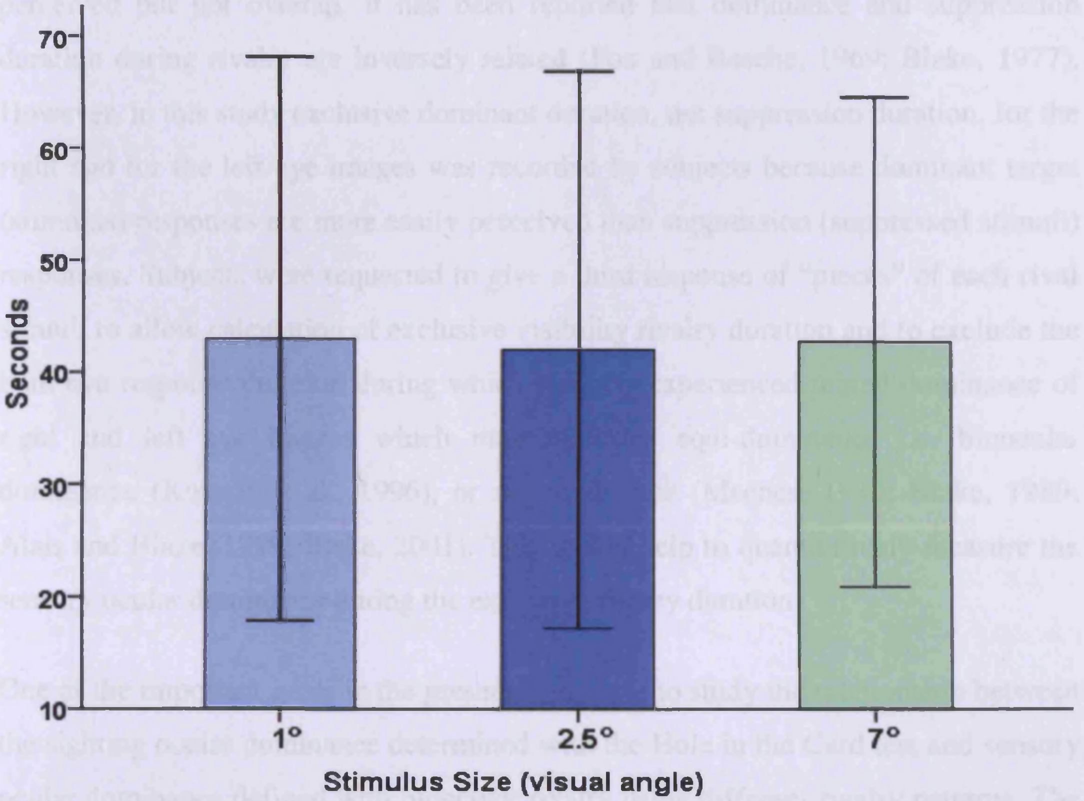

Figure 6.13: Effect of the field size on CERD. Error bars indicate standard deviations.

6.4 Discussion

In the present study the conventional method of binocular rivalry was performed using bi-stable, static (Blake, 1989; Freeman and Nguyen, 2001) of equally strong high contrast stimuli which reflect a stronger binocular rivalry procedure (Breese, 1899, 1909; Levelt, 1965; Liu et al., 1992), using contour rivalry of simple stimuli, i.e. orthogonal gratings of opposite orientations (O'Shea et al., 1997; Tong et al., 1998; Handa et al., 2004 a; Handa et al., 2006; Fagard et al., 2008). This would strongly validate the method of binocular rivalry was used in this study. Further, present study used binocular contour rivalry of different alphapatitical letters 'A' and 'S' (Wheatstone, 1838; Hayashi and Bryden, 1967) for letter detection. In addition complex stimuli were used for word (WAS and SAW) detection.

During rivalry two perceptual phases are usually encountered for each monocular stimuli consistency of being visible (dominance phase) or invisible (suppression phase) (Fox and Rasche, 1969). In the present study fluctuation between dominance and suppression periods was unpredicted and some patches from each image were perceived but not overlap. It has been reported that dominance and suppression duration during rivalry are inversely related (Fox and Rasche, 1969; Blake, 1977). However, in this study exclusive dominant duration, not suppression duration, for the right and for the left eye images was recorded by subjects because dominant target (stimulus) responses are more easily perceived than suppression (suppressed stimuli) responses. Subjects were requested to give a third response of "pieces" of each rival stimuli to allow calculation of exclusive visibility rivalry duration and to exclude the both eye response duration during which subjects experienced mixed dominance of right and left eye images which may indicates equi-dominance i.e. binocular dominance (Kovacs et al., 1996), or no dominance (Meenes, 1930; Blake, 1989; Alais and Blake, 1999; Blake, 2001). This would help to quantitatively measure the sensory ocular dominance during the exclusive rivalry duration.

One of the important goals in the present study was to study the relationship between the sighting ocular dominance determined with the Hole in the Card test and sensory ocular dominance defined with binocular rivalry using different rivalry patterns. The results showed the higher incidence of right sighting ocular dominance (91% of the total subjects) and it was been found, in general, to show a higher dominance duration or the longer exclusive visibility duration of the right eye. There was, in general, consistency between sighting and sensory ocular dominance, as evidenced previously (Porac and Coren, 1978; Blake and Camisa, 1979; Handa et al., 2004 a). However other adult studies reported inconsistency between sighting and sensory ocular dominance where they concluded that sighting and sensory ocular dominance defined with binocular rivalry are independent conditions (Ooi et al., 2001; Mapp et al., 2003; Seijas et al., 2007). Ooi et al (2001) reported that sighting ocular dominance cannot predict sensory ocular dominance measured with the balance technique and vice versa, where no positive correlation between the two conditions was found. However, their rival stimuli were diversified and occupied different retinal areas and they used colour rivalry. Further, they did not measure the exclusive visibility in dominant and in non dominant eye separately (Ooi et al., 2001).

In the present study the cumulative duration during which one or the other rival stimuli was exclusively visible was calculated and it was found that the CERD was varied among the slides (rival stimuli) with longer duration was shown with stimuli with spatial frequency of 2c/d that occupied in the field size of 1°, average mean duration of exclusive visibility was 46 seconds. These findings are in agreement with those of O'shea et al (1997) who found the peak of rivalry at 2c/d for the field size of 2°. However, in their study spatial frequency on the exclusive visibility was inversely related to the field size. For example with the field size of 4 deg the peak of exclusive visibility was at about 1 c/d while in the present study neither field size nor spatial frequency has a significant effect on the exclusive visibility. The present study showed the least stimuli dominancy duration was exhibited in rival stimuli containing words where the average mean duration of CERD was 25.4 seconds from which the significant difference in CERD among all rivalry stimuli patterns used in this study, was generated. Hence CERD in the present study varied between 76.7 % and 43.3 % of the total rivalry duration. In a study by Wade (1975) the exclusive visibility of rival stimuli, monocular stimuli, i.e. either vertical or horizontal gratings of 1 c/d , was 84% of rivalry period (Wade, 1975).

Rivalry stimuli used in this study differ in their ability to detect the sensory ocular dominance. From the foveal size field (1°) stimuli, targets with 2c/d were able to show the sensory ocular dominance more than that of 1c/d. Rival stimuli of macular size field (2.5 deg), 2c/d and 4c/d were both able to show the sensory ocular dominance, especially 2c/d. For the larger field size (7deg), target stimuli with lower spatial frequency (2c/d) were more able to detect the sensory ocular dominance than that of 4c/d. However, larger field size of rival stimuli were found to cause confusion for binocular rivalry (Meenes, 1930; Blake et al., 1992). In the study by O'shea et al (1997), with larger field size (8 deg) subjects were given their responses of exclusive visibility according to the inner 6° gratings area (O'Shea et al., 1997). Further, high spatial frequency may give low retinal contrast, and failure of rivalry at low contrast stimuli is evidenced (Liu et al., 1992) where stable summation of rival stimuli would result as 'dichoptic plaid' and therefore failure of rivalry at high spatial frequency (4-8 c/d) (O'Shea et al., 1997).

Handa et al (2004a) indicated that the significant difference between dominant and non-dominant eye in term of exclusive visibility duration was found at 4 c/d spatial frequency where the mean duration of exclusive visibility in dominant eye was significantly longer than that in non-dominant eye (fellow eye). Although they used different methods of balance technique and different rival stimuli contour (diamond patches with different sizes). Handa et al reported that at low spatial frequencies (i.e. 1c/d and 2c/d) rival stimuli were not able to show significant differences between dominant and non dominant eye in terms of exclusive visibility duration. These results are partially in agreement with our findings, where the rival stimuli of 1c/d at 1° field size were not markedly able to detect the ocular dominance.

The relationship between binocular rivalry i.e. exclusive visibility of rival gratings stimuli and spatial frequency have been studied (Hollins, 1980; O'Shea et al., 1997).

The present study investigated the effect of spatial frequency or field sizes on exclusive visibility for right and left eye responses (CERD). There was no effect of different spatial frequencies used in the present study (2c/d and 4c/d) on the average mean of CERD regardless the field sizes used. Similarly different field sizes used in the present experiment (1°, 2.5° or 7°) showed no significant effect on CERD regardless of spatial frequency. These results are not in agreement with those of O'shea et al (1997) who examined the possible effects of spatial frequency and field size on binocular rivalry in term of "spread of exclusive visibility" in 4 adult subjects. They found inverse relationship between the spatial frequency of orthogonal sinusoidal gratings (.5,1,2,4,8,and 16 c/d) over field sizes ranged from .5° to 8° (.5°,1°,2°,4° and 8° deg) and spread of exclusive visibility in binocular rivalry, i.e. the duration of exclusive visibility was longer at low spatial frequency and vice versa. Further, they found an increase of exclusive visibility with decrease of the field size (O'Shea et al., 1997).

Hollins (1980) found a curvilinear relationship between the exclusive visibility period of binocular rivalry and spatial frequency with the highest period of exclusive visibility showed at 3 c/d spatial frequency. Hollins rival stimuli were sinusoidal gratings presented in a consistent field size of 2 degrees and were shown vertically to one eye and horizontally to the other eye.

Letter rival stimuli in the present study showed the least ability in detecting the sensory ocular dominance, while those with word detection (WAS/SAW) showed the greatest ability in detecting the ocular dominance, despite the shortest cumulative dominant duration (total duration of the exclusive visibility for right and left eye images).

In the present study the effect of rival stimuli individually on the CERD was investigated. Findings showed significant difference between means of CERD among targets (stimuli) used in rivalry. However, one of the most interesting findings in this part was that the target containing word stimuli (WAS/SAW) was the only source of this significant difference where this stimuli provoked a markedly different response from subjects, i.e. more mixed or piecemeal. This may be attributed to the presence of the central 'A' acting as 'fusion lock'. This is supported by a recently evidenced hypothesis that binocular fusion and rivalry can co-exist with one another (Carlson and He, 2000). Although this has, previously, been an issue of controversy (Wolf, 1986; Blake, Yang and Wilson, 1991; Harrad et al., 1994). Earlier Creed (1935) suggested that binocular fusion and binocular rivalry can be simultaneously observed indicating that the fusion aspect related to the background of contour rivalry (Creed, 1935). This may imply that different perceptual properties have different isolated mechanisms in the visual system (Creed, 1935). Thus, integration responses from subjects in the present study for the word stimuli acquired the longer duration of the trial period. This may indicate that the presence of the fusion property within the rivalry contour may cause inhibition to the rivalry which simultaneously strives to control over the condition. Similar observation has been reported by Carlson and He (2000) who found that rivalry overruled fusion where rivalry was perceived in 84% of an experimental trial while in our experiment rivalry extended for only 43.3% of the trial duration. However they used a different methodological procedure and rivalry stimuli used were quantitatively and functionally different (different contour and colors) that associated with differences in flickering frequencies which usually results in fusion condition that reside as 'a visual beats'. Interestingly, their hypothesis that *"the inter-ocular differences in visual attributes that are predominantly processed in the parvo-cellular pathway will lead to rivalry, and differences in visual attributes that are predominantly processed in the magnocellular pathway tend to integrate"* implied that parvocellular visual system predominant the rivalry process (Carlson and He, 2000). Based on their hypothesis, word stimuli, in the present study, would be processed in the magnocellular system to induce fusion and partially in parvocellular system to induce rivalry, so little rivalry was provoked. However these two conditions were not superimposed, rather they were dissociated over short trial duration (60 seconds) yet they were occupying the same spatial zone. This would strongly support the axiomatic fact that parvocellular visual system and magnocellular visual system independently process different visual properties (Livingstone and Hubel, 1987).

Taking parvo- and magno cellular visual systems into consideration it was necessary to decide which slide/s (rivalry stimuli patterns) to use in the next work in evaluating the sensory ocular dominance in a dyslexic population (chapter 7). Stimuli should include those mainly processed in parvocellular system to induce rivalry. Therefore, inter-ocular difference of rival stimuli visual attributes that are more likely to be processed in parvocellular system should included; central vision occupying, static, high contrast spatial pattern and shape discrimination such as orientation and letter detection (Livingstone and Hubel, 1987). However, since it is reported that the Magnocellular system is impaired in dyslexic subjects (Skottun, 2000; Stein, 2000; Stein, Talcott and Walsh, 2000b; Stein, 2001; Nandakumar and Leat, 2008) it is worth including rival stimuli that are relevant to the magnocellular function such as word stimuli with fusional lock.

The following recommendations for the selection of slides are follows:

- Slides B&E were excluded as they appeared less able to detect ocular dominance compared to other slides
- Although slide F seemed able to distinguish eye dominance, it was excluded because a large field size usually causes confusion for binocular rivalry (Blake, 1989).
- Slide G was also less able to detect significant dominance but was retained because it contains a letter and letters identification belongs to the parvocellular system. It was also retained as it is important slide for dyslexic population.
- Although slide H provoked a significantly greater proportion of mixed 'rivalry', it was still able to produce a verdict for dominance. Further it may reflect the magnocellular function.

Therefore the following slides were chosen for the study of dyslexia subjects: A, D, C, G, and H which are representing stimuli patterns of 1° (2c/d), 2.5° (2c/d), 2.5° (4c/d), 1° (letter), 2.5° (word) respectively.

Chapter 7

Investigation of binocular rivalry and sensory dominance in subjects with dyslexia and MIS

Chapter 6 established a methodology suitable for examining sensory dominance in subjects selected from the general adult population. This chapter reports the use of this method in subjects with dyslexia and dyslexia and MIS.

7.1 Introduction

During reading, brief fixation pauses are separated by quick eye saccades. Visual information that the eyes pick up during each fixation phase is translated to both hemispheres of the visual cortex, and to read correctly it is essential to recognise the orientation and sequences of letters and words. Orton (1925, 1928) argued that the memories or anagrams of letters and words are recorded in the correct orientation (form and sequence) in one hemisphere (the dominant hemisphere) and in reversed orientation in the other hemisphere (the non-dominant hemisphere). For accurate reading, the dominant hemisphere usually suppresses the non dominant hemisphere where the mirror image is laid down. Failing to establish this sensory perceptual dominance due to weak or incomplete dominance of one visual hemisphere would result in 'visual confusion' (Orton, 1925; Orton 1928). Orton reported that letters reversal errors and mirror writing tend to be particularly more common in children with "Strephosymbolia" (a Greek word that means reversed symbols referring to children with reading difficulties (Orton, 1925; Orton 1928). Crichley also believed that reversal errors and mirror writing are common in children with "congenital word blindness"(Critchley, 1970). Orton (1925) reported high percentage of his patient to be "ambinocular" and he concluded that "confused cerebral dominance" was the entire cause of reversal errors and mirror writing in children with reading difficulty. He suggested that the incomplete elision of the memory image in the non-dominant hemisphere would result in confusion of right-left or left-right presentation of letters or word sequences which result in delay in image selection (Orton, 1925). The theories about the neural mechanism behind these errors (due to the instability of ocular dominance) were described in section 1.9.5 of the major introduction of this thesis. Several studies since Orton have examined relationships between ocular dominance stability and reading ability. Stein and Fowler claimed that establishing stable ocular dominance is essential to avoid visual perceptual confusion during reading where unstable letters or words (Stein and Fowler, 1982) reported by some children with reading difficulties, so called "visual ambilateral" dyslexics (Fowler and Stein, 1980), may be attributed to unstable motor ocular dominance (Stein and Fowler, 1980; Stein and Fowler, 1981; Stein and Fowler, 1982). Several studies have investigated the correlation between dyslexia and instability of ocular dominance as identified with the Dunlop test (Stein and Fowler, 1980; Stein and Fowler, 1982; Bigelow and McKenzie, 1985; Evans et al., 1994a). Using the Dunlop test, it has been found that a majority of dyslexic children (65%) exhibited unstable ocular dominance, i.e. inconsistence response in the Dunlop test (Fowler and Stein, 1980; Stein and Fowler, 1981; Stein and Fowler, 1982). In contrast, only 20% dyslexic subjects from the unselected school children exhibited unstable responses in the Dunlop test (Stein et al., 1986). This led the authors to suggest a causal relationship between dyslexia and instability of ocular dominance (Fowler and Stein, 1980; Stein and Fowler, 1981; Stein and Fowler, 1982; Stein and Fowler, 1985; Stein et al., 1986). The authors believed that the Dunlop test is of a sensory motor variety and they hypothesized that failure of exact coordination between retinal (foveal) signals of an image (of binocularly viewed small target) and ocular motor control may result in confusion and therefore instability of motor ocular dominance which can cause visual confusion in reading and non-reading tasks. Further, several authors have found the test to be less useful (Bishop et al., 1979; Newman et al., 1985; Aasved, 1987; Ygge et al., 1993a; Evans et al., 1994a) where they failed to attain to the similar results or the conclusion of Stein and Fowler. Similarly, Bigelow and McKenzie (1985) did not find a correlation between reading disability and reversal error, nor any increase in the time taken to discriminate left-right mirror figures in dyslexic children with unstable motor ocular dominance (Bigelow and McKenzie, 1985). Conflicting results from the Dunlop test suggest that the test is "unreliable" (Evans et al., 1994a). It has been suggested that visual confusion may be more complicated by binocular retinal rivalry when different images from either eye are alternating suppressed (Cornelissen et al., 1991), and since confusion of orientation of written material in dyslexia is mainly caused by faulty or incomplete sensory dominance or "confused cerebral dominance" (Orton, 1925), it was essential to investigate the sensory dominance in terms of binocular rivalry. Although sensory visual input obviously plays a substantial part in reading, there appears to be no consensus in the published literature concerning the assessment of sensory ocular dominance in dyslexic population and its relation to reading performance.

7.1.1 Aims

Primary aim:

- The principle goal was to establish and evaluate the presence of equal sensory dominance in dyslexic subjects, with and without MIS. Two steps ware taken toward this goal;

    1. Investigating equi-dominance (equal sensory dominance) in a dyslexic population quantitatively by evaluating the mixed sensory ocular dominance, i.e. when both eyes are equally dominant at a time.
    2. Investigating the quality of equi-dominance in terms of stability of dominance duration.

Secondary aims:

- To investigate the laterality of sighting ocular dominance in dyslexic adults with or without MIS by assessing the sighting ocular dominance measured with Hole in the Card (HIC) test in dyslexia groups compared to control group.

- To evaluate the association of left eye sighting dominance and dyslexia, with and without MIS.

- To evaluate the association between the prevalence of crossed eye sighting dominance / hand dominance and dyslexia (with and without MIS).

- To evaluate the consistency between sighting and sensory ocular dominance in dyslexic subjects (with and without MIS).

7.1.2 Hypotheses

- Dyslexic subjects show more mixed sensory ocular dominance in terms of longer piecemeal duration, during which binocular dominancy occurs, i.e. the right and left eye are dominated at the same time during rivalry of two different stimuli.

- Dyslexic subjects show more unstable sensory dominance by exhibiting more switching responses during dominance duration in binocular rivalry.

- Incidence of left sighting dominance is more common in dyslexic subjects.

- Incidence of crossed eye sighting/hand dominance is more common in dyslexic subjects.

- Inconsistency between sighting and sensory ocular dominance is more common in dyslexic subjects

7.2 Methods

7.2.1 Participants

Dyslexic and control subjects in this study were the same subjects that participated in the previous study in Chapter 4 (Investigating binocular vision functions in dyslexic adult population). Dyslexic subjects consisted of 56 university students, 27 of whom had MIS, and controls were 33 students (see section 6.2.1)

Inclusion / Exclusion criteria were the same criteria proposed in chapter 4 (see section 4.2.2).

Ethical approval was obtained from Cardiff School of Optometry and Vision Science Ethical Committee and all procedures follow the tenets of the Declaration of Helsinki.

Prior to the experiments, written informed consent was provided by all subjects after the methodology had been explained to them and the opportunity was given to the subjects to ask further questions. Subjects were free to withdraw at any time without penalty.

7.2.2 Procedures

All subjects were required to attend a single scheduled time at School of Optometry and Vision Sciences. The investigation of binocular rivalry lasted approximately 15 minutes. Prior the experiment, all subjects were screened for monocular visual acuities using LogMAR chart (BAILEY LOVIE Chart # 5, National Vision Research Institute of Australia) and for absence/ presence of squint using cover/ uncover test. Sighting ocular dominance was assessed using HIC test after binocular rivalry examination, as described in section (6.2.2). This test was repeated three times.

7.2.2.1 Test stimuli

Binocular rivalry was produced by presenting static, continuous test stimuli to both eyes simultaneously. Test stimuli included in this study were the slides recommended from the study in Chapter 6; slide A,D,C,G and H which represented stimuli patterns of 1°(2c/d), 2.5° (2c/d), 2.5° (4c/d), 1° (A/S) and 2.5° (WAS/SAW) respectively. In addition it was decided finally to add a new test stimulus to the group of the aforementioned stimuli, slide I which represent striped stimulus of 4c/d spatial frequency occupied in 1° visual angle. This slide of the specific stimulus pattern was added to provide consistency between slides, i.e. pairs of stimulus patterns of similar size and two different spatial frequencies. The slide was created by using the same software computer programme (Corel DRAWx3 Version 13).

Therefore six sets of stimulus patterns were presented for each subject. Table 7.1 shows stimuli field sizes and rival pattern types accordingly.

Field size	1°			2.5°		
(slide) **Stimuli pattern**	(A) 2c/d	(I) 4c/d	(G) letters	(D) 2c/d	(C) 4c/d	(H) words

Table 7.1: Target stimuli occupied the field size

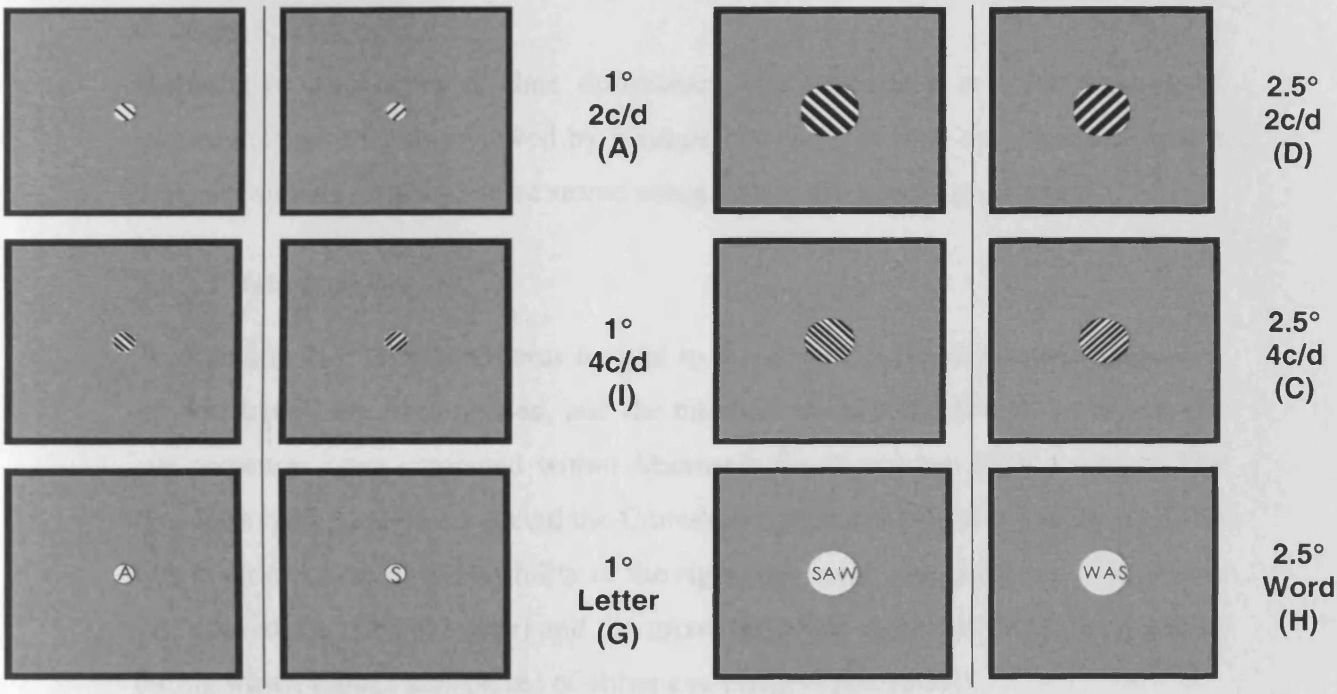

Figure 7.1: Target stimuli used in the study

7.2.2.2 Presentation of test stimuli and procedure

Fixed high contrast (100%) square wave gratings presented in orthogonal directions, tilted to the right at 45°, seen by the right eye, and tilted to the left at 135°, seen by the left eye. Letter stimuli ('A' presented to the right eye and 'S' presented to the left eye). Word stimuli ('WAS' presented to the right eye and 'SAW' presented to the left eye.

The procedure and test conditions were identical to that described in chapter 6 (sections 6.2.3 & 6.2.4).

Quantitative assessment of time dominancy was calculated as total duration of exclusive target visibility viewed by a single eye and / or both eyes image during a trial, and subject responses were stored using a software computer program.

7.2.2.3 Data analysis

Trial duration for all subjects was revised to 60 seconds for each pair of slides used, i.e. 524 trials have been revised, and the numbers of switches for the right and left eye responses were computed within Microsoft Excel version 2003 program. The binocular rivalry analysis targeted the Cumulative Exclusive Rivalry Duration CERD (the duration of exclusive visibility of the right eye image plus duration of exclusive visibility of the left eye image) and the mixed response duration MRD (the duration during which subject sees pieces of either eye images (piecemeal).

SPSS version 16 statistical program was used to analyze the data.

Chi-Square test, applying Cross-tabulation test was used to;

- Evaluate the association between the proportion of left eye dominance and group population
- Evaluate the association between the proportion of crossed eye hand dominance and group population
- Evaluate the association between proportion of inconsistent sighting/sensory ocular dominance and group

One way ANOVA between groups was used to;

- Evaluate the effect of different rivalry patterns on [CERD] and [MRD], for the three groups.

Evaluate the effect of group on the rivalry rate (RR) during CERD.

One way repeated measure ANOVA was used to;

Evaluate the effect of the slides on MRD in each individual group.

Evaluate the effect of the slides on the rivalry rate during cumulative exclusive rivalry duration [RR]

7.3 Results

7.3.1 Prevalence of sighting ocular dominance

The results of sighting dominance using HIC test in the three groups are shown in Figure 7.2. The graph shows that the prevalence of right eye dominance is higher in the control group (84.8%) whilst right and left eye dominance were almost equally distributed in subjects with dyslexia and in those with MIS, where the prevalence of right eye dominance compared to the prevalence of the left eye dominance in dyslexic subjects without and with MIS were 54.2/44.8 % (R/L; dyslexia) and 59.3/40.7% (R/L; dyslexia with MIS) respectively.

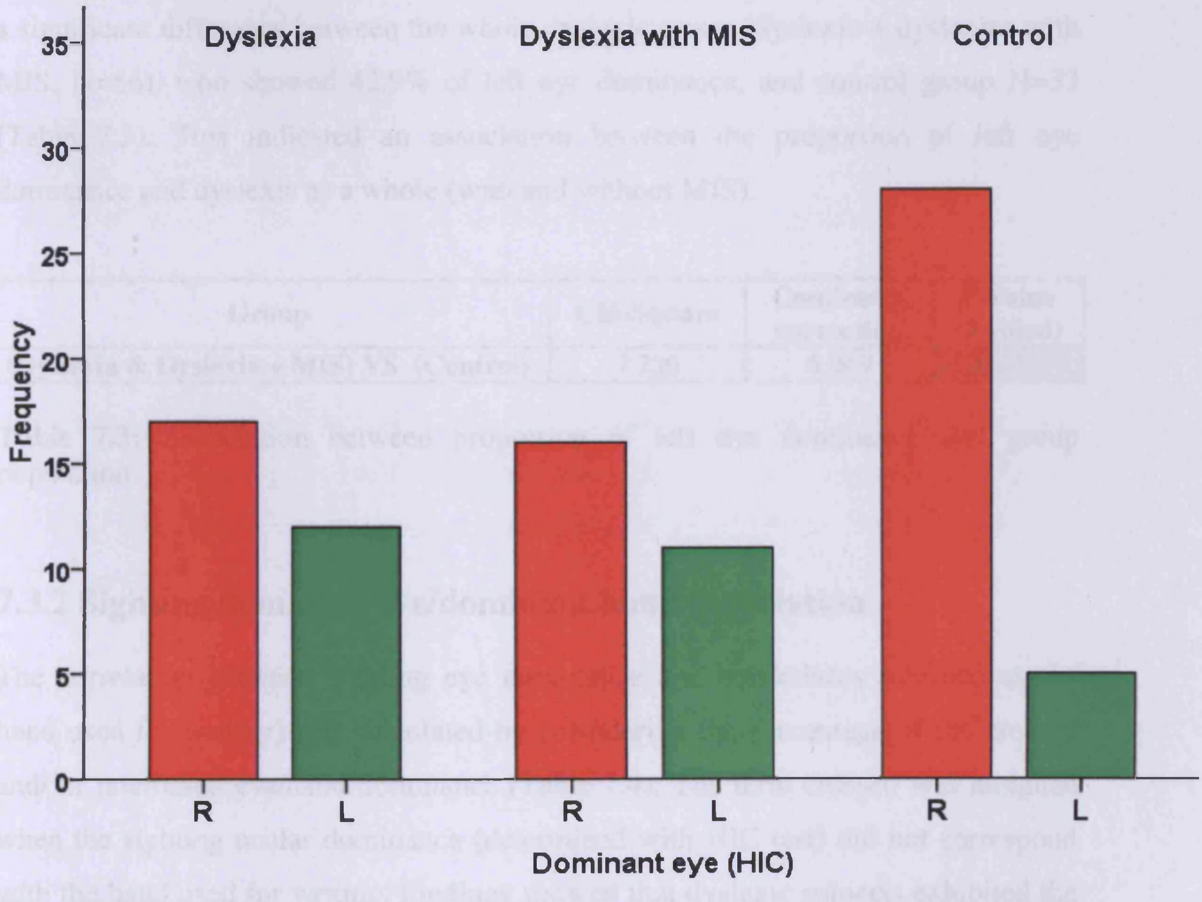

Figure 7.2: Frequency of sighting ocular dominance in the three groups.

The difference in the proportion of left eye dominance between the three groups was assessed using Chi-Square test, applying Cross-tabulation test. Table 7.2 shows the incidence of left eye and Chi-Square p-value.

Group	N	Incidence of left eye		Chi-Squared	P-value (2-sided)
		Count	%		
Dyslexic	29	13	44.8	7.362	0.025
Dyslexic+MIS	27	11	40.7		
Control	33	5	15.2		

Table 7.2: Incidence of left eye sighting dominance in the three groups and Chi-Squared test.

There was a significant difference in the proportion of left eye dominance among the three groups. This means, there was significant association between the proportion of left eye dominance and the group case identified as dyslexia, dyslexia with MIS and control.

Chi-Squared value with continuity correction (for 2 by 2 categorical variables) found a significant difference between the whole dyslexic group (dyslexic + dyslexics with MIS, N=56), who showed 42.9% of left eye dominance, and control group N=33 (Table 7.3). This indicated an association between the proportion of left eye dominance and dyslexia as a whole (with and without MIS).

Group	Chi-Square	Continuity correction	P-value (2-sided)
(Dyslexia & Dyslexia + MIS) VS (Control)	7.256	6.049	0.014

Table 7.3: Association between proportion of left eye dominance and group population

7.3.2 Sighting dominant eye/dominant hand correlation

The correlation between sighting eye dominance and handedness (defined as the hand used for writing) was calculated by considering the percentage of the crossed and/ or uncrossed eye/hand dominance (Table 7.4). The term crossed was assigned when the sighting ocular dominance (determined with HIC test) did not correspond with the hand used for writing. Findings showed that dyslexic subjects exhibited the highest percentage of crossed eye/hand dominance and they showed the lowest incidence of uncrossed eye/hand dominance (41.4% of them showed right eye to right hand dominance while none showed left eye to left hand dominance). The control group exhibited the highest percentage of uncrossed eye/hand dominance (84.8%; 81.8% of whom showed right eye/right hand dominance) followed by the dyslexia with MIS group (70.4; 55.5% of whom showed right eye/right hand dominance).

Incidence of Sighting dominant eye to dominant hand	Group	N	%	
			crossed	uncrossed
	Dyslexia	29	58.6	41.4
	Dyslexia with MIS	27	29.6	70.4
	Control	33	15.2	84.8

Table 7.4: Sighting eye dominance and hand dominance.

The association between crossed or un-crossed eye/hand dominance and the studied group population was investigated by using Chi-Squared test. Table 7.5 shows the incidence of crossed eye/hand dominance and Chi-Square p-value.

Group	N	Count	% within case	Chi-Square	P-value (2-sided)
Dyslexic	29	17	58.6	13.341	0.001
Dyslexic+MIS	27	8	29.6		
Control	33	5	15.2		

Table 7.5: Frequency of crossed eye/hand dominance and Chi-Squared test.

The significant P-value indicates there was a significant difference between the proportions of eye hand laterality (crossed or uncrossed) among the three groups. This means, there was a significant association between the proportion of crossed eye/hand dominance and the group case (identified as dyslexia, dyslexia with MIS and control).

Chi-Square value with continuity correction found a highly significant difference between the whole dyslexic group (dyslexic + dyslexics with MIS, n=56) and control group n=33 (Table 7.6). This indicated an association between the proportion of crossed eye/hand dominance and dyslexia as a whole (with and without MIS).

Group	Chi-Square	Continuity correction	P-value (2-sided)
(Dyslexia) VS (Dyslexia + MIS)	4.755	3.655	0.056
(Dyslexia) & (Dyslexia + MIS) VS (Control)	8.082	6.816	0.009

Table 7.6 Association between crossed eye/hand dominance and group population

7.3.3 Consistency between sighting and sensory ocular dominance

The correlation between sighting and sensory ocular dominance was examined by considering the percentage of the inconsistency or consistency between sighting and sensory ocular dominance (i.e. RE/RE or LE/LE) derived with slide I.

Slide I was chosen as it demonstrated similar results of cumulative exclusive rivalry durations (CERD) across the three groups. The results showed that dyslexic subjects exhibited the highest percentage of consistency between sighting and sensory ocular dominance, while both dyslexics with MIS and control exhibited similar but lower for consistency (Table 7.7).

	Group	N	%	
			inconsistence	consistence
Consistency between sighting and sensory ocular dominance	Dyslexia	25	24	76
	Dyslexia with MIS	26	46.2	53.8
	Control	29	44.8	55.2

Table 7.7: Consistency between sighting (HIC) and sensory (with slide I rival stimuli) ocular dominance.

Participation: One subject from the dyslexic group did not perform slide I in binocular rivalry (BR) test and 3 subjects did not demonstrate exclusive visibility for the rivalry duration. From the dyslexia with MIS group one subject did not perform slide I in BR test and from the control group, three subjects did not perform slide I in BR test and one did not demonstrate exclusive visibility for the rivalry duration.

The association between consistent sighting/sensory ocular dominance and group was investigated using Chi-Squared test for independence by applying Cross-tabulation to evaluate the association between two categorical variables with two or more categories in each i.e. consistency of sighting/sensory ocular dominance (consistence =1 or inconsistence =2) and the population case (dyslexia, dyslexia with MIS, control). Table 7.8 shows the incidence of inconsistence sighting/sensory ocular dominance and Chi-Square p-value.

Group	N	Count	% within case	Chi-Square	P-value (2-sided)
Dyslexic	25	6	24	3.343	0.188
Dyslexic+MIS	26	12	46.2		
Control	29	13	44.8		

Table 7.8: Incidence of inconsistence of sighting/sensory eye dominance and Chi-Squared test between inconsistency of sighting/sensory dominance and the 3 groups.

In terms of inconsistency of sighting/sensory ocular dominance, the p value indicated there was no significant difference between the proportions of inconsistency of sighting/sensory ocular dominance among the three groups.

As expected, Chi-Squared value with continuity correction found no significant difference between dyslexic and dyslexic with MIS groups, and there was no significant difference between the whole dyslexic group (dyslexic + dyslexics with MIS, n=51) and the control group n=29 (Table 7.9) in terms of proportion of inconsistency of sighting/sensory ocular dominance.

Group	Chi-Square	Continuity correction	P-value (2-sided)
(Dyslexic) VS (Dyslexia + MIS)	2.739	1.855	0.173
(Dyslexic) & (Dyslexia + MIS) VS (Control)	0.708	0.363	0.547

Table 7.9 Association between crossed eye/hand dominance and group population

7.3.4 The effect of different rivalry patterns on the cumulative exclusive rivalry duration [CERD] and mixed response duration [MRD], for the three groups

Descriptive and comparative statistics between the three groups are illustrated in table 7.10. The table illustrates that the three groups behaved similarly in their responses for slides where for all slides CERD tended to be longer than MRD, where MRD was longer than CERD.

ANOVA found no significant difference between the three groups in terms of the effect of different rivalry patterns on MRD and/or on CERD, for each slide.

Slide	Group	N	CERD Mean(SD)	P value	MRD Mean(SD)	P value
A	Dyslexia	29	43.56(12.20)	0.414	16.43(12.20)	0.414
	Dyslexia with MIS	27	38.40(14.43)		21.59(14.43)	
	Control	33	39.67(17.99)		20.32(17.99)	
I	Dyslexia	28	39.71(16.64)	0.691	20.28(16.64)	0.691
	Dyslexia with MIS	26	42.81(11.39)		17.18(11.39)	
	Control	30	42.36(14.71)		17.63(14.71)	
D	Dyslexia	29	32.27(15.62)	0.263	27.72(15.62)	0.263
	Dyslexia with MIS	27	35.66(14.77)		24.33(14.77)	
	Control	33	38.88(16.71)		21.11(16.71)	
C	Dyslexia	29	34.05(15.41)	0.145	25.94(15.41)	0.145
	Dyslexia with MIS	27	38.06(11.43)		21.93(11.43)	
	Control	33	41.59(16.83)		18.40(16.83)	
G	Dyslexia	29	38.90(11.92)	0.751	21.09(11.92)	0.751
	Dyslexia with MIS	27	37.51(11.81)		22.48(11.81)	
	Control	33	39.93(12.88)		20.06(12.88)	
H	Dyslexia	28	23.58(16.95)	0.781	36.41(16.95)	0.781
	Dyslexia with MIS	26	25.29(14.66)		34.70(14.66)	
	Control	30	26.52(15.98)		33.47(15.98)	

Table 7.10: Descriptive and comparative statistics between the three groups in term of effect of different rivalry patterns on MRD and CERD.

Results for the effect of different rivalry patterns on MRD in dyslexia, dyslexia with MIS and control groups are graphically presented in figure 7.3.

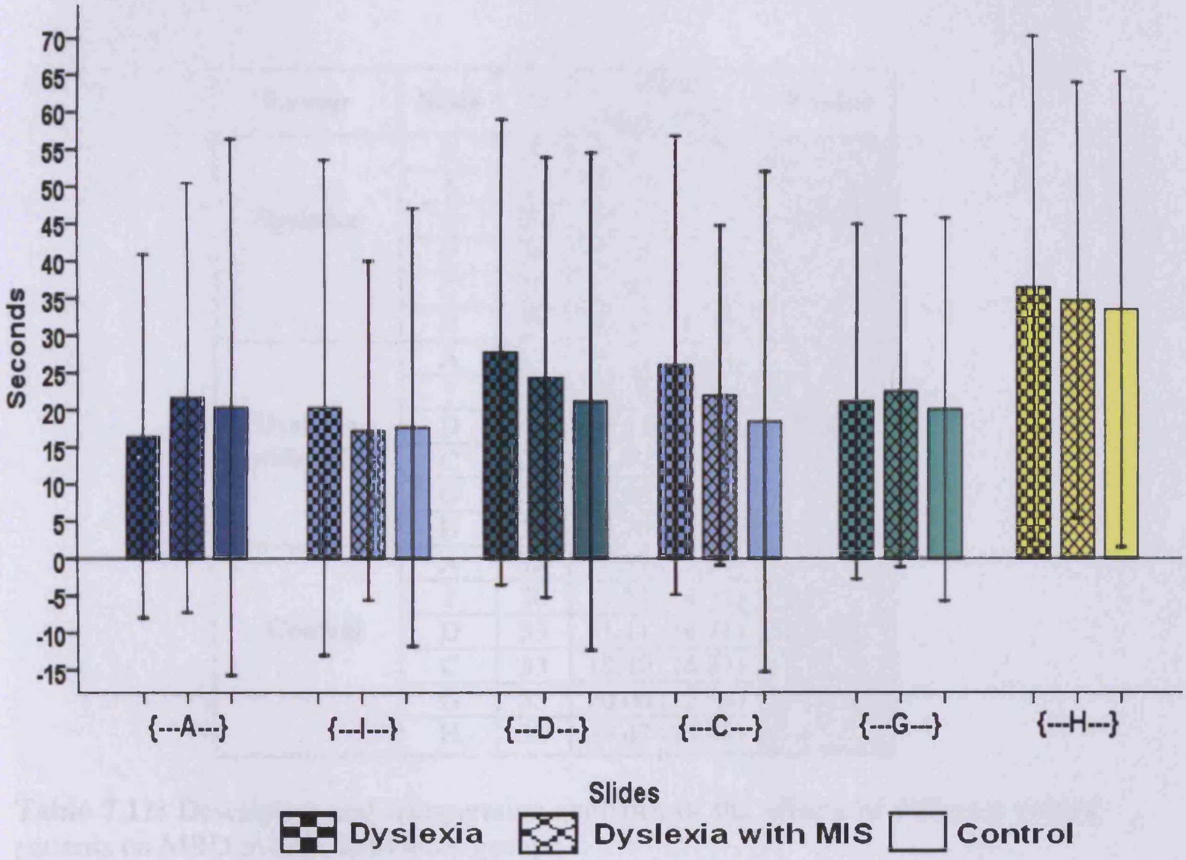

Figure 7.3: Comparisons between the three group samples in terms of Effect of different rivalry patterns on MRD.

7.3.5 Effect of the slides on MRD in each individual group

One way repeated measure ANOVA revealed a significant difference in MRD among the rivalry stimuli (slides) used in the three groups where P value of Wilks' Lambda Multivariate tests in dyslexia, dyslexia with MIS and control group were 0.000, 0.001 and 0.001 respectively. Descriptive and comparative statistics of the effects of different rivalry patterns on MRD in each individual group are shown in table 7.11.

Group	Slide	N	MRD Mean (SD)	P value
Dyslexia	A	29	16.43 (12.20)	0.000
	I	28	20.28 (16.64)	
	D	29	27.72 (15.62)	
	C	29	25.94 (15.41)	
	G	29	21.09 (11.92)	
	H	28	36.41 (16.95)	
Dyslexia with MIS	A	27	21.59 (14.43)	0.001
	I	26	17.18 (11.39)	
	D	27	24.33 (14.77)	
	C	27	21.93 (11.43)	
	G	27	22.48 (11.81)	
	H	26	34.70 (14.66)	
Control	A	33	20.32 (17.99)	0.001
	I	30	17.63 (14.71)	
	D	33	21.11 (16.71)	
	C	33	18.40 (16.83)	
	G	33	20.06 (12.88)	
	H	30	33.47 (15.98)	

Table 7.11: Descriptive and comparative statistics of the effects of different rivalry patterns on MRD in each individual group.

Slide H would seem to produce more mixed responses for all groups, compared to other slides. Pairwise comparisons showed that in the dyslexia group there were significant differences between slide H and A, I and G and between slide A and D and slide A and C.

In dyslexia with MIS slide H was the source of significant differences and there was a border line significance difference between slides G and I (p=0.053).

Similarly, in the control group slide H was the source of significant differences while there were no significant differences between the remainder of the slides. (See table 7.12).

Significant differences in CERD between slides	Dyslexia		Dyslexia with MIS		Control	
	slides	P value	slides	P value	slides	P value
	H-A	0.000	H-A	0.021	H-A	0.032
	H-I	0.007	H-I	0.000	H-I	0.000
	H-G	0.000	H-D	0.021	H-D	0.010
	A-D	0.002	H-C	0.001	H-C	0.003
	A-C	0.007	H-G	0.007	H-G	0.001

Table 7.12 Significance differences between slides in terms of CERD.

All other comparisons were not significantly different (in dyslexia group $p \geq 0.238$, in dyslexia with MIS group the borderline $p=0.053$ was between slides G and I, while $p\geq0.145$ in the other comparisons, and in the control group $p\geq0.111$ for the other comparisons).

Results for dyslexia, dyslexia with MIS and control groups are graphically presented in figure 7.4.

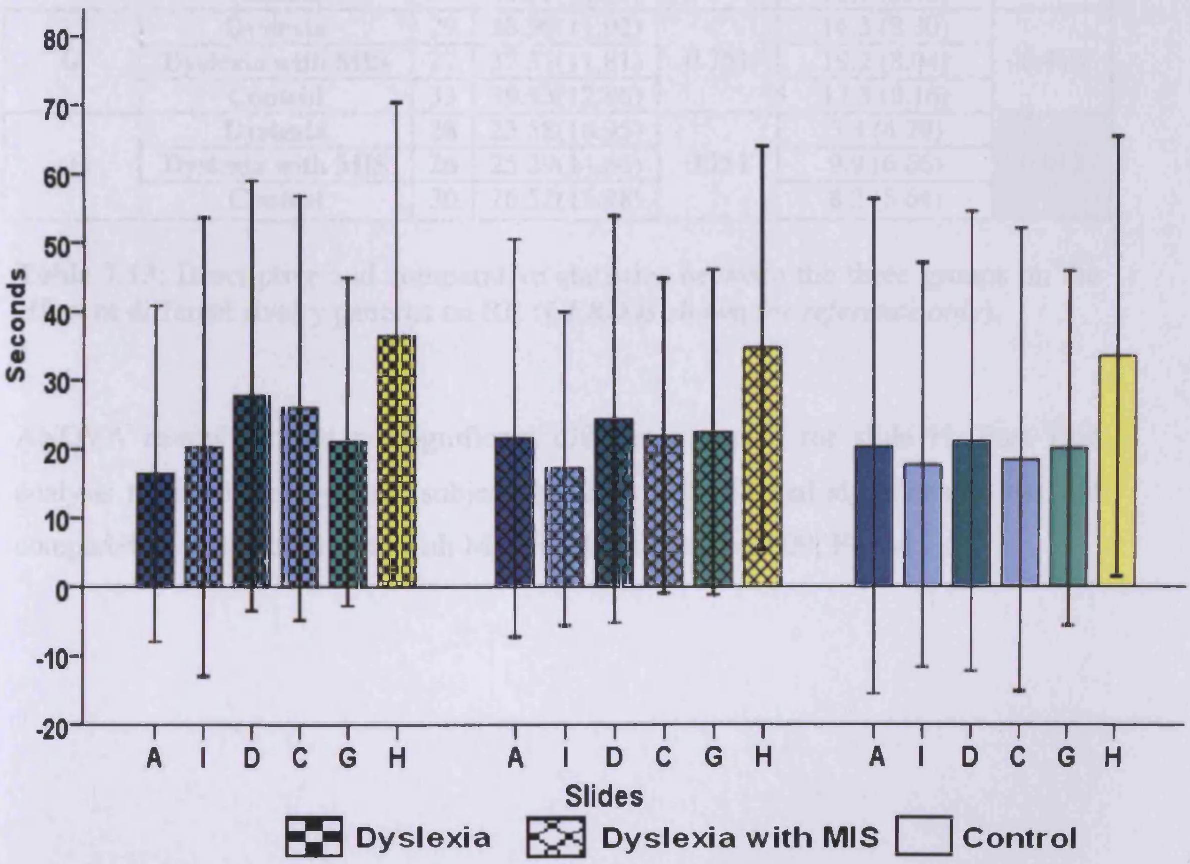

Figure 7.4: Effect of the slides (rivalry stimulus types) on MRD in dyslexia, dyslexia with MIS and on control group.

7.3.6 Stability of dominance duration

7.3.6.1 Comparing the effect of group on the rivalry rate (RR) during CERD

Statistical analysis comparing the three groups in terms of effects of different rivalry pattern on CERR (number of switches during CERT) is shown in Table 7.13.

Slide	Group	N	CERD Mean (SD)	P value	RR Mean (SD)	P value
A	**Dyslexia**	29	43.56(12.20)	0.414	15.4 (9.47)	0.967
	Dyslexia with MIS	27	38.40(14.43)		14.9 (7.15)	
	Control	33	39.67(17.99)		15.4 (9.81)	
I	**Dyslexia**	28	39.71(16.64)	0.691	16.4 (9.87)	0.573
	Dyslexia with MIS	26	42.81(11.39)		18.9 (7.02)	
	Control	30	42.36(14.71)		17.2 (8.79)	
D	**Dyslexia**	29	32.27(15.62)	0.263	14.2 (9.44)	0.452
	Dyslexia with MIS	27	35.66(14.77)		17.4 (9.97)	
	Control	33	38.88(16.71)		16.2 (9.09)	
C	**Dyslexia**	29	34.05(15.41)	0.145	16.0 (9.98)	0.418
	Dyslexia with MIS	27	38.06(11.43)		19.0 (8.93)	
	Control	33	41.59(16.83)		18.7 (9.40)	
G	**Dyslexia**	29	38.90(11.92)	0.751	16.3 (8.30)	0.416
	Dyslexia with MIS	27	37.51(11.81)		19.2 (8.04)	
	Control	33	39.93(12.88)		17.3 (8.16)	
H	**Dyslexia**	28	23.58(16.95)	0.781	5.3 (4.29)	0.012
	Dyslexia with MIS	26	25.29(14.66)		9.9 (6.66)	
	Control	30	26.52(15.98)		8.2 (5.64)	

Table 7.13: Descriptive and comparative statistics between the three groups on the effect of different rivalry patterns on RR (*CERD is shown for reference only*).

ANOVA results showed no significant difference except for slide H. Post Hoc analysis revealed that dyslexic subjects without MIS showed significantly less RR compared to dyslexic subjects with MIS for this slide (p=0.009; Figure 7.5).

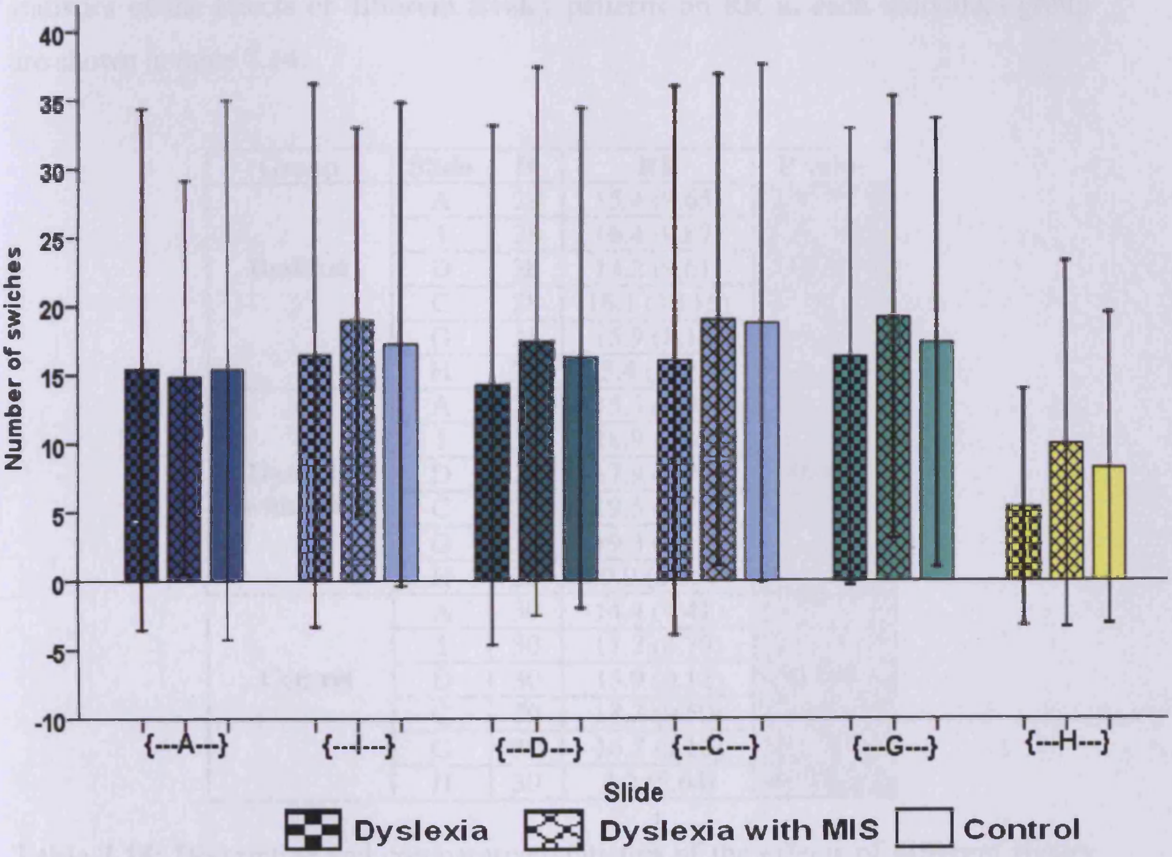

Figure 7.5: Comparisons between the three groups in terms of Effect of different rivalry patterns on RR.

7.3.6.2 Effect of the slides on the rivalry rate during cumulative exclusive rivalry duration [RR]

One way repeated measure ANOVA revealed a significant difference in RR among rival stimuli used in an individual group, where the p value of Wilks' Lambda Multivariate tests was 0.000 in all individual groups. Descriptive and comparative statistics of the effects of different rivalry patterns on RR in each individual group are shown in table 7.14.

Group	Slide	N	RR	P value
Dyslexia	A	28	15.4 (9.65)	0.000
	I	28	16.4 (9.87)	
	D	28	14.2 (9.61)	
	C	28	16.1 (10.15)	
	G	28	15.9 (8.14)	
	H	28	5.4 (4.29)	
Dyslexia with MIS	A	26	15.3 (6.94)	0.000
	I	26	18.9 (7.02)	
	D	26	17.9 (9.79)	
	C	26	19.5 (8.77)	
	G	26	19.3 (8.18)	
	H	26	9.9 (6.66)	
Control	A	30	14.4 (9.41)	0.000
	I	30	17.2 (8.79)	
	D	30	15.9 (9.12)	
	C	30	18.3 (9.50)	
	G	30	16.7 (8.16)	
	H	30	8.2 (5.64)	

Table 7.14: Descriptive and comparative statistics of the effects of different rivalry patterns on RR in each individual group.

The number of switches during the CERD tended to be least for slide H, for all groups. Pairwise comparisons confirmed that in the dyslexia group slide H was the source of significance differences. Similarly, in dyslexia with MIS slide H showed significant differences with all other slides, but there were also significant differences between slides A and I, A and C, and between slide A and G.

Similarly, in the control group slide H was the source of significance differences and there was also a border line significance difference between slides A and I ($p = 0.050$), whilst there were no significant differences between the remainder of slides (see Table 7.15 for detail).

	Dyslexia		Dyslexia with MIS		Control	
	slides	**P value**	**slides**	**P value**	**slides**	**P value**
Significant differences between slides	**H-A**	0.000	**H-A**	0.021	**H-A**	0.003
	H-I	0.000	**H-I**	0.000	**H-I**	0.000
	H-D	0.000	**H-D**	0.021	**H-D**	0.000
	H-C	0.000	**H-C**	0.001	**H-C**	0.000
	H-G	0.000	**H-G**	0.007	**H-G**	0.000
	-	-	**A-I**	0.016	-	-
	-	-	**A-C**	0.009	-	-
	-	-	**A-G**	0.043	-	-

Table 7.15: Significance differences between slides in terms of RR.

All other comparisons were not statistically significant (in dyslexia group $p \geq 0.541$, in dyslexia with MIS group $P = 1.000$ and in the control group p values for the other comparisons were ≥ 0.05).

Results for dyslexia, dyslexia with MIS and control groups are graphically presented in figure 7.6.

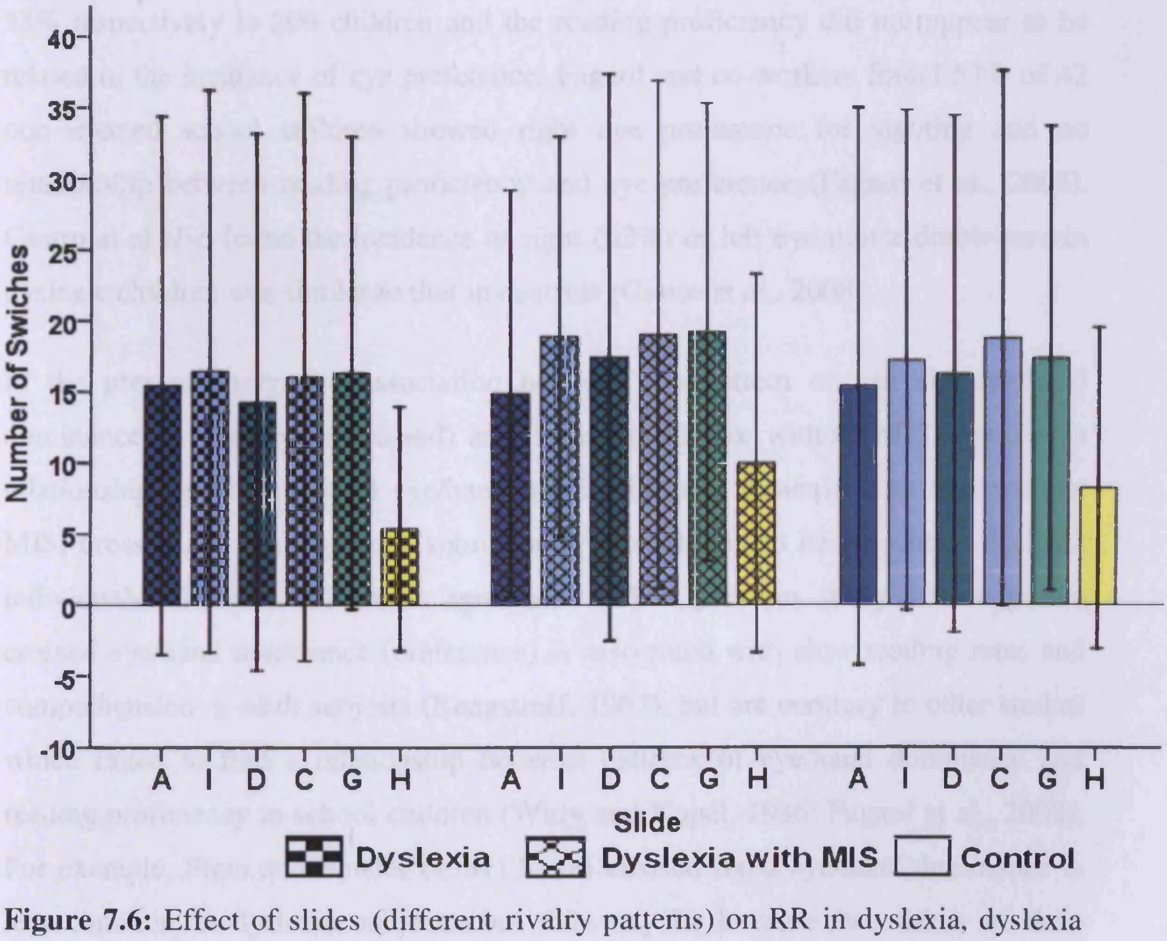

Figure 7.6: Effect of slides (different rivalry patterns) on RR in dyslexia, dyslexia with MIS, and on control group individually.

7.4 Discussion

One of the aims in this study was to investigate the laterality of sighting ocular dominance in dyslexic adults (with or without MIS) by assessing the incidence of sighting ocular dominance measured with the HIC test in dyslexia groups compared to a control group. A high prevalence of right eye dominance has been found in the control group (84.8%) whilst dyslexic groups demonstrated approximately equal distribution of right or left sighting dominance. The results also suggested an association between left 'eyedness' (measured by sighting ocular dominance) and dyslexia.

These results support what has been suggested in early studies, that left eye preference was associated with reading difficulty in dyslexic children (Dearbon, 1931; Monroe, 1932) in terms of the accuracy of mirror reading (Monroe, 1932). However, other studies have found eye preference to be unrelated to reading proficiency (Witty and Kopel, 1936; Fagard et al., 2008). Witty and Kopel (1936) found the incidence of right eye preference and left eye preference was 63% and 33% respectively in 200 children and the reading proficiency did not appear to be related to the incidence of eye preference. Fagard and co-workers found 57% of 42 non-selected school children showed right eye preference for sighting and no relationship between reading proficiency and eye preference (Fagard et al., 2008). Castro et al also found the incidence of right (62%) or left eye motor dominance in dyslexic children was similar to that in controls (Castro et al., 2008).

In the present study, the association between the pattern of eye sighting/hand dominance (crossed or un-crossed) and dyslexia (with or without MIS) revealed a relationship between crossed eye/hand dominance and dyslexia with and without MIS; crossed eye dominance is significantly more likely to be present in dyslexic individuals. These results are in agreement with a previous study that suggested crossed eye/hand dominance (preference) is associated with slow reading rates and comprehension in adult subjects (Rengstroff, 1967), but are contrary to other studies which failed to find a relationship between patterns of eye/hand dominance and reading proficiency in school children (Witty and Kopel, 1936; Fagard et al., 2008). For example, Stein and Fowler (1981) found crossed fixed eye/hand dominance is less common in dyslexic subjects, but this may be because two thirds of their dyslexic cohort presented with an unstable dominance any way (Stein and Fowler, 1981).

Assessment of sighting ocular dominance at distance may reflect an irrelevant association between the sighting dominant eye and reading ability as the test may fail to connect the ocular motor process to the perceptual foveal signals during reading when the eyes are converged (Bettman et al., 1967; Porac and Coren, 1976; Stein and Fowler, 1982). However, the results presented here regarding crossed eye/hand dominance support Orton (1925) in his reversal theory of 'Strephosymbolia' (synonymous to dyslexia); that dyslexic children more often show crossed eye/hand dominance (also known as mixed dominance). This also supports the idea that failure to develop normal cerebral lateralization for the reading process may be the major cause of dyslexia (Orton, 1925; Critchley, 1970). The results here show that the incidence of crossed eye/hand dominance in dyslexic group was twice that in MIS dyslexics. This may imply that the contribution of reversal errors in reading is less in the MIS dyslexic group compared to the dyslexics without MIS.

In the present study the analysis also investigated the inconsistency between sighting and sensory ocular dominance derived from slide 'I' (1°, 2c/d rival stimuli) and revealed no association with dyslexia. This result is in agreement with other studies in a non-dyslexic adult population (Schor, Landsman and Erickson, 1987; Ooi et al., 2001; Mapp et al., 2003; Ehrenstein, Arnold-Schulz-Gahmen and Jaschinski, 2005; Seijas et al., 2007) where sighting and sensory ocular dominance were considered to be independent conditions. This result would perhaps be surprising to many optometrists who continue to use motor ocular dominance testing to indicate in fact, sensory dominance in the clinical setting.

If it is believed that crossed eye hand dominance may be an indirect indicator of undeveloped cerebral lateralization (Fagard et al., 2008), then it might also imply that confusion in cerebral dominance during reading (because the central vision is served by both ipsilateral and contralateral fibres that carry the binocular central perceptual information to both hemispheres could be important (Bigelow and McKenzie, 1985). It has been suggested in the literature that unstable motor ocular dominance, as identified with the Dunlop test, is a major cause of dyslexia (Fowler and Stein, 1980;

Stein and Fowler, 1981; Stein and Fowler, 1982; Stein and Fowler, 1985; Stein et al., 2000a), but this is in conflict with other studies (Bishop et al., 1979; Newman et al., 1985; Evans et al., 1994a). Furthermore, it appears that no study has really investigated the possibility of faulty development of sensory ocular dominance during the fixation stage in dyslexia and little is known about the hypothesis of equal ocular dominance in dyslexia (Orton, 1925).

The ultimate goal in the present study was to establish the amount of equal sensory dominance (equi-dominance or mixed dominance) in dyslexic adult cohorts, with and without MIS. Firstly the equi-dominance condition was assessed by quantitatively evaluating the mixed sensory ocular dominance. Secondly, the quality of equi-dominance was investigated in terms of stability of dominance duration.

For the first goal the results showed that the dyslexia group, compared to controls, showed longer MRD for slides I, D and C that represented striped rivalry patterns of 1° (4c/d), 2.5° (2c/d) and 2.5° (4c/d) respectively while they showed the least MRD for slide 'A' that represented 1° (2c/d). Longer mixed response duration for larger size stimuli may refer to the abnormal foveal-parafoveal interaction suggested in dyslexic individuals (Bouma and Legein, 1977; Boden and Giaschi, 2007); attributed to reduced automatic focusing of visual attention in dyslexic subjects. This has been related to a sluggish deficit of the magnocellular system (Facoetti et al., 2003; Skottun and Skoyles, 2006a; Boden and Giaschi, 2007). Longer MRD for small size rival stimuli with 4c/d spatial frequency in dyslexic students may be due to sluggish visual attention to crowded stimuli (Stein and Walsh, 1997; Spinelli et al., 2002) and therefore delay the ability to rule out the dominance sensory input. However dyslexia subjects showed the least MRD for slide A (that represented 1°; 2c/d) compared to dyslexia with MIS and control groups, which indicated that they exhibited longer dominance duration for this particular slide. This result cannot be explained in terms of magnocellular deficit of dyslexia, which in terms of contrast sensitivity, was reported for static stimuli of less than 4c/d but not above (Martin and Lovegrove, 1984), and the reasons for this result is unclear.

Dyslexics with MIS exhibited a trend of longer MRD compared to controls (but shorter than the response durations of the dyslexia group) for slides C and D. Similarly, this may be attributed to the deficit of visual attention. However dyslexics with MIS were similar to the controls by showing more sensitivity to slide I but less

sensitivity to slide A (in terms of MRD). If it is considered that slide G, 1° (A/S) may be represented as a modified 2c/d stimulus and therefore it resembles slide A. Dyslexia with MIS and the control group responded to slide G in a similar way to slide A but the dyslexia group showed different response to slide G compared to their response to slide A. So it can be considered that the high level (cortical) processing for 1° (both 2c/d and 4c/d) in MIS dyslexic group may be 'normal', based on the present control results. However, as no study has directly addressed the normal responses for the given rival stimuli, the aforementioned conclusion is equivocal.
For slide H, the 2.5 ° (WAS/SAW) rivalry stimulus, all the three groups behaved significantly differently compared to other slides, where they showed longer MRD than CERD. Again, this may be attributed to the presence of the central 'A' acting as a 'fusion lock', as discussed in chapter 6. This is in line with the hypothesis that 'the inter-ocular differences in visual attributes that are predominantly processed in the parvocellular pathway will lead to rivalry, and differences in visual attributes that are predominantly processed in the magnocellular pathway tend to integrate' (Carlson and He, 2000). A trend of longer MRD was exhibited by dyslexic followed by MIS dyslexic groups compared to control. This may be attributed to reduced automatic focussing of visual attention in dyslexic subjects which related to deficit of the magnocellular system (Facoetti et al., 2003; Skottun and Skoyles, 2006a; Boden and Giaschi, 2007). Another explanation is that it may be due, to some extent, to the equi-dominance interpreting the sensory visual inputs with visual confusion in the dyslexic subjects.

The other primary goal was to investigate the quality of equi-dominance in terms of stability of dominance (amount of switching) in dyslexia groups compared to controls. The results showed that dyslexic without MIS subjects exhibited the trend of most stable dominance while MIS dyslexic subject exhibited the most unstable responses. The only significant difference between the three groups was demonstrated in slide H (WAS/SAW stimuli) where the dyslexia group showed a very stable response (less switching) compared to the MIS group. This may be related to a delay in selection due to visual confusion between either presented stimuli image in one (dominant) hemisphere and the memory image in the other (non dominant) hemisphere which results in confusing the word sequence orientation or sequence (Orton, 1925). Excessive sensory input switching in MIS dyslexia group may be attributed to cortical hyperexcitability of their sensory visual system (Wilkins, 1995) which, perhaps, led to an unstable image. These results failed to support our hypothesis that dyslexia subjects, with or without MIS, possess increased equal sensory ocular dominance by showing more unstable response of dominance duration. Taken together, distinct conclusions are precluded due to the absence of studies that directly and empirically address the issue of equal sensory ocular dominance in dyslexia. Mixed findings from the investigation of equal sensory dominance in terms of MRD and stability of CERD analysis of the present results may undergo different stimuli conditions used in the experiment where specificity of rival stimulus is typically crucial to provide a conceivable explanation of possible faulty development of sensory visual pathways. However, it is widely known that the parvocellular system and magnocellular system process different visual properties in segregated manner (Livingstone and Hubel, 1987). Accordingly, in this study, the parvocellular visual system is dominanting the rivalry process (Carlson and He, 2000), processing the inter-ocular difference of stimulus attributes that are appropriate to this system including static stimuli occupying the central vision, and high contrast spatial pattern and shape discrimination, as in orientation and letter detection (Livingstone and Hubel, 1987). The rivalry stimuli used in the present study possess the aforementioned visual spatial characteristics that are all relevant to the parvocellular system functions, but they also contain low spatial frequencies which are processed in the magnocellular visual system (Livingstone and Hubel, 1987). Further, the magnocellular visual system may, simultaneously, take part by inducing fusion related to the background of contour rivalry (Creed, 1935). Consequently, it is necessary to develop more appropriate rivalry stimuli with parameters that directly and distinctly assess either sensory visual pathway, with the emphasis on the spatial characteristics that may reflect the magnocellular deficit found in dyslexia, such as contrast sensitivity for low spatial frequency (Martin and Lovegrove, 1984). In future work, we need to investigate this area more thoroughly and care must be taken in regards of number of subjects (more subjects may more adequately cover the wide variety of responses possible in such a study).

Chapter 8

Conclusions and future work

8.1 Summary of findings

This thesis has presented a series of studies that examine visual attributes of adults with dyslexia amongst the university student population. The initial literature review has described the prevalence, theories and factors thought to influence dyslexia such as gender and IQ. It is clear that dyslexia is a complex condition and to find correlates is not difficult, but to establish causes and therefore strategies for support is an on-going challenge. Dyslexia is a lifelong condition, and this thesis had at its core a desire to examine visual stress and effect of visual fatigue in adults with dyslexia as almost all the previous research on these areas is either on children or non-dyslexic populations.

In the university setting, adult learners who have dyslexia and/or MIS are supported well – they can be given extra time in written examinations or alternative forms of examinations, pastoral and computing support and coloured filters as necessary. Whilst extra time in written examinations is a frequent strategy, there seems to be an arbitrary amount given and no scientific evidence to demonstrate its effectiveness. This gives rise to the concern that if adult learners with dyslexia spend longer over written work, will their visual system (and therefore, potential to learn) benefit, or actually become fatigued? This question determined the main experiments in chapters 4 and 5. However, before this could be investigated it also became clear that even the subjective assessment of symptoms in adults with dyslexia was not validated, i.e. no universal approach to questionnaires was apparent. Chapters 2 and 3 presented the development and validation of a tool to assess visual stress in adults with dyslexia – a novel finding.

Ocular dominance is a factor referred to frequently in the published literature for dyslexia, but results are often conflicting. The remainder of this thesis utilised a new method of sensory ocular dominance testing, and applied it to different cohorts.

8.2 Conclusions

Many questions that can be applied to people with dyslexia exist in the published studies and educational texts, to evaluate visual stress or visual correlates. There is frequent overlap of questions but none of the questionnaires have been validated for this population. This study evaluated the responses to a large collection of questions in a single questionnaire that was completed by age and gender matched groups of adults with and without dyslexia. Rasch analysis was carried out on the response data to identify the questions that might be most useful for dyslexia. For example, questions about words fading or disappearing seemed to be selective for the most severe visual stress scores.
Choosing the right questions was just the first step in developing a useful tool. In chapter 3, this new questionnaire was applied to the target population, adults with dyslexia. One question was rejected in the validation process, resulting in a 15-item questionnaire that was valid and reliable. This is a new finding and it is hoped that this will become the tool of choice in future work concerning adults with dyslexia and their visual symptoms. This chapter also established the possible factors that can influence scores of visual stress such as gender and pattern glare. The short nature of the CVSQAD has the added advantages of saving time during the examination of the dyslexic population.

Chapter 4 examined the visual attributes of adults with dyslexia with and without MIS compared to control subjects. This was carried out in order to gather baseline information before the subjects were visually fatigued. Of note was the finding that adults with 'dyslexia' tended to have exo-disparity compared to those with 'dyslexia and MIS'. Another novel finding was that instability of binocular vision was significantly more likely to occur in adults with dyslexia compared to controls – the first time this has been noted in adults. Amplitudes of accommodation and near point of convergence have frequently been reported to be deficient in children, but here for the first time is a similar finding in adults with dyslexia.

Chapter 5 presented the results of visual fatigue in the cohorts. This study has shown that visual fatigue has a different effect on certain aspects of binocular vision functions depending on whether subjects have dyslexia or dyslexia with MIS. An increase of near point of convergence appears to be an indicator of visual stress in all subjects, whilst dyslexic subjects with MIS showed a decrease in their amplitudes of accommodation and associated phorias at near – all important features for clinicians to be aware of when managing such patients. However some variables did not show the significant difference, this may be due to small sample size in dyslexia and dyslexia with MIS groups where power calculation showed that sample size in dyslexia and dyslexia with MIS should be 44 and 52 respectively to achieve 80 % power with a p value of 0.05, while the controle group showed the right sample size (33) (using G*Power 3.1.2 softwear programme).

Ocular dominance is always of interest in dyslexia, but the Dunlop test has received much criticism. Chapter 6 reports the development of a new methodology on the synoptophore for assessing sensory ocular dominance in a quantitative way. The relative effects of field size, spatial frequency and letters/words were explored. It was apparent that choice of target was influential in any judgement about dominance. A modified version of this method was then applied to the target cohorts – adults with dyslexia and controls. Crossed eye/hand dominance featured significantly in the dyslexic groups, with also a tendency towards more instability in sensory ocular dominance.

8.3 Suggested future work

In view of the findings of this thesis, the following experiments are proposed for future work:

a) Investigate the effect of colured filters on visually induced fatigue.

The present thesis demonstrated the effect of visually induced fatigue on visual discomfort levels in a dyslexic population compared to control. Further study is necessary to investigate the effect of the coloured filters upon the visual discomfort in dyslexic population.

b) Investigate the repeatability of binocular rivalry using the same rivalry stimuli in the present thesis.
c) Investigate how the university students use the extra time in the examination. This can be approached by a questionnaire survey.

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Appendices

Appendix I: Developing the Cardiff Visual Stress Questionnaire for Adults with Dyslexia (CVSQAD)

1.1 Example of visual stress questionnaire, (taken from Irlen, 1991)

Self –test

Do you or someone you know have difficulty reading?
Take the following test:

	Yes	No
Do you skip words or lines when reading?	___	___
Do you reread lines?	___	___
Do you lose your place?	___	___
Are you easily distracted when reading?	___	___
Do you need to take breaks often?	___	___
Do you find it harder to read the longer you read?	___	___
Do you get headaches when you read?	___	___
Do your eyes get red and watery?	___	___
Does reading make you tired?	___	___
Do you blink or squint?	___	___
Do you prefer to read in dim light?	___	___
Do you read close to the page?	___	___
Do you use your finger or other markers?	___	___
Do you get restless, active, or fidgety when reading?	___	___

If you answered yes to three or more of theses questions, then you might be experiencing the effects of a perception problem called Scotopic Sensitivity Syndrome, for the first time, there is a simple methods that can help people overcome this problem quickly and easily. Educators are encouraged to consider a training course to become a Certified Irlen Screener.

1.2 Example of visual stress questionnaire, (taken from Conlon et al., 1999)

Items and Original Response Scale Used on the Visual Discomfort Scale

Response categories: Visual Discomfort Scale
0 = Event never occurs
1 = Occasionally. A couple of times a year
2 = Often. Every few weeks
3 = Almost always

|Never|..............................|Occasionally|..............................|Often|..............................|Almost always|

Items used

(1) Do your eyes every feel watery, red, sore, strained, tired, dry, gritty, or do you rub them a lot, when viewing a striped pattern?
(2) Do your eyes every feel watery, red, sore, strained, tired, dry or gritty, after you have been reading a newspaper or magazine with clear print?
(3) Do your eyes every feel watery, red, sore, strained, tired, dry or gritty, when working under fluorescent lights?
(4) How often do you get a headache when working under fluorescent light?
(5) Do you ever get a headache from reading a newspaper or magazine with clear print.
(6) When reading, do you ever unintentionally reread the same words in a line of text?
(7) Do you have to use a pencil or your finger to keep from losing your place when reading a page of text in a novel or magazine?
(8) When reading do you ever unintentionally reread the same line?
(9) When reading do you ever have to squint to keep the words on a page of clear text from going blurry or out of focus?
(10) When reading, do the words on a page of clear text ever appear to fade into the background then reappear?
(11) Do the letters on a page of clear text ever go blurry when you are reading?
(12) Do the letters on a page ever appear as a double image when you are reading?
(13) When reading, do the words on the page ever begin to move or float?
(14) When reading, do you ever have difficulty keeping the words on the page of clear text in focus?
(15) When you are reading a page that consists of black print on white letters, does the background ever appear to overtake the letters making them hard to read?
(16) When reading black print on a white background, do you ever have to move the page around, or continually blink to avoid glare which seems to come from the background?
(17) Do you ever have difficulty seeing more than one or two words on a line in focus?
(18) Do you ever have difficulty reading the words on a page because they begin to flicker or shimmer?
(19) When reading under fluorescent lights or in bright sunlight, does the glare from bright white glossy pages cause you to continually move the page around so that you can see the words clearly?
(20) Do you have to move your eyes around the page, or continually blink or rub your eyes to keep the text easy to see when you are reading?
(21) Does the white background behind the text ever appear to move, flicker, or shimmer making the letters hard to read?
(22) When reading, do the words or letters in the words ever appear to spread apart?
(23) As a result of any of the above difficulties, do you find reading a slow task?

1.3 Example of visual stress questionnaire, (taken from Evans et al., 1996b)

No.	*Summary of question*
1	Have you had an eye examination with an optometrist (optician)?
2	Were you given glasses at your last eye examination?
3	Has the child ever had a turning eye, eye operation, eye exercises or patching?
4	Was the birth premature/overdue or complicated or were there any severe illnesses/ operations in the first year?
5	Has your child ever suffered from epilepsy, or any fits or convulsions?
6	Is your child in good physical condition and healthy?
7	Is your child taking any medication?
8	Is the distance vision normally clear?
9	Does distance vision ever blur?
10	Are reading and writing in a book normally clear?
11	Do words in a book ever go blurred?
12	Do words in a book ever jump around?
13	Do words in a book ever go smaller/bigger?
14	Do words in a book ever fade or disappear?
15	Do words in a book ever get faint colours around them?
16	Do you ever experience double vision (see two things when there is only one)?
Have you or anyone else ever noted the following with respect to your child?	
17	Holding reading or materials unusually close or far away?
18	Closing or covering one eye?
19	Frequent eye rubbing?
20	Excessive blinking?
21	Tilting head when reading or writing?
22	Moves head when reading?
23	Uses finger as marker?
24	Confuses letters or words?
25	Reverses letters or words?
26	Skips, re-reads or omits words or lines?
27	Reads slowly?
28	Tires easily/short attention span?
29	Light sensitive?
30	Did parents or any other children in the family have learning problems?
31	Did parents or any other children in the family have a turning eye, patching or eye exercises?
32	Did parents or any of the other children in the family ever have migraine headaches?
33	Are the parents or any of the other children in the family colour-blind?
34	Did any relatives have epilepsy?

1.4 Example of visual stress questionnaire, (taken from Evans and Joseph, 2002)

Questionnaire

First name---------------------------------------Last name---------------------------------------Course---------------------------------------
Born---------------------------------------Date tested---------------------------------------First language---------------------------------------
Tick if had any specific difficulties at school with the following:
Reading ☐ Spelling ☐ Writing ☐ Maths ☐ Other---------------------------------------
Last eye examination---------------------------------------

Has anyone ever noticed your eye(s) turning inwards or outwards?		Yes ☐	No ☐
Have you ever received eye exercises or patching?		Yes ☐	No ☐
Visual Symptoms (with any Rx usually used for reading)			
When you are reading or writing in a book, is it normally clear?		Yes ☐	No ☐
Do words in a book ever:	Go blurred?	Yes ☐	No ☐
	Jump around?	Yes ☐	No ☐
	Go smaller/bigger?	Yes ☐	No ☐
	Fade or disappear?	Yes ☐	No ☐
Do you ever experience double vision when reading (see two things when there is only one)?		Yes ☐	No ☐

If you do experience double vision when reading, how often is it:
hardly ever/rarely, only if reading for a very long time/when reading for a moderate time/often, if reading for a fairly short time

Do you ever experience sore or tired eyes when reading? Yes ☐ No ☐

If you do suffer from sore or tired eyes, how often:
hardly ever/rarely, only if reading for a very long time/when reading for a moderate time/often, if reading for a fairly short time

Have you or anyone else ever noticed that you do any of the following?

	Yes	No	If so, please give details
Holds reading unusually far away:	☐	☐	---------------------------------------
Closes or covers one eye:	☐	☐	---------------------------------------
Frequently rubs eye(s):	☐	☐	---------------------------------------
Blinks excessively:	☐	☐	---------------------------------------
Skips, re-reads or omits words or lines:	☐	☐	---------------------------------------
Reads slowly:	☐	☐	---------------------------------------
Light sensitive:	☐	☐	---------------------------------------

Approximately how many times have you had a headache (migraine or otherwise) in the last 3 months?
For some people headaches can be triggered by, or tend to follow, near visual tasks such as reading, sewing, computer work, etc. To what exter do you think that your headaches are triggered by reading:
not at all/rarely/occasionally/quite often/very often

1.5 Example of visual stress questionnaire, (taken from Grisham et al., 1993)

School of Optometry
University of California
Berkeley, CA 94720

Symptom Survey

Name__________________________ **Phone**__________ **Date**_____

Address____________________________________ **ZIP**__________

Age_____ **Sex**______ **Major**______________ **Years of College**_____

Please indicate which of the following symptoms you are presently experiencing related to your present activity. Rate the intensity of the symptoms by circling the appropriate number in each row.

	None	Mild		Moderate			Severe	
Tired eyes	0	1	2	3	4	5	6	7
General fatigue	0	1	2	3	4	5	6	7
Sore eyes (eye pain)	0	1	2	3	4	5	6	7
Itchy eyes	0	1	2	3	4	5	6	7
Dry eyes	0	1	2	3	4	5	6	7
Watery eyes	0	1	2	3	4	5	6	7
Blurred distance vision	0	1	2	3	4	5	6	7
Blurred near vision	0	1	2	3	4	5	6	7
Fluctuating vision (in & out of focus)	0	1	2	3	4	5	6	7
Double vision	0	1	2	3	4	5	6	7
Headache	0	1	2	3	4	5	6	7
Sleepiness	0	1	2	3	4	5	6	7
Eye strain	0	1	2	3	4	5	6	7
Dizziness/nausea	0	1	2	3	4	5	6	7
Squinting	0	1	2	3	4	5	6	7
Sensitive to light	0	1	2	3	4	5	6	7

	None	Mild		Moderate				Severe
When reading, do you:								
see print move-jump, pulsate, or float.	0	1	2	3	4	5	6	7
lose your place.	0	1	2	3	4	5	6	7
skips letters, words or phrases.	0	1	2	3	4	5	6	7
reread the same line.	0	1	2	3	4	5	6	7
close one eye or tilt your head to one side.	0	1	2	3	4	5	6	7
shade the page.	0	1	2	3	4	5	6	7
blink alot.	0	1	2	3	4	5	6	7
see flashes of light or colored spots on the page.	0	1	2	3	4	5	6	7

1.6 This questionnaire is designed to identify symptoms of visual stress when reading

For each question, if given a choice, please circle your answer.

There are no right or wrong answers. Do not spend too long on any one question. Your immediate answer will usually be more accurate than a long thought out response.

ABOUT YOU

1) What is your age? ....

2) What is your gender? Male / Female

3) Do you wear glasses (for sight correction)? Yes No

   i. All of the time *or* some of the time

   ii. For reading *or* distance *or* both

4) Do you ever wear contact lenses (for sight correction)? Yes No

5) Are you right or left handed (the hand used in writing)? R or L

6) Have you visited an optometrist within the last two years? Yes No

7) Have you ever been told you have a 'lazy eye'? Yes No

8) Have you ever had to wear a patch over one eye? Yes No

9) Have you ever been told to use 'eye exercises'? Yes No

10) Have you ever had coloured overlays or tinted spectacles prescribed for you to help you in reading, etc.? Yes No

11) Have you been diagnosed with dyslexia? Yes No

12) Have you ever been told you are particularly sensitive to light? Yes No

13) Have you ever been told you are sensitive to 'pattern glare' Yes No

ABOUT VISUAL SYMPTOMS

14) Do you have any particular difficulties with reading?

Never						Always
0	1	2	3	4	5	6

15) Do you have any difficulties with spelling?

Never						Always
0	1	2	3	4	5	6

16) Do you misread numbers or copying them incorrectly?

Never						Always
0	1	2	3	4	5	6

17) Do you suffer with severe headache or migraine?

Never						Always
0	1	2	3	4	5	6

18) Would you say that your headaches are associated with reading or studying?

Never						Always
0	1	2	3	4	5	6

19) How often do you get tired eyes when reading for a SHORT time (e.g. 30 minutes)?

Never						Always
0	1	2	3	4	5	6

20) How often do you get tired eyes when reading for a LONG time (e.g. 3 hours)?

Never						Always
0	1	2	3	4	5	6

21) How often do you get double vision when you read for a SHORT time?

Never						Always
0	1	2	3	4	5	6

22) How often do you get double vision when you read for a LONG time?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

23) Have you ever been told that your handwriting is difficult to read?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

24) **When you read,** do the words ever go blurred?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

25) ....Fade or disappear?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

26) ....Jump around or move?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

27) ....Get smaller or bigger?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

28) ....Get faint colour around?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

29) **When copying written work from a whiteboard (or similar)**, do the words ever go blurred?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

30) ....Fade or disappear?

<u>**Never**</u>						Always
0	1	2	3	4	5	6

31) ....Jump around or move?

Never						Always
0	1	2	3	4	5	6

32) ....Get smaller or bigger?

Never						Always
0	1	2	3	4	5	6

33) .... Get faint colour around?

Never						Always
0	1	2	3	4	5	6

34) Do you have difficulty in changing your focus from reading material on the board (at distance) to in a book (at near) and vice versa?

Never						Always
0	1	2	3	4	5	6

35) <u>During reading or studying</u>, have you or any one else ever noticed that you do any of the following?

A-Skip or omit words or lines?

Never						Always
0	1	2	3	4	5	6

B- Re-read words or lines?

Never						Always
0	1	2	3	4	5	6

C- Confuses letters or words, e.g. orientation or progression of written material?

Never						Always
0	1	2	3	4	5	6

D- Reverse letters (b-d, p-q) or words (saw-was)?

Never						Always
0	1	2	3	4	5	6

E- Use your finger as a marker?

Never						Always
0	1	2	3	4	5	6

F- Hold reading or materials unusually close or far away?

Never						Always
0	1	2	3	4	5	6

G- Read slowly?

Never						Always
0	1	2	3	4	5	6

H- Blink a lot?

Never						Always
0	1	2	3	4	5	6

I- Rub your eyes frequently?

Never						Always
0	1	2	3	4	5	6

J- Cover one eye?

Never						Always
0	1	2	3	4	5	6

K- Tilt your head when reading or writing?

Never						Always
0	1	2	3	4	5	6

36) Do you have problems tracking print as you read or copy?

Never						Always
0	1	2	3	4	5	6

37) Do you have any difficulties remembering what words look like, e.g. when you are copying information from the board or screen?

Never						Always
0	1	2	3	4	5	6

38) Do you do a lot of 'crossing out' when you write?

Never						Always
0	1	2	3	4	5	6

39) Do you use coloured overlays (coloured transparent plastic sheet) to help with reading, etc.?

Never						Always
0	1	2	3	4	5	6

40) Do you use tinted spectacles to help with reading, etc.?

Never						Always
0	1	2	3	4	5	6

41) Do you use coloured paper to help with reading, etc.?

Never						Always
0	1	2	3	4	5	6

42) Do you find coloured papers (rather than white) helpful when reading, etc.?

Never						Always
0	1	2	3	4	5	6

43) Have you felt an improvement in symptoms with coloured filters or papers?

Never						Always
0	1	2	3	4	5	6

1.7 Table shows the Rasch fitting statistics for the 40 items with 4 response categories

ENTRY NUMBER	RAW SCORE	COUNT	MEASURE	MODEL S.E.	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD	PTMEA CORR.	EXACT MATCH OBS%	EXACT MATCH EXP%	ITEM
37	16	78	2.22	.29	2.75	4.8	1.85	1.4	A .24	82.1	82.2	Q40
10	98	78	-1.01	.17	2.31	6.3	2.44	6.4	B .32	37.2	53.2	Q23
40	54	78	.33	.19	1.99	4.5	1.59	2.2	C .55	53.8	62.8	Q43
38	27	78	1.49	.23	1.67	2.8	.91	-.1	D .50	71.8	74.3	Q41
39	56	78	.26	.19	1.66	3.3	1.37	1.5	E .61	57.7	62.2	Q42
31	28	78	1.43	.23	1.57	2.4	1.42	1.1	F .46	66.7	73.5	Q35J
29	72	78	-.26	.17	.95	-.2	1.36	1.8	G .61	57.7	57.8	Q35H
32	75	78	-.35	.17	1.30	1.7	1.24	1.2	H .60	50.0	57.4	Q35K
27	53	78	.36	.19	1.27	1.5	1.16	.7	I .61	64.1	63.5	Q35F
36	35	78	1.08	.21	1.25	1.2	.80	-.5	J .62	69.2	69.3	Q39
34	81	78	-.53	.17	1.17	1.1	1.04	.3	K .73	55.1	56.3	Q37
25	62	78	.06	.18	1.12	.8	1.01	.1	L .67	62.8	60.4	Q35D
30	76	78	-.38	.17	.91	-.5	1.08	.5	M .63	48.7	57.3	Q35I
28	92	78	-.84	.17	1.08	.5	.97	-.1	N .74	55.1	53.5	Q35G
4	70	78	-.20	.18	.87	-.8	1.03	.2	O .60	60.3	58.5	Q17
9	65	78	-.04	.18	.99	.0	1.02	.2	P .65	57.7	59.5	Q22
5	70	76	-.21	.18	.87	-.7	.99	.0	Q .62	60.5	57.8	Q18
19	33	78	1.18	.22	.98	.0	.78	-.6	R .61	73.1	71.0	Q32
7	130	78	-1.88	.17	.96	-.2	.97	-.1	S .73	47.4	51.5	Q20
2	90	78	-.79	.17	.95	-.2	.88	-.7	T .75	59.0	53.5	Q15
17	36	78	1.04	.21	.95	-.2	.84	-.4	t .62	64.1	68.9	Q30
16	73	78	-.29	.17	.93	-.4	.94	-.2	s .68	60.3	57.6	Q29
14	37	78	.99	.21	.94	-.2	.66	-1.2	r .67	67.9	68.5	Q27
15	43	78	.74	.20	.93	-.3	.75	-.9	q .68	70.5	66.9	Q28
20	37	78	.99	.21	.91	-.4	.80	-.6	p .65	69.2	68.5	Q33
6	82	78	-.56	.17	.91	-.5	.89	-.6	o .67	62.8	56.1	Q19
13	60	78	.12	.18	.85	-.9	.70	-1.4	n .76	65.4	61.3	Q26
35	96	78	-.95	.17	.74	-1.8	.83	-1.1	m .72	44.9	53.5	Q38
26	81	78	-.53	.17	.82	-1.1	.78	-1.3	l .76	64.1	56.3	Q35E
18	49	78	.51	.19	.80	-1.1	.64	-1.6	k .74	66.7	65.0	Q31
11	80	78	-.50	.17	.76	-1.6	.80	-1.1	j .74	67.9	56.4	Q24
12	39	78	.91	.21	.77	-1.3	.72	-.9	i .66	71.8	67.9	Q25
21	67	78	-.10	.18	.74	-1.6	.77	-1.2	h .75	67.9	59.1	Q34
1	75	78	-.35	.17	.73	-1.8	.71	-1.7	g .78	64.1	57.4	Q14
3	92	78	-.84	.17	.70	-2.2	.73	-1.7	f .78	53.8	53.5	Q16
8	46	78	.62	.20	.71	-1.7	.68	-1.3	e .70	71.8	65.7	Q21
22	90	78	-.79	.17	.69	-2.2	.71	-1.9	d .79	60.3	53.5	Q35A
23	111	78	-1.36	.16	.59	-3.1	.65	-2.5	c .83	61.5	51.5	Q35B
33	92	78	-.84	.17	.58	-3.1	.60	-2.8	b .84	64.1	53.5	Q36
24	88	78	-.73	.17	.58	-3.1	.56	-3.1	a .85	64.1	54.2	Q35C
MEAN	66.4	77.9	.00	.19	1.06	.0	.97	-.3		61.8	60.8	
S.D.	25.2	.3	.87	.02	.46	2.1	.36	1.6		8.5	7.2	

Appendix II - Validation of Cardiff Visual Stress Questionnaire for Dyslexic adults (CVSQAD)

2.1 This questionnaire is designed to identify symptoms of visual stress when reading

For each question, if given a choice, please circle your answer.

There are no right or wrong answers. Do not spend too long on any one question. Your immediate answer will usually be more accurate than a long thought out response.

ABOUT YOU

43) What is your age? ....

44) What is your gender? Male / Female

45) Do you wear glasses (for sight correction)? Yes No

i. All of the time *or* some of the time

ii. For reading *or* distance *or* both

46) Do you ever wear contact lenses (for sight correction)? Yes No

47) Are you right or left handed (the hand used in writing)? R or L

48) Have you visited an optometrist within the last two years? Yes No

49) Have you ever been told you have a 'lazy eye'? Yes No

50) Have you ever had to wear a patch over one eye? Yes No

51) Have you ever been told to use 'eye exercises'? Yes No

52) Have you ever had coloured overlays prescribed for you to help you in reading, etc.? Yes No

53) Have you ever had coloured lenses prescribed
for you to help you in reading, etc.? Yes No

54) Have you been told or diagnosed with dyslexia? Yes No

55) Have you officially diagnosed and/or had a statement of being a dyslexic student? Yes No

56) Have you ever been told you are particularly sensitive to light? Yes No

57) Have you ever been told you are sensitive to 'pattern glare' ? Yes No

ABOUT VISUAL SYMPTOMS

58) Do you have any particular difficulties with reading?

Never			Always
0	1	2	3

59) Do you have any difficulties with spelling?

Never			Always
0	1	2	3

60) How often do you get tired eyes when reading for a LONG time (e.g. 3 hours)?

Never			Always
0	1	2	3

61) How often do you get double vision when you read for a SHORT time?

Never			Always
0	1	2	3

62) **When you read,** do the words ....Fade or disappear?

Never			Always
0	1	2	3

63) ....Jump around or move?

Never			Always
0	1	2	3

64) ....Get smaller or bigger?

Never			Always
0	1	2	3

65) ....Get faint colour around?

Never			Always
0	1	2	3

66) **When copying written work from a whiteboard (or similar)**, do the words ever go blurred?

Never			Always
0	1	2	3

67) ....Fade or disappear?

Never			Always
0	1	2	3

68) ....Get smaller or bigger?

Never			Always
0	1	2	3

69) .... Get faint colour around?

Never			Always
0	1	2	3

70) Do you have difficulty in changing your focus from reading material on the board (at distance) to in a book (at near) and vice versa?

Never			Always
0	1	2	3

71) <u>During reading or studying</u>, have you or any one else ever noticed that you do any of the following?

A-Skip or omit words or lines?

Never			Always
0	1	2	3

B- Use your finger as a marker?

Never			Always
0	1	2	3

72) Do you do a lot of 'crossing out' when you write?

Never			Always
0	1	2	3

2.2 Item fit statistics for the 16 items

ENTRY NUMBER	RAW SCORE	COUNT	MEASURE	MODEL S.E.	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD	PTMEA CORR.	EXACT MATCH OBS%	EXACT MATCH EXP%	ITEM
16	122	56	-1.57	.19	**1.55**	**2.6**	**1.90**	**3.4**	**A .37**	**41.1**	**53.8**	**Q30**
12	31	56	1.50	.22	1.18	.9	1.30	1.1	B .55	58.9	62.0	Q27
8	37	56	1.24	.20	1.21	1.1	1.22	.9	C .60	50.0	58.3	Q23
3	132	55	-2.07	.21	1.19	.9	.99	.0	D .58	60.0	59.9	Q18
5	41	56	1.08	.20	1.16	.9	1.04	.3	E .59	62.5	55.1	Q20
13	80	56	-.22	.17	1.16	.9	1.15	.9	F .57	39.3	46.8	Q28
2	128	56	-1.80	.20	.95	-.2	1.13	.6	G .46	55.4	56.8	Q17
4	56	56	.53	.18	1.08	.5	1.10	.5	H .54	50.0	49.5	Q19
11	28	56	1.65	.23	.96	-.1	.91	-.2	h .55	67.9	64.0	Q26
14	114	56	-1.29	.18	.96	-.2	.90	-.4	g .56	46.4	50.2	Q29A
6	73	56	-.01	.18	.92	-.4	.90	-.5	f .66	50.0	46.1	Q21
1	103	56	-.93	.18	.81	-1.1	.89	-.5	e .65	46.4	47.9	Q16
15	99	56	-.80	.18	.89	-.6	.83	-.9	d .73	39.3	46.4	Q29B
7	36	56	1.28	.21	.75	-1.3	.61	-1.7	c .74	62.5	58.6	Q22
9	76	56	-.10	.17	.66	-2.2	.73	-1.6	b .66	58.9	46.5	Q24
10	31	56	1.50	.22	.58	-2.2	.52	-2.1	a .68	71.4	62.0	Q25
MEAN	74.2	55.9	.00	.20	1.00	.0	1.01	.0		53.8	54.0	
S.D.	36.9	.2	1.25	.02	.24	1.2	.31	1.3		9.6	6.2	

Appendix III- The effect of induced visual fatigue on binocular vision functions in adults with dyslexia

3.1 A sample from the reading material used to induce visual fatigue

The Dolphin

A king and queen had several children, but loved them only if they were good and beautiful. One, Alidor, being ugly, in time left his parents secretly. More distressed over their reputation than his fate, they sent after him, but he had chosen his path with care and vanished. He met a young man in service to the King of the Woods and heard of his beautiful daughter Livorette, and so resolved to go there. Once there, Livorette and all her ladies laughed at his ugliness. The queen, however, drew him aside and inquired after him. He soon became a favorite at the court because of his intelligence and courtesy, but Livorette still laughed at him, and being madly in love with her, Alidor soon became melancholy. Trying to distract himself, he fished, but he caught nothing, and Livorette mocked him for it. One day, he caught a dolphin. The dolphin asked him to put it back, promising to help him, and reasoned with him about the princess. When he freed it, he despaired, but it came back and gave him an abundance of fish. It then discussed how to win Livorette, saying it would be necessary to deceive her. He brought back the fish, and then turned himself into a canary. In this form, he wooed the princess but would not speak to anyone else.After a night, he persuaded the princess to take him to her parents, where he claimed to be a king of an island. They agreed. Alidor visited the court in his own shape, and the queen told him all about the match. That night, after staying in the princess's bedroom until she slept, he went to the seashore and sat on a rock. Grognette the fairy, a dwarf, came out and cursed him for sitting o n her rock, saying she would make him suffer.Meanwhile, a prince sent ambassadors to woo Livorette. She seemed disposed to accept them. However, she grew ill, and a doctor, hidden from knowledge of her rank, said she was going to have a child. Soon after, she had a son. The king decided to have them both killed; the queen managed to have it deferred. Alidor grew mad with the despair, and the dolphin no longer appeared.When the baby was four, the king had every man give him a gift. When Alidor's made the baby reach for him, the king said he was the father and had Alidor, the princess, and the son thrown into the sea in a barrel. There Alidor, though still mad, summoned the dolphin, and Livorette had him order the dolphin to obey her. Then she had the dolphin conjure them out of the barrell to a magnificient island, and explain how she came to have a child, and then restore Alidor's sanity and make him handsome. They landed on the island, and she forgave Alidor his deceit. The dolphin had them made king and que en of it.However, Grognette had forbidden her to consider Alidor her husband without her parents' consent.The queen had learned what the king had ordered for Livorette and reproached him. At last he confessed that he had had no peace since then. They consu lted a fairy, who sent them to the dolphin's island. They were shipwrecked, but saved alive. They could not recognize Alidor, or their daughter, or the child, who made them welcome, but Livorette revealed the truth. Their marriage was concluded.

The Pig King

A king and his queen had no children after seven years. One day, the queen slept in the garden, and three fairies saw her. One gave her a son and that no man could harm her; the second, that no one could offend her, and the son should have every virtue; the third, that she would be wise, but the son should be a pig until he had married three times.Soon after, the queen had a son in the form of a pig. The king at first thought to throw the pig into the sea, but decided against it, and had him raised as a child. He learned to talk, but wallowed in mud whenever he could. One day, he told his mother that he wished to marry and persisted until the queen persuaded a poor woman to give her oldest daughter to him. The girl was persuaded by her mother but resolved to kill her bridegroom their wedding night. In the night, he stabbed her with his hooves, and she died. He then asked to marry her sister, and she was persuaded, but she died as her sister had. Finally, he married the third. The third sister behaved politely to him, and returned his caresses. Soon after their marriage, the prince revealed a secret to her: he took off his pigskin and became a handsome young man in her bed. Every morning, he put the skin back on, but she was glad to have a man as her husband. Soon, she gave birth to a child, a son in human form. But finally, the princess revealed the secret to the king and queen and told them to come to the bedchamber at night. They did, and saw their son. The king had the pigskin, lying to one side, torn to pieces, and then abdicated and had his

3.2 Descriptive and comparative statistics for pre-post induced fatigue data (BV measures) differences within and between the three groups

Variable	Group	N	Mean (SD)	P	Mean difference	Post-Hoc
Stereo-acuity	1. Dyslexia	29	0.000(0.00)	0.45	1-2= -1.481	0.46
	2. Dyslexia + MIS	27	1.48(8.18)		1-3= -.303	0.96
	3. Control	33	0.30(1.74)		2-3= 1.178	0.59
Associated phoria (near)	1. Dyslexia	29	-0.344(1.47)	0.09	1-2= .581	0.34
	2. Dyslexia + MIS	27	-0.93 (2.18)		1-3= -.299	0.73
	3. Control	33	-0.05(0.77)		2-3= -.880	0.08
Associated phoria (distance)	1. Dyslexia	29	-0.03(0.64)	0.22	1-2= .113	0.91
	2. Dyslexia + MIS	27	-0.15(0.99)		1-3= -.337	0.42
	3. Control	33	0.30(1.33)		2-3= -.451	0.23
Dissociated phoria (near)	1. Dyslexia	29	-0.12(1.92)	0.52	1-2= .175	0.93
	2. Dyslexia + MIS	27	-0.29(1.96)		1-3= -.332	0.74
	3. Control	33	0.21(1.39)		2-3= -.508	0.51
Dissociated phoria (distance)	1. Dyslexia	29	0.07(0.86)	0.91	1-2= .013	0.99
	2. Dyslexia + MIS	27	0.06(1.07)		1-3= -.112	0.93
	3. Control	33	0.18(1.65)		2-3= -.126	0.92
Amplitude of accommodation (RE)	1. Dyslexia	29	0.01(1.71)	0.88	1-2= .091	0.96
	2. Dyslexia + MIS	27	-0.08(0.96)		1-3= .160	0.87
	3. Control	33	-0.15(0.99)		2-3= .068	0.98
Amplitude of accommodation (LE)	1. Dyslexia	29	-0.19(1.85)	0.88	1-2= -.022	0.99
	2. Dyslexia + MIS	27	-0.17(1.08)		1-3= .136	0.92
	3. Control	33	-0.33 (0.96)		2-3= .159	0.89
Amplitude of accommodation (BE)	1. Dyslexia	29	-0.03(1.73)	0.22	1-2= .603	0.19
	2. Dyslexia + MIS	27	-0.63(0.96)		1-3= .307	0.62
	3. Control	33	-0.33(1.07)		2-3= -.296	0.65
Near point of convergence	1. Dyslexia	29	1.55(2.95)	0.59	1-2= -.466	0.76
	2. Dyslexia + MIS	27	2.02 (2.99)		1-3= .172	0.96
	3. Control	33	1.38(1.24)		2-3= .639	0.58
(BO) Vergence reserves (break)	1. Dyslexia	29	-2.69(15.54)	0.76	1-2= -1.393	0.90
	2. Dyslexia + MIS	27	-1.29(10.93)		1-3= -2.265	0.74
	3. Control	33	-0.42 (8.74)		2-3= -.872	0.96
(BO) Vergence reserves (recovery)	1. Dyslexia	29	-1.72(12.10)	0.54	1-2= -2.872	0.51
	2. Dyslexia + MIS	27	1.15(8.18)		1-3= -1.330	0.85
	3. Control	33	-0.39 (8.06)		2-3= 1.542	0.81
(BI) Vergence reserves (break)	1. Dyslexia	29	0.86 (5.38)	0.37	1-2= 1.973	0.39
	2. Dyslexia + MIS	27	-1.11 (7.45)		1-3= 1.680	0.48
	3. Control	33	-0.82(3.97)		2-3= -.292	0.98
(BI) Vergence reserves (recovery)	1. Dyslexia	29	0.28(4.17)	0.79	1-2= .757	0.81
	2. Dyslexia + MIS	27	-0.48(5.32)		1-3= .669	0.84
	3. Control	33	-0.39(4.37)		2-3= -.087	0.99
Vergence amplitude (break)	1. Dyslexia	29	-1.83 (16.38)	0.94	1-2= .579	0.99
	2. Dyslexia + MIS	27	-2.41 (13.27)		1-3= -.585	0.98
	3. Control	33	-1.24(9.32)		2-3= -1.164	0.94
Vergence amplitude	1. Dyslexia	29	-1.45(13.01)	0.76	1-2= -2.114	0.75
	2. Dyslexia + MIS	27	0.67(10.46)		1-3= -.660	0.97

(recovery)	**3. Control**	33	-0.79 (8.99)		2-3= 1.454	0.86
Accommodation facility	**1. Dyslexia**	29	0.89(3.08)	0.82	1-2= .396	0.86
	2. Dyslexia + MIS	27	0.50(3.19)		1-3= .426	0.83
	3. Control	33	0.47(2.36)		2-3= .030	0.99
Vergence facility	**1. Dyslexia**	29	1.21 (2.51)	0.94	1-2= .040	0.99
	2. Dyslexia + MIS	27	1.17 (4.21)		1-3= .282	0.94
	3. Control	33	0.92(3.10)		2-3= .242	0.96

Appendix IV- Ethical approvals

SCHOOL OF OPTOMETRY AND VISION SCIENCES

HUMAN SCIENCE ETHICAL COMMITTEE

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Project Number: 1244

Project title: The Assessment of Symptoms of Visual Stress when reading – A questionnaire

Lead investigators: Mrs Mana Alazazia, Dr Christine Purslow, Prof. Rachel North
Date:

With reference to the above application, I am pleased to confirm that approval has been granted.

Please inform the Research Ethics Committee immediately of any changes to the protocol, changes to personnel involved, or of any unforeseen circumstances arising from the study.

Signed:

Date: 24/11/07

SCHOOL OF OPTOMETRY AND VISION SCIENCES

HUMAN SCIENCE ETHICAL COMMITTEE

Project Number: 1277

Project title: The effect of induced visual fatigue on the severity of the visual stress symptoms and binocular visual function in dyslexic and normal student populations.

Lead investigators:

Date: 15th January 09

With reference to the above application, I am pleased to confirm that approval has been granted.

Please inform the Research Ethics Committee immediately of any changes to the protocol, changes to personnel involved, or of any unforeseen circumstances arising from the study.

Signed:

J.M. Woodhouse,
Chairman

Approval form